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Composites - Design Manual

J A Quinn

3rd Edition

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Third Edition

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Composites - Design Manual

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Preface

‘Composites - Design Manual’ follows the theme of the previous ‘Design Data - Fibreglass Composites’ which has been widely used throughout the composites industry.

The essential aspect of the book is practical information for the Engineer, Designer and Specifier to facilitate the design and procurement of GRP, CFRP and ARP composites. It goes into much greater depth than the previous book and includes Carbon and Aramid composites. It has many tables, figures and examples to make life easier for those involved with the practicalities of composites.

The book doesn’t attempt to be academic many of the equations could be derived when needed by the engineer but that would time consuming and open to error. Hence the book collects together all those items of information, data and equations that are needed on a day to day basis. The specifier of composites is also catered for as the book allows an increased understanding of what is possible and sensible, thus avoiding the specification of a property or shape which may be uneconomic. Laminate analysis is specifically excluded as it would require a book to itself and is well covered in several very good texts. Nevertheless the user of laminate analysis will find this book a powerful aid to the design process.

It is intended to regularly update the book in order maintain the relevance of the information. We would gratefully accept comments and suggestions about the content. Similarly, relevant contributions, particularly pertinent design data, will be seriously considered and of course acknowledged.

The 2nd metric edition addresses the very kind comments of users of the 1st edition. Sections have been extended and clarified where appropriate together with an extensive revision throughout which includes a further chapter on the economic aspects of composites materials and their manufacture.

The third edition has been significantly enhanced with numerous additions and changes. Also the opportunity has been taken to incorporate the use of imperial units (Lb, ft, inches etc), while retaining the metric units. This may appear to be a retrograde step to those who have struggled to go metric over the last few decades. However it is simply a practical response to the way the World is. The largest market for composites, the USA, is heavily involved with imperial units and is likely to stay that way for decades to come. This is in spite of the extensive use of metric units by the scientific community. Hence most examples are worked through with both sets of units.

Thus this edition supersedes the ‘US edition’ of 1996 which was produced specifically for the North American market.

1 Materials

In general terms a composite is simply a mixture of two or more materials which has enhanced properties over the individual materials. We are interested specifically in polymer composites which are generally reinforced with fibre. The aim is to produce a material which has higher strength and or stiffness than the original polymer.

All Plastics are Polymers

There are two types of polymers–

- Thermoplastic polymers - melt when heated
- Thermoset polymers - don't melt when heated.

The major constituents of Composites are the reinforcement fibre - in any one form or a combination of several forms - and the matrix. The latter is usually a thermosetting polymer known as the resin, such as polyester or epoxide, which has been catalysed and accelerated by adding chemicals or by applying heat. There are many other materials which can be added to the mix to enhance or reduce a particular property, but they are of less significance in terms of both effect on cost and effect on properties. Prudent selection of a combination of fibre and resin allows access to a family of materials which have an immense range of properties. Although there are other types of fibre occasionally used, this document is concerned generally with the three types of fibre which dominate the field of composites: glass, carbon and aramid.

Resin Options.

The family of polymer composites splits into those which use thermosetting resins and those which use thermoplastic. The thermosets represent most of the current usage but the thermo-plastics composites are becoming increasingly more

important. This document is concerned only with the thermoset composites.

The thermoset resins used in composites are isotropic materials which allow load transfer between the fibres. But there are several other duties. The matrix protects notch sensitive fibres from abrasion and it forms a protective barrier between the fibres and the environment thus preventing attack from moisture, chemicals and oxidation. It also plays an important role in providing shear, transverse tensile and compression properties. The thermo-mechanical performance of the composite is also governed by the matrix performance. Hence resins could be classified by any of these characteristics, whichever is appropriate to the circumstances.

Polyester Resins

The most commonly used resin type is polyester. Polyester resins are versatile, they have good mechanical and physical properties and they are the most economic option for the majority of applications. They are available in a multiplicity of variants specially formulated to best achieve the particular set of characteristics required. The required characteristics of the resin system are very diverse. The performance of the composite is of primary concern but the resin system must also have very good moulding characteristics to meet the demands of the particular moulding process employed. The versatility of polyesters is very well suited to these requirements and is generally the first option to be considered. If polyester resin can meet the technical requirements then it is generally the most economic choice.

In order to provide the designer and specifier with pragmatic information, product information has been provided by Cray Valley Ltd. The following pages give details of their resins and gel coat products.

The thermosets which are used as the matrix resins in composites are:

- **ORTHOPHTHALIC POLYESTER** (General purpose, undemanding applications)
- **DCPD** (General purpose, undemanding applications, low viscosity, low emissions, low shrink)
- **ISOPHTHALIC POLYESTER** (General purpose, improved chemical and mechanical performance)
- **ISOPHTHALIC NPG** (Improved chemical performance)
- **URETHANE METHACRYLATE** (General purpose, high strain to failure, low smoke and toxicity)
- **EPOXY VINYL ESTER** (chemical resistance, high strain to failure)
- **EPOXY** (High mechanical performance)
- **PHENOLIC** (Excellent fire resistance, low smoke)

and also less commonly used are:

FURANE, SYANATE ESTER, HET ACID, BISPENOL A, BISMALEIMIDE, POLYIMIDE

CRAY VALLEY

The following pages cover information on polyester resin, gel coat and top coat products from Cray Valley. The products listed represent the core range, but alternative variants may be available on request. Physical and mechanical properties detailed are indicative, full specifications are included with individual product data sheets.

Data sheets detail intended use areas, conditions of use and shelf life. Further details are available from Cray Valley Applications manual or Cray Valley Technical Service. Materials hazards and recommended storage and handling precautions are comprehensively detailed in individual product safety data sheets.

Fig 1.1 GENERAL PURPOSE GRADE POLYESTER. HAND OR SPRAY LAY UP.

		Physical and Chemical Properties								Mechanical Properties of Cast, Non-Reinforced Resin						
		Internal test methods				Gelation tests				Flexural Strength	Flexural Modulus	Tensile Strength	Elong'n at Break	HDT		
		Grades	SVT1	SVT2		Method	Gel time	Cure time	Peak Exotherm	ISO 178	ISO 178	ISO 527	ISO 527	ISO 75		
			Viscosity	5rpm / 50rpm	Monomer					MPa	GPa	MPa	%	°C		
GENERAL PURPOSE GRADE POLYESTER. HAND OR SPRAY LAY UP.														Comments		
NORSODYNE ®	General Purpose	ENCORE 5	2.5	8 / 4	42	SGT8	20.5	30	165	86	4.7	50	2.5	75	Orthophthalic, White pigmented, low reactivity, low styrene emission.	
		ENCORE 12	2.7	18 / 6	42	SGT8	20.5	27.5	145	86	4.7	50	2.5	75	Orthophthalic, White pigmented, low reactivity, low styrene emission.	
		ENCORE 13	2.7	18 / 6	42	SGT8	20.5	27.5	145	86	4.7	50	2.5	75	Orthophthalic, Low reactivity, Low styrene emission, Rapid cure. Requires ≥1.5% MEKP(50%).	
		ENCORE 20	2.5	15 / 5	43	SGT8	11	26	135	78	3.9	56	2.6	62	Lloyd's approved, Orthophalic, Low styrene emission, 1 - 4 mm laminate thickness.	
		ENCORE 21	2.5	15 / 5	42	SGT8	11	26	140	78	3.9	56	2.6	62	Lloyd's approved, Orthophalic, White pigmented, Low styrene emission, 1 - 4 mm laminate thickness.	
		ENCORE 30	2.5	15 / 5	44	SGT8	18	35	140	78	3.9	56	2.6	62	Lloyd's approved, Orthophalic, Low styrene emission, 5 - 10 mm laminate thickness.	
		ENCORE 31	2.5	15.5 / 5	42	SGT8	18	38.5	140	78	3.9	56	2.6	62	Lloyd's approved, Orthophalic, White pigmented, Low styrene emission, 5 - 10 mm laminate thickness.	
		ENCORE 40	2.3	13 / 5.5	43	SGT8	19	35	140	78	3.9	56	2.6	62	Lloyd's approved, Orthophalic, White pigmented, Low styrene emission, 5 - 10 mm laminate thickness.	
		ENCORE 218	2.5	10 / 4.5	41	SGT1	13.5	22.5	155	86	4.7	50	2.5	75	Low reactivity, White pigmented, controlled cure, laminating resin.	
		QUICKCURE 30	2.5	15.5 / 5	43.5	SGT8	18	35	140	78	3.9	56	2.6	62	Lloyd's approved, Orthophalic, Low reactivity, Rapid cure, 5 - 10 mm laminate thickness.	
		QUICKCURE 30L	2.5	15.5 / 5	43.5	SGT8	18	35	140	78	3.9	56	2.6	62	Lloyd's approved, Orthophalic, Low reactivity, Rapid cure, Low styrene emission, 5 - 10 mm laminate.	
		QUICKCURE 31L	2.5	15.5 / 5	43.5	SGT8	18	33	140	78	3.9	56	2.6	62	Lloyd's approved, Low reactivity, Low styrene emission, White pigmented, 5 - 10 mm laminate thickness.	
ENYDYNE ®	General Purpose	ENYDYNE 20	2.55	15 / 5	41	SGT8	11	26	160	80	4	50	1.8	63	DCPD modified, medium reactivity, Low styrene emission, rapid cure, 1-4mm laminate thickness..	
		ENYDYNE 21	2.55	15 / 5	40	SGT8	11	26	155	80	4	50	1.8	63	DCPD modified, medium reactivity, Low styrene emission, rapid cure, 1-4mm laminate thickness. White pigmented.	
		ENYDYNE 30	2.55	15 / 5	41	SGT8	18	37	150	80	4	50	1.8	63	DCPD modified, medium reactivity, Low styrene emission, rapid cure, 5-10mm laminate thickness..	
		ENYDYNE 31	2.25	15 / 5	39	SGT8	18	35	152	80	4	50	1.8	63	DCPD modified, medium reactivity, Low styrene emission, rapid cure, 5-10mm laminate thickness. White pigmented.	
		ENYDYNE 50	2.55	15 / 5.5	43	SGT8	40	60	110	80	4	50	1.8	63	DCPD modified, medium reactivity, Low styrene emission, thick sections, long green time	
NORSODYNE ®	Sheeting Grades	6347007	2	N/A	41	SGT3	18	32	185	105	4.5	51	2.5	68	Translucent laminates, machine or hand laminating.	
		6367007	1.8	N/A	44	SGT10	12.5	23	185	102	4.6	51	2.5	68	Translucent laminates, continuous process.	
		E8821	3	N/A	39	SGT29	38	51	170	80	4	50	1.8	63	DCPD modified, good glass and filler wetout for continuous sheet manufacture.	

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Fig 1.2 SANITARY GRADES

	Physical and Chemical Properties									Mechanical Properties of Cast, Non-Reinforced Resin					
	Grades	Internal test methods			Gelation test				Flexural Strength	Flexural Modulus	Tensile Strength	Elong'n at Break	HDT		
		SVT1	SVT2		Method	Gel time	Cure time	Peak Exotherm							
		Viscosity	5rpm / 50rpm	Monomer											
		ISO 178	ISO 178	ISO 527					ISO 527	ISO 75					
		dPa.s	dPa.s	%					Number	Minutes	Minutes	°C	MPa	GPa	
SANITARY GRADES														Comments	
ENYDYNE ®	Cast Shower Trays	E8799	3.5	N/A	37	SGT1	5.5	12	165	75	3.6	55	1.6	63	DCPD modified, medium reactivity. General purpose
		E8938	1.5	N/A	35	SGT9	7.5	17.5	150	67	3.4	45	1.6	64	Low Shrinkage, Low Exotherm, controlled cure rate, High filler loading
		E8964	1.5	N/A	35	SGT9	12	25	155	67	3.4	45	1.6	64	Longer Gel time version of Enydyne E893
NORSODYNE ®	Cast Shower Trays														
		6343-103	3.5	N/A	40	SGT1	5.5	13	170	78	3.9	56	2.6	62	General purpose casting resin.
ENYDYNE ®	Acrylic Reinforcement	E9807	1.0	15/5	47.5	SGT13	6.25	13.5	192	75	3.5	44	1.8	62	DCPD modified, Medium reactivity, White pigmented, accelerated, cure controlled. Accepts high filler loading.
		E8966	4.75	25/8.5	27	SGT9	5.5	22.5	1.35	80	4.1	50	1.2	90	DCPD modified resin. Rapid laminate cure, good glass wet out, Filled

Fig 1.3 CHEMICAL RESISTANT AND FIRE RETARTANT GRADES

		Physical and Chemical Properties								Mechanical Properties of Cast, Non-Reinforced Resin					
		Internal test methods			Gelation tests				Flexural Strength	Flexural Modulus	Tensile Strength	Elong'h at Break	HDT		
		SVT1	SVT2												
		Grades	Viscosity	5rpm 50rpm	Monomer	Method	Gel time	Cure time						Peak Exotherm	
			dPa.s	dPa.s	Content %	Number	Minutes	Minutes	°C	ISO 178	ISO 178	ISO 527	ISO 527	ISO 75	
CHEMICAL RESISTANT AND FIRE RETARTANT GRADES															Comments
NORSODYNE ®	Chemical Resistant	6394-211	4.5	15 / 6	47	SGT1	6	14	210	110	3.6	80	5	110	Resilient Isophthalic resin. Accelerated. Good heat and chemical resistance.
		6395-211	4.5	15 / 6	43	SGT8	7	16	210	110	4	65	1.3	90	Rigid Isophthalic resin. Accelerated. Good heat and chemical resistance.
		6397-111	3.5	20 / 6	45	SGT8	18	32	200	90	3.3	75	3.9	72	Medium reactivity Isophthalic resin. Accelerated. Lloyd's approved.
		6398-210	3.6	14 / 6	48	SGT1	17	30	210	78	3.5	62	2.5	115	Medium reactivity Terephthalic resin. Good adhesion to PVC.
		16030V	3.5	N/A	42	SGT27	23	-	-	118	3.8	72	3.5	90	High reactivity Tetrahydrophthalic resin. Unaccelerated. Good Hydrolytic resistance.
		84-5100	5.75	Thixotropic	45	SGT3	18	-	-	120	3.5	60	2	100	Rigid Isophthalic resin. Accelerated. Good heat and chemical resistance.
		84-5174	5.9	Thixotropic	45	SGT1	18	-	-	120	3.5	60	2	100	Rigid Isophthalic resin. Accelerated. Good heat and chemical resistance.
	Fire Retardant	6356M	3.5	20 / 6	32	SGT8	20	31	140	57	4.1	36	1.3	72	Medium reactivity filled resin. Accelerated. BS476 part 7 Class 2.
		6357	3.5	15 / 6	37	SGT8	13	21	185	86	4.0	39	2.2	85	Medium reactivity unfilled resin. Accelerated, BS476 Part 7 Class 2
		6357D	3.5	16 / 6	37	SGT8	25	38	180	86	4.0	39	2.2	85	Longer gel time variant of Norsodyne 6357
		6357L	4	22 / 6	38	SGT8	18	27	180	86	4.0	39	2.2	85	Low styrene emission variant of Norsodyne 6357
		6417	4	17 / 6	32	SGT8	18	30	160	86	5.2	30	1.4	85	Medium reactivity filled resin. Accelerated. BS476 part 7 Class 1.
		6410	4	35 / 8	25	SGT8	13	33	130	37					Medium reactivity filled resin. Accelerated. BS476 part 7 Class 1, BS476 part 6 Class O

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Fig 1.4 PULTRUSION, COLD PRESS AND RTM GRADE POLYESTERS

			Physical and Chemical Properties							Mechanical Properties of Cast Non-reinforced Resin					
			Internal test methods			Gelation tests				Flexural Strength	Flexural Modulus	Tensile Strength	Elong'n at Break	HDT	
			SVT1	SVT2											
		Grades	Viscosity	5rpm / 50ppm					Monomer	Method	Gel time	Cure time	Peak Exotherm	ISO 178	
			dPa.s	dPa.s	%	Number	Minutes	Minutes	°C	MPa	GPa	MPa	%	°C	
PULTRUSION, COLD PRESS AND RTM GRADE POLYESTERS															Comments
NORSODYNE®	Pultrusion	6394	7	N/A	41.5	SGT24	3	4	285	110	3.6	80	5	110	High reactivity, Resilient Isophthalic resin, Good pull through rate.
		E8840	5.25	22.5 / 10.5	28	SGT24	1.5	2.5	225	90	3.8	65	2.2	80	Filled , grey pigmented. Fire retardant, Medium reactivity Orthophthalic
		E8861	15.5	N/A	48	SGT24	5	6	260	100	4.1	50	1.5	100	Low shrink, high reactivity DCPD resin.
	Cold Press	6370002	2	N/A	42	N/A	27.5	31	225	84	5.1	50	1	100	High reactivity Orthophthalic, medium chemical resistance.
	Hot Press	E8717	9	N/A	35.5	SGT24	2	2.65	265	100	4.1	56	1.25	90	High reactivity Orthophthalic, Synthetic slate manufacture.
		E8673	1.65	N/A	47.5	SGT24	6.5	7.25	285	85	4.5	50	1.2	130	DCPD, high reactivity, Synthetic slate manufacture.
	Resin Transfer Moulding	E8759	2.75	N/A	42	SGT17	32.5	37.5	165	100	4.2	60	2	85	High reactivity, clear, rapid cure. BS476 Pt7 Class 2
		E8781	4.25	N/A	38	SGT2	28	45	185	125	3.8	76	2.5	74	Medium reactivity, general purpose resin, medium chemical resistance.
		E8817	3	N/A	40	SGT30	23	30	190	125	3.8	76	2.5	74	Medium reactivity, White pigmented, good mechanical properties.
		E8830	3	N/A	40	SGT30	23	30	190	125	3.8	76	2.5	74	Medium reactivity, good mechanical properties, clear-neutral laminate colour.
		E8833	2.8	Thixotropic	36.5	SGT20	4.25	8.5	190	80	3.2	50	1.2	95	High reactivity, filled, white pigmented, shrink controlled.
		E8853	2.75	N/A	42	SGT17	32.5	37.5	165	100	4.2	60	1.2	95	High reactivity, Grey pigmented, rapid cure. BS476 pt7 Class 2.
		6501	2.5	N/A	41	SGT17	6.5	14	140	80	4.5	55	1.5	85	High reactivity Orthophthalic, Shrink controlled.
		6502	2.5	N/A	41	SGT16	4	8	200	115	4.8	76	2.5	74	Medium reactivity, general purpose resin, medium chemical resistance.
		6502201	2.5	N/A	41	SGT1	4.5	8.5	200	115	4.8	76	2.5	74	Medium reactivity, accelerated, General purpose resin.
		6502204	2.5	N/A	41	SGT1	4.5	8.5	200	115	4.8	76	2.5	74	Medium reactivity, accelerated, white pigmented, general purpose resin.

Fig 1.5 SMC, BMC PRESS MOULDING GRADES

		Physical and Chemical Properties							Mechanical Properties of Polymerised unreinforced Resin					
		Internal test methods			Gelation tests									
			SVT3		Method	Gel time	Cure time	Peak Exotherm	Flexural strength	Flexural modulus	Tensile Strength	Elong'n at Break	HDT	
		Grades	Viscosity	Monomer										
									ISO 178	ISO 178	ISO 527	ISO 527	ISO 75	
dPa.s	%	Number	Minutes	Minutes	°C	MPa	GPa	MPa	%	°C				
SMC, BMC PRESS MOULDING GRADES													Comments	
NORSODYNE®	Resins	M05501	10.5	35	SGT25	1.66	2.25	275	110	3.8			125	Standard and Low shrink SMC
		M4721	13	33	SGT25	1.75	2.33	275	104	3.4	60	2	125	Low shrink Injectable BMC
		M0070C	13.5	34	SGT25	1.02	1.66	280	100	3.6			135	Low shrink High Gloss system
		M00400	14.5	33	SGT25	0.5	1.06	270	120	3.6	50	2	140	High Reactivity resin for Low Profile formulations
		M71101	10.5	39	SGT25	3.33	4.06	280	140	3.6	85	3	105	Isophthalic for Impact Resistant formulations
		M04960	4	35	SGT25	1.75	2.33	270	90	2	42	5	95	Class A resin for "Tough" formulations
		E8673	1.65	47.5	SGT28	0.4	0.7	270	85	4	50	1	130	DCPD resin for Synthetic slate manufacture.
		E8717	9	35.5	SGT24	2	2.35	265	80	3.9	50	1.2	80	Orthophthalic resin for synthetic slate manufacture.
	Additives	A151	30	70	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Low Shrink
		A154	57	60	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Low Profile Non-Thickenable.
		A158	4	60	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Low Profile Thickenable.

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POLYCOR® Gel Coats from Cray Valley

All Cray Valley Gel Coats are free from heavy metal pigments, including both lead and cadmium grades. The pigments have been carefully selected based upon the performance, including resistance to chemicals, water and UV stability. Each pigment paste uses a fully reactable resin, bonding seamlessly with the gel coat, which maximises the final properties and appearance of the product.

- ☐ POLYCOR® LO-VOC
- ☐ POLYCOR® LO-VOC HP
- ☐ POLYCOR® ISO
- ☐ POLYCOR® ISO/NPG
- ☐ POLYCOR® HWR
- ☐ POLYCOR® SANDING
- ☐ POLYCOR® TOOLING
- ☐ POLYCOR® TOP COATS
- ☐ POLYCOR® INDUSTRIAL
- ☐ POLYCOR® MI

POLYCOR® LO-VOC gel coats have very low styrene content, excellent physical properties, and are easy to apply whether by brush or spray. They were developed because, unlike in the marine industry, not all gel coats are in permanent contact with water. This high quality product was designed specifically for the production of flat panels, industrial pieces, construction and transportation markets. It has excellent weathering and good water resistance, but other benefits include good surface hardness and excellent gloss. These Gel coats help to reduce styrene emission by as much as 50%. This is achieved not by the use of film forming additives but by using a monomer content of only 30% in the gel coat formulation. The result of this has been a reduction of styrene emission in both the application and curing stages of the production process.

POLYCOR® LO-VOC HP was designed specifically for use in the marine industry. It has good surface hardness, high gloss and excellent water and weather resistance, which is better than standard gel coats. It can be used both above and below the water line.

POLYCOR® ISO gel coats are based on a pure Isophthalic resin and contain no orthophthalic. This results in excellent physical properties, water resistance and UV light stability. These gel coats can be used to manufacture a wide variety of parts, which include flat panel production, marine, tanks, construction, and sanitary and industrial pieces. Specific grades are available suitable for each market sector.

POLYCOR® ISO/NPG gel coats have been formulated to give excellent resistance to water and certain chemicals. These high performance gel coats are ideal for use in marine or sanitary applications. They are based on a pure Isophthalic unsaturated polyester resin containing no Orthophthalic and the glycol portion of the polymer contains a minimum of 70% NPG for optimum performance. They are available either pigmented or as a clear version specifically for cultured marble applications.

POLYCOR® HWR gel coat uses a high technology unsaturated polyester base resin developed to give excellent weather and water resistance and it is designed to be used where exterior durability is critical. It has been approved for use in the automotive industry and is widely used within the marine industry, where it is applied both above and below the water line. Exhaustive testing for exposure to the elements both with accelerated exposure and with natural weathering in Florida show that it is still the leading gel coat for exterior applications.

POLYCOR® SANDING gel coats have been specifically formulated for use as a sanding substrate. Sanding gel coats are used for GRP parts that will be subsequently painted. They can be used for both room temperature and heated moulding (RTM) applications. They use a very flexible pure Isophthalic unsaturated Polyester base resin. This results in a product with good flexibility, which is easy to sand, but also has a relatively high heat distortion temperature. They have been successfully used on heated paint lines working at temperatures up to 120°C.

POLYCOR® TOOLING gel coat has been specifically designed for the manufacture of high quality GRP moulds. These precision formulated gel coats use selected resins with a high heat distortion temperature to withstand the repeated moulding of GRP laminates. A high chemical resistance to styrene means that the original gloss of the mould will last much longer than conventional tooling gel coats. After 10 releases from a mould manufactured using POLYCOR® TOOLING gel coat, almost 100% of its original gloss remains. The same test with a conventional tooling gel coat can result in a 50% (or more) reduction of its original gloss! These gel coats provide a high gloss, hard and durable surface for GRP moulds.

POLYCOR® TOP COATS provide a hard, tough, durable, flat finish to improve the cosmetic effect of the part and improve the water resistance. They cure tack free, unlike standard gel coats, which allows them to be used like a paint to seal and hide a substrate. They should not be used in permanent contact with water and they should not be used as a gel coat.

POLYCOR® INDUSTRIAL are economical gel coats which offer a commercial advantage to customers manufacturing panels or industrial pieces where a good looking finished part is essential but where weather and water resistance is not critical. They use an Iso-modified resin base, are easy to use and provide a high gloss surface with low fibre pattern.

POLYCOR® MI gel coats are a range of fire retardant gel coats designed to meet the French fire tests. Certain grades are also available for use with phenolic composites.

Epoxy vinyl ester resins

Epoxy vinyl ester resins are exemplified by Derakane* resin from Dow Plastics. They offer superior mechanical, chemical resistance, and curing properties because of their unique molecular structure. Derakane* resins' resistance to cracking makes them particularly suitable for use in fabricating laminated glass-fibre vessels, pipe-work, and other components. The superior properties of Derakane* epoxy vinyl ester resins become apparent when their molecular structure is compared with that of conventional bisphenol A-fumaric acid, or isophthalic, polyesters. Chemical attack on these resins occurs through the hydrolysis of ester groups, or the splitting of unreacted carbon-carbon double bonds by oxidation or halogenation. In cured bisphenol A-fumaric acid polyesters, and in isophthalic polyesters, ester linkages occur throughout the molecular chain, making it very susceptible to attack by hydrolysis. As well as ester linkages, carbon-carbon double bond linkages also occur at random throughout the chains of such polyesters; not all of the bonds react during polymerisation. In Derakane* epoxy vinyl ester resins, the double bonds are at the ends of the molecular chain, and react more completely on polymerisation; the structure is therefore more chemically resistant. The number and arrangement of the polar groups in epoxy vinyl ester resins make them less polar than polyester types. They are therefore less susceptible to the effects of water.

Derakane 411 series resins are bisphenol-A epoxy based vinyl esters, designed to provide superior toughness and a high degree of chemical resistance. They show very high resistance to a wide range of acids, alkalis, bleaches and organic solvents. It is the preferred choice for maximum resistance to caustic alkalis, hypochlorite bleaches and hot water. Excellent mechanical properties over entire service temperature range; very high damage resistance, even down to -50°C. (Important for transport and installation of GRP at low temperatures.)

Derakane 441-400 is also based on bisphenol A epoxy resin but has been modified to give higher mechanical and thermal properties. In corrosion properties it can be considered as midway between Derakane 411-45 and Derakane 470-36.

Derakane 470 series resins are novolac epoxy based vinyl esters, designed to provide maximum chemical resistance and high temperature performance. They show outstanding resistance to strong acids, oxidising media and organic solvents, over a wide range of service temperatures. Preferred choice for high temperature applications: ducting; fume handling; stacks; chlorine processes and process streams containing organic media / solvents. They have high resistance to thermal ageing and by careful design, can be used for high temperature flue gas handling equipment operating at temperatures up to 220°C.

(Continued on page 7)

Fig 1.6 Typical properties of Derakane* liquid resins

Property		441-400	411-45	470-30 /470-30S	470-36	510A-40	510N	8084
Viscosity (mPa.s at 25°C/ 77°F)		400	440	480	200	350	250	350
Styrene content (weight %)		33	45	30	36	40	38	40
Specific gravity (at 25°C/ 77°F)		1.07	1.04	1.09	1.08	1.23	1.16	1.02
Uncatalysed storage stability(dark, months at 25°C/ 77°F)		4	6	3/5	3	4	4	6
Typical room temperature properties of unreinforced, clear resin castings made from Derakane*								
Property		441-400	411-45	470-30 /470-30S	470-36	510A-40	510N	8084
Tensile strength,	MPa	90	81	68	73	73	76	75-80
	Ksi	13	11.7	9.9	10.6	10.6	11	10.9-11.6
Tensile elongation	%	7	5	3-4	3-4	5	3-4	8
Tensile modulus,	GPa	3.6	3.3	3.5	3.5	3.4	3.4	3.1
	Ksi	522	479	508	508	493	493	450
Flexural strength	MPa	166	124	125	133	124	138	135
	Ksi	24	18	18.1	19.3	18	20	19.6
Flexural Modulus	GPa	3.5	3.1	3.7	3.8	3.5	3.6	3.2
	Ksi	508	450	537	551	508	522	464
Specific gravity		1.13	1.12	1.16	1.15	1.34	1.25	1.13
Av coefficient of linear thermal expansion from 25°C to 100°C from 77°F to 212°F	10 ⁻⁶ cm/cm/°C	60	65	57	53	60	60	70
	10 ⁻⁶ in/in/°F	33	36	32	29	33	33	39
Heat Distortion Temperature (at 1.82 MPa applied stress) (at 264 Psi applied stress)	°C	118	102	150	145	110	120	80-90
	°F	244	216	302	293	230	248	176-194
Barcol Hardness (GYZJ 934-1)		35	35	40	40	40	40	30-35

(Continued from page 6)

Derakane 470-30 offers higher solvent resistance, and because of its higher viscosity is the preferred choice for filament winding. Derakane 470-36 offers higher alkali resistance and is used for scrubbers operating at high temperatures. Preferred choice for hand-lay-up.

Derakane 510A-40 resin is a brominated bisphenol-A epoxy based vinyl ester designed to offer the maximum degree of fire retardance combined with enhanced chemical resistance and toughness. Outstanding resistance to caustic alkalis hypochlorite bleaching chemicals and hot water. Corrosion resistance otherwise similar to Derakane 411 series resins. Preferred choice where highest fire retardance is required. Standard recommendation for external fire retardant layer on GRP equipment.

BS. 476 (Part 7) Class 1 and ASTM E-84 Flame Spread Rating (FSR) <25 possible with Antimony Pentoxide additive.

Derakane 510N is a brominated, novolac epoxy based vinyl ester, designed to provide high fire retardance with outstanding corrosion resistance at high temperatures. Exceptional resistance to high temperature corrosive flue gas condensates. Preferred choice for high temperature fume/flue gas handling equipment where fire retardance is required. Ideal for ducting and fume stacks. Derakane 8084 is a rubber-modified epoxy vinyl ester resin designed to offer increased adhesive strength, superior resistance to abrasion and severe mechanical stress, while giving greater toughness and elongation. It is the resin of choice as a primer resin to prepare a substrate surface (steel or concrete) for application of a corrosion resistant lining.

Phenolic Resin

The oldest synthetic polymers are thermoset Phenolic resins having been first made and used commercially around 1900. They were typically cured at high temperatures (140°C - 180°C) and usually high pressures. The primary applications, as a result of their excellent resistance to high temperature, includes moulding materials, industrial / decorative laminates, printed circuit boards, grinding wheels, foundry binders and friction material binders.

A new range of phenolic resole resins was developed in the 1970's which were designed to cure at low temperature and pressure through the use of acid-based catalysts. These resins and their catalysts have been developed and refined to make them suitable for all the composites production processes.

Phenolics will not support combustion until fire conditions are very severe. The fire performance of the resin is achieved without the use of additives other than reinforcing fibres. When they are induced to burn they release only minimal quantities of smoke or toxic fumes. When phenolic composites do burn a carbon char is rapidly formed which insulates and protects underlying material. Thus they are generally regarded as having outstanding fire resistance. They also retain high levels of physical properties at elevated temperatures.

Phenolic resins are red-brown in colour when cured and, if pigmented, are not light stable. Paint finishes, which will not significantly impair the fire properties, are generally used to improve the aesthetics. Thixotropic phenolic surface pastes are used in order to give a good paintable surface. These materials may be pigmented to match paint colour if necessary and they are light-stable once painted. A decorative finish direct from the mould is not a practical proposition yet but developments are in-hand.

As an example of the range of materials available some of the products of Borden Chemical Co are listed in the following table.

Fig 1.7 Selection of Standard Cellobond Phenolic Resin/Catalyst by Process

Process	Resin	Catalyst
Hand Lamination	J2042L or J2018L	P10 or P382
Spray Deposition	J2042L or J2018L	P15 or P382
Warm Press Moulding	J2018L or J2033L	P10, P15 or P382
Resin Transfer Moulding	J2027L or J2033L	P382
Vacuum Injection	J2027L	P10, P15 or P382
Resin Infusion (e.g. SCRIMP)	J2027L	P382
Continuous Lamination	J2027L	P10, or P382

Reinforcements

Options

The fibres fall into three main families of Glass, Aramid and Carbon. There are other fibres but they are relatively insignificant.

The most important property of the fibre is its elastic modulus, it must be significantly stiffer than the matrix. This allows it to pick up the stress applied to the composite. Since the fibre is now attempting to carry the stress it must have sufficient strength available so that it doesn't fail. Therefore it must have high strength. The point is that high strength on its own is of no value. If the fibre has insufficient stiffness then it can't take advantage of the high strength.

- Reinforcement orientation

The reinforcement fibres may be orientated in an infinite variety but there are in use three main categories.

- **UNIDIRECTIONAL** In which all the fibres lie in one direction.
- **BI-DIRECTIONAL**. In which the fibres lie at 90 degrees to one another. This is achieved either by the use of woven fabric, non-woven fabric or by the use separate layers of fibres each unidirectional but successively laid at 90 degrees.
- **RANDOM** (in-plane Isotropic) In which the fibres are randomly distributed and are in-plane.

Fig 1.8 Chemical Composition of Glass Fibre (Ref Owens Corning)

	Composition % (indicative)	
	E Glass	ECR Glass
SiO ₂	52 – 56	52 – 56
Al ₂ O ₃	12 - 16	10 - 15
B ₂ O ₃	5 - 11	-
CaO	15 - 25	18 - 25
MgO	0 - 5	0 – 5
Na ₂ O + K ₂ O	0.5 - 2	0.5 - 2
Fe ₂ O ₃	0.05 - 0.5	0.05 - 0.5
ZnO	-	2 - 5
TiO ₂	0 - 1	0 - 3

Fig 1.9 Chemical Composition of Glass Fibre (Ref Lubin)

Grade of Glass fibre	A (High Alkali)	C (Chemical)	E (Electrical)	S (High Strength)
Components	72.0	64.6	54.3	64.2
Silicon Oxide	0.6	4.1	15.2	24.8
Ferrous Oxide	-	-	-	0.21
Calcium Oxide	10.0	13.2	17.2	0.01
Magnesium Oxide	2.5	3.3	4.7	10.27
Sodium Oxide	14.2	7.7	0.6	0.27
Potassium Oxide	-	1.7	-	-
Boron Oxide	-	4.7	8.0	0.01
Barium Oxide	-	0.9	-	0.2
Miscellaneous	0.7			

Glass fibre

Glass fibres are the most commonly used reinforcing fibres and there are several very good reasons for this. They have good properties both in an absolute sense and relative to weight. They have very good processing characteristics and they are inexpensive. The processing characteristics of particular types of glass fibre have been modified and optimised over many years to achieve the required performance, such as chop ability, low static build up, conformance to complex shape etc. and resin compatibility requirements such as fast wet out, good fibre/matrix adhesion etc.

In the 1940's the only fibre available to the embryonic GRP industry was 'A' glass. This had either a silane or a chrome surface finish (size) as the linking agent between the resin and the glass. It performed well in many applications but showed significant loss of strength in wet conditions.

'E' glass was developed to improve the performance and in particular to enhance the electrical properties. Both types of glass were available for perhaps a decade but economics decreed that only one type of glass could be sustained for the general-purpose business and that it should be 'E' glass. Hence production of 'A' glass almost ceased throughout the world in the 1960's.

There are significant differences between the various types of glass fibres which are available for the manufacture of composite materials none of which is perfect. They each have their benefits and drawbacks such that it is necessary to select the most appropriate for the particular circumstances

As a broad generalisation glass fibres can be categorized into two sets. Those with a modulus around 70 GPa and with low to medium strength (i.e. E,A,C,ECR), and those with a modulus around 85 GPa with higher strength (i.e. R & S2 glass). The density of glass fibre is about 2.5 g/cc which is high in comparison to other reinforcing fibres but by metallic standards very low (aluminium has a density of about 2.8 and steel 7.8).

E Glass

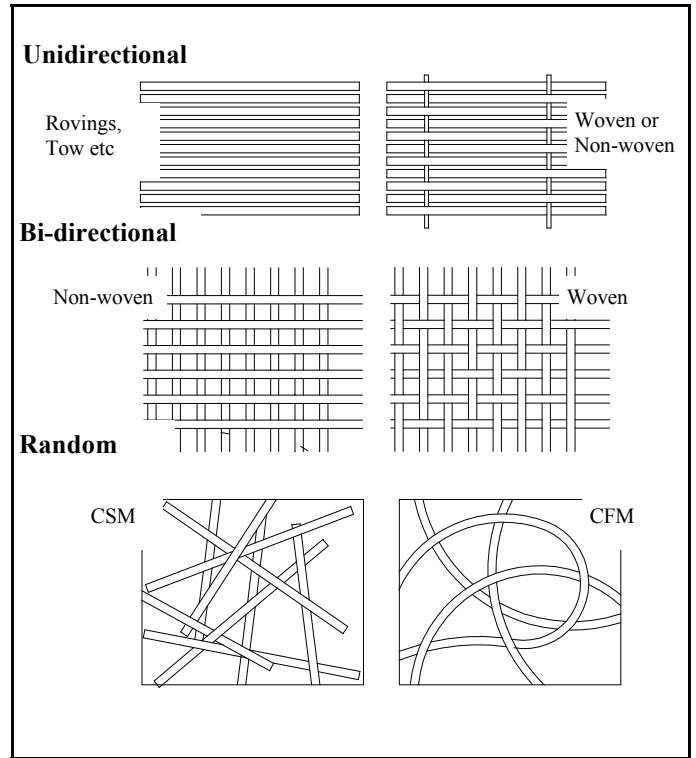
The major constituents of glass are sand, limestone and clay. The ingredients are mixed, finely ground and then fed into a furnace (known as a tank). The temperature of the tank is about 1500°C this melts the materials to form molten glass. In the bottom of the tank are platinum dishes, known as bushings, which have thousands of tiny holes. The glass pours through the holes where it is gathered together and pulled so that it is stretched and drawn down to the filament diameter required. Air and water cool and solidify the filaments.

The filaments are coated with an aqueous chemical mixture known as the sizing. This protects the glass during its processing stages from severe degradation. It also imparts many of the characteristics which are required for manufacture of the composite and required for the composite to achieve many of its properties in service.

The filaments are collected into a strand and may be chopped

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Fig 1.10 Reinforcement Format Options



E Glass		
Fibre type	Known as	Mass
Unidirectional	Roving	600 - 4800 Tex*
	Unidirectional fabric	200 - 1200 g/m ²
Bi-directional	Woven roving	200 - 1200 g/m ²
	Non-woven fabric	200 - 1200 g/m ²
Random	Chopped strand mat	225 - 600 g/m ²
	Continuous strand mat	300 - 600 g/m ²

A Glass		
Fibre type	Known as	Mass
Random	Fibramat® Reinforcing Mat #	150 - 600 g/m ²
Random	Fibramat® Surfacing Mat #	40 - 200 g/m ²

ECR Glass ®		
Fibre type	Known as	Mass
Unidirectional	Roving	600 - 4800 Tex*
	Unidirectional fabric	200 - 1200 g/m ²
Bi-directional	Woven roving	200 - 1200 g/m ²
	Non-woven fabric	200 - 1200 g/m ²
Random	Chopped strand mat	300 - 600 g/m ²
	Veil / Tissue	30 g/m ²

S2 - Glass ®		
Fibre type	Known as	Mass
Unidirectional	Roving	600 - 4800 Tex*
	Unidirectional fabric	200 - 1200 g/m ²
Bi-directional	Woven roving	200 - 1200 g/m ²
	Non-woven fabric	200 - 1200 g/m ²

Carbon		
Fibre type	Known as	Mass
Unidirectional	Tow	1k - 40k*
	Unidirectional fabric	200 - 800 g/m ²
Bi-directional	Woven roving	200 - 800 g/m ²
	Non-woven fabric	200 - 800 g/m ²
Random	Veil / Tissue	10 - 100 g/m ²

Aramid ®		
Fibre type	Known as	Mass
Unidirectional	Yarn	21 - 316 Tex*
	Roving	508 - 790 g/m ²
Bi-directional	Woven roving	60 - 460 g/m ²
	Non-woven fabric	60 - 460 g/m ²

* Tex = g/km

** k = Number of individual filaments in a 'tow' (a bundle). The linear density varies from one carbon fibre type to another. Hence 1k in one type of carbon may have a different linear density to another.

See reference section for contact details

(Continued from page 9)

into short lengths for incorporation into compounds or wound into a “cheese” (or “doff” in the USA) for use in such processes as filament winding, pultrusion or they may be used for the manufacture of glass fibre fabric.

Chopped strand mat uses an intermediate form of package from the bushing known as a cake. Many hundreds of these are fed through a chopper and allowed to fall randomly onto a moving belt. A binder is applied (either an emulsion or a powder), which after passage through an oven, locks the strands together into a mat.

Cake packages are also combined to form rovings which are multi-end. These are known as conventional rovings and are used in spray-up and in the manufacture of sheet moulding compound.

Reinforcement materials are available in a variety of formats to suit the processes and design requirements most likely to be encountered. They may be classified as unidirectional, bi-directional and random configurations. Some of the more common variants are shown in the following tables together with the relevant nomenclature and an indication of the range of mass in which they are available.

‘A’ Glass

A source of ‘A’ glass reinforcement materials is Fibrmat Limited which was established in 1983 as the UK based manufacturing facility to service the European markets of the Reinforced Plastics Industry.

Fibrmat employs the Modigliani process for the manufacture of its Conformat range of continuous strand mats and Surmat continuous filament surfacing mats and veils. In the process molten glass is drawn from a furnace, through a bushing plate and spun onto a revolving drum. Size and binder are applied to the fibres as the furnace traverses the drum. The rate at which the furnace traverses the drum controls the filament diameter, and the gear racking on the drum controls the pattern in which the fibres are laid down onto the drum.

The process draws fibres of a known filament diameter, in a predetermined pattern, to weight tolerances within $\pm 10\%$. Mats may be produced comprising solely monofilaments, or solely stranded fibres, or varying combinations of each in a

variety of fibre patterns. Once the target weight of the mat being produced has been achieved, the “condensed” mat is cut from the drum ready for the second stage of processing.

The condensed mat is then expanded, both in length and width, and the binder cured in the oven, to produce a continuous strand mat of predetermined fibre distribution. A condensed mat will expand up to 100 times its original length. The expanded, cured mat is then wound into rolls for packaging.

The suitability of A glass as a substitute for C glass was investigated by Maloney (1.3).

In this work C glass and A glass laminates were immersed in 20 different reagents for up to 360 days after which time the flexural strength was determined. The tests showed that the A glass material and the C glass material were equivalent under a wide variety of chemical environments including distilled water.

Carbon (Graphite) fibre

In 1963 Leslie Phillips, Bill Watt and Bill Johnson at the Royal Aircraft Establishment, Farnborough, planned the series of experiments which led to their discovery and invention of high modulus, high-strength, carbon fibres. The results were made public in 1966 and a new industry was born

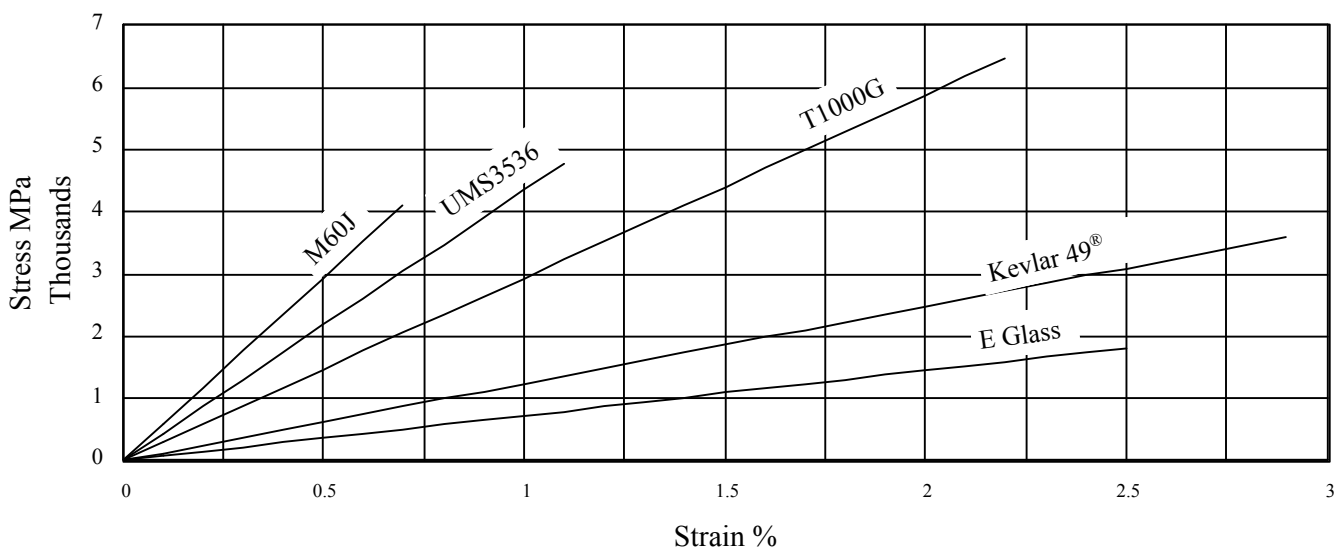
Carbon fibres are the predominant reinforcement used to achieve high stiffness and high strength. The term carbon fibre covers a whole family of materials which encompass a large range of strengths and stiffness'.

Carbon fibre is most commonly produced from a precursor of PAN fibre which is processed by first stretching it to achieve a high degree of molecular orientation. It is then stabilised in an oxidising atmosphere while held under tension. The fibres are then subjected to a carbonising regime at a temperature in the range 1000 to 3500 °C. The degree of carbonisation deter-

(Continued on page 11)

Fig 1.11

Stress/Strain curves
Reinforcement Fibres



(Continued from page 10)

mines such properties as elastic modulus, density and electrical conductivity. As an alternative to the use of PAN, routes via the use of Pitch and Rayon have been successfully utilised and such fibres are commercially available. These fibres tend to be of lower performance than PAN based fibres they also tend to be of lower cost due to their use of a lower cost precursor.

The elastic modulus, strength, strain and density of a range of carbon fibres commercially available is shown in Fig 1.12

Stress/strain curves are shown graphically in fig 1.11 for Toray® T300, T1000G and M60J. They are compared with Kevlar 49® and 'E' glass. The 'work horse' in the carbon fibre field is T300 fibre from Toray. This fibre has very respectable modulus, strength and strain to failure both in the absolute sense and relative to their cost. This allows them access to many market areas which are strongly driven by commercial considerations as well as technical requirements. They have tensile moduli of about 230 GPa (33 Msi), tensile strength of 3200-3500 MPa (465-500 Ksi) and strain to failure of 1.5%. Thus unidirectional composites can be produced from them which will have typical properties as follows:

Longitudinal Tensile modulus 125-135 GPa (18-20 Msi)

Longitudinal Tensile Strength 1700-1800 MPa (245-260 Ksi)

M60J fibre has an extremely high modulus (588GPa / 85Msi) approaching three times that of steel. This is moderated by the low strain to failure (0.7%) which will result in relatively low impact resistance. But never the less the tensile strength is still higher than that of T300.

At the other end of the performance scale, carbon fibres have been developed whose strength can only be described as remarkable. Toray have developed T1000G fibre which has a tensile strength of 6370 MPa (925 Ksi) together with a very respectable modulus of 294 GPa (43 Msi).

The primary characteristic of carbon fibre composites is without doubt their very high specific stiffness (i.e. the ratio of elastic modulus to density). In fact the elastic modulus of CFRP can be very high even in an absolute sense. Unidirectional CFRP composites using high modulus fibre can be of the same order or even exceed the modulus of steel.

Torayca M60J fibre as a unidirectional composite can have a modulus of 350 GPa (50 Msi). This compares with the modulus of steel of about 210 GPa (30 Msi). The composite density is about 1.6 Mg/m³, giving a specific modulus of 218 for the M60J composite. The comparative quantity for steel with a density of 7.8 Mg/m³ would be 27. Therefore the composite is 8 times better than the steel..

It is generally the case that fibres must be placed in more than one direction to accommodate and sustain the complex loading systems that are applied to most structures. Thus it is rare that the composites designer is able to utilise these properties to the fullest extent.

Although the modulus is the primary reason for the use of CFRP's, they can have superb strength performance, but generally not simultaneous with the highest modulus performance. Usually the designer must choose either high modulus or high strength. The exception to this is T1000G fibre which has both very high strength and very high modulus.

* See reference section for contact details

Aramid fibres

Aromatic Ether Amide or Aramid fibres are organic, man made fibres which have found application in the composites field. There are various forms available; Dupont produce KEVLAR® aramid; Akzo produce under the trade name TWARON®. Aramid fibres are generally characterised as having reasonably high strength, medium modulus and a very low density. Their composites fit well into a gap in the range of stress/strain curves left by the family of carbon fibres at one extreme and glass fibres at the other.

Aramid fibres are fire resistant and perform well at high temperatures. They are insulators of both electricity and heat.

They are resistant to organic solvents, fuels and lubricants. A major distinction of aramid fibres is that they are highly tenacious in the non composite form and do not behave in a brittle manner as do both carbon and glass fibres.

The tensile stress/strain curve of aramid fibres is essentially linear to failure. They have two distinct categories, those in which their elastic modulus is about the same as glass fibre, typically 60-70 GPa (9-10 Msi) and those with a modulus at about twice this level. Kevlar 29 falls into the first category and Kevlar 49 into the higher modulus category. It is generally the higher modulus material which finds use in composites. But the lower modulus aramids do have applications in composites in those circumstances where high strain to failure or high work to failure are required most notably in ballistic applications. The specific performance of aramids is their primary advantage, that is their strength/weight and stiffness/weight ratios. As the density of aramid is in the range 1.39-1.44 the high modulus aramids can have higher specific modulus than some carbon fibres and all of the glass fibres. If specific strength is the selection criteria then they outperform all of the glass fibres and all but the higher strength carbon fibres.

The very low density, high tensile strength and high tenacity make aramid fibres highly suitable for ballistic applications either as a 'dry' fabric or as a composite.

It should be noted that some aramids have a relatively very low compressive strength. Thus when used in compression or flexure special attention is required.

Flax fibres

Flax is a member of the ligno-cellulose family of natural fibres which includes hemp, jute and kenaf. It has been traditionally used in textile production but is emerging as a valid contender as a reinforcement for polymers composites.

As it is a 'natural' material, flax is sensitive to moisture and is relatively variable in quality. This is primarily due to weather conditions but also due to the practice of dew-retting. In this process the flax is left on the land for a few weeks. This has the effect of loosening the fibre bundles from the woody core of the plant.

Ceres b.v. * have developed a process which loosens the fibre bundles without the necessity to perform dew-retting. This flax is called Duralin. It has improved the quality, consistency and reduced moisture absorption. The strength and modulus are both good but when the particularly low density is taken into account the specific performance is excellent. Consequently those applications which have appropriate conditions i.e. dry and moderate temperature are suitable for flax reinforced composites.

Fig 1.12 Properties of Reinforcement Fibres

			Density	Fibre Modulus		Ultimate Strength		Strain to failure virgin fibre	Strain to failure - Typical
Fibre	Mnf.	Type	g/cc	GPa	Msi	MPa	Ksi	%	%
GLASS	Various	E glass	2.57	72.5	10.5	3331	483	4.59	2.5
	OCF	ECRGLAS	2.71	72.5	10.5	3330	483	4.59	2.5
	OCF	S-2 Glass	2.47	88	12.8	4600	667	5.23	3
	Vetrotex	R	2.55	86	12.5	4400	638	5.1	3
	Various	C	2.46	74	10.7	2350	341	3.2	2.5
	Fibrmatt	A	2.46	73	10.6	2760	400	3.6	2.5
CARBON	Toray	T300	1.76	230	33.4	3530	512		1.5
		T300J	1.78	230	33.4	4210	611		1.8
		T400H	1.8	250	36.3	4410	640		1.8
		T700S	1.8	230	33.4	4900	711		2.1
		T800H	1.81	294	42.6	5490	796		1.9
		T1000G	1.8	294	42.6	6370	924		2.2
		M35J	1.75	343	49.7	4700	682		1.4
		M40J	1.77	377	54.7	4410	640		1.2
		M46J	1.84	436	63.2	4210	611		1
		M50J	1.88	475	68.9	4120	598		0.8
		M55J	1.91	540	78.3	4020	583		0.8
		M60J	1.94	588	85.3	3920	569		0.7
		M30S	1.73	294	42.6	5490	796		1.9
		M40	1.81	392	56.9	2740	397		0.7
	Hexcel	AS4C	1.77	226	32.8	3860	560		1.7
		AS4D	1.78	241	35.0	4207	610		1.7
		IM4	1.73	276	40.0	4138	600		1.5
		AS4	1.79	221	32.1	3930	570		1.7
		IM6	1.76	276	40.0	5240	760		1.7
		IM7	1.77	276	40.0	5379	780		1.8
		IM8	1.8	303	43.9	5447	790		1.7
		IM9	1.79	290	42.1	6343	920		2
		UHM	1.87	441	64.0	3447	500		0.8
	Tenax	IMS3131	1.76	295	42.8	4120	598		1.4
		IMS5531	1.8	290	42.1	5500	798		1.9
		HTA/HTS	1.77	238	34.5	3950	573		1.5
		UMS3536	1.81	435	63.1	4500	653		1.1
		UMS2526	1.78	395	57.3	4560	661		1.1
		HMA	1.77	358	51.9	3000	435		0.7
		UTS	1.8	240	34.8	4800	696		2
ARAMID	Dupont	Kevlar 49	1.44	124	18.0	3620	525		2.9
		Kevlar 29	1.44	58	8.4	3620	525		3.7
	Akzo Nobel	Twaron	1.44	80	11.6	3150	457		3.3
		Twaron HM	1.45	121	17.5	3150	457		2
FLAX	Ceres bv	Dew Retted	1.4	50 - 70	7.3 - 10.2	900	131		1.5 - 2.5
		Duralin	1.4	50 - 70	7.3 - 10.2	800	116		1.5 - 2.5

FLEMINGS INDUSTRIAL FABRICS

DUOMAT

DESCRIPTION

DUOMAT is a glass fibre stitchbonded combination material consisting of bi-directional Woven Rovings with a chopped strand deposit to one or both sides. The stitching yarn used is texturised polyester and due to the absence of a chemical binder the material has excellent drape and wet-through characteristics and is compatible with most thermoset resins in normal commercial use.

APPLICATIONS

DUOMAT is normally used for structural mouldings produced by the hand-lay process requiring improved strength and stiffness. Typical end uses for DUOMAT include: Boat Building, Chemical Tanks and Pressure Vessels, Pipes and Ducting, Building Panels, Roofing Systems.

TYPICAL MECHANICAL PROPERTIES *

		<i>SDM/800/450</i>	<i>SDM/800/300</i>	<i>SDM/600/300</i>	<i>SDM/600/150</i>
Glass Content	% wt	42	45	41	44
Nominal Thickness per Layer	mm	2	1.6	1.4	1.2
	inches	0.079	0.063	0.055	0.047
Tensile Strength UTS	MN/m ²	173	190	190	210
	Ksi	25.1	27.6	27.6	30.5
Tensile Modulus E(t)	GN/m ²	11.7	13.3	12	13.5
	Msi	1.70	1.93	1.74	1.96
Flexural Strength (UFS)	MN/m ²	270	280	300	320
	Ksi	39.2	40.6	43.5	46.4
Flexural Modulus E(f)	GN/m ²	12.3	12.5	12.1	12.2
	Msi	1.78	1.81	1.75	1.77

* The mechanical properties shown in the tables are indicative of values possible in controlled conditions. Various factors such as resin type and glass content will have an influence on specific laminate properties. Flemings Textiles Ltd accept no responsibility for the accuracy of the information contained herein and advises users to verify the properties of laminates produced in their own environment.

FLEMINGS INDUSTRIAL FABRICS

ULTICLOTH & UD-ULTICLOTH

DESCRIPTION

ULTICLOTH is a glassfibre reinforcement material comprised of non-woven bi-directional rovings produced by a process known as warp and weft insertion. Warp and weft rovings are held together by a 'tricot' stitch of low tex polyester yarn. This method of production produces a fabric with 'straight line' rovings without crimp and shows significant benefits in mechanical properties when compared to standard woven rovings.

UD-ULTICLOTH has a high proportion of the reinforcement rovings in the zero degree (warp) direction and is used in applications having stress concentrations in specific directions.

APPLICATIONS

ULTICLOTH can be used in any application where a conventional Woven Roving would be considered for use.

Typical end uses include: Boat Building, Chemical Plant, Automotive Mouldings, Structural Poles, Roofing Systems.

TYPICAL MECHANICAL PROPERTIES *

		<i>UC/800</i>	<i>UC/600</i>	<i>UC/300</i>	<i>UDUC/600</i>
Glass Content	% wt	50	50	50	52
Nominal Thickness Per Layer	mm	1	0.7	0.4	0.6
	inches	0.039	0.028	0.016	0.024
Tensile Strength UTS	MN/m ²	320	310	280	440
	Ksi	46.4	45.0	40.6	63.8
Tensile Modulus E(t)	GN/m ²	16.2	16.3	17.5	21
	Msi	2.35	2.36	2.54	3.05
Flexural Strength UFS -	MN/m ²	511	502	451	600
	Ksi	74	73	65	87
Flexural Modulus E(f) -	GN/m ²	15.2	15	14.4	18
	Msi	2.20	2.18	2.09	2.61

FLEMINGS INDUSTRIAL FABRICS

ULTIMAT

DESCRIPTION

ULTIMAT is a glass fibre stitchbonded combination material consisting of non-woven bi-directional Rovings with a chopped strand deposit to one or both sides. The stitching yarn used is texturised polyester and due to the absence of any other binder the material has excellent drape and wet-through characteristics.

APPLICATIONS

ULTIMAT is normally used for structural mouldings produced by the hand-lay process requiring high strength and stiffness. Typical end uses for ULTIMAT include: Boat Building, Chemical Tanks and Pressure Vessels, Pipes and Ducting, Building Panels, Roofing Systems.

TYPICAL MECHANICAL PROPERTIES *

		SUM/800/450	SUM/600/300	SDM/600/150	SDM/300/150
Glass Content	% wt	44	48	49	43
Nominal Thickness Per Layer	mm	1.8	1.2	1	0.7
	inches	0.071	0.047	0.039	0.028
Tensile Strength UTS	MN/m ²	280	270	290	240
	Ksi	40.6	39.2	42.1	34.8
Tensile Modulus E(t)	GN/m ²	14.2	15.5	15.9	14.9
	Msi	2.06	2.25	2.31	2.16
Flexural Strength UFS	MN/m ²	405	380	420	360
	Ksi	58.7	55.1	60.9	52.2
Flexural Modulus E(f)	GN/m ²	12.9	12.8	14	12
	Msi	1.87	1.86	2.03	1.74

FLEMINGS INDUSTRIAL FABRICS

NEOMAT

DESCRIPTION

NEOMAT is a glassfibre reinforcement comprised of randomly distributed chopped strands mechanically bonded by a needle punching process.

NEOMAT is primarily intended for closed mould processes. The needle punching process produces a three dimensional reinforcement material which has excellent mould filling, drapability and handling characteristics. Due to the absence of chemical binders, NEOMAT wets out quickly and evenly and is compatible with most thermoset resin systems in normal commercial use.

FLEMINGS INDUSTRIAL FABRICS

NEEDLECLOTH

DESCRIPTION

NEEDLECLOTH is a glassfibre reinforcement comprised of randomly distributed chopped strands mechanically bonded to a Woven Roving substrate by a needle punching process.

NEEDLECLOTH is primarily intended for closed mould processes. The needle punching process produces a three dimensional reinforcement material which has excellent mould filling, drapability and handling characteristics. Due to the absence of chemical binders, NEEDLECLOTH wets out quickly and evenly and is compatible with most thermoset resin systems in normal commercial use.

FLEMINGS INDUSTRIAL FABRICS

POLYMAT

DESCRIPTION

POLYMAT is a stitchbonded reinforcement consisting of a deformable high loft Polyester core, sandwiched between two layers of glassfibre chopped strand matting.

POLYMAT is primarily intended for use in closed mould processes such as RTM and Vacuum Infusion etc.

PERFORMANCE CHARACTERISTICS

- High deformability
- Cold preformable
- Conformability to complex shapes
- Fast wet-out
- Ease of handling and cutting
- Good cavity filling
-
- Excellent surface finish

TYPICAL MECHANICAL PROPERTIES *

		PM/M450/ A01/M450
Glass Weight	g/m ²	900
	oz/ft ²	2.95
Core Weight	g/m ²	170
	oz/ft ²	0.56
Nominal Thickness	mm	3
	inches	0.12
Tensile Strength UTS	MN/m ²	101
	Ksi	14.6
Tensile Modulus E(t)	GN/m ²	10.4
	Msi	1.51
Compressive Strength UCS	MN/m ²	148
	Ksi	21.5
Compressive Modulus E(c)	GN/m ²	11.4
	Msi	1.65
Flexural Strength UFS	MN/m ²	303
	Ksi	43.9
Flexural Modulus E(f)	GN/m ²	8.8
	Msi	1.28
Interlaminar Shear	MN/m ²	21.7
	Ksi	3.1

Multiaxial Reinforcing Fabrics

Multi-axial Reinforcing fabrics are a form of reinforcement that organises unidirectional fibres into layers or plies of variable weight and orientation, and then stitches them together with a light thread. This results in fabrics with predictable, repeatable properties for the manufacture of composites. Laminates made from Multi-axial Fabrics require less resin for wet-out and yield higher reinforcement levels than do random chopped/continuous mat or woven rovings.

By way of example it is convenient to consider a specific set of products. A major supplier of Multi-axial fabrics is Saint-Gobain BTI in the UK. They produce the COTECH® product range in numerous configurations and weights.

COTECH® multiaxial technology

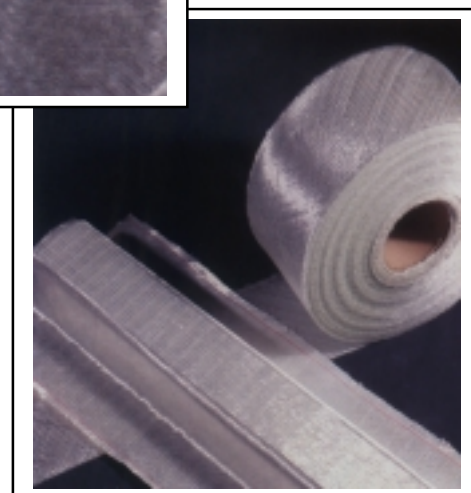
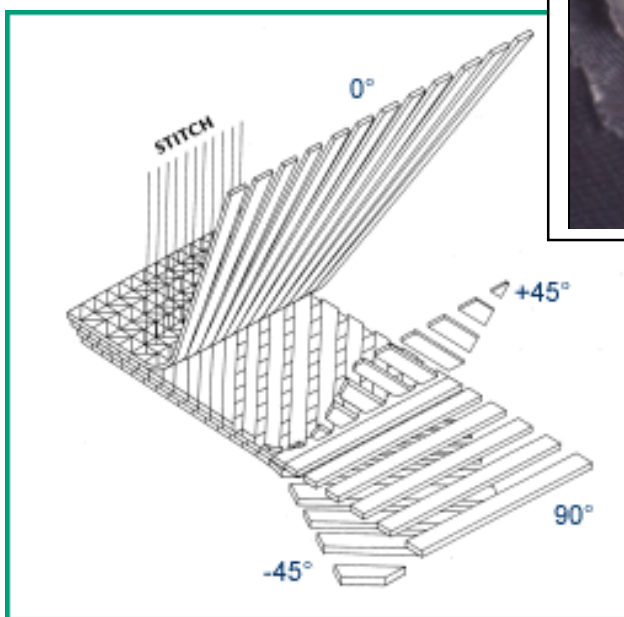
All COTECH® reinforcing fabrics are made up of 2 or more layers of unidirectional fibres stitched together with a light polyester thread. Being stitched, they do not exhibit the crimping effect associated with woven fabrics - crimping that leads to resin rich areas, heavy print through and loss of performance.

Many applications require reinforcement at more than just the traditional 0° & 90° (warp & weft) directions. Multiaxials include the $\pm 45^\circ$ orientations that take the loads normally associated with torsion.

Most fabrics are available in combination form with chopped strand mat (CSM) backing. Combination fabrics allow quicker lay-up by reducing the individual number of layers required.

The advantages of COTECH® stitched fabrics over wovens

- Quicker to wet-out
- No resin-rich areas
- Less print-through
- Better performance (tensile & flexural)
- Improved fatigue and impact resistance
- Easier handling - the fabrics stay intact even when cut
- Labour savings - by using fewer multi-layer, heavyweight fabrics



COTECH® Product List & Specifications

Description	Reference	Weights in each axis (g/m ²)				Dry Thickness mm	Lloyds* Approved (see note for DNV)
		0°	-45°	90°	+45° CSM		
E-glass Biaxial ±45° All weights available with CSM	EBX 254		127		127	0.20	✓
	EBX 318		159		159	0.30	✓
	EBX 424		212		212	0.40	✓
	EBX 446		223		223	0.40	✓
	EBX 602		301		301	0.45	✓
	EBXM 602/225		301		301	0.80	✓
	EBXhd 736		368		368	0.50	
	EBX 802		401		401	0.60	✓
	EBX/EBXhd 936		468		468	0.70	✓
	EBX 1002		501		501	0.80	✓
	EBX 1202		601		601	0.90	✓
E-glass Triaxial 0°/±45°	ETLX 583	283	150		150	0.45	
	ETLX 751	283	234		234	0.60	
	ETLX 895	425	234		234	0.65	
	ETLX 1027	425	301		301	0.85	
	ETLX 1169	567	301		301	0.90	✓
	ETLX 1769	567	601		601	1.25	
E-glass Triaxial -45°/90°/+45°	ETTX/ETTXhd 1027		301	425	301	0.85	
	ETTX 1169		301	567	301	0.95	
	ETTXhd 1769		601	567	601	1.20	
E-glass Quadriaxial 0°/-45°/90°/+45°	EQX 610	142	150	165	150	0.55	(✓)
	EQX 868	283	150	283	150	0.65	(✓)
	EQX 1034	283	234	283	234	0.80	
	EQX 1168	283	301	283	301	0.90	(✓)
	EQX 2336	567	601	567	601	1.50	(✓)
E-glass Biaxial 0°/90°	ELTpb 284	142		142		0.35	
	ELT 566	283		283		0.50	✓
	ELT 850	425		425		0.70	✓
	ELT 1134	567		567		1.00	✓
E-glass Biaxial Combination 0°/90°/CSM	ELTM 600/150	283		283	150	0.70	✓
	ELTM 600/225	283		283	225	0.75	✓
	ELTM 600/300	283		283	300	0.85	✓
	ELTM 850/225	425		425	225	1.05	✓
	ELTM 850/300	425		425	300	1.10	✓
	ELTM 850/450	425		425	450	1.20	✓
	ELTM 1700/150	850		850	150	1.50	
E-glass 0° UD	ELpb 425	425		40		0.45	
	ELpb 567	567		50		0.50	✓
E-glass 0° UD /CSM	ELM 1134/100	1134			100	1.10	
Carbon	CBX 300 6k		150		150	0.35	
	CBX 340 6k		170		170	0.40	
	CBX 400 12k		200		200	0.45	
	CBX 440 12k		220		220	0.50	
	CBX 600 12k		300		300	0.65	
	CBX 636 24k		318		318	0.70	
	CBX 800 24k		400		400	0.90	
	CBX 1200 48k		600		600	1.30	
	CBX 1600 48k		800		800	1.80	
	CQX 800 12k	188	200	200	200	0.90	
	CQX 1309 12/24k	376	301	331	301	1.40	
	CLT 1600 48k	830		830		1.80	
Aramid	ARBX 350		175		175	0.45	
	ARBX 400		200		200	0.50	
	AREBX 440		75/145		75/145	0.45	

*Most E-glass fabrics have DNV Approval. (✓) means going through Lloyds Re-Approval

All weights nominal. Other weights & variations available to order (subject to minimum order quantity).

(October 2001)

Technical Fibre Products Composites Division specialise in producing advanced fibre non-wovens for a wide variety of uses and applications.

Fibres can be bonded with tailored levels of organic binders where required to optimise end product strength, chemical resistance, and flexibility.

Non-woven fibre products

Optimat is a range of fibre non-wovens. These products are made using a unique wet-forming process based on the principles of paper-making. This results in a very even distribution of fibre in the plane of the sheet. These products offer a cost effective means of realising the material advantage of speciality fibres in a variety of composite structures. The fibres are bound with a small amount of organic binder which is selected for compatibility with the final matrix system.

Optimat Standard Series						
Fibre Type		201	202	203	204	206
		Glass	Polyester	Carbon	Nickel coated carbon	Aramid
		Chemically resistant C glass, Electrical grade E glass	Polyethylene Terephthalate (PET)	Pan based carbon, 200 or 250 GPa modulus	Pan based carbon, 200 or 250 GPa modulus. Coated with nickel 20, 33, 42 or 50%	Par aramid, 2.8 GPa strength, 70 GPa modulus, chopped staple fibrid (pulp)
Fibre Length	mm	3,6,12,25 or mixture	6 or 12 or mixture	3,6,12,25 or mixture	3,6,12,25 or mixture	3,6,12,25 or mixture
Fibre Diameter	micron	12 or 6.5	12 or 6	6.8	10 (at 42% Ni)	12 (staple)
Basis Weight	g/m ²	10 to 200	6 to 200	8 to 200	8 to 100	10 to 150
Binder Content	%	1 to 20	5 to 20	1 to 20	1 to 20	1 to 20
Binder Types		Acrylic, Polyester, Polyvinyl Alcohol	Acrylic, Polyester, Polyvinyl Alcohol	Acrylic, Polyester, Polyvinyl Alcohol	Acrylic, Polyester, Polyvinyl Alcohol, Phenolic	Acrylic, Polyester, Polyvinyl Alcohol, Phenolic
Tensile Strength	N/mm ²	up to 12	up to 10	up to 20	up to 15	up to 8
Mat Density	kg/m ³	140	120	80	120	80
Surface Resistivity	Ohm			< 100	< 1	
Forms		Continuous rolls of width 10 to 1650 mm, precision cut sheet, Die stamped shapes				

Optimat 201 - Glass

Applications

Aerospace

The superior fibre distribution of Optimat 201 makes it the ideal material for surface finishing for interiors. Use of Optimat 201 can result in weight and cost saving by reducing paint and resin content and by eliminating the need to grind or polish. Optimat 201 is used to prevent galvanic corrosion by separating dissimilar conductive materials e.g. aluminium / carbon fibre,

Defence

Optimat 201, blended with precise amounts of conductive fibre is used to reduce radar cross section in marine, land vehicle and aircraft applications.

Recreational

Optimat 201 is used as a surface layer giving a smooth finish combined with improved impact and wear resistance.

Commercial

Optimat 201 with chemically resistant "C" glass is used as a surfacing layer to improve the corrosion resistance of vessels and pipe work for the chemicals industry. Optimat 201 imports superior wear resistance to the surface of high speed industrial rolls, is used in printing, textiles and papermaking. Optimat 201 blended with conductive fibres is used to provide protection from static discharge.

Electronic

Superior temperature resistance combined with low basis weight and even fibre distribution make Optimat 201 a key material in the development of the next generation of printed circuit boards.

Optimat 202 - Polyester

Applications

Aerospace

The superior fibre distribution of Optimat 202 makes it the ideal material for adhesive carriers. Because of its electrical transparency Optimat 202 is used as a surfacing layer for Radomes.

Defence

Optimat 202, blended with precise amounts of conductive fibre is used to reduce radar cross section in marine, land vehicle and aircraft applications.

Recreational

Optimat 202 is used as a surface layer giving a smooth finish combined with improved impact and wear resistance, the improved drape of the polyester fibre allows its use on complex shapes where glass surface veils would crease or wrinkle. The opacity and whiteness of Optimat 202 make it a suitable base for screen printing which permits the incorporation of special effects or written messages in the body of the composite.

Commercial

Optimat 202 has good resistance to acids and better drape than glass. It is used in reaction vessels and other components with complex double curvatures. Optimat 202 is used to replace glass chopped strand in applications where a flexible laminate is preferred.

Pultrusion

Optimat 202 is used extensively as a surfacing veil in the pultrusion process. The use of Optimat 202 improves surface finish, reduces die wear and pulling tares and improves UV resistance in pultruded parts.

Optimat 203 - Carbon

Applications :

Chemical Vessels and Pipe work

Optimat 203 is used as a surfacing veil for electrical grounding and improved corrosion resistance. Optimat 203 tape is used as a conductive layer for "spark testing" of tank liners.

Computer Case

Heavier grades of Optimat 203 are pre-pregged and used to produce compression moulded cases for portable electronic goods. In addition to high strength and stiffness these cases have integral EMI/RFI shielding.

Electronics

Optimat 203 is used to provide EMI/RFI shielding for enclosures, static protection in assembly areas and as a reflective layer in satellite dishes.

Fuel Cells

Chemical resistance in combination with electrical conductivity makes Optimat 203 an ideal material for the construction of fuel cells.

Sports Goods

Optimat 203 is used to improve strength, stiffness and surface finish in a variety of sports goods.

Pultrusion

The use of Optimat 203 as the outer surface layer on unidirectional pultrusions increases hoop strength and improves surface finish. Optimat 203 can be supplied in narrow coils to suit pultrusion applications.

Optimat Coloured and Decorative Veils

Technical Fibre Products have developed a range of coloured polyester veils, initially targeted at the general composites industry.

The use of coloured veils in composite fabrications can offer the following benefits

- Improved surface finish
- Solid, even surface colour
- Reduced pigment content
- Batch to batch colour consistency
- Improved UV and weathering resistance
- Reduced gel coat thickness

A standard range of colours is available as well as a bespoke colour matching service. In addition to coloured polyester veils TFP have developed a range of design led decorative veils containing holographic/coloured sparkle fibres.

Optimat 204 - Nickel coated carbon

Applications

Aerospace

Optimat 204 is used to provide areas of very high conductivity, these may be used for lightning strike protection, as an EMI/RFI shield for the protection of avionics or as a heated layer for de-icing.

Automotive

Optimat 204 can be used in composite bulkheads and body panels to provide EMI/RFI shielding or as a heating pad for seats.

Architecture

Optimat 204 is used to provide protection from electronic surveillance in secure buildings or rooms. When incorporated in composite cladding Optimat 204 can be used as a resistive heating layer to prevent the dangers associated with icing.

Recreational

Optimat 204 may be used as a surface layer giving a smooth finish combined with an attractive metallic sheen.

Commercial

Optimat 204 is used whenever high levels of electrical conductivity are desired, its low basis weight and excellent fibre dispersion find applications in conductive tapes, electrical connectors and bench mats. For resistive heating applications the uniformity of fibre distribution eliminates hot spots especially at connector points.

Optimat 206 - Aramid

Applications

Aerospace

The superior fibre distribution of Optimat 206 makes it the ideal material for adhesive carriers.

Automotive

Optimat 206 can be used to improve impact resistance to protect the surface finish of composite panels from damage by stones.

Defence

Optimat 206, blended with precise amounts of conductive fibre is used to reduce radar cross section in marine, land vehicle and aircraft applications.

Recreation

Optimat 206 is used as a surface layer giving a smooth finish combined with improved impact and wear resistance particularly in skis, snow and surf boards and competition canoes.

Commercial

Optimat 206 is an excellent substrate for friction products where it is used as a coating base for clutch, brake and automatic transmission systems. It imparts superior wear resistance to the surface of high speed industrial rolls, used in printing, textiles and papermaking.

Electronics

Superior temperature resistance combined with low basis weight and even fibre distribution make Optimat 206 a key material in the development of the next generation of printed circuit boards.

Tecnofire Intumescent

Intumescent materials have the property that they expand considerably when heated. This increase in volume is much larger than the normal thermal expansion shown by other materials. There are several mechanisms that produce an intumescent reaction. The most common mechanism results from the expansion of chemically bound water molecules.

The intumescent reaction can provide a means of producing an expanded insulating char which is resistant to attack by fire. Ideally the reacted intumescent will be resistant to erosion by the gas turbulence that exists in fire situations and will not degrade within the fire resistance period required.

Technical Fibre Products have developed a range of products which have extended the potential applications for intumescent products beyond their traditional gap filling role. The products manufactured by TFP are based on a combination of exfoliating graphite and mineral fibre. In fire conditions, the graphite increases considerably in volume leaving a stable insulating layer of mineral fibres.

The range includes products with expansion characteristics of 3:1, 6:1, 9:1 and 18:1. All products in the range are durable, have low smoke toxicity and have been formulated with the environment in mind. Products can be supplied in a wide range of roll or sheet sizes.

Tecnofire intumescent are compatible with most resin systems. For pultrusion applications, they can be supplied laminated to polyester or glass veils to give improved strength, processing characteristics and surface appearance.

Prepreg Advanced Composites Group Ltd

Prepregs are available in a wide range of woven and unidirectional carbon, glass, aramid, Dyneema®, ceramic fabric, metallic fabric and hybrid reinforcements. Conventionally prepreg requires a high temperature cure. This has significant disadvantages including, high cost, micro cracking and thermal distortion. Low temperature moulding Prepreg LTM® has been developed by Advanced Composites Group which can greatly reduce or eliminate these problems.

Processing LTM® Prepreg

Pattern or mould is prepared in normal way using wood, plaster, syntactic foam, GRP etc.

Lay up LTM® prepreg as normal prepreg. Apply vacuum bag and carry out oven or autoclave cure, initially at ambient, or low elevated temperature (up to 60°C) as desired. Remove LTM® mould/component from pattern/mould Postcure free-standing to maximum temperature required (up to 200°C approximately).

Use as mould or component up to 200°C approx.

Alternatively, LTM® Prepreg can be hot-press moulded using short mould cycles to improve productivity compared to normal prepreg.

LTM® Prepreg can be made from any form of carbon, aramid, or glass fibre reinforcement available. The range of variants of resin systems is shown in the following table. Design data for Advanced Composites Group prepregs are given in chapter 6.

**Fig 1.13 Prepreg Advanced Composites Group -
Product Selection Guide**

	LTM10 Series	LTM20 Series	LTM30 Series	LTM40 Series	LTM100 Series	MT Series
Resin Type	High Temp Service, Low Temp Cure, Epoxy	Toughened, Low Temp Cure, Epoxy	Intermediate Temp service, Phenolic resistant, Low Temp Cure, Epoxy	High Temp, Toughened, Low Temp Cure, Epoxy	High Temp Service, Low Temp Cure, Cyanate Ester	Toughened, 120°C Cure, Epoxy
Typical Cure Temp	20°C - 80°C	30°C - 60°C	40°C - 60°C	50°C - 80°C	75°C	120°C
	68°F-176°F	86°F-140°F	104°F-140°F	122°F-176°F	167°F	248°F
Maximum Tg	210°C	130°C	170°C	>200°C	370°C	150°C
	410°F	266°F	338°F	>392°F	698°F	302°F
RT Mech. Performance	Good	Excellent	Good	Excellent	Good	Excellent
120°C/248°F Wet Mech Performance	Excellent	Poor	Excellent	Excellent	Very Good	Poor
250°C/ 482°F Mech. Performance	N/A	N/A	N/A	N/A	Excellent	N/A
Thermal Stability Performance	210°C	120°C	170°C	> 200°C	250°C	100°C - 150°C
	410°F	248°F	338°F	>392°F	482°F	212°F-302°F
	Prolonged Exposure	Prolonged Exposure	Prolonged Exposure	Prolonged Exposure	Prolonged Exposure	Prolonged Exposure
Suitable for RT Service & Machining	Postcure Required	No Postcure Required	Postcure Required	Postcure Required	Postcure Required	Postcure Required
Out Life at RT	2 - 30 days	2 - 30 days	2 - 10 days	3 - 30 days	3 days	14 - 90 days
Storage Life at -18°C	1 year	6 months	6 months	6 months	6 months	1 year
Typical Applications	High Temp service Tooling and Parts	Intermediate Temp service Tooling and Parts	Tooling for "Aggressive" Prepreg Materials e.g. Some Phenolics	High Temp service parts	Ultra high temp Tooling and Parts	Parts
Toughness	Fair	Good	Fair	Fair	Fair	Good to outstanding
Flame Retardency	Poor	Poor	Poor	Poor	Outstanding	Poor
Dielectric Properties	Fair	Fair	Fair	Fair	Very Good	Fair
Out gassing	Fair	Fair	Fair	Fair	Very Good	Fair

Internal mould release agent (IMR)

Product dissolved in the resin mix, highly soluble in the carrier solvent ie styrene. During cure product drops out of solution and migrates to the surface due to volumetric shrinkage, pressure and temperature.

The following criteria are desirable:

- Total solubility in the system
- Minimal effect on cure
- Minimal effect on colour
- No negative and preferably positive influence on properties.
- No silicone, non-stearate and no natural waxes which would adversely affect painting or bonding with adhesives.
- A consistent clean release with no build-up or mould fouling caused by deposits.
- Measurable reduction in cycle time.

Using an internal requires careful introduction. Each release agent application is not an individual event it is part of a long running sequence. Each moulding relies as much on the previous moulding as it does on the IMR it deposits during its own cycle. (This is a continuous process in pultrusion).

IMR's are more commonly associated with mechanised processes, but can assist in difficult highly detailed hand lay-up mouldings. One major advantage is consistency and in any high volume production, externally applied release systems rely solely on operator skill, not always meeting the requirements of the de-signer or formulating chemist.

Applications are RTM, cold press and pultrusion.

External Mould Release Agent

Externals are applied to the mould surface and as such rely on care and attention during application to ensure successful release. The following criteria are desirable:

- Easy application with clear instructions.
- Harmful organic solvents should be avoided if possible.
- Good wetting of mould surfaces.
- Surface tension should be correct for gel coat application.
- Quick drying.

Chemical Release Co Ltd

A major supplier of release agents to the composites industry is **Chemical Release Co Ltd (CRC)**. They are specialists in this field and have been selected to illustrate these materials. CRC will supply or develop specific release agents for all moulding processes

Whether release agents are incorporated into the moulding resin or applied externally to the mould surface, correct selection can optimise not only cycle time, but also consistency of surface finish maintaining detail, minimising post-mould operations prior to painting or bonding and help fibre wet out. When considering a release system as well as identifying product performance requirements, it is pertinent to consider: In manufacture are any harmful by-products generated or pollution caused, is it safe to store, transport and use, in use what pollution is generated and what will it cost to deal with.

To work well a release agent must fit within the scope of the overall process and be cost effective. Application should be simple with clearly defined steps, drying times should be short and cure time, if any must not delay the process. The product must not contain any ingredients which will affect the final product properties or post mould treatment, traces must be totally removable. Finally the release from the mould surface must be smooth and clean, without any pre-release prior to cure. For internals addition rates vary with mould material, complexity of moulding, other additives such as fillers. In general metal moulds require less and composite moulds require more. Quality is paramount, release agents are a small cost on the total product, but if out of specification the consequential loss is many times the value of the release agent.

All of CRC products are manufactured to ISO9000 standards. Follow manufacturers instructions regarding shelf life, storage and mixing. CRC only sell release agents and can supply or develop specific release agents for all moulding processes, in all thermoset resin, rubber and thermoplastic matrices. They

Process	Resin Matrix	Product	Inter-	Application, addition level
Pultrusion	Polyester / Vinyl ester /	PAT654/M	INT	1% to 2% on resin
	Epoxy or Vinyl ester	PAT 656 range	INT	2% on resin
	Phenolic	PAT 656/A or 659/B	INT	2% on resin
Filament Winding	All thermosets	PAT 607	EXT	Wipe over surface
RTM / ColdPress	Polyster gel coat	PAT 672	INT	0.25% to 0.5%
RTM / Cold Press / Casting	Polyester	PAT 657/C	INT	1 % to 1.5 % on resin
	Epoxy (hot or cold)	PAT656/3	INT	2% on resin
SMC / DMC	Polyester	PAT 668	INT	2% on matrix
	Phenolic	PAT 659/B	INT	2 % on resin
HLU / SU	Polyester	PAT 623/B	EXT	Wipe on, polish off
	Epoxy	PAT 607	EXT	Wipe on
	Phenolic	PAT 921/A	EXT	Wipe on polish off (may be used with inter-



- Easy to polish.
- Minimal transfer to moulding.
- Predictable multiple release.

Wax external release agents are used typically in low volume manufacturing where products are individual and cycle times are not critical.

Semi-permanent release agents are used for high volume production where surface finish is critical and mould turn around needs to be quick. This type of release agent such as **Marbocote**, supplied by CRC, will give multiple releases because it bonds to the mould to give a micron thick chemically inert surface.

Marbocote External Release System

The Marbocote system has unique, characteristics: -

1. Non aromatic, and environmentally friendly.
2. Performance equals or exceeds that of other semi permanents. The application technique allows large areas to be covered without concern for streaks, which can be totally removed when applying the final coat or buffing after cure.
3. Smooth consistent finish gives more cycles between application
4. Surface finish can be controlled to avoid pre-release.

Basic Application for Sealer and Release Agent

Always work with clean lint free cloths, change the application cloth twice daily or if it dries out.

1. Wipe over the tool surface, no problem to do large areas or two or three small moulds at a time, so that the surface is wet, avoid runs & pools, do not over apply.
2. Allow the release to separate slightly or de-wet the surface before wiping. Some small areas of the mould will look dry, (normally in about 1-2 minutes) then using a clean cloth gently wipe over the surface with the aim of spreading the liquid and removing the excess rather than wiping it completely dry.
3. Allow 15 minutes between coats. Leave for 1 hour after the final coat for best results. Lightly buff to achieve best finish.

MARBOCOTE Semi permanent Release Agents From			
Process	Resin Ma-	Product	Type
All Processes	Epoxy Polyester Vinyl ester Phenolic	RS415	Mould Surface Sealer
		GRP	Release Agent to retain
		445	Release Agent to retain
		75 CEE	For High Slip & Condi-

PRODUCT CODE - PAT 607/PCM

DESCRIPTION

External release agent, water based, white opaque liquid. 7% active ingredients

Resin types Polyester / epoxy / phenolic - all thermosets

Processes

Filament winding, compression moulding, contact moulding

Special advantages

- no silicone, natural wax or metallic stearate
- safe to use, store & transport, simple instructions
- wets all surfaces evenly without forming puddles
- quick drying with no waxy deposits
- easy to remove from moulding - wash with water
- stable solution - very little settlement

Notes

Room temperature storage, avoid freezing, Shake well to re-disperse, See separate sheet

PRODUCT CODE - PAT 654M

DESCRIPTION

Internal release agent, brown liquid at 25°C, paste consistency at lower temperatures, 100% active ingredients

Resin types: polyester, vinyl ester, Modar

Processes : Pultrusion (See pultrusion application sheet)

Special advantages

- No silicone, natural wax or metallic stearate
- Safe to use, store & transport
- Increased fibre wet out - better physical properties (10%)
- Good solubility & no effect on resin- non acidic - no die erosion, no reaction with fillers or catalyst
- Good paint adhesion for on line painting
- Better surface cure -Good surface finish, good weathering, good dispersion of fillers
- Lower scrap rates, easier running, less downtime, longer die life, lower pull force.

Competitive products

Zinc stearate - poor paint adhesion, poor surface finish, white powder. with limited solubility in system, lower surface hardness of laminate, high aspect ratio uses extra resin to wet out

Notes : Store at 20°C, Stir well to re-disperse, add to resin & mix well before any other component.

PRODUCT CODE - PAT 657C

DESCRIPTION

Internal release agent pale yellow liquid, 100% active ingredients

Resin types: polyester

Processes: RTM, Casting, Non-gel coated mouldings or back face of gel coated moulding.

Special advantages

- No silicone, natural wax or metallic stearate
- Safe to use, store & transport
- Better physical properties
- Improved filler dispersion
- Low cost
- No effect on resin gel times

Notes: Store at 20°C. Stir well to re-disperse. Add to resin & mix well before any other component. See notes on internals. Treatment of mould with an external may be necessary dependant on mould construction, for metal every 100 mouldings, for composite every 40 mouldings. Addition rate 1% to 1.5% by weight on resin

Release agents for **PULTRUSION**

OVERVIEW

The pultrusion process is the only FRP process which has to use an Internal Mould Release agent (IMR) traditionally zinc stearate and acidified esters have been used, however problems with surface finish, adhesive bonding, poor weathering properties and rapid die erosion have led to the development of a new generation of IMR's.

Our products have low pull forces, good surface finish and extended die life. Larger profiles can be made on your existing machines.

PAT release agents do not increase resin viscosity, they are liquids not powders.

KEY BENEFITS

- Low pulling force, long die life
- Good surface finish
- Improved filler dispersion and glass fibre wet out
- No effect on painting or bonding
- Easy and safe to use, store and transport
- Non-acidic, all fillers including carbonate types can be used

PRODUCTS

PAT GRADES	ADDITION LEVEL	RESIN
PAT-672 & PAT-654/M	0.5 to 1%	Polyester
PAT-654/M	0.5 to 2%	Vinyl Ester
PAT-672 & PAT-656/B3R	2%	Epoxy
PAT-659/A	0.5%	Phenolic (water)
PAT-659/B	0.5%	Phenolic (solvent)
PAT-654/M	1%	Modar

PULTRUSION GENERAL INFORMATION

Always pre-coat the die before starting with release agent and apply to dry fibres just before the wet fibres enter the die.

When finishing production or storing the die coat with our release agent (which is guaranteed neutral pH).

When starting up add double release agent for the first resin mix, it is important for a smooth start up.

Also we have noted that our customers add additional release at difficult times for instance if due to poor tex control and glass packing is too high.

The mechanism is that thermoset resins cure from liquid phase to solid through a process of polymerisation and cross-linking. During this change the release agent is forced to the surface. PAT release agents are temperature stable and formulated to be mobile in the curing resin. Once cured there is no blooming or migration of the release agent.

An important note is that using our neutral products basic fillers such as calcium carbonate can be used with no reaction.

Our release agents should be stirred before use and then added to the resin and mixed well. Warm temperatures are good for this type of additive (low temperatures cause increase in viscosity).

Release agents for *FILAMENT WINDING*

OVERVIEW

Filament winding on polished, smooth steel mandrels needs a special release agent. The release function is normally achieved with:

- 1) Wax or silicone grease, which gives build up problems and contaminates the wound tube or pipe.
- 2) Release film which is wound onto the mandrel, this leaves marks in the bore or I.D. and often can get trapped inside the bore and is difficult to remove.
- 3) Semi permanents do not have necessary slip and are generally not used.

KEY BENEFITS

- Water based, no environmental concerns
- Contains no silicone or natural wax
- Excellent wetting of all surfaces
- Transfer to moulding can be washed off with water
- Simple to apply, quick drying
- Excellent release
- Tube has very smooth bore

PRODUCT

PAT-607/PCM is specially developed water based micro emulsion, no silicone or natural wax is used and the PAT-607/PCM film forms on polished and chromed steel perfectly.

As well as this application because any transfer to moulding can be washed off simply with water, it is also used for epoxy casting and aerospace moulding.

PREPARATION

- 1) Ensure surface to be treated is clean & degreased.
- 2) Apply PAT-607/PCM with a lint free cloth over the surface using slight pressure, and then wipe over again with the same cloth to remove excess, if streaks appear the application is too slow, or too much has been applied. To avoid streaks go over the area being treated again with the wet cloth, this keeps the material well distributed as it dries and minimises streaks. Good application technique comes with practice.
For filament winding it is best applied to a spinning mandrel.

Alternatively spray a thin even coat. For either method aim for a drying time of approximately 2 minutes at 20° C, this shows the correct amount has been applied.

For either method thin coats are essential for a good surface finish to avoid build up.

- 3) If required polish with a clean lint free cloth.
- 4) Leave for 10 minutes at room temperature and repeat to achieve a total of 5 coats.

PRODUCTION

- 1) Spray or apply a coat using same technique.
- 2) Allow to dry and if necessary polish with a lint free cloth.

TECHNICAL ASSISTANCE

All products have been rigorously tested to meet your performance expectations and are manufactured to ISO 9001 quality standard and also ISO 14001 environmental control standard.

For further information or assistance regarding filament winding please contact us, we are always happy to help.

Release agents for RESIN TRANSFER MOULDING & COLD PRESS MOULDING

OVERVIEW

External release agents have a limited life and when re-applying the release agent the mould is out of production. PAT internal mould release (IMR) is added directly to the gel coat and resin to greatly extend the number of de-mouldings between external release agent applications. This keeps the mould in production for longer, and the surface quality of the moulding is improved and more consistent.

KEY BENEFITS

- No effect on cure
- No effect on pigment
- Totally soluble and stable in the resin, no separation
- No negative influence on laminates properties
- Good surface finish, excellent release
- No pre release
- Easy and safe to use, store and transport
- Inhibits resin build up on mould
- No effect on painting or bonding

PRODUCTS

PAT GRADES	ADDITION LEVEL	RESIN
PAT-657/C	0.6 to 1%	Polyester & DCPD
PAT-656/B3R	1.2%	Epoxy
PAT-672	0.5 to 1%	Polyester gel coat

GELCOAT

Add 0.5% by weight of PAT-672 to gel coat and mix well, it is better to add to a large quantity of gel/resin to get the best accuracy when adding small percentages. By having an IMR the external release applied will last longer and the surface will be improved.

Notes

The addition level can be adjusted; it can be increased up to the point where the surface feels greasy. Normal addition range is 0.5% to 1% based on gel/resin weight.

RESIN

In the RTM process surfaces which are not gel coated suffer from abrasion of the release agent when the mould is closed caused by the glass fibre. This leads to rapid build up of polymerised styrene, partially cured resin and other contaminants.

Cleaning the build up usually involves solvents and aggressive scrubbing which will damage the surface.

By using 0.6% of PAT-657/C in the resin (PAT-656/B3R at 1.2% for epoxy resin), the build up is greatly reduced and cleaning is necessary much less frequently.

Addition level can be increased up to 1% as necessary, a greasy surface means too much is being added and should be reduced slightly.

MECHANISM

Essentially PAT internal mould release agents are soluble in the liquid resin, as polymerisation and cross linking occurs during the cure process, our product drops out of solution and is forced to the surface.

PAT release agents do not affect resin/gel coat bond. All products have been rigorously tested to meet your performance expectations and are manufactured to ISO9001 standard and also ISO 14001 environmental control standard.

Lantor® nonwovens for the FRP industry:

1. Lantor Coremat® for hand lay-up and spray-up
2. Lantor SORIC® for closed moulded systems
3. Lantor FinishMat® surfacing veils

1. Lantor Coremat®

Lantor Coremat® is a nonwoven core material designed to replace glass in hand lay-up and spray-up laminates. Using Lantor Coremat® saves production time and costs. Furthermore, Lantor Coremat® adds an impressive stiffness to your product and minimizes the use of resin as all Lantor Coremats are filled with microspheres.

Why use Lantor Coremat®?

- improved stiffness
- resin and weight savings
- constant quality and thickness
- regular surface
- better drapeability
- production efficiency
- certified by independent renowned institutes, such as Lloyd's, Registro Italiano Navale, Det Norske Veritas, American Bureau of Shipping.

Working with Lantor Coremat®

Lantor Coremat® requires no special tools or skills other than your current craftsmanship. The first layer of Lantor Coremat® is simply laid down onto the wet outer layer of glass fibre and impregnated with resin. The styrene soluble binder quickly dissolves and the material can be easily moulded into any shape. In fact it shapes itself during roll-out. Then the finished layers of glassfibre are applied and rolled out to finish the lamination. The result is faster lamination with reduced weight and resin usage!

Function of Lantor Coremat® in Laminates

Lantor Coremat® improves stiffness by eliminating several layers of glass fibre.

No unnecessary cutting, impregnating and rolling of several layers of glass fibre to obtain the thickness of the core!

Applications of Lantor Coremat®

Lantor Coremat® can be used to replace the core in laminates of e.g.: boats and yachts, ski boxes, horse trailers, swimming pools, kit cars, cladding panels, telephone booths, wind mills, airplanes, trailers, and many more. In thin laminates with Plywood and foam, the core can also be replaced by Lantor Coremat®.

Resin compatibility of Lantor Coremat®

- polyester
- vinylester
- epoxy

Product range:

Lantor Coremat® XX and XW - The Standard (width 100 and 127 cm)

	P24241 1 mm	P24302 2 mm	P24303 3 mm	P24304 4 mm	P24305 5 mm
Resin: kg/m ²	0.6	1.2	1.8	2.4	3.0

Lantor Coremat® Xi - The new standard

Lantor has improved its traditional Coremat XX with more drapeable properties and by incorporating a Resin Indicator. This new standard, Lantor Coremat® Xi, allows you to control the impregnation of your laminates and so to optimize production and to minimize the use of resin.

- Resin Indicator
- Extra certainty

	R3030 2 mm	R3030 3 mm	R3030 4 mm	R3030 5 mm
Resin: kg/m ²	1.2	1.8	2.4	3.0

Lantor Coremat® XM- Better drapeability

The microspheres are configured in a hexagon pattern so that the most flexible mat is obtained with a microspheres load up to 55%. The distinctive hexagon structure allows for rapid and easy impregnation in most complex mouldings.

- Better drapeability
- Extra resin savings.

	M55002 2mm	M55003 3 mm	M55004 4 mm
Resin: kg/m ²	1	1.5	2

2. Lantor SORIC®

Lantor SORIC is a nonwoven core material designed for closed moulded systems, it enables closed moulding production of nearly all GRP products, in particular in vacuum injection and pressure injection. Also Lantor SORIC® saves production time and costs. Furthermore, Lantor SORIC® adds an impressive stiffness to your product and minimizes the use of resin as all Lantor core-materials are filled with microspheres. In fact Lantor SORIC® is the only product which combines impressive resin flow properties in closed moulding together with low weight core properties in the end product.

Why use Lantor SORIC®?

- Impressive resin flow
- Pressure resistant
- Improved stiffness of laminates
- Resin and weight savings
- Constant quality and thickness
- Regular surface
- Production efficiency
- Processing temperature up to 140 °C

Applications of Lantor SORIC®

Lantor SORIC can be used to replace the core in laminates of e.g.: boats and yachts, ski boxes, horse trailers, swimming pools, kit cars, cladding panels, telephone booths, wind mills, airplanes, trailers, and many more

Resin compatibility of Lantor SORIC®

- polyester
- vinylester
- epoxy

Product range

	SORIC	SORIC	SORIC	SORIC
	2 mm	3 mm	4 mm	5 mm
Resin consumption kg/m ²	1.2	1.8	2.4	3.0

3. Lantor FinishMat® surfacing veils

Lantor FinishMat® surfacing veils incorporate a range of synthetic technical nonwovens that find wide application in GRP tank and pipe winding, pultrusion, closed moulding and vacuum moulding processes.

Given the physical and chemical environment to which GRP products often are exposed, these processes typically demand a high level of specialised properties for chemical resistance and surface enhancement. Lantor FinishMat® surfacing veils provide these properties and are used by leading GRP companies world-wide.

Why use Lantor FinishMat® surfacing veils?

Lantor FinishMat® surfacing veils assure excellent chemical and weather resistance, high tensile strength properties, quick resin pick-up and good resin retention. Lantor FinishMat® surfacing veils offer rapid wet-out and uniform surface quality for a proper resin-rich barrier layer.

Processes:

Filament winding:

Filament wound GRP pipes and tanks require corrosion resistant, glass free inner and/or outer liners to guarantee an extended life time. Lantor® BV offers a comprehensive range of nonwoven liners which combines excellent protection together with excellent processing properties.

Pultrusion:

Pultruded profiles require an excellent surface quality: smooth surface, weather resistance and no print through of the glass fibres pattern. This can be achieved by applying the Lantor FinishMat® surfacing veils, which also provide excellent processing properties.

Closed moulding:

In closed mould processes the surface quality is extremely important. This can be achieved by applying the Lantor FinishMat®, a binder-free needle punched acrylic surfacing veil - either with or without a gel coat. Lantor Finishmat® provides excellent surface finish, good weather resistance and can be easily conformed into complex designs. The veils can be applied after the layer of cured gel-coat or gel-coat-free with pigmented resin systems.

For contact details see reference section.

Curing Agents for UP resins from Akzo Nobel Chemicals

In ambient temperature processing of unsaturated polyester (UP) resins, a wide variety of methods are used. This wide choice and the large variety of end products in which these resins are used requires that the processes be optimized. One of the main components in ambient temperature UP resin formulations is the cure system: the combination of a peroxide / accelerator / promoter / inhibitor. The role of the cure system in the processing of UP resins, and the fact that many problems in processing can be overcome by the correct selection of the cure system, is often underestimated. The differences in various catalyst systems used in ambient temperature curing of UP resins and the importance of selecting the proper cure system will be discussed.

INTRODUCTION

UP resins are used in the production of a wide variety of products. Three main application areas are:

- Non-reinforced applications e.g. gel coats.
- Filled applications e.g. polymer concrete, synthetic marble.
- Reinforced applications e.g. boats, pipes, tanks, tubs & showers.

It is possible to make this wide variety of products due to the rather easy way in which UP resins can be processed. Although there are numerous types of processes such as casting, hand-laminating, sprayup, resin transfer moulding, continuous laminating, filament winding and cold press moulding, the actual processing of the UP resin is the same. A liquid resin applied to a mould or pattern is cured or hardened into a rigid plastic material. Although this seems rather simple, actual practice is very often different; a high degree of skill and a good knowledge of the process and raw materials is needed to make high quality products that meet market requirements.

The first choice is which type of UP resin to use. The physical and chemical properties of the end product are primarily determined by the chemical structure of the resin. For this reason a wide variety of UP resins are commercially available, ranging from general purpose orthophthalic based resins, to premium resins (e.g. isophthalic and dicyclopentadiene-based), to high performance resins (e.g. vinyl esters).

MEKP

The most commonly used organic peroxide in ambient temperature curing of UP resin is methyl ethyl ketone peroxide, commonly referred to as MEKP. First used in UP in the early 40's, its ease of use, availability, and overall good performance have made it the first choice as a catalyst for decades. MEKP formulations consist of two parts; the organic peroxide and the diluent. The diluent, which is actually the major component of MEKP formulations, consists mainly of plasticizers, glycols, and water. This is required in all MEKP formulations to ensure that the products are safe to manufacture, handle and transport.

Although no two MEKP formulations are the same, and a wide variety are available, a distinction can be made between two basic types of MEKP formulations.

MEKP formulations with hydrogen peroxide levels of 1.2-3.0%, and MEKP type-4 / MEKP type-3 ratios of 1.5-2.5, can be referred to as General Purpose MEKP.

The second type of MEKP formulations have hydrogen peroxide levels of 0.5-1.5% and MEKP type-4 / MEKP type-3 ratios of 0.5-3.0%. These are used in applications that have specific performance requirements, such as vinyl ester (VE) resins and gel coat resins, where standard MEKPs can give problems. Selecting the appropriate MEKP catalyst is the first requirement in developing an optimized cure system.

AAP

The other most commonly used ketone peroxide is acetyl acetone peroxide (AAP) [also known as 2,4-pentanedione peroxide). AAP is manufactured from acetyl acetone and hydrogen peroxide.

Commercially available products vary widely from manufacturer to manufacturer. Although many types of AAPs are feasible, mainly the cyclic form is found due to its chemical and physical stability.

Unlike MEKPs, AAP contains 10-20% water as part of the non-peroxide component. AAP has vastly different safety properties than MEKP and is classified as a non-regulated organic peroxide.

BPO

Dibenzoyl peroxide (BPO) is one of the oldest commercially available organic peroxides, and was the first peroxide used in curing UP resin. BPO is manufactured from the reaction of benzoyl chloride with hydrogen peroxide under aqueous conditions (Figure 4). The wet granular BPO is obtained as 70-80% active material with the remainder as water.

Dry BPO, i.e. 98%, is obtained by drying or removing water from the 70-80% material. Initially, 98% BPO was used in curing UP resin. Dry BPO dissolves very quickly in styrene / UP resin while wet granules do not. However the use of dry BPO is hazardous both to ship and handle. It was for this reason that various formulated BPO products were introduced. Today many such formulations are commercially available ranging from 50-78% granules, highly viscous BPO pastes (30-55%), 40% BPO emulsions and suspensions, and 20-35% fine BPO powders. Regardless of a formulation's BPO content, the active catalyst component is still BPO, and the large variations observed with different MEKPs are usually not found.

Optimal Catalyst Selection

In order to choose an optimal cure system for processing resins, one must realize what the various steps in the curing process are, what factors influence it, and which process parameters can be utilized to follow the cure. The curing of UP resin starts with the addition / mixing of the peroxide and the resin system (it will be assumed here that pre-accelerated resins are used). The generation of free radicals starts by the induced decomposition of the peroxide by the accelerator.

As the concentration of the radicals formed initially is low, the

Curing Agents for UP resins from Akzo Nobel Chemicals (cont)

majority will be consumed by the inhibitors present in the resin. Referred to as the inhibition time or potlife, any processing such as rolling, pouring, or laminating of the resin must take place during this phase.

As concentration of the free radicals increase, the inhibitors are consumed and the actual start of the polymerization or cure begins. This manifests itself by an increase in the viscosity of the resin leading to gelation. The time from mixing in the cure system until this gelation starts is called gel time. Gel time is a very important process parameter as the manufacturing of the product must be finished within this time. The polymerization reaction of an UP resin is an exothermic reaction, which means that the temperature in the product will increase after the gelation. The highest temperature achieved in the process is called the peak exotherm.

The speed of polymerization or cure is very strongly influenced by temperature. The higher the temperature, the faster the cure reaction will be. This will have a distinct influence on the total process time. Too high a peak exotherm should be avoided as this can cause failures in the end product such as:

- “White fibers” - adhesion failure between the UP resin and the glass reinforcement caused by rapid shrinkage of the resin.
- “Delamination” - caused by a boiling of the styrene monomer.
- “Exotherm cracking” - cracking due to excessive heat generation.

In general, dependent on the UP resin used, a peak exotherm of approximately 80 - 120°C (175 - 250°F) is acceptable.

After demoulding, the end product will show certain properties with respect to hardness, mechanical strength, chemical resistance and thermal stability.

These end properties are, in general, related to the residual styrene content in the product. This means that a high residual styrene content is an indication of an insufficient cure. A determination of the residual styrene content is therefore a good indication of the degree of cure of the UP resin.

During an ambient temperature cure, a full cure with a very low residual styrene content will in most cases be difficult to achieve. To achieve optimal end properties and/or a low residual styrene content, a postcuring of the end product at elevated temperatures may be necessary. In general, an optimal cure can be achieved within a few hours when the product is postcured at or slightly above the heat distortion temperature (HDT) of the UP resin used.

This text is extracted from :

OPTIMAL CATALYST SELECTION FOR AMBIENT TEMPERATURE CURING OF UNSATURATED POLYESTER RESINS

by Bryce Milleville, Research Manager, Akzo Nobel Research, Dobbs Ferry, NY.

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Trade name	Features	Delivery form	HLU/SU	RTM	Filament winding	Continuous laminating	Pultrusion	HPM	Polymer concrete	Bodyfillers	Coatings	Buttons	Gelcoats	Vinylesters
Butanox 28	very high reactive MEKP	liquid									x	x		
Butanox HBO-50	high reactive MEKP	liquid	x	x		x					x		x	
Butanox M-50	standard medium reactive MEKP	liquid	x	x	x	x			x		x	x	x	
Butanox M-60	standard medium reactive MEKP	liquid	x	x	x	x			x		x	x	x	
Butanox LA	low reactive MEKP	liquid	x	x	x	x			x		x		x	x
Butanox LPT	very low reactive MEKP	liquid	x	x	x								x	x
Butanox LPT-IB-94	very low reactive MEKP	liquid	x	x	x								x	x
Trigonox 44B	fast cure AAP	liquid	x	x		x			x					
Trigonox 113	medium reactive COX	liquid	x	x		x			x					
Trigonox HM	standard MIBKP	liquid			x	x	x					x		x
Cyclonox SLN-C	low reactive COX	powder									x			
Cyclonox BT-50	standard COX paste	paste								x				
Cyclonox 11	high reactive COX	liquid	x								x	x		
Cyclonox LE-50	standard medium reactive COX	liquid	x							x	x	x		
Cyclonox LR	low reactive COX	liquid	x							x	x	x		
Trigonox 51	AAP mixture with low peak exotherm	liquid	x	x	x				x					
Trigonox 61	fast cure MEKP/AAP mixture	liquid	x	x	x	x			x		x		x	
Trigonox 63	fast cure MEKP/AAP mixture	liquid	x	x	x	x			x					
Trigonox 71	low reactive ketone peroxide mixture, very low peak exotherm	liquid	x		x									
Trigonox 75	medium reactive MEKP. with reduced peak exotherm	liquid	x	x										
Trigonox 82	low reactive MEKP with very low peak exotherm	liquid	x	x	x									
Trigonox 524	AAP/ perester with efficient cure	liquid		x		x								
Lucidol CH-50 X	BPO powder for standard applications	powder	x	x			x		x					x
Lucidol CH-50 L	BPO powder for transparant applications	powder	x	x										x
Lucidol BT-50	standard BPO paste	paste								x				
Lucidol BL-50	very low water content BPO paste	paste								x				

Specialities

Cadox 40-E	pumpable suspension BPO	susp.	x	x	x				x					x
Lucipal 20	20 % BPO on filler	powder							x	x				
Trigonox KSM	high reactive perketal mixture	liquid					x	x						
Trigonox C	tert.butylperbenzoate	liquid					x	x						x
Trigonox 93	tert.butylperbenzoate/promoter	liquid		x		x	x							x
Trigonox BPIC-C75	percarbonate, high efficiency	liquid					x	x						x
Trigonox 141	high reactive, efficient perester	liquid					x	x						x
Trigonox 21	standard tert.butylperoctoate	liquid				x	x	x						x
Trigonox 21LS	Trigonox 21, for a long compound shelf life	liquid					x	x						x
Trigonox 42S	tert.butylperoxyisononanoate	liquid					x	x						x
Trigonox 42PR	tert.butylperoxyisononanoate/promoter	liquid		x		x	x							x
Trigonox 22-B50	standard perketal for a long compound shelflife	liquid					x	x						x
Trigonox 29-B50	standard perketal for a long compound shelflife	liquid					x	x						x
Trigonox K-80	cumenhydroperoxide	liquid				x								x
Trigonox 239	cumenhydroperoxide/ promoter	liquid												x
Perkadox 16	high reactive percarbonate	powder					x							x

MEKP = Methylethylketone peroxide, AAP = acetylacetoneperoxide, COX = cyclohexanone peroxide,
MIBKP = Methylisobutylketoneperoxide, BPO = dibenzoylperoxide



Llewellyn Ryland Ltd

Polyester Colour Pastes and Gel Coats

Founded over 200 years ago Llewellyn Ryland is one of the oldest manufacturing companies in England.

The long experience gained in the creation of highly refined lacquers, paints and varnishes evolved into the production of specialist colour pastes and gelcoats for the early reinforced plastics - composites industry.

Today, Llewellyn Ryland products are manufactured under a Quality System approved by the British Standards Institute (BSI) in accordance with BS.EN ISO 9002:1994.

Products manufactured by Llewellyn Ryland include the following

Polyester Colour Pastes

Over 27,000 different colours have been matched since 1951. A vast range of colours is kept in stock including the Llewellyn Ryland range of opaque, transparent and polychromatic/ metallic shades, the complete BS.5252 range and the RAL range of colours.

All colours are available in lead-free versions where required. A minimum order quantity for all stock colours is 1/2 kg, special colours only 5 kg.

Despatch time for standard colours is 24 hours.

Gelcoats / Flocoats

Polyester gelcoats in Clear, White and any colour in brush and spray viscosities.

Polyester flocoats in Clear, White and any colour in brush and spray viscosities - and also textured / slip-resisting versions.

Modar gelcoats.

A minimum order quantity for all colours/grades is only 25 kg.

Mould Preparation Products

PVA release agents available in Clear, Blue, Glossy or Matt.

Bonding Pastes

Specialised products for bonding GRP/GRP, GRP/PVC, GRP/ timber, GRP/metal, GRP/PU, etc.

Standard Colour Range

The Llewellyn Ryland Standard Colour Range has evolved over the past 40 years as a most popular selection of colours used in a wide variety of applications for composite mouldings.

In addition to the 83 colours listed in Llewellyn Ryland Standard Colour Range, organic based variants where applicable are available when increased lightfastness is required.

All Llewellyn Ryland colours are available as polyester colour pastes (minimum order only 1/2 kg) and in a wide range of polyester colour gelcoats (minimum order only 25 kg) - both with very quick delivery.

BS.5252 Colour Range

The British Standard BS.5252 establishes a framework within which 237 colours have been selected as the source for all building colour standards and the means of co-ordinating them.

A colour is only standardized when it is included in another British Standard, such as those derived for
Paints (BS.4800),
Vitreous enamels (BS.4900),
Plastics (BS.4901) and
Sheet and Tile flooring (BS.4902).

Each separate standard contains only a proportion of BS.5252.

The BS.5252 framework itself locates and relates the colours in terms of selected steps in the visual attributes of hue, grey-ness and weight.

In addition to the 237 colours listed in the BS.5252 colour range, organic based variants where applicable are available when increased lightfastness is required.

All BS.5252 colours are available as polyester colour pastes (minimum order only ½ kg) and in a wide range of polyester coloured gelcoats (minimum order only 25 kg) - both with very quick delivery

RAL Colour Range

RAL was established in Germany in 1925 as a committee for rationalizing terms and conditions for orders and deliveries. RAL was a common foundation of industry, trade and public authorities. The first range of German industrial colours was given into the custody of RAL in 1927

Whilst the RAL colour range may have originated in Germany, the colours are used as standards in all West European countries and consequently in all countries throughout the world trading with Europe.

The 175 colours illustrated are relevant to composites manufacture with applications in land transport, machinery, architecture, design, etc. Please contact us if you require any further information regarding the RAL colour range.

In addition to the 175 colours listed in the RAL colour range, organic based variants where applicable are available when increased lightfastness is required.

All RAL colours are available as polyester colour pastes (minimum order only ½ kg) and in a wide range of polyester coloured gelcoats (minimum order 25 kgs) - both with very quick delivery.

2 Properties of Composites

Mechanical Characteristics

- Strength and Stiffness
- Fatigue
- Creep
- Impact

Physical

- Fire
- Thermal Expansion

Environmental

- Temperature effects
- Corrosion

- chemical
- galvanic
- stress

Moisture effects

- on general properties
- blistering
- rain erosion

Weathering

Lightening

Mechanical Characteristics

Strength and Stiffness

Composites are not homogeneous, their properties are dependent on many factors, the most important of which are type of fibre, quantity of fibre (volume fraction) and the degree of fibre alignment. It can be seen from the typical stress/strain curve (fig 2.1) that they are generally completely elastic up to failure and exhibit neither a yield point nor a region of plasticity. They tend to have low strain to failure. The resulting area under the stress/strain curve, which represents the work done to failure, is relatively small when compared to many metals. This may be construed as a disadvantage to those more experienced with working with materials which have a substantial amount of 'yield' available to accommodate obscure local stresses. In steel design these may simply cause local yielding and thus dissipate the stress and hence be ignored. However with composite materials as with concrete, timber, cast iron etc. the designer must ensure that all circumstances have been taken into account. In any event although the steel designer may have 10 or 15 % strain to failure available it is rare that it may be utilised. Normally the design would be restricted to probably less than 0.5% strain

As the examples in fig 2.1 are unidirectional composites the stress / strain curves apply only in the direction in which the fibres lie. At right angles to the fibre direction the stress / strain curve is profoundly different, it is more closely associated to that of the matrix material.

The families of carbon, aramid and glass fibre reinforcements are conveniently segregated by their Young's Modulus into three quite separate bands. The carbon fibres are always highest, the glass fibres are always lowest and aramid fibre composites lie in between the other two

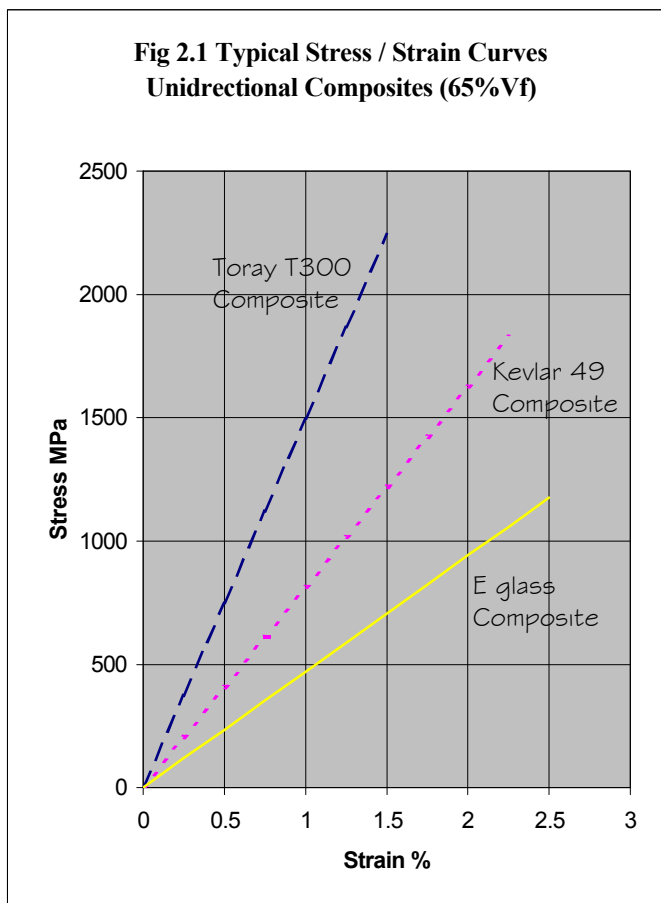
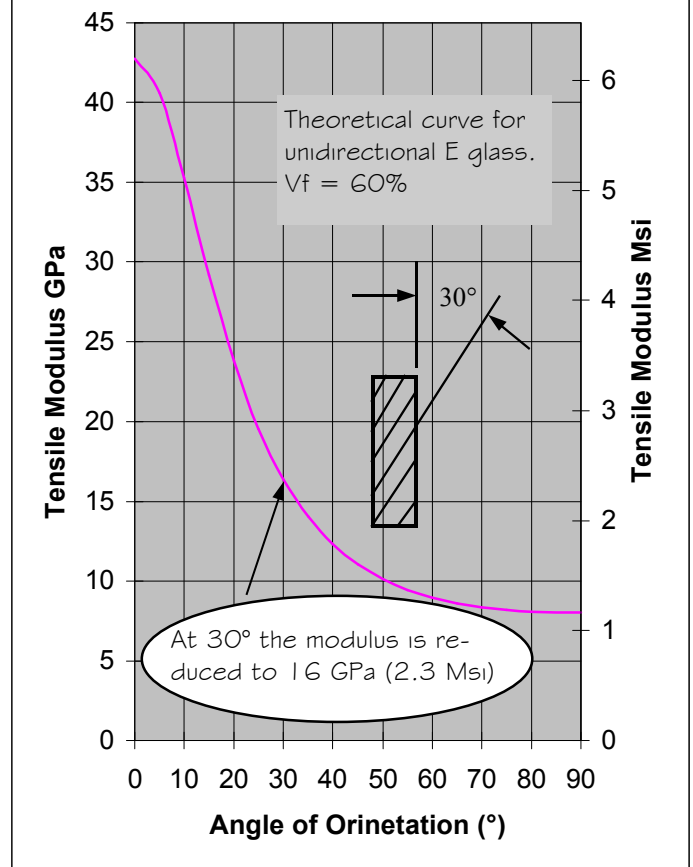


Fig 2.2 Effect of Fibre Orientation on Tensile Modulus



Glass fibre composites

- Effect of fibre volume fraction and orientation

The properties of composites are dependent on the properties of both the fibre and the matrix, the proportion of each and the configuration of the fibres. If all the fibres are aligned in one direction then the composite is relatively stiff and strong in that direction but in the transverse direction it has low modulus and low strength. When a unidirectional composite is tested at a small angle from the fibre axis there is a considerable reduction in modulus. This is illustrated in fig 2.2. If the stress is applied 10 degrees off-axis from then unidirectional glass fibre the tensile modulus is reduced by about 19%. At 20 degrees off-axis the modulus is reduced to about half of the modulus in the direction aligned with the fibres. The message is very clear, that unidirectional composites must be manufactured with a high degree of accuracy to ensure that the fibres are precisely aligned with the direction of the stress.

A similarly shaped, but more pronounced, curve occurs for laminate tensile strength when tested off-axis. This is due to the greater difference between the strengths of the fibre and matrix than between their moduli.

Fig 2.3 & 2.4 show the effect of fibre volume fraction and reinforcement configuration on strength and stiffness. Four types of reinforcement are shown, chopped strand mat, woven roving, (bi-directional), unidirectional woven roving and continuous roving. This data has been generated from 'unit strength' and 'unit modulus' data in BS 4994 and BS6464 for polyester and epoxy glass fibre laminates. In these standards the modulus and strength of laminates have each been characterised according to the mass of reinforcement used. This is valid for an appropriate range of fibre volume fractions.

The constant values have then been used to produce the curves shown in the figures. Unidirectional laminates have the highest modulus and strength (if tested parallel to the fibre axis). At right angles to the fibre axis the properties are of course considerably lower. (see fig 2.2) Bi-directional reinforcement has next highest stiffness and strength. But only in the orthogonal directions. At an angle of 45 degrees to the fibre axis the properties are much lower (theoretically 25% of the value in the fibre direction). Generally with such laminates it is important to ensure that they are only stressed in the fibre direction.

Random mat laminates (chopped strand mat and continuous strand mat) have the lowest stiffness and strength. But the properties are in theory equal in all directions in the plane of the laminate. The use of such materials simplifies the design process considerably and it is usual to assume that they are isotropic (in the plane of the laminate, not through the thickness).

In practice it is very difficult for the reinforcement manufacturer to achieve a perfectly random distribution of the fibres. There is usually a slight bias in favour of either the direction in which the reinforcement mat has been manufactured, or the transverse direction. The bias tends to be consistent for a particular manufacture as it is dependant on the details of their particular process. In order to ensure that a bias is avoided it is prudent to lay successive layers of mat at right angles to each another.

It can be seen in Fig 2.4 that E glass fibres (which have a modulus of about 70 GPa) produce composites with modest moduli which in the case of unidirectional fibres and the highest feasible fibre volume fraction of say 0.7, gives a modulus of 50 GPa. At right angles to this, in the transverse direction, the modulus approaches that of the resin itself at about 4 GPa. Figs 2.4 to 2.6 have been plotted from data obtained from ref 1 in which laminates made from polyester resin and E glass fibre are characterised. Unidirectional reinforcement was used in a woven format so that there was only a tiny amount of fibre in the transverse direction (weft).

Conversion from Mass fraction to and from volume fraction is given in chapter 4.

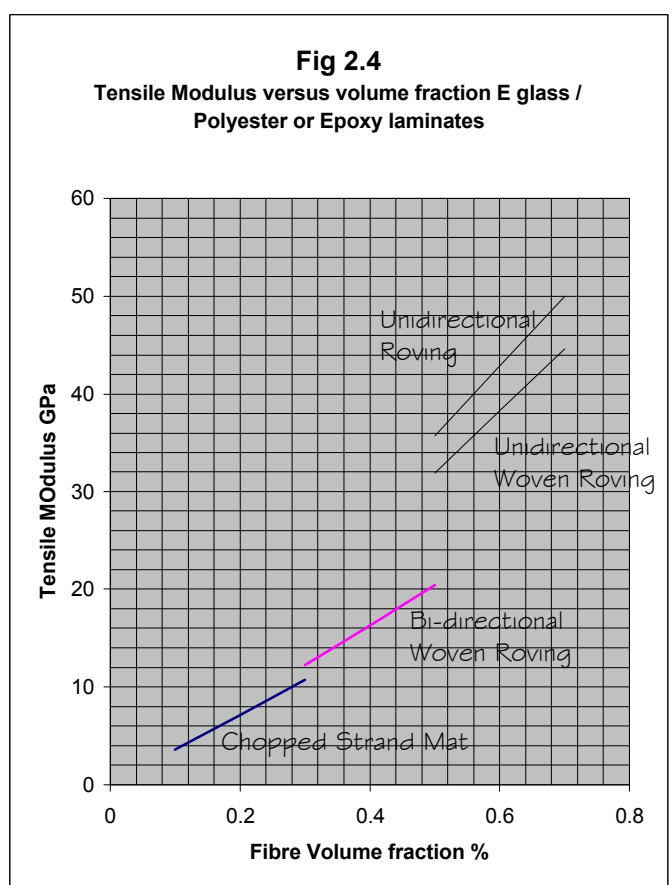
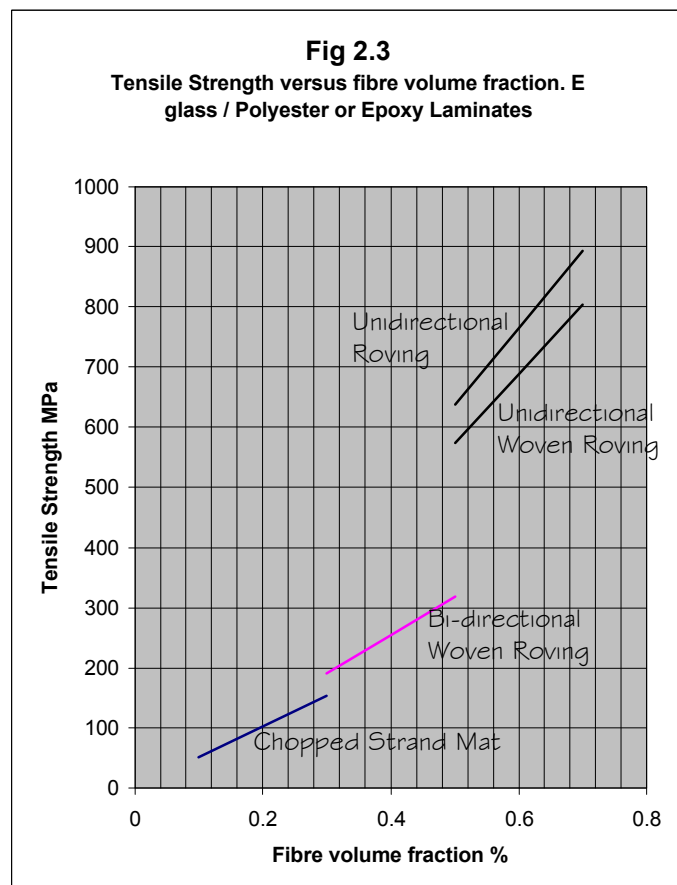
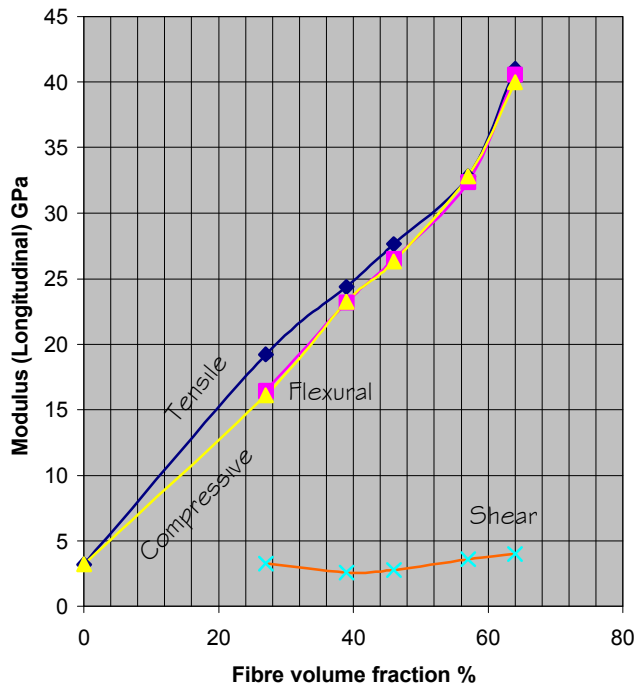


Fig 2.5 Longitudinal Modulus versus fibre volume fraction Unidirectional Woven E glass / polyester

Ref 2.1



A comparison of the data in Fig 2.5 for tensile modulus of unidirectional woven roving may be made with Fig 2.4 (from a different source). They are obviously very similar. It can also be seen that shear modulus is independent of fibre volume fraction.

The Tensile, Compressive, Flexural and Shear strengths of unidirectional E glass/Polyester laminates is illustrated in Fig 2.7 for a range of fibre volume fractions. It is clear that tensile and flexural strengths are highly dependant on fibre content. Although compressive strength has some dependence on fibre volume fraction it is less significant than for either tensile or compressive strengths. It is somewhat surprising that shear strength is independent of fibre volume fraction. Tensile and flexural strengths are effectively the same as one would expect as the lay-up is the same through the thickness. However the compressive strength is significantly lower. This is due to the local buckling of the fibre filaments

The effect on Poisson's ratio of the quantity of fibre present in the laminate is illustrated in Fig 2.7 for a unidirectional E glass laminate. The scale has been exaggerated to illustrate the effect. For many practical cases, where the volume fraction is in the range 55-65% Poisson's ratio for unidirectional

Fig 2.6 Longitudinal Strength versus fibre volume fraction Unidirectional Woven E glass / polyester

Ref 2.1

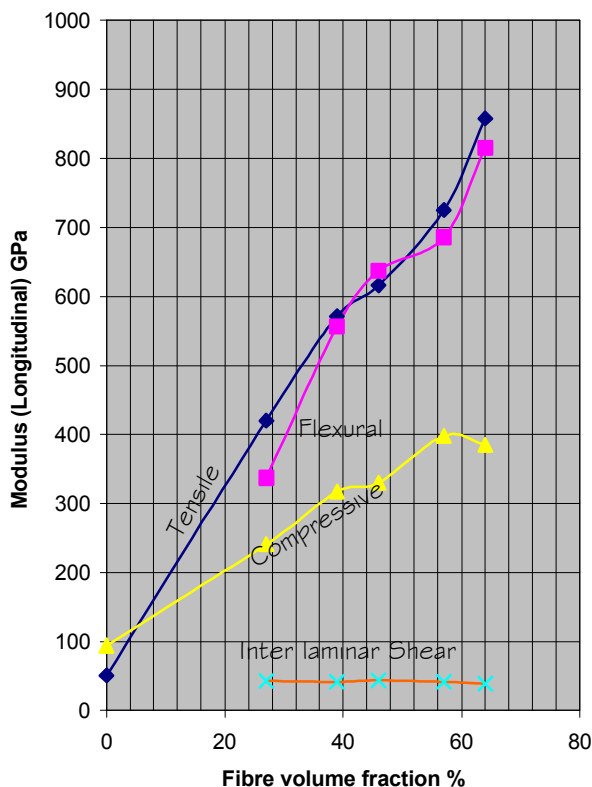
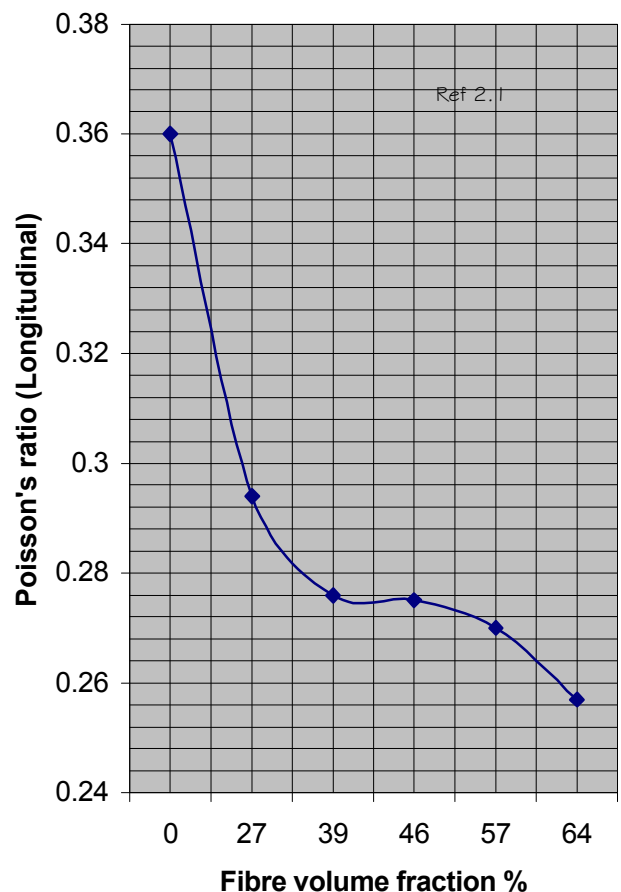


Fig 2.7 Effect of Vf on Poisson's Ratio - Unidirectional E glass Woven Roving



Figs 2.8 and 2.9 show the effect of variation in the fibre angle on tensile and compressive strength and modulus for a unidirectional composite. It should be noted that in these examples the fibre volume fraction is unusually low (27% compared with a more usual value of about 60%) but nevertheless the principle is valid and the effect is apparent. Higher fibre volume fraction accentuates the difference between 0 degree and 90 degree properties.

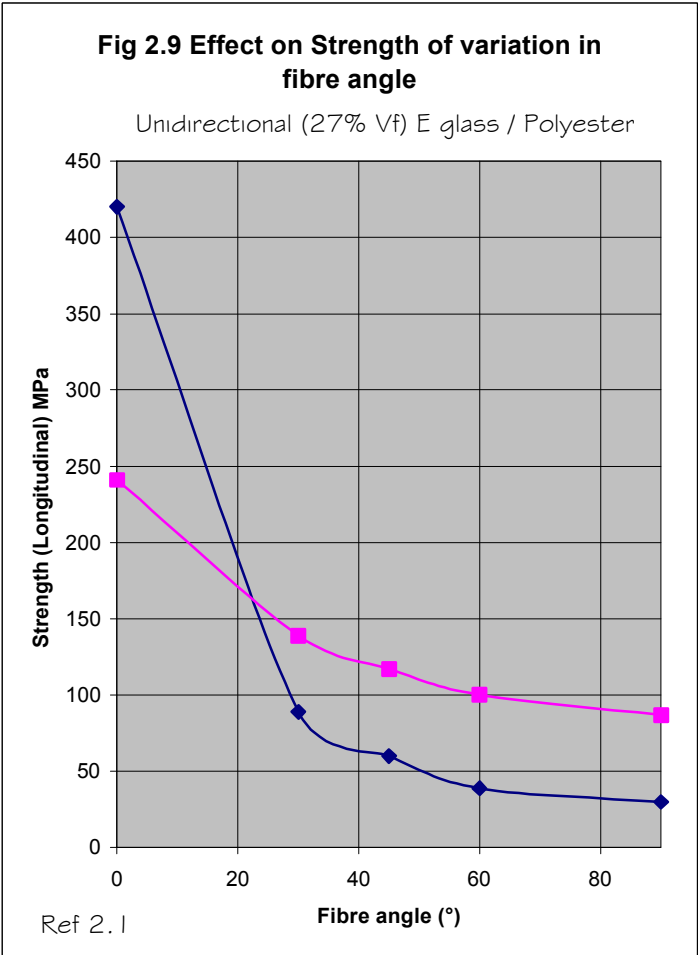
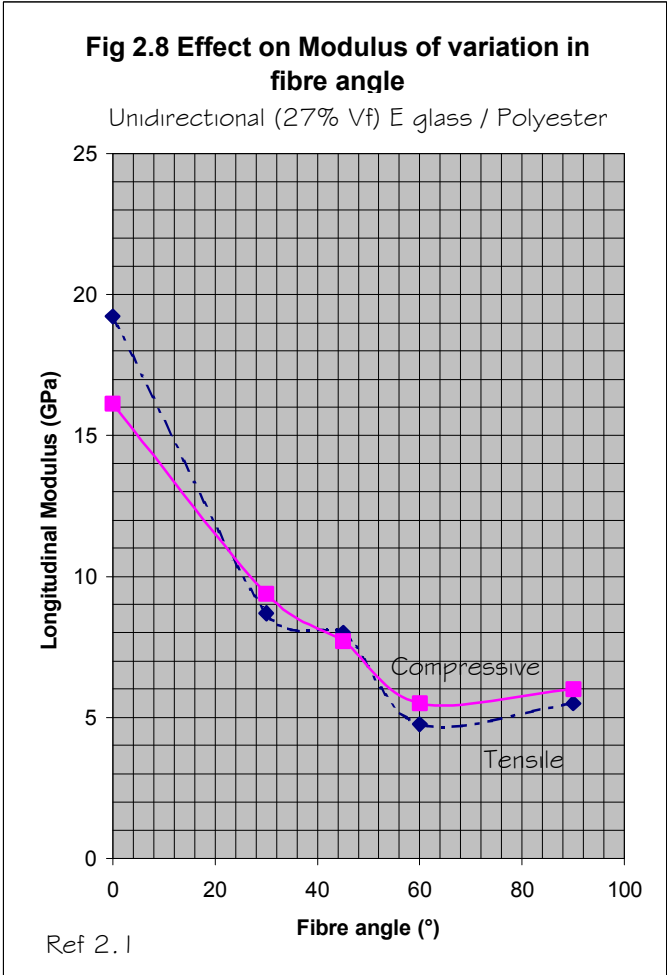


Fig 2.10 Effect of Fibre configuration on Modulus

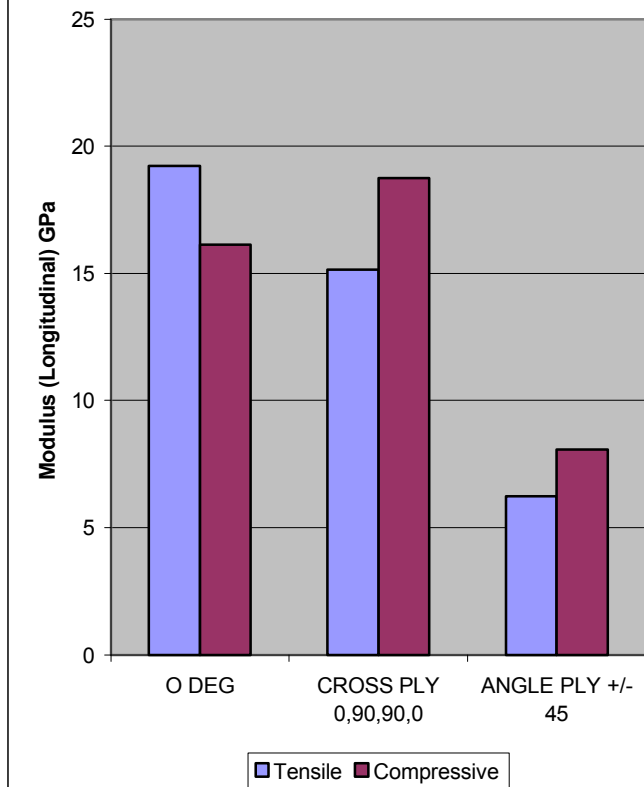


Fig 2.10 shows the effect on tensile modulus of variation in the reinforcement geometry (unidirectional, cross-ply and angle-ply). Similarly Fig 2.11 shows the effect on tensile strength of the variation in reinforcement geometry.

CSM laminates (random) have a typical fibre volume fraction of about 20% and a tensile modulus at that volume fraction of about 9 GPa (1.3 Msi). Fig 2.12 shows the variation of tensile modulus with fibre volume fraction for such laminates. The data is presented for a range of laminates which were tested together with the regression line for the data. The regression intercepts the y axis at a value which implies that the resin has a modulus of 4 GPa (0.58 Msi). This is reasonably close to the actual value of about 3.5 GPa (0.5 Msi).

The use of S2 or R glass improves the composite modulus to about 60 GPa (8.7 Msi) for unidirectional and 20 GPa (2.9 Msi) for woven fabric (bi-directional) constructions. This is at some monetary disadvantage. They are both more expensive than E glass and they are only available in a fairly limited range of material types and resin compatibilities. Probably the most important virtue of S2 and R glasses is their strength which is considerably higher than E glass.

Fig 2.11 Effect of Fibre configuration on Strength

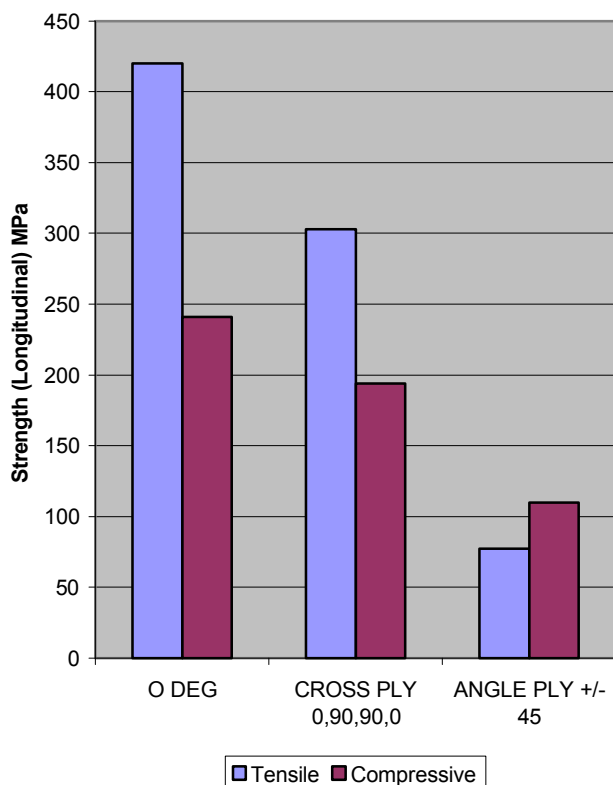
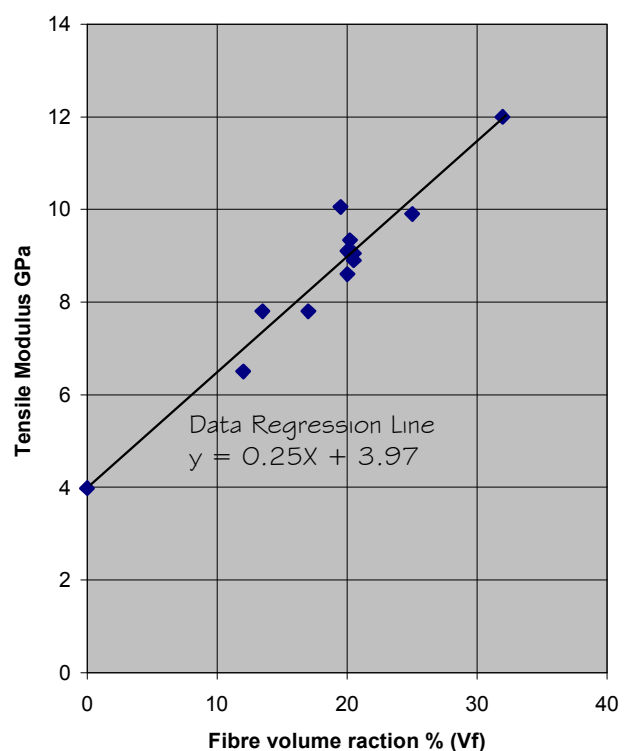


Fig 2.12 Effect of Vf on Tensile Modulus CSM 'E' glass / Polyester



Mechanical properties - CFRP

The dominant carbon fibres in current use have a tensile modulus of about 230 GPa (33 Msi), tensile strength of 3200-3500 MPa and strain to failure of 1.5%. A typical example is T300 fibre from Toray.

Unidirectional composites produced from T300 fibre have the following typical properties:

Longitudinal Tensile modulus 125- 135 GPa (18 - 20 Msi)

Longitudinal Tensile Strength 1400-1800 MPa (203 - 260 Ksi)

Figs 2.13 & 2.14 have been drawn to illustrate the effect of reinforcement geometry on strength and stiffness (in the longitudinal and transverse directions). The geometries compared are unidirectional, woven fabric (5 harness satin) and pseudo-isotropic (0,+/-45,90). They are not strictly comparable as each is drawn from a different data source. However they are sufficiently valid for comparative purposes.

Carbon fibres are available which, in a unidirectional composite, will give a tensile modulus of about 250 GPa (36 Msi), which compares very favourably with steel at about 210 GPa (30 Msi) . As this composite is unidirectional it has very low modulus in the transverse direction.

The principal attribute of carbon fibre composites is there very high specific stiffness (the ratio:- modulus / density). A unidirectional composite of T300 carbon fibre has a specific modulus of about 80 which compares with steel at about 27. Hence the composite material can be 3 times lighter if tensile stiffness is the design criterion. The specific modulus of unidirectional carbon fibre composites can be as high as 160 when very high modulus fibre is used. Composites which are other than unidirectional of course have lower specific moduli but nevertheless they still compare very favourably with metals.

Although high specific modulus is the principal reason for the use of carbon fibre composites they also enjoy excellent strength. However the highest strength fibres don't have the highest modulus. The designer must therefore decide between strength and stiffness as the primary design criterion.

Fig 2.13 Effect of Fibre configuration on Tensile Strength

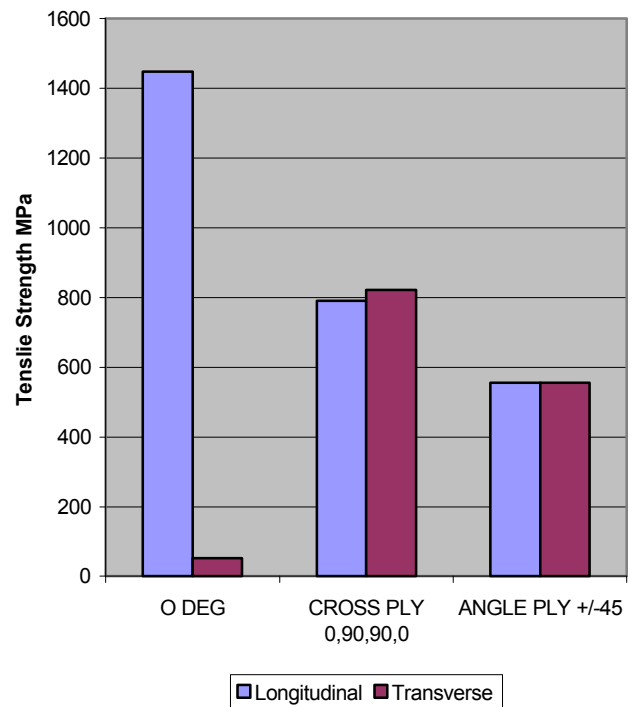
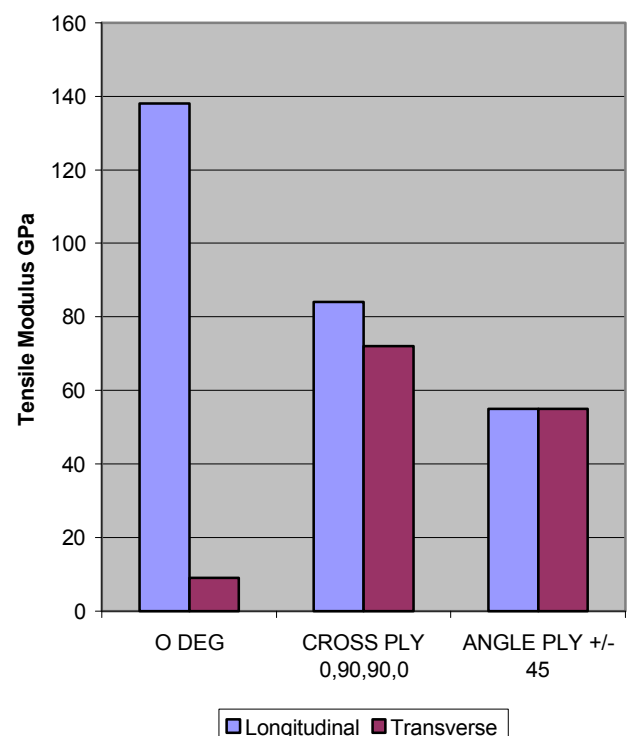


Fig 2.14 Effect of Fibre Configuration on Tensile Modulus



ARAMIDS Mechanical properties

Unidirectional aramid composites have high tensile strength of 1200 - 1400 MPa and a very low density (1.35). This high specific tensile strength is an important attribute which makes them particularly suited to use as tension members.

Some aramids exhibit a relatively low compressive yield strength of about 230 MPa (33 Ksi). Hence composites using these fibres must be carefully designed, particularly for compression or bending. Thus although they are particularly suited to use in tension member applications they are generally not suited to bending applications.

The aramids which have high modulus are the variant most commonly used as composites reinforcement. They produce a tensile modulus for unidirectional composites of about 75 GPa (11 Msi). This is very similar to aluminium, however as this figure is for a unidirectional composite the associated transverse modulus is only about 5 GPa (0.7 Msi).

The tensile modulus and tensile strength of two aramid composites are compared with other common composites in Figs

2.15 & 2.16. It can be seen in Fig 2.15 that the tensile modulus of unidirectional and bi-directional aramid composites are a reasonable compromise between the low modulus glass fibre composites and the much higher modulus carbon fibre composites.

Similarly it can be seen in Fig 2.16 that the tensile strength of aramid composites is a compromise between E glass and XAS carbon fibre composites.

A chopped strand mat composite is included in the diagrams, for comparison purposes, as one extreme of the available property range. It should not be assumed that such composites are not worth considering in structural applications. On the contrary, in spite of the relatively low mechanical performance they find valid use in marine, automotive and construction industries etc. It should also be noted that their properties are quasi-isotropic which is not the case with those composites which are highly aligned.

Consequently the family of composite materials covers an extremely broad range of strengths and stiffness' to suit virtually every circumstance, from the mundane to the exotic.

Fig 2.15 Tensile Modulus of Common Composites

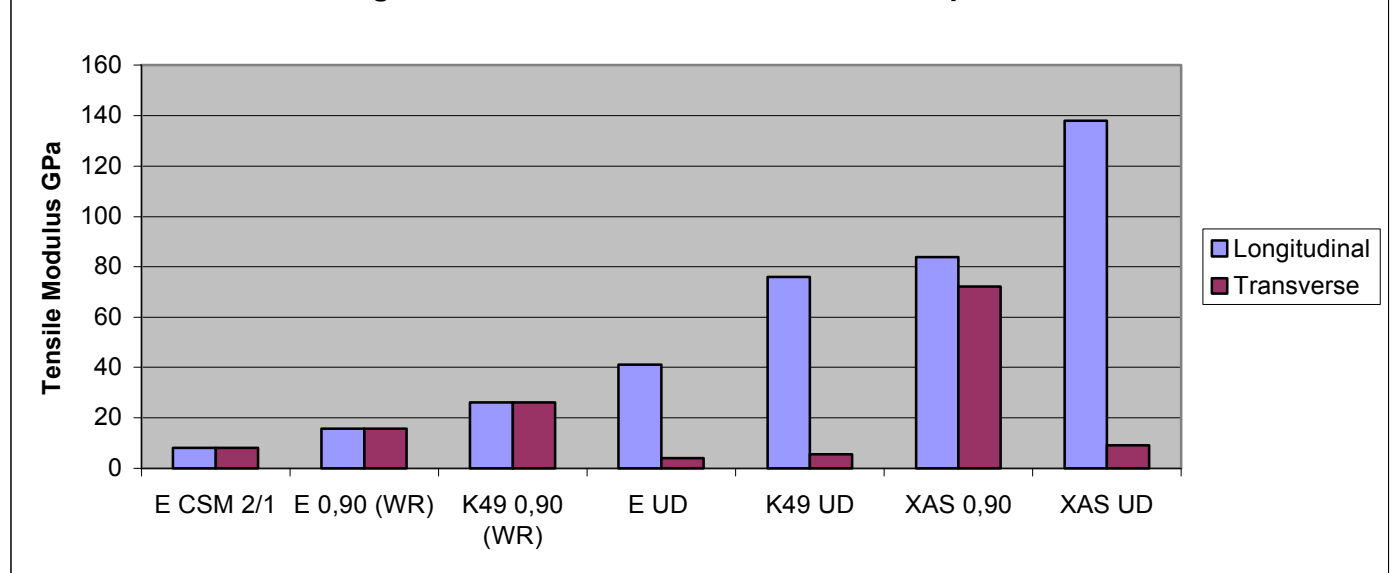
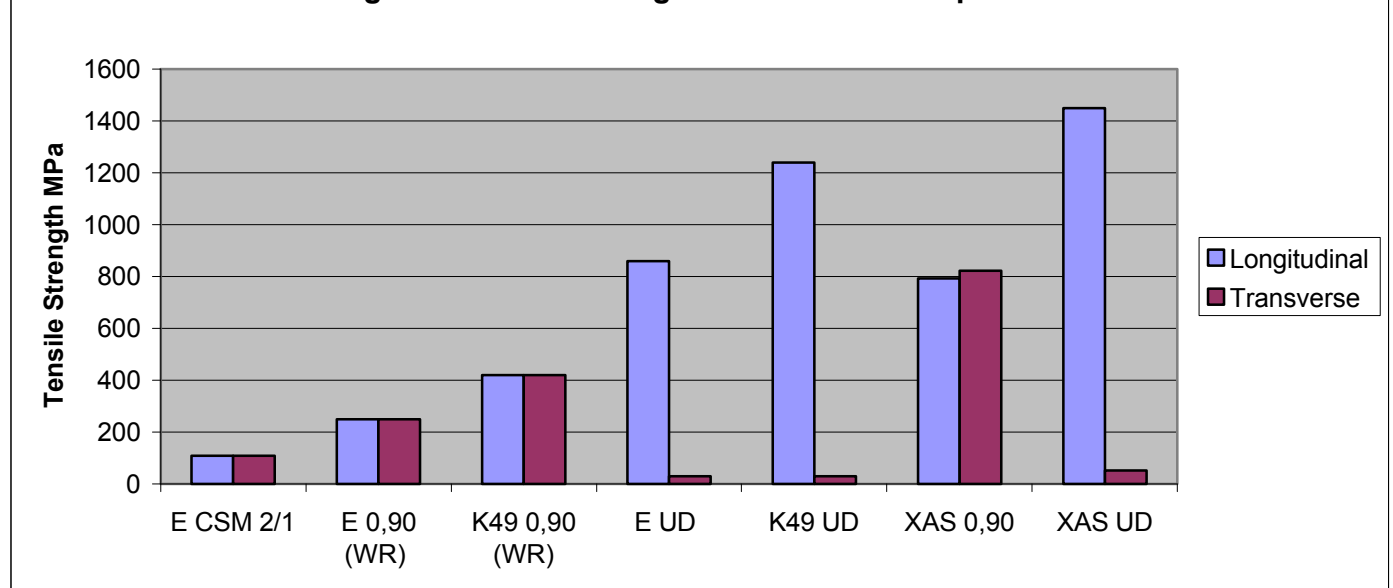


Fig 2.16 Tensile Strength of Common Composites



FATIGUE

CFRP

The fatigue performance of carbon fibre composites is generally far superior to both metals and other composites. This is particularly the case for unidirectional composites loaded in the fibre direction, where they are relatively insensitive to tension fatigue damage, even at very high stress levels. ref 2.6. This does not necessarily apply to all constructions. Fatigue life is reduced in those composites whose performance is dominated by the matrix such as +/- 45 degree lay-up. Nevertheless the non-unidirectional lay-ups still have very good fatigue performance. For example CFRP / EPOXY in any of the lay-ups: 0 degree, +/-45 degree, quasi-isotropic or 90 degree, stressed to an amplitude of 53-58% of short term ultimate, each have a fatigue life of 10 million tension/tension cycles. By comparison aluminium 2024 T3 and 4130 grade steel have values of 28% and 44 % respectively. Ref 2.7.

Fig 2.16 is a simplification of data presented in Ref 2.8, which compares a brittle epoxy/carbon fibre system and a tough epoxy carbon fibre system. MY720 / LY556 resin with ST3 fibre is the former and MY720 resin with HTA fibre the latter. The benefit in initial strength and fatigue performance is evident. The ratio of short term life to fatigue life at 10 million cycles for these two systems is 80% and 70% respectively (note the absolute values are in reverse order).

GRP

E glass composites have a relatively low modulus which often results in them experiencing strains which approach the cracking strain of the matrix. This allows a fatigue process to occur which results in a reduced fatigue life.

The fatigue performance of E glass / epoxy in a (90°,0°,90°,0°,90°) configuration is shown in fig 2.18 (ref 2.9) for zero-tension cyclic loading as: Monotonic strength of 419 MPa and slope of the curve of 42.5 MPa per decade of cycles.

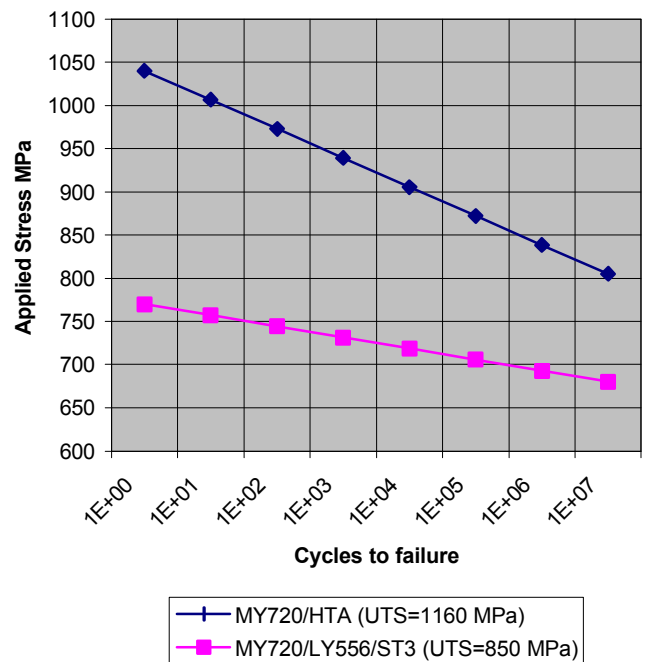
The fatigue performance of Glass fibre laminates using Polyester resin and phenolic resin are compared in fig 2.19

The graph is a simplification of data presented in ref 29. It was determined using Chomarat Rovimat 800/100 which is a combination of 800 g/m² bi-directional woven roving and 100 g/m² chopped strand mat.

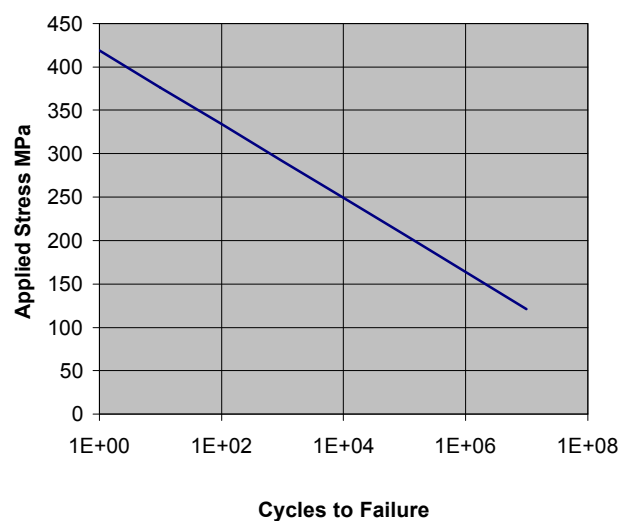
The resins used were :-

- BP Chemicals Phenolic resin J 20272 (Glass content by weight 71%)
- Jotun Polymers Iso/NPG resin -Norpol 20-80 (Glass content by weight 49%)

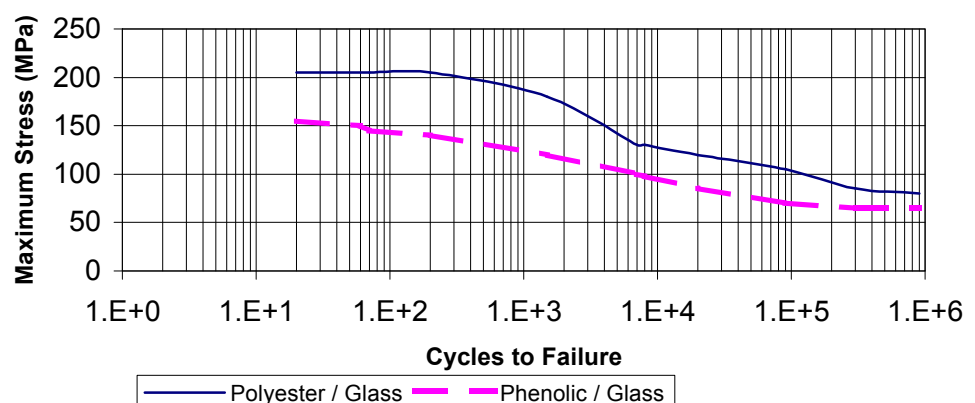
**Fig 2.17 Tension-Tension Fatigue (R=0.1)
Carbon fibre Bi-directional**



**Fig 2.18 Zero - Tension Fatigue 'E' glass
(90°,0°,90°,0°,90°) - Epoxy**



**Fig 2.19 Fatigue of Polyester and Phenolic
Glassfibre Laminates S - N Curves R = ±1**



**Fig 2.20 Flexural Fatigue Performance
'E' glass Woven Roving & CSM**

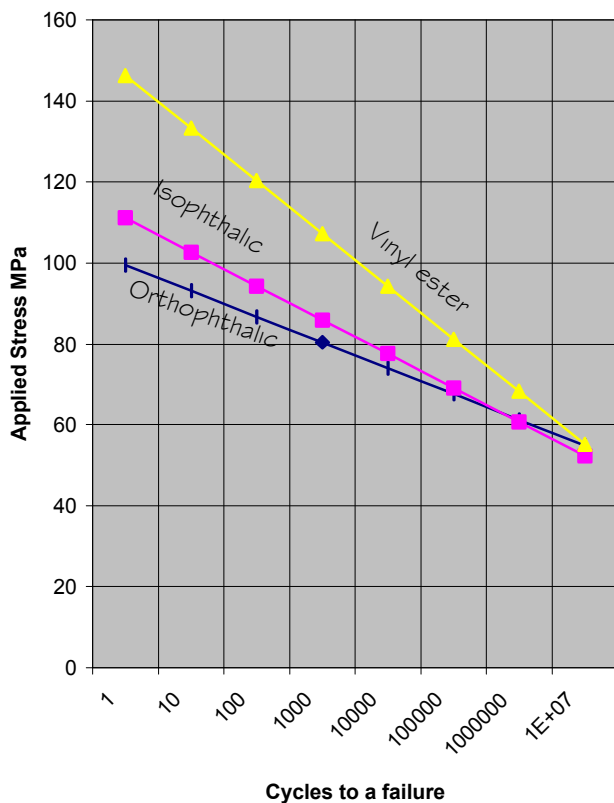


Fig 2.20 illustrates the flexural fatigue performance of an E glass woven roving and chopped strand mat laminate. Three resin types are compared : Orthophthalic, Isophthalic and Vinyl ester. The Isophthalic is better than the orthophthalic and the vinyl ester is significantly better than both. The simplification of the data was extracted from Ref 10.

Owen (ref 8) advocates that for CSM laminates much of the scatter associated with fatigue test data can be eliminated by the presentation of the data as fractions of the ultimate strength of the adjacent specimen cut from the laminate.

The basic data is still required for design work but nevertheless this is a useful technique. Sims (Ref 11) assumes a straight line relationship for tension-tension fatigue of an E glass fabric (fine weave) Epoxy laminate This is illustrated in Fig 2.21 which has been drawn from the model.

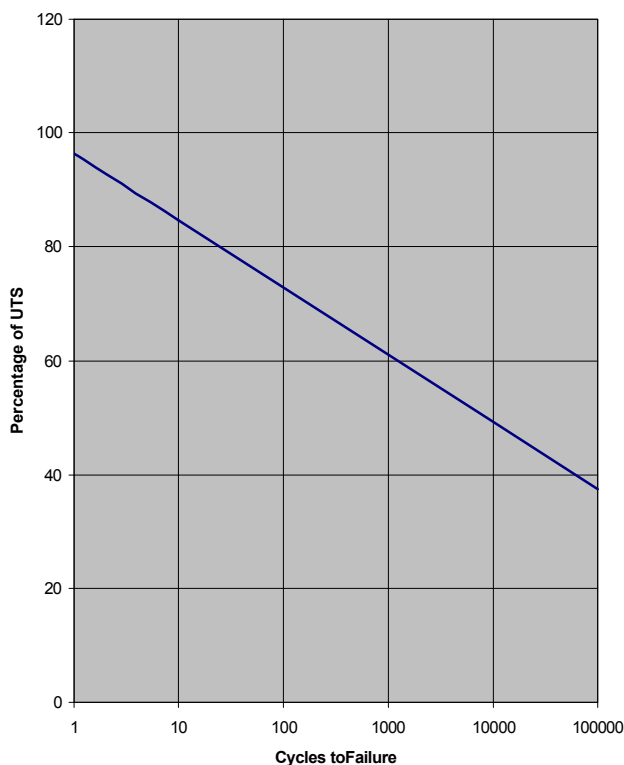
Aramids

The fatigue behaviour of aramids can be excellent, but under other circumstances it may be very poor. For instance, unidirectional Kevlar 49 composites in Tension / tension fatigue are superior to S glass and E glass composites and 2024-T3 aluminium. Only Unidirectional carbon fibre composites are superior.

However in flexural fatigue at fairly low number of cycles they have poorer fatigue strength than E glass. This is due to the innate poor performance of Kevlar 49 when subject to compression.

The problem is alleviated at high level of cycles, ($10^6 - 10^7$) where the excellent inherent fatigue performance of the aramid results in Kevlar 49 and E glass having similar performance. (Ref 12)

**Fig 2.21 'E' glass Fine weave fabric /
Epoxy
Tension / Tension Fatigue (R=0.1)**



CREEP & STRESS RUPTURE

Polymers are visco-elastic materials and they deflect continuously with time under load. On the other hand the reinforcing fibres are effectively totally elastic at other than very high temperature or stress. The creep performance of the composite is dependant on which of these (the resin or the fibre) is dominant.

Unidirectional composites when subjected to axial tensile load resist long term creep very well. The totally elastic performance of the fibres dominates the behaviour of the composite. But when under compression or off-axis loading then the matrix properties take on a more significant role. Under these circumstances and particularly at elevated temperatures the creep performance of the composite requires particular attention.

The most creep resistant construction is unidirectional reinforcement, followed by 0°,90° non-woven construction. Woven construction of 0°,90° degree fibres has the disadvantage that the fibres tend to straighten out thus increasing creep.

Laminates with random fibre array are the least resistant to creep (e.g. CSM & CFM) but this may be alleviated to some extent by the use (if practical) of high volume fraction of fibre.

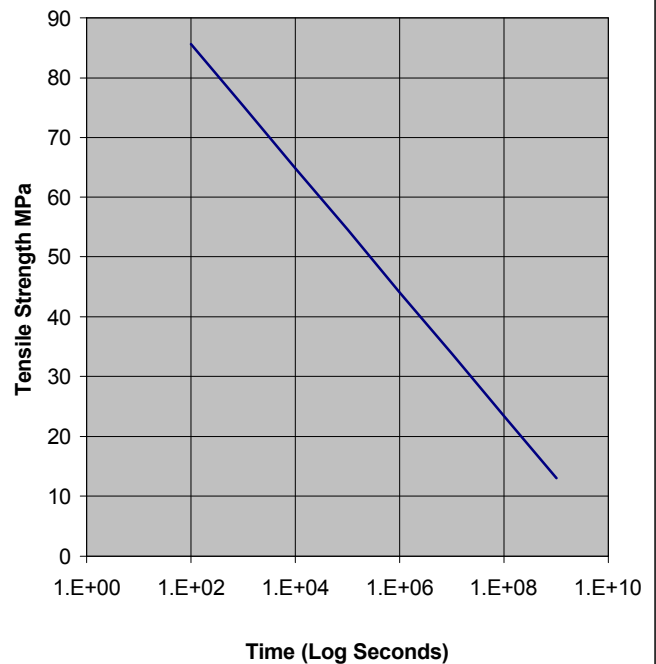
Fig 2.22 illustrates the stress rupture performance of a glass fibre laminate consisting of woven roving and chopped strand mat together with isophthalic polyester resin. The test was carried out in water at 40°C. It was concluded that a 25 year life is indicated at a continuous stress level of 15 MPa (2.2 Ksi) which is 12.3% of the initial strength of 122 MPa (17.7 Ksi) in air at 20°C. (Ref 16)

The creep performance of carbon fibre composites in the fibre direction is comparable with “low relaxation” steel and is significantly better than “standard” steel. This is illustrated in fig 2.23 which has been drawn from data in ref 13. Creep curves are also shown for E glass fibre and Kevlar49® fibre unidirectional composites. In each case the resin is Derakane® Epoxy vinyl ester.

It can also be seen from fig 2.23 that in spite of their high inherent tensile strength, and even in unidirectional configurations, aramid fibre composites have creep rates generally very much higher than glass or carbon composites.

**Fig 2.22 Stress Rupture in Water @ 40°C
CSM / WR Isophthalic**

Ref 2.16



**Fig 2.23 Creep Data at 50% UTS
Unidirectional (62% Vf) Pultruded
composites compared to steel**

Ref 2.13

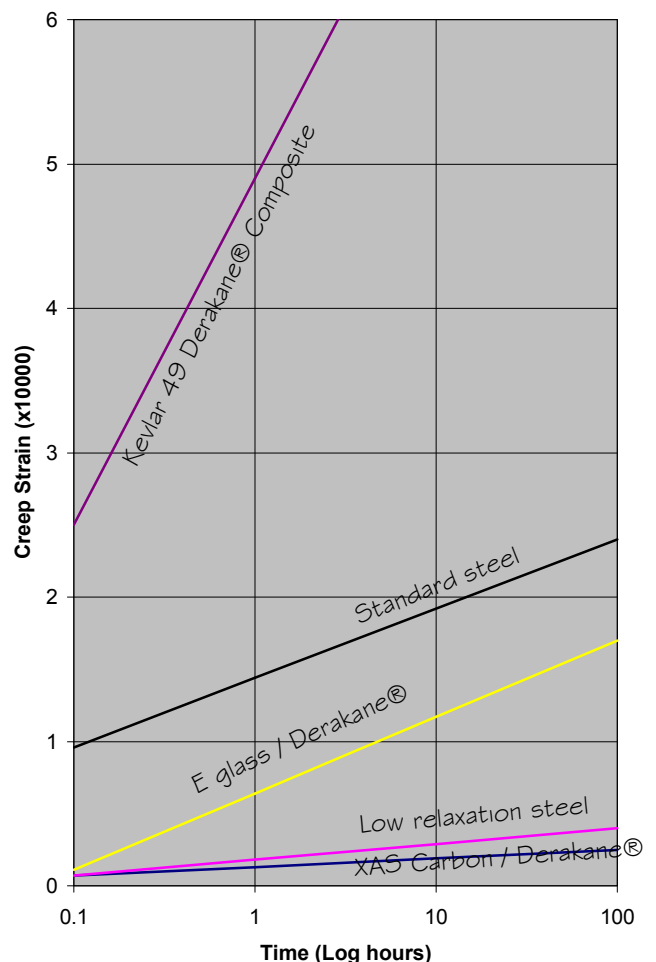
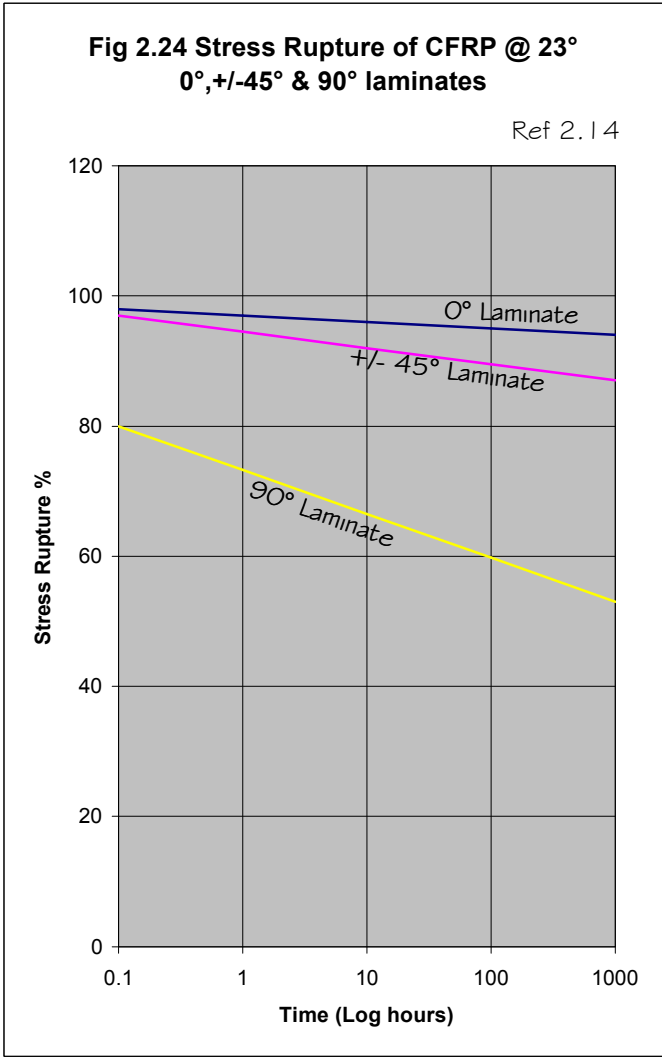


Fig 2.24 is a simplification of data presented in Ref 14 where 0°,90°, and +/-45° degree constructions are compared in terms of their resistance to long term loading. The data is normalised i.e. presented as a percentage of longitudinal short term strength (1535 MPa, 220 Ksi)), transverse short term strength (63 MPa, 9 Ksi) and short term shear strength (200 MPa, 29 Ksi) respectively. It should be noted that all data shown in figs 2.17 to 2.23 for fatigue and creep are straight line simplifications of the real data. They are intended to illustrate trends and not to be used



Holmes and Just (Ref 2.28) developed an empirical model for creep strain of GRP beyond the primary creep range in the following equation:

$$\epsilon = m.(t / t_0)^n$$

where ϵ = creep strain
 t = time (hours)
 t_0 = 1 hour (unit time)
 n = gradient of curve
 m = value of strain after 1 hour

Values of n for glass fibre composites have been determined as:

	n
Chopped strand mat laminates	0.08-0.1
Bi-directional (Woven) laminates	0.03-0.04
Uni-directional Laminates	0.008-0.01

IMPACT

Because unidirectional carbon fibre composites are fully elastic and have low failure strain of typically 1.5 % their ability to absorb impact energy is limited. This can be improved by the incorporation of higher strain fibres such as E glass or Aramid both of which have considerably higher strain to failure than the normal range of carbon fibres.

Fig 2.25 shows the residual flexural strength after impact for woven carbon fibre fabric (T300) and epoxy resin compared with a toughened epoxy. The toughened epoxy is able to absorb more strain energy which limits the damage and results in more flexural performance being retained.

The impact behaviour of glass fibre composites is often underrated due to experience with very flimsy laminates. This is generally incorrect and is illustrated in fig 2.26 and fig 2.27. These have been drawn from graphs in ref 15 which compare three types of glass fibre laminate with steel and aluminium on a weight basis. The former uses a blunt missile and the latter, pointed. It can be seen that for blunt missiles the glass fibre laminates are probably the best options. Even for pointed missiles the glass fibre laminates are better than mild steel. Aluminium is probably the best option in this case but there is only a marginal benefit over woven roving.

Generally aramid composites have the best ballistic impact performance for minimum weight. Thus they dominate the body armour market. They are more expensive than glass fibre laminates, but cost is generally not the critical factor in this field.

Fig 2.25 Residual Flexural Strength after Impact

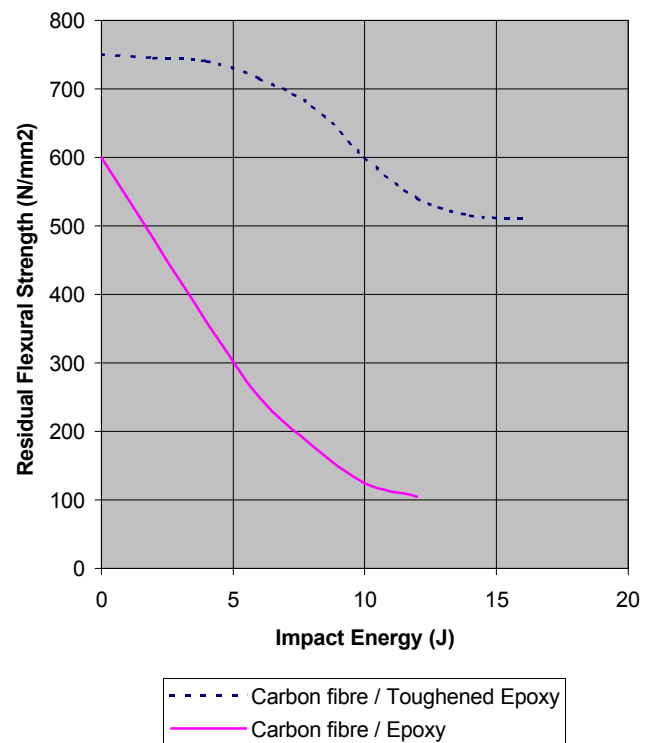


Fig 2.26 Impact Penetration Speed versus mass.

Missile = 16 mm dia **Flat ended**

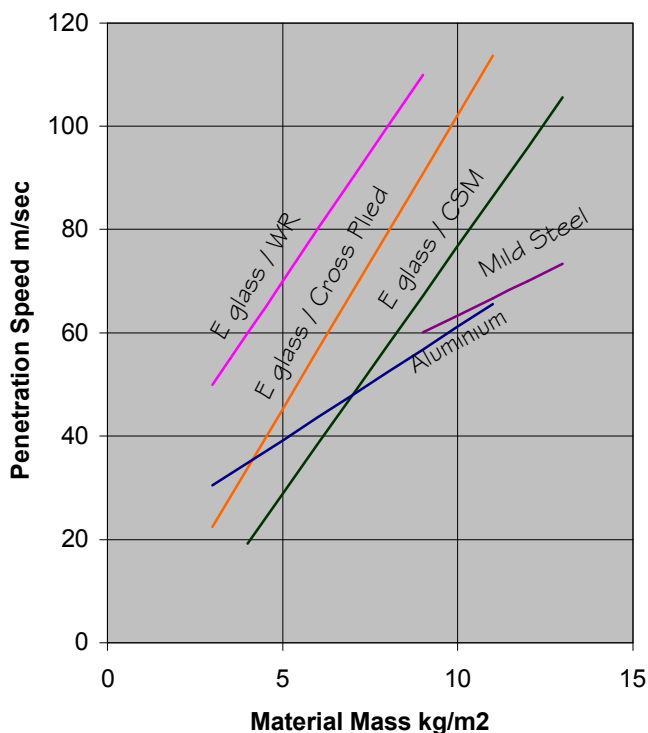
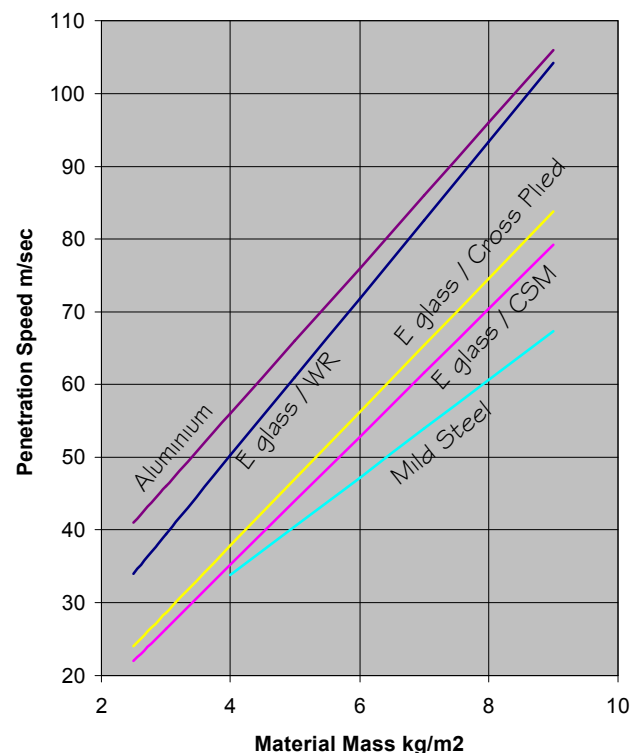


Fig 2.27 Impact Penetration speed versus Mass. Missile = 16mm dia **Pointed**



PHYSICAL CHARACTERISTICS

FIRE PROPERTIES

The factors by which fire performance is assessed include:

- Surface spread of flame,
- Fire penetration,
- Ease of ignition,
- Fuel contribution,
- Oxygen index. (That is the minimum oxygen content that supports combustion.)

Each factor is more or less significant depending on the particular circumstances. In short, there is no single simple test by which composites can be assessed and compared in terms of their fire resistance. The fire performance of composites covers a wide spectrum, ranging from highly flammable to non-burning. The degree of flammability of a composite is governed by the following factors:

- Matrix type
- Quantity and type of fire retardant additives included;
- Quantity and type of fillers included;
- Reinforcement type, its volume fraction and its construction.

The dominant factor is of course the polymer matrix. Of the commonly used polymers in composites the approximate fire resistance in ascending order (without fire retardant additives) is:

- Phenolic (Excellent fire resistance)
- Epoxy
- Modar
- Vinylester
- Polyester (burns readily)

Polyesters, in spite of their relatively poor intrinsic fire resistance, can have very low flammability by the incorporation of suitable fire retardant additives and a reasonably high glass fibre content. A very low flammability polyester can have the following performance:

- BS476 Part 7:1971 Class 1 (Surface spread of flame)
- BS476 Part 6:1968 Class 0 (Fire propagation)
- BS476 Part 3:1958 Class AA (Fire penetration and spread of flame)
- ASTM E84 Flame spread of 25 (On a scale: Asbestos cement board = 0, Red oak flooring = 100)

This level of fire performance is difficult to achieve with polyester and may be expensive both in terms of cost and performance, particularly weathering and corrosion resistance. However if polyester will do the job it is generally the preferred choice due to its versatility and general good properties. By way of example the fire resistance properties of Derakane® resins is given in the table.

Phenolic resins achieve very high level of fire resistance without the inclusion of fire retardant additives. They have extremely low smoke emission and virtually no toxic combustion products. (Ref 2.17)

Fig 2.27 Ignition resistance test results of laminates made with DERAKANE* resins

TEST TYPE DESIGNATION	TEST	DERAKANE 510A RESIN	DERAKANE 510N RESIN	DERAKANE 510-C-350
in/min				
60 -Second Burning Test (3)	ASTM D757	0.04	----	----
Intermittent exposure Test (4)	HLT 15	100	----	----
Tunnel Test Flame Spread (4)	ASTM E84	---	----	----
Unfilled		30	75	115
3% Antimony Trioxide		10	20	20
2.0% APE 1540 (5)		20	----	---
2.5% APE 1540		----	35	35
3.75% APE 1540		----	25	25
(1) Results shown in the table were obtained from controlled and/or small scale bench tests. They are not necessarily predictive of product performance in a real fire situation. DERAKANE* resins are organic materials and the resins and products made from them will burn under the right conditions of heat and oxygen supply. This numerical flame spread rating is not intended to reflect hazards presented by this or any other material under actual fire conditions.				
(2) Typical properties: not to be construed as specifications.				
(3) 60% Glass: press moulded at 60 psig, benzoyl peroxide cure.				
(4) 25% Glass, 1/8" thick, hand lay-up with MEKP and cobalt naphthenate cure. Glass sequence: 10-mil C-veil, three 1.5 ounce mats, 10-mil veil.				
(5) Product of Nyacol Products Inc				

Thermal expansion coefficients of composites

The thermal expansion of composites is dependent on several factors. Type of reinforcement, type of matrix, geometry of reinforcement and volume fraction. The table shows the thermal expansion coefficients for a variety of composites. The two negative values are a result of the negative fibre expansion coefficients which both carbon and aramid fibres exhibit. It is possible to tailor the expansion coefficient of a composite to a specific requirement. For example to match that of aluminium or even to be zero over a given temperature range.

Fig 2.28 Thermal expansion coefficient
/ °C x10⁻⁶

	Unidirectional composite 0 deg	Unidirectional composite 90 deg	Bi-directional Composite (Fibre direction)
E Glass / Polyester	8.6	14.1	9.8
Carbon XAS HP / Epoxy	-0.3	28	1.9
Aramid K49 / Epoxy	-4	79	3.2
Volume fraction of fibres = 65%			

ENVIRONMENTAL

Temperature Effects

The limiting factor for the use of composites in above ambient temperature conditions is generally the temperature resistance of the resin rather than the fibres. This is particularly the case with glass and carbon fibre which are well in excess of the resin performance.

As a general rule both the strength and the stiffness of composites are unimpaired by the effect of low temperature and under some circumstances they may be enhanced. However low temperatures tend to make polymers less flexible and therefore there may be a tendency towards damage by fatigue.

High temperatures are more problematic. As temperature is increased all resins soften and reach a stage at which the polymer passes from a glass-like state to a rubbery state. This is the glass transition temperature (T_g). Beyond the T_g the properties of the polymer change dramatically. Hence this is a limit to the usable temperature range for all normal applications. However the effect the fibres have is to improve the T_g of the composite above that of the matrix resin.

MOISTURE EFFECTS

- On general properties

Moisture can penetrate all organic materials by a diffusion process which it will do until the equilibrium level is reached. All polymers are susceptible to its effects which in general result in a reduction in mechanical properties and glass transition temperature. The loss of property is a function of the degree of moisture pickup and Fig 2.30 illustrates a typical moisture pickup curve for a totally immersed glass fibre/polyester composite. Resin systems can be selected which have excellent resistance to the effects of moisture. See fig 2.31.

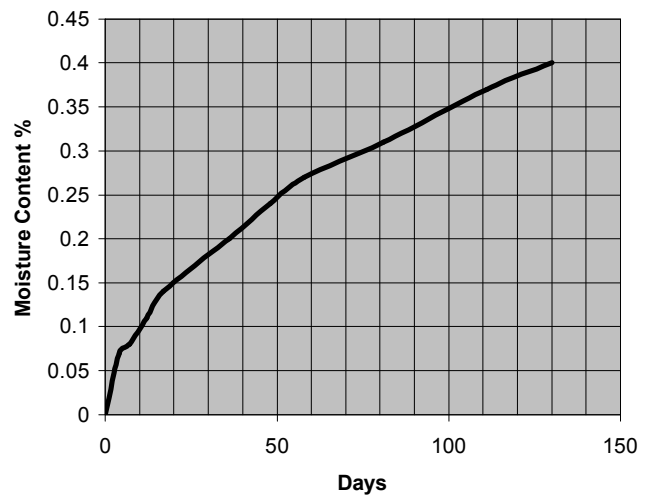
However the glass transition temperature can be reduced to 75% of its dry value by the effect of a moisture content of 4%. Flexural strength can be reduced to 50% of the dry value by the effects of 1.5% moisture content. (Ref 7)

The designer must therefore take the effect moisture into account at the design stage. If the composite is to be subjected to a wet environment then "wet properties" must be used in the design process.

- Blistering

It has been observed that gel coated polyester laminates reinforced with glass fibre may form unsightly blisters on their surface after lengthy contact with water. In particular boat hulls and swimming pools have been affected. The mechanism by which blisters occur is thought to be basically os-

Fig 2.30 Moisture Pick-up with time Unidirectional E glass Rod

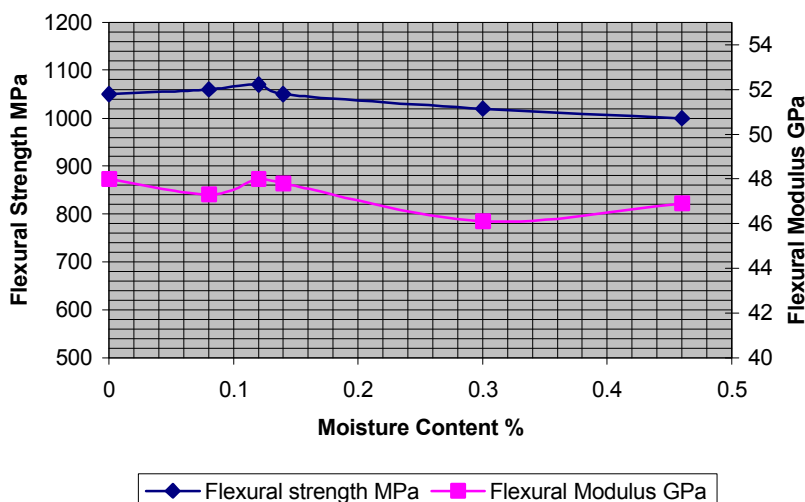


mot. The laminating resin and gel coat resin are permeable to water molecules, which pass into the resin albeit very slowly. Any voids in the laminate will pick up moisture. If the resin system is hydrolytically unstable (able to decompose by reaction with water) then salts may be present in the water to allow the gel coat to act as a semi-permeable membrane and thus create an osmotic cell. Pressure builds up sufficient eventually to create a blister. Considerable experimentation has shown that to prevent blistering there are two major considerations: raw material selection and production techniques. The use of water resistant resins, and preferably 'powder bound' chopped strand mat rather than 'emulsion bound' are the most important aspects of material selection. Production techniques must ensure thoroughly impregnated and wetted glass fibre and the correct resin / glass ratio. (Refs 23 & 24).

- Rain erosion

A significant aspect of weathering is the erosive effect of rain in rapidly moving air. This is the case, for example, in high speed flight and with helicopter blades. In which case radomes, antennae covers, fairings and the leading edge of helicopter blades etc. are susceptible to erosion from rain, snow and ice. The rate of erosion is a function of speed, angle of impact, mass and frequency. An unpainted edge cap on an aircraft rotodome which had been exposed for 19 years had a strength retention of 68%. (Refs 7 & 25). The most common method of countering its effects are by the use of rain erosion resistant finishes such as polyurethane. These can be so beneficial that rain erosion can be reduced from "badly degraded" to "no drop in Tensile or flexural strength or modulus". The advent of improved fibres has also significantly diminished the problem.

Fig 2.31 Effect of Moisture Content on Flexural Strength and Modulus



E Glass and A Glass Laminates in Water

Fig 2.32 illustrates the performance, in water, of E glass and A glass laminates with silane or chrome surface finish on the glass. The laminates were unidirectional and were tested in three point bending. (2.30).

It is shown that laminates made from E glass are superior to those made from A glass when immersed in water. Also that chrome treatment is more sensitive to the effect of heat and moisture than is silane treatment. (2.34)

It was this type of work which was used to justify the change from A glass to E glass and the extensive use of silane as the linking agent on glass fibre reinforcement.

This would seem to be reasonable particularly if the laminate was to be immersed in water for long periods. However there are other environments which are also highly appropriate to the use of GRP most notably long term exposure to out door conditions and short and long term exposure to chemical substances.

Long-term outdoor exposure tests were carried out and reported the following:

“ --- panels made from various types of chopped strand mat (A glass & E glass) were exposed in a frame on the roof of one of our buildings for a period of 2 1/2 years. On removal the samples were examined visually and it was noted that a very slight fibre pattern had appeared on the exposed surface of each laminate. Before testing, each panel was then stored under normal laboratory conditions for three months. The results obtained, were unexpected, showing, no fall in flexural strength under these conditions.” Ref 2.34)

E glass has good electrical properties and would be the

choice for those applications which are dominated by electrical requirements. However this does not preclude the use of A glass which, although not as good as E glass, may be perfectly adequate for the particular application.

E glass has higher tensile strength (3.6 GPa) than A glass (3 GPa). This is in reality of very little consequence in most applications. Factors such as fibre content, whether the reinforcement is random, bi-directional or unidirectional are far more profound in this respect. Also many applications are not strength dependant but stiffness dependant. In which case it is Young's modulus which will dominate the design process and not strength. The difference between the two fibres in this respect is trivial.

The early work showed that E glass had better resistance to water than A glass. Hence E glass was the likely choice if the laminate was to be permanently immersed in water. However later work by Maloney (2.32) on more modern products showed comparable performance to C glass in distilled water. This would allow more confidence in the use of A glass in wet applications.

Hence it would be wrong to exclude, per se, A glass from applications which have exposure to water. For example normal out door exposure of E and A glass laminates in the UK for 2 1/2 years showed no difference between them (2.30).

WEATHERING

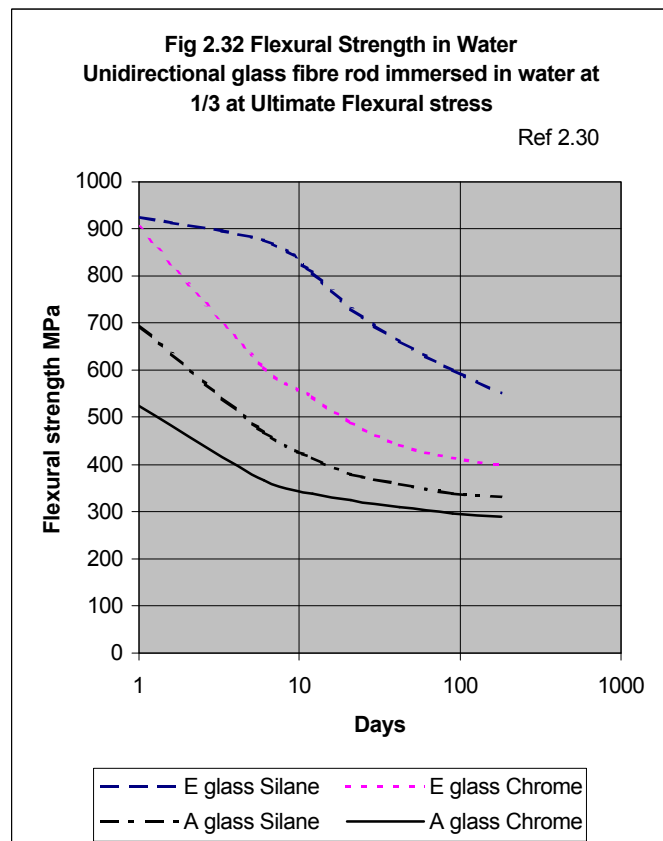
The mechanical performance of composites is degraded by the effects of temperature, moisture, sunlight, wind, dust, acid rain etc. These effects are under the general heading of weathering. There are several mechanisms attributed to weathering. Most notably: leaching from the resin of chemical constituents; sun-light attack on the resin causing embrittlement and erosion of the resin due to its degradation and the effect of wind and airborne particles. Thus the environment is allowed access to the fibres. However Jones (Ref 27) concluded that for an epoxy /carbon composite in flying service : “___ Generally there is no indication of increasing degradation with length of time in service, the maximum deterioration occurs in the first year___” The most effective options to counter the effects of weathering are to use resins applicable to the environment. To incorporate ultra-violet stabilisers in the matrix and to incorporate chemical resistant fibres (C glass, ECR-GLAS or polyester) in the surface of the composite.

LIGHTNING

Carbon fibre reinforced composites are more susceptible to damage from lightning than aluminium. Hence the use of CFRP in aircraft has prompted investigation into methods for their protection from lightning strike. It is well known that aircraft are at risk and have been lost as a result of damage from lightning strike. The losses have been due to both structural damage to the aircraft and to electrical effects on systems and elements which are critical.

CFRP is a poor conductor of electricity it therefore has neither the ability to dissipate electricity, as does aluminium, nor does it have the insulating ability of GRP.

The most common method of protecting CFRP against 'arc root' damage from lightning is by the use of surface metallisation. This is achieved by either flame spray or by moulding-in a layer of aluminium mesh or tissue. The CFRP is insulated from the layer by a thin layer of GRP. This is a very brief reference to a complex topic about which further work is required. An excellent review is given in Ref (26).



GALVANIC CORROSION

Glass fibre and aramid fibre composites do not suffer from this problem. However carbon fibre is a conductor of electricity and relative to various metals its composites are highly noble. Therefore if carbon composites are used in contact with metals galvanic corrosion can take place. The severity of the corrosion depends upon distance between the composite and the metal, the extent of the polarisation and the efficiency of the electrolyte. If the conditions are favourable then the metal (being more anodic) will corrode away. This is of course disastrous if the two were bonded together as a structural joint. The situation is overcome by simply ensuring that the carbon composite and the metal do not come into contact by the application of a suitable coating.

ENVIRONMENTAL STRESS CORROSION (ESC)

Even though the resin itself may be highly resistant to corrosion from acid or alkali, glass fibre composites can fail by the process known as Environmental Stress Corrosion cracking or simply Stress Corrosion.

The glass fibre is the reinforcement element of the composite and is the main provider of the strength and stiffness. All materials, including composites have surface flaws, cracks, scratches etc. An important function of the glass fibre reinforcement is to prevent any crack in the resin from penetrating through the laminate. Thus the glass fibres act as crack stoppers.

The environmental stress corrosion of glass fibre composites is a mechanism of failure where a laminate, which is under stress and is exposed to either an acid or an alkali, can fail at a much lower stress than would be expected from strength measurements in air. The failure can be *catastrophic*. The resistance of the glass fibre to the aggressive environment dominates the phenomenon.

The matrix has several roles; it must act as a chemical barrier to prevent any aggressive environment from reaching the glass fibre reinforcement. But more importantly, to avoid stress corrosion, it must be tough.

Environmental stress corrosion cracking occurs when an environment which is aggressive to the reinforcement, gains access to it. Normally the glass fibre reinforcement is protected from the environment by the resin system. All polymers allow liquids to permeate through them to a small degree and may degrade the reinforcement. Thus the life of a laminate exposed to an aggressive environment, although probably many decades, is never the less finite. The degree of degradation is a function of factors such as temperature, time exposed, rate of permeation, type of aggressive medium and of course if there is a crack in the laminate which would allow direct access to the reinforcement.

The process is that the acid or alkali medium gains access to the glass fibre, either by diffusion or via a surface crack. Having gained access, the aggressive medium attacks the fibre and degrades it very rapidly. In which case the fibre has not performed one of its primary duties, which is to act as a crack stopping device. The crack propagates further, allowing the aggressive medium access to the next fibre. This is also attacked and fails and so on.

Work has shown (ref 20) that polyester resin is impermeable to hydrochloric acid and thus discounted the permeability mechanism for those particular laminates. This implies that the propagation of cracks between fibre and the laminate surface is the route for the environment ingress. This may be the case generally. Having gained access, the environment may or may not degrade the fibre very rapidly. But it has been shown (ref 22) that E glass is susceptible to acid attack. In sulphuric acid E glass strand suffers maximum strength loss in 1 to 6 N acid and hydrochloric acid has a similar effect. Hence the fibre is not able to perform one of its primary duties, to act as a crack stopping device. Matrix cracks propagate allowing the acid access to the next fibre. This is attacked by the acid and fails and so on.

When a glass fibre laminate is broken normally, the appearance of the failure surface is characteristically fibrous. Filaments of glass fibre protrude from the surface giving a brush like appearance. By contrast when stress corrosion failure occurs the failure surface is characteristically rock like. It is devoid of protruding filaments. Under microscopic examination the filaments can be seen to have broken flush with the surface.



Fig 2.33 Failure surfaces due to ESC

Fig 2.33 shows the effect of ESC on an E glass fibre / polyester laminate. The laminate was cut from the base of a tank which has failed by ESC. The laminate is approximately 30 mm thick but was separated into the two parts by hand. We see the two surfaces of the crack which has propagated through the thickness of the tank due to the applied stress and the aggression of the tank contents on the E glass reinforcement.

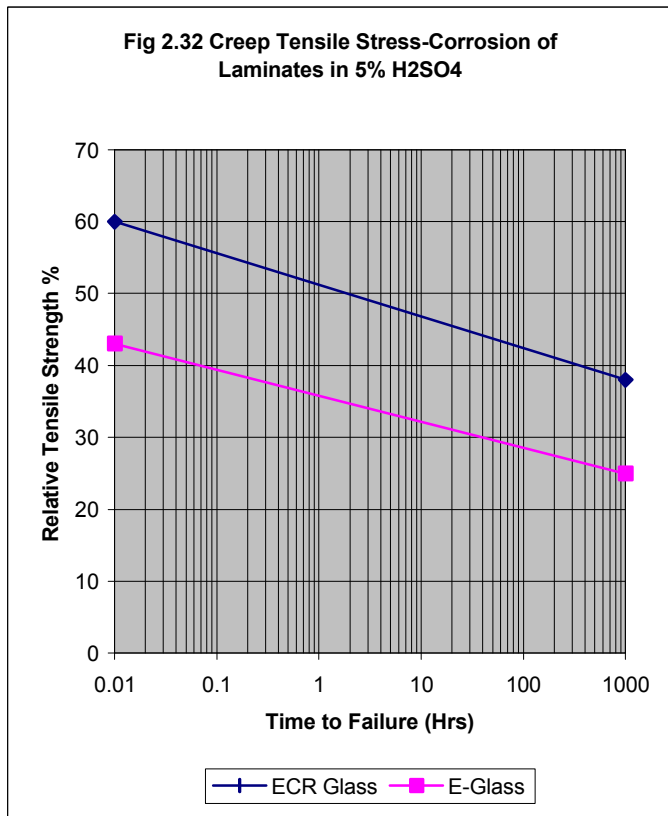
Cracks in composites are not uncommon they range from a very simple scratch to very obvious damage which might be caused, for instance, by impact. Normally they are arrested when they reach a reinforcement fibre. However if the environment, which then has access to the fibre reinforcement, is aggressive to it, then catastrophic failure can occur. This could result in loss of life and serious damage to other equipment.

(Continued on page 18)

(Continued from page 17)

ECRGLAS glass strand (chemically resistant grade of glass) shows a much-prolonged retention of strength in mild acids in comparison to E glass.

Fig 2.32 compares an E glass laminate with a similar ECR-GLAS laminate in tension when exposed to 5% H₂SO₄. The tensile strength of the E glass laminate reduced to 38% in less than 1 hour, whereas the ECRGLAS laminate took about 1000 hours to degrade the same amount.



There appear to be three types of specimen failure (ref 20). At high loads, failure is similar to dry failure under tension. At lower loads the failure surface is stepped, but at very low loads the fracture surfaces are very smooth.

A further complication is that some aggressive agents do not attack the fibre but severely degrade the polymer. Tests using 0.5M orthophosphoric acid (ref 2.21) with E glass/epoxy showed rapid micro cracking of the laminate but the fibres alone were found to be virtually crack free. It is therefore dangerous to generalise in this field and necessary to refer to relevant data or carry out accelerated stress corrosion trials.

The timescale over which the process takes place is perhaps the most important parameter. As an example Fig 2.33 has been drawn as a simplification of data in Ref 22. It considers ESC of a pipe fabricated with Chopped strand mat and Isophthalic resin. The chemical environment is HCl at 20°C. This shows that if a strain of 1% is applied failure occurs after a period of about 5,000 minutes (3 1/2 days). This is without the presence of an initial crack.

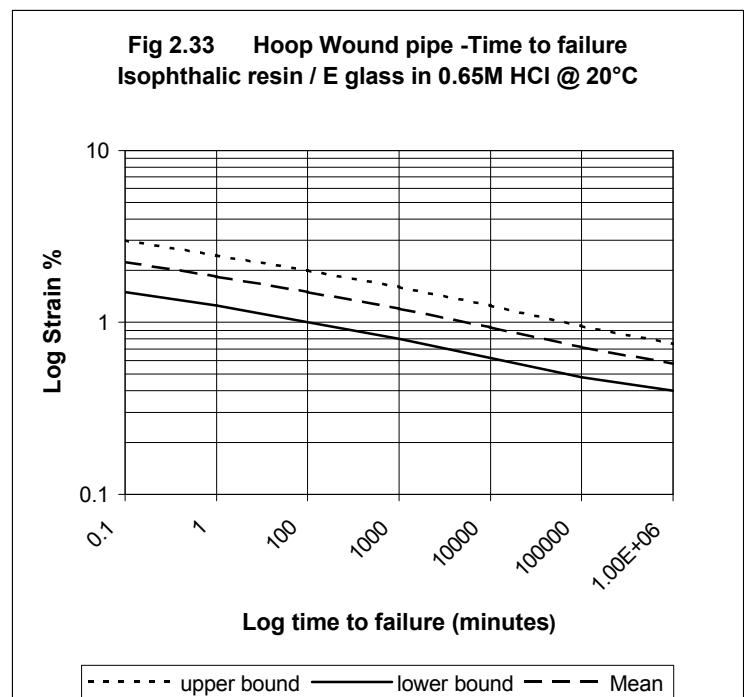
The following table has again been produced as a simplification of data again from Ref 2.22. It shows that at a strain of 1% failure occurs in a hoop wound pipe of E glass / Isophthalic resin, as follows:

Time to Failure	
Gel coated laminate	10 ⁶ minutes = 1.9 years
Non-Gel coated laminate	200 minutes
Cracked Gel coat	30 minutes

It is clear that the use of a gel coat has a substantial benefit. However it is imperative that there is no crack present in the gel coat otherwise the benefit is removed and the situation in fact worsened.

It is an essential part of the design process to take into accounts all of the likely modes of failure. These are very contrasting and include the effect on the structural integrity of a vessel of a minor crack occurring in the gel coat surface of the laminate. If the contents of the vessel are benign to the glass fibre (which is generally the case) then it is of little consequence. But if the contents of the vessel are aggressive to the glass fibre reinforcement then steps should be taken to ensure that either a minor crack cannot occur or that if it does occur that a barrier is in place to prevent failure. Options available are, for instance, the use of gel coat and barrier layer resins with high strain to failure and or the use of multi-layers of synthetic veil or a corrosion resistant grade of glass fibre if necessary.

It should be noted that the most chemically resistant resin is not necessarily the most effective option to avoid stress corrosion. It has been shown (Ref 2.22) that the toughness of the resin is more important than its chemical resistance in a stress corrosion situation. .



CHEMICAL CORROSION RESISTANCE

Chemical corrosion properties - GRP

E glass is highly resistant to most chemicals but it is attacked by both mild acids and mild alkalis. The extensive use of glass fibre reinforcement in chemical plant is reliant upon the corrosion resistance of the polymer matrix and its ability to ensure that the glass fibres do not become exposed to the environment. (see "stress corrosion")

Other glass fibres, notably ECR glass shows an improvement over E glass in a corrosive environment which may gain access to it. Bare E glass in distilled water retains about 65% of its short term ultimate tensile strength after 100 days. This compares with R glass which has a strength retention under the same conditions of 75% after 100 days. (Ref 2.18)

It is well known that C glass has high resistance to chemical attack, it was introduced specifically for this purpose. Its availability came into doubt in the early 1980's which triggered work to ascertain the suitability of A glass as a substitute.

In fact basic work had already been carried out by Maloney (Ref 2.32). In this work C glass and A glass laminates were immersed in 20 different reagents for up to 360 days after which time the flexural strength was determined. The tests showed that the A glass material and the C glass material were equivalent under a wide variety of chemical environments including distilled water.

Lake & Henrich (2.33) evaluated the corrosion resistance of resins for hot/wet chlorine service. This work included a comparison of the use C glass and A glass veils and the use of A glass as the reinforcement mat. It showed that the substitution of A glass veil and A glass mat for the standard C veil and E glass mat can improve resistance to chlorine.

Chemical Corrosion properties - ARAMIDS

Aramid fibres fall into two main categories with respect to their chemical resistance. PPTA fibres of which Kevlar 49 is an example are chemically quite stable and have high resistance to neutral chemicals. But they are susceptible to attack particularly by strong acids and also by bases. On the other hand Technora aramid fibre exhibits extremely high strength retention in both acids and alkalis.

Tests carried out in 40% aq. H_2SO_4 at 95°C for 100 hours showed 90% strength retention for Technora fibre compared to 20 % for PPTA fibre. (Ref 2.19). To put this into context, E-glass fibres would have ceased to exist under these conditions.

Chemical Corrosion properties - RESINS

Composites are inherently corrosion resistant and can show substantial cost benefits when used in environments which are extremely aggressive. Hence glass reinforced plastics have been used extensively in chemical plant structures for many years.

The polymers used are selected on the basis of their ability to withstand the aggression of the chemical environment whether it should be strong acid, strong alkali or perhaps simply salt water.

In general terms the order in which polymers are corrosion resistant is:

- ORTHOPHTHALIC POLYESTER (Low corrosion resistance)
- ISOPHTHALIC POLYESTER
- VINYLESTER
- BISPHENOL
- EPOXY

This is a very simplistic guide and should not be taken too literally. There are certainly specific examples where the order can be reversed. Consequently the resin manufacturers advice should be sought to determine the suitability of a resin system in a particular aggressive environment.

Corrosion Resistance of Epoxy Vinyl ester

The following table (pages 2.20 - 2.21) gives details of the corrosion resistance of epoxy vinyl ester from DOW. They are included for guidance. The resin manufacture should be consulted for confirmation of expected performance.

The following notes apply to the table.

*Trademark of The Dow Chemical Company

1. Double synthetic veil should be used in inner layer.
2. Post-cure recommended to increase service life.
3. Benzoyl Peroxide - DMA cure system recommended to increase service life.
4. Recommended provided that solvent used for dissolution is also recommended.
5. Satisfactory up to maximum stable temperature for product.
6. Check with corrosion technical service lab for specific recommendations.
7. Probably satisfactory at higher temperatures, but temperature shown is the highest for which information is available.
8. Double surfacing veil and 5 mm corrosion liner should be used.
9. Double surfacing veil.
10. Call for recommendations if sulphuric acid is present.
11. DERA-KANE* 411 series preferred.
12. If service is marginal use DERA-KANE* 470-30 resin.
13. ECR Mat is recommended in the corrosion liner.
- 14 This is just a small selection of the chemicals which have been tested or used with Derakane* epoxy vinyl ester resins. For further information contact the Dow Chemical Co.

Chemical Resistance Guide

Maximum service temperature vs. chemical environment of DERA KANE resins

DERAKANE RESIN:- CHEMICAL ENVIRONMENT	Concen tration %	411 Deg C	441-400 Deg C	470 Deg C	8084 Deg C	510A Deg C	DERAKANE RESIN:- CHEMICAL ENVIRONMENT	Concen tration %	411 Deg C	441-400 Deg C	470 Deg C	8084 Deg C	510A Deg C
Acetic Acid	10	100	100	100	65	100	Chlorine Dioxide Generator Effluent, R2 System		65	80	80	65	65
	15	100	100	100	65	100	Chlorine Water <6>	Satd	95	95	100	80	95
	25	100	100	100	65	100	Chlorine, dry gas <8>	100	100	120	120	80	105
	50	80	80	80		80	Chlorine, wet gas <8>	100	100	120	120	80	105
	75	65	65	65			Chloroacetic Acid <6>	25	50	50	50		65
Acetic Acid, Glacial	100	NR	NR	40	NR	NR		50	40	40	40		50
Acetone	10		80	80		80		Conc.	NR	NR	NR	NR	NR
	100	NR	NR	NR	NR	NR	Chlorobenzene	100	NR	30	40	NR	NR
Air One Sided (Uninsulated) Air Temp	180	210	230		190		Chloroform	100	NR	NR	NR	NR	NR
Immersion		100	120	150		110	CHLOROTHENE* SM						
Alcohol, Butyl	All	50	50	50		50	1,1,1-Trichloroethane inhibited	100	40	50 <7>	50 <7>	NR	40
Alcohol, Ethyl	95	30	30	40	NR	30	Chlorotoluene	10	30	40	40	NR	30
Ammonia	Liquified Gas	NR	NR	NR	NR	NR	Chromic Acid	10	65	65	65	65	65
Ammonia <7>	Gas	40	40	40	40	40		20	50	65	65	50	65
Ammonia, Aqueous (See Ammonium Hydroxide)								30	NR	NR	NR	NR	NR
Aniline	100	NR	NR	20	NR	NR	CHROMIC ACID: Sulphuric Acid Mixture						
Anodize (15% sulphuric)			100				(Maximum Total Concentration 10%)	10	50	65	65	50	50
Aqua Regia <6>							Chromium Plate		55	55	55	55	55
Barley Solution	75	75			75		Copper Cyanide, Potassium Cyanide,	oz per gal	80	80	80	80	80
Beer			50	50			Potassium Hydroxide l						
Beet Sugar Liquor	80	80			65		Crude Oil, Sour	100	100	120	120	65	100
Benzene <12>	100	NR	NR	40	NR	NR	Crude Oil, Sweet	100	100	120	120	65	100
Benzene: Ethylbenzene <12>	.33 to .66	NR	30	40	NR	NR	Cryogenic Temperatures <6>						
Benzene Hydrochloric Acid (Wet)<12>	NR	30	40	NR	NR		DMA4 WeedKiller 2,4-D (Dimethylamine)	50	65	65		50	
Benzene, Vapor <12>		30	30	50	NR	NR	Deionized Water	100	80	80	80	80	80
Benzyl Alcohol	All	NR	30	40	NR	NR	Demineralized Water	100	80	80	80	80	80
Benzyltrimethylammonium Chloride	60	40	40	40		40	Dibutyl Ether	100	80	100	100		
Bisulfite in Scrubber	Gases	80	180	180		90	Dibutyl Sebacate	All	50	65	65	50	50
Black Liquor (Kraft)	Thin	80	80	80		80	Dichloroethane <12>	100	NR	NR	30	NR	NR
	Thick	95	105	105		95	Dichloroethylene	100	NR	NR	NR	NR	NR
Brass Plating Solution		80	80	80	80	80	Dichloromethane (Methylene Chloride)	100	NR	NR	NR	NR	NR
3% Copper, 1% Zinc, 5.6% Sodium Cyanides, 3.0% Sodium Carbonate <1>							Diesel Fuel	100	80	100	100	65	80
Brine	All	100	100	100	80	100	DOWANOL* DB Diethylene Glycol						
Bromine, Dry Gas		40	40	40	40	40	n-Butyl Ether						
Bromine, Liquid	100	NR		NR	NR	NR	(see also Butyl CARBITOL)	100	30	40	40	NR	30
Bromine, Wet Gas	100	40	40	40	40	40	DOWANOL DB Glycol Ether <12>	100	30	40	40	NR	30
Bunker C Fuel Oil	100	100	105	105	65	100	DOWANOL EB Glycol Ether						
Butyl Alcohol	All	50	50	50 <7>	NR	50	(Ethylene Glycol n-butyl ether)	100	40	40	40	NR	40
Butyl CELLOSOLVE Solvent	100	40	40	40		30	DOWANOL PM Glycol Ether	100	NR	NR	20	NR	NR
Calcium Hydroxide <1>	15	80	80	65	80	80	DOWCLEN* Solvent	100	50	50	50		50
	25	80	80	80	80		DOWCLEN EC Solvent		40	50	50		40
	100	100	100	100	80	100	Ethanol (Ethyl Alcohol)	95	30	30	40	NR	
Calcium Hypochlorite <1>, <2>, <3>, <5>, <6>,<14> <11>	All	80	80		80	80		50	40	40	65	NR	40
Carbon Dioxide Gas		100	180	180	80	165		10	50	50	65	50	50
Carbon Disulfide	100	NR	NR	NR	NR	NR	Flue Gas <6>		165	180	205 <7>		165
	Fumes	40	65	65	NR	40	Flue Gas, Wet	All	80	100	100	80	80
Carbon Tetrachloride	100	65	80	80		65	Fluosilicic Acid <1>	10	80	80	80	65	80
Carbon Tetrachloride, vapor		80	95	95		80		25	40	40	40	40	40
Castor Oil	100	70	70	70	70	70		35	40	40	40	40	40
Chlorine Dioxide <6>	All	95	95	95	80	95		98			40		
Chlorine Dioxide, Wet <6>	Satd	95	95	95	80	95	FREON 11	100	30	40	40	NR	30
							Fuel Oil	100	80	100	100	65	80

NR : Not Recommended

(Continued)

DERAKANE RESIN:- CHEMICAL ENVIRONMENT	Concen tration %	411 Deg C	441-400 Deg C	470 Deg C	8084 Deg C	510A Deg C
Gasohol (5% MEOH)	100	50	50	50	50	50
Gasohol (Up to 10% Alcohol)	40	40	50	NR	NR	
Gasohol (10-100% Alcohol)	NR	NR	40	NR	NR	
Gasoline, Leaded	100	80	80	80	65	80
Gasoline, Aviation	100	80	80	80	65	80
Gasoline, No Lead, No Methanol	100	50	65	65		50
Hydraulic Fluid	100	80	80	80		80
Hydrobromic Acid	18	80	80	80	80	80
	25	80	80	80	80	80
	48	65	65	65	65	65
	62	40	40	40	40	40
Hydrochloric Acid <9>	10	80	110	110	80	100
	15	80	110	110	80	100
<8>, <13>	20	80	110	110	80	100
<8>, <13>	37	65	80	80	65	80
Hydrochloric Acid, Fumes + Free Chlorine <8>, <13>				180	180	
Hydrochloric Acid, Fumes <9>			100	180	180	80 100
Hydrofluoric Acid <1>	10	65	65	65	65	65
	20	40	40	40	40	40
	25	40	40	40	40	40
	35	40	40	40	40	40
Hydrogen Bromide, wet gas	100	80	80	80	80	80
Hydrogen Chloride, dry gas <6>	100	100	180	180	80	100
Hydrogen Chloride, wet gas <6>	100	100	180	180	80	100
Hydrogen Fluoride, vapor<1>		80	80	80	80	80
Incinerator Gases <6>			180	180		165
Jet Fuel (JP-4)	100	80	80	80	65	80
Kerosene	100	80	80	80	65	80
Lithium Hypochlorite <1>, <2>, <3>, <5>, <6>, <14>	All	80	80			80 80
Mercaptoacetic Acid	All	NR	30	40	NR	NR
Methyl Alcohol (Methanol)	5	50	50	50	50	50
	100	NR	NR	40	NR	NR
Methyl Ethyl Ketone <6>, <12>	100	NR	NR	NR	21	NR
NR						
Methylene Chloride	100	NR	NR	NR	NR	NR
Mineral Oils	100	100	120	120	65	100
	100	NR	NR	NR	NR	NR
Monochlorobenzene	100	NR	30	40	NR	NR
Nitric Acid	5	65	80	80	65	65
	40	NR	NR	30	NR	NR
Nitric Acid Fumes		80	80	80	80	80
Nitric Hydrofluoric Acid <1>, <6>	8	100	100	140		100
Oil, Sour Crude	100	100	120	120	65	100
Ozone	5	60	60	60	60	60
Phenol (Carbolic Acid)	5			50	NR	
Phenol	88	NR	NR	20	NR	NR
Phosphoric Acid	85	100	80	100		
	100	100	100	100	80	100
Salt Brine	30	100	100	120	80	
Sea Water		80	100	100	80	80
	50	40	40	50	40	40

DERAKANE RESIN:- CHEMICAL ENVIRONMENT	Concen tration %	411 Deg C	441-400 Deg C	470 Deg C	8084 Deg C	510A Deg C
Sodium Hydroxide <1>, <2>, <14>, <11>	5	80	80	65	80	80
	10	80	80	65	80	80
	25	80	80	80	80	80
	50	100	100	80	80	80
Sodium Hypochlorite <1>, <2>, <3>, <5>, <6>, <14>, <11>	5.25	80	80		80	80
	10	80	80		80	80
	18	80	80		80	80
Styrene	100	NR	40		NR	NR
Sulphur dioxide, (dry or wet)		100	100	120	80	100
Sulphuric Acid	25	100	100	100	80	100
Sulphuric Acid Cont.	70	80	80	80	80	80
	75	40	40	50	40	40
	93	NR	NR	NR	NR	NR
Sulphuric Acid, Vapour		100	120	180	80	100
Toluene	100	30	40	50	NR	30
Trichloroacetic Acid	50	100	100	100		100
Trichloroethane	100	40	50	50	NR	40
Trichloroethylene	100	NR	NR	NR<6>	NR	NR
Water Deionized <2>	100	80	80	80	80	80
Water, Distilled <2>	100	80	80	80	80	80
Xylene	100	30	40	50 <7>	NR	30

NR : Not Recommended

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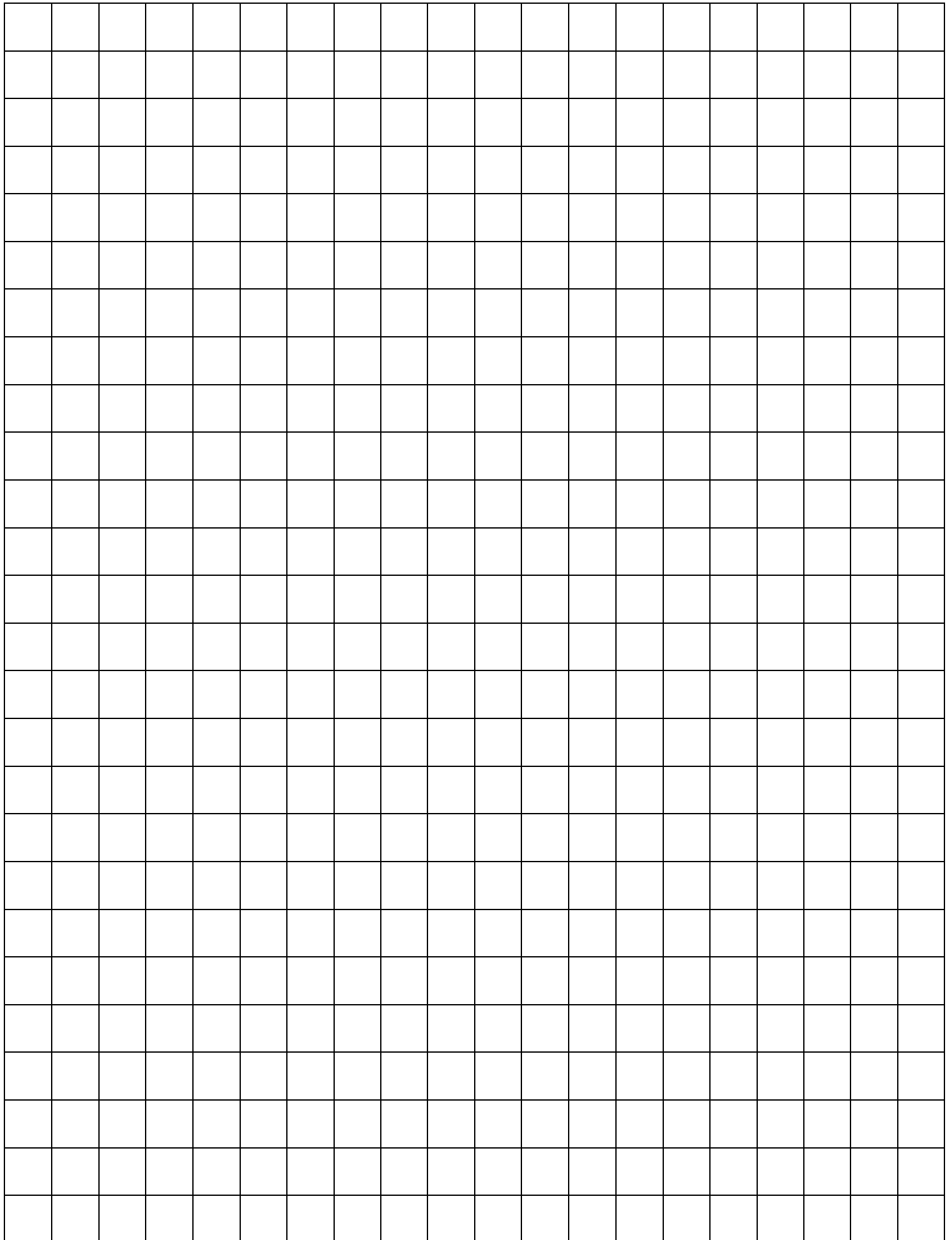
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3 Composites Production Processes

Composite materials are converted into components by a set of processes which are to a large extent unique. It is convenient to classify them to understand the underlying principles. This can be done in many ways but the method chosen here is in four categories:

OPEN MOULD

A single mould is used hence only one surface of the moulded product is smooth.

CLOSED MOULD

Two matched moulds are used hence two smooth surfaces are produced.

WOUND

In which the mould rotates allowing the reinforcement to be wound onto its outer surface.

CONTINUOUS

Those processes which produce linear shapes of theoretically any length.

These classifications sub divide further into individual processes. A complicating factor is that some of the processes can be combined to suit the particular requirements of a product. Nevertheless the processes are described and classified in their basic form to allow comparison. In order to produce a composite component each process has to perform a set of fundamental tasks. Some of these are trivial for a particular process but it is valuable to consider them for each process in order to understand the process and appreciate its benefits and limitations. This approach has been used in the process descriptions which are in the form of a set of reference charts. (see Process Descriptions).

The **primary characteristics** of the production processes are :
Labour content

Cycle time

Viable production quantity

Capital cost of equipment

Size of component that can be produced

Fundamental shape that can be produced

These characteristics are tabulated to allow easy reference and comparison of the process options.

Composites are complex materials which have evolved in tandem with the processes to meet not only the physical property requirements but also those properties demanded by the process. Hence many of the characteristics of the reinforcement materials are so designed not to enhance the physical properties of the

finished composite but to enable the composite to be processed efficiently. Characteristics such as ease of chopping (choppability), static, wet out, wet through, mouldability, drape, wet strength, dry strength and many more all determine how well a composite can be produced. Each characteristic is associated with particular moulding processes. Some characteristics which may be essential for one process are irrelevant for another. For instance a glass fibre roving to be used for filament winding does not need to have good chopping characteristics. Therefore an attempt has been made to classify the reinforcement materials according to the processes which are most applicable or for which they have been specifically designed. (See material selection charts)

A variety of factors can dictate that a particular process must be used for the production of a product. However it is more usual that there is a choice of process which will be suitable. This may be from the criterion of performance or shape, but generally production cost is the most important factor in process choice.

Production cost is, amongst other factors, a function of production rate. There are various ways of measuring production rate and in the following process data sheets different methods are used as appropriate to the process.

Number of mouldings per hour is used for Cold press and RTM.

Weight of laminate per hour is used for Hand lay-up and Spray-up.

Cycle time is used for Autoclave, Vacuum moulding, Hot press moulding and Filament winding.

Number of metres per hour is used for Pultrusion.

3.1.0 PROCESS DESCRIPTIONS

A systematic approach to the description of the processes has been adopted in order to allow their comparison and hopefully to make them more easily understood. The processes have been broken down into the fundamentals which are basic to composite processes in general.

In some processes one or two of the fundamentals may be hidden or trivial and it is necessary to stretch the imagination to discuss them. Nevertheless the general approach is useful and has been adhered to for the sake of completeness.

Only the principles of each process are described. There are many variations of each process which have been developed to solve particular problems. Similarly there are many combinations of processes, where two quite different processes have been combined to suit a specific application.

The fundamentals are:

FIBRE PLACEMENT

The means by which the fibre is placed in or onto the mould in the position and orientation required.

MATRIX APPLICATION

The method of applying the resin to the reinforcement. It may be applied by brush or by pouring etc.

WET THROUGH

This is the penetration of the reinforcement strand by the resin.

WET OUT

Physical wetting of the surface of the filaments by the resin. (This is mainly achieved by surface chemistry and is the fibre manufacturer's area of expertise).

CONSOLIDATION

Removal of air from the laminate and the compaction of the laminate.

CONFORMATION

The method of ensuring that the laminate conforms to the mould surface. This may be achieved by use of a roller in hand and spray lay-up, or by the use of two mould surfaces.

CURE

The chemical change in the resin from a liquid to a solid.

RELEASE The process of removal of the composite from the mould.

PROCESSES FOR COMPOSITE MATERIALS

The processes may be classified as follows:

OPEN LAY UP

HAND LAY UP

SPRAY UP

INTERMEDIATE

COLD PRESS

RTM / RESIN INJECTION

AUTOCLAVE/VACUUM BAG

COMPRESSION MOULDING

HOT PRESS

CONTINUOUS PRISMATIC

PULTRUSION FAMILY

CONTINUOUS SHEET

WINDING PROCESSES

FILAMENT WINDING

DESCRIPTION

Hand Lay-up is the simplest of the moulding processes. The reinforcement mat is simply laid into an open mould. Resin is then applied with a brush after which the laminate is rolled and allowed to cure.

FIBRE PLACEMENT

The reinforcing material is laid in the mould by hand. It may be trimmed to the precise shape required or allowed to overlap the mould edge. Very complex shapes require several small pieces of mat to achieve the required shape. Multi-layers of mat are built up to the required thickness.

MATRIX APPLICATION

The resin is applied by stippling the resin into the reinforcement, generally by a simple paint brush, or paint roller or by spray gun.

WET THROUGH / WET OUT

The stippling action mechanically forces the resin into the reinforcement to ensure penetration of the fibre bundle.

CONSOLIDATION

The laminate is rolled with a split-washer roller which ensures resin penetration through the reinforcement and forces the entrapped air to the surface.

CONFORMATION

Only the adhesion of the resin to the mould maintains the reinforcement in intimate contact with the mould surface. Hence the ability to conform to very complex mould shapes is dependent on the conformability of the reinforcement used and its springiness. CSM is tested for its ability to conform to small radii, both internal and external.

Minimum Radii:

5 mm (0.2in) Internal, 10 mm (0.4 in) External

CURE

Usually cold cure systems are used for hand-lay-up with an accelerator as well as a catalyst. Occasionally hot cure is used in which case the accelerator is not necessary. It is good practice to post cure cold-cured laminates at an elevated temperature. e.g. 80°C for 2 hours or 40°C for 16 hours according to the resin manufacturers instructions.

RELEASE

The mould is prepared by the application of Polyvinyl alcohol to the mould surface and allowed to dry and / or non-silicon wax polished into the mould surface. Release is achieved by tapping wedges between the mould and the moulding around the periphery of the mould. Alternatively compressed air may be used to gently blow them apart.

MATERIALS

Fibre: CSM is used for the majority of production and WR if higher volume fraction is required. WR gives intrinsically stronger and stiffer laminates than CSM. Occasionally Needle mat and Roving are used. Surfacing veil is used to improve surface finish and corrosion resistance. It is applied immediately to the gel coat to reinforce it. Alternately it may be used with the laminating resin to produce a resin rich, smooth surface.

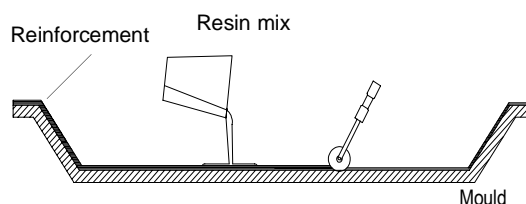
Resins: Polyester is used for the majority of applications. Also used are vinyl ester, epoxy and phenolic, if the application demands their use.

Other: Typical catalyst and accelerator are MEKP and Cobalt Napthanate.

Gel coat, which is a thixotropic version of the laminating resin, may be applied to the mould surface to produce a resin rich, smooth surface.

CRITICAL FACTORS

	RANGE	TYPICAL
SIZE	0.5 m ² - 300 m ² (5ft ² - 3000ft ²)	3 m ² (30ft ²)
PRODUCTION RATE (of laminate)	1 - 10 kg/hr. (2-25 Lb/hr)	3 kg/hr (6 Lb/hr)
PRODUCTION QUANTITY	1 - 500	20
LABOUR CONTENT		very high
CAPITAL	very low	<£1000

Hand lay-up

3.1.2 PROCESS DATA SHEET

SPRAY LAY-UP

DESCRIPTION

Catalysed and accelerated resin, together with chopped glass fibre are simultaneously sprayed onto an open mould. The laminate is rolled and then allowed to cure. After which release and trimming to size can take place.

FIBRE PLACEMENT

Continuous glass fibre (Roving) is chopped in the chopper unit of the spray gun by the action of a rotating blade against a polyurethane roller. The resulting chopped strands are blown from the gun by the exhaust from the air motor which drives the chopper.

The operator directs the spray gun in the desired direction and the strands of glass fibre impinge on the mould surface in a random array. Spray guns can deposit glass fibre at the rate of 2-5 kg/min (4-10lb/min), but they are generally operated only in short bursts giving an overall material throughput of about 20 kg (40 Lb) of laminate per hour.

MATRIX APPLICATION

Resin is sprayed from the gun concurrent with the chopped glass fibre. The two streams meet approximately at the mould surface. The ratio of glass fibre to resin is adjusted by running each separately for a fixed time period (typically 15 sec.) and weighing the quantities of each. The gun is adjusted to give the desired ratio which is typically 2.5/1 resin /glass (by weight).

WET THROUGH AND WET OUT

As soon as the resin comes into contact with the fibre the process of wet through and wet out starts. The low viscosity of the resin aids the breakdown of the strands into individual filaments to allow their wet out with resin.

CONSOLIDATION

After the spray pass the operator uses a roller (split washer or similar) to quickly consolidate the laminate. After a short

while (30-60 seconds) the strands filamentise and a second pass with the roller conforms the laminate to the mould surface and completes the air removal and consolidation.

CONFORMATION

The ability of sprayed, chopped glass fibre to conform to intricate mould details is dependent on the cross sectional size of the strand and the speed at which it can filamentise when wet with resin. Obviously the larger the mould radius the better. A minimum of 6 mm radius on mould details is preferred.

CURE

The two spray up system types are "twin-pot" and "catalyst injection".

Whichever system is used the reaction process only starts at the gun. This implies that highly reactive, fast curing resin systems may be used with little fear of premature gelation. This then allows rapid demould time. The twin-pot system has two pressure pots each containing resin, one having catalyst and the other having accelerator. Hence the pot life of the resin is not a problem.

RELEASE

Release systems and procedure is exactly the same as for hand- lay-up.

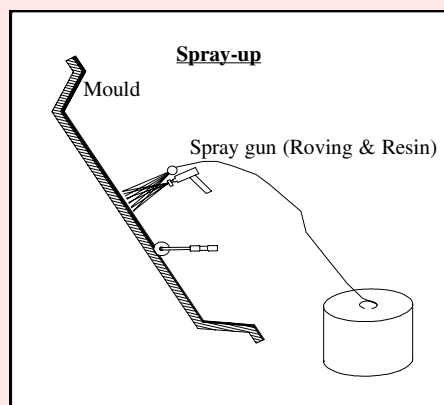
MATERIALS USED

Fibre

Grades of Glass fibre roving are particularly designed to be suitable for spray up. They have good choppability together with low static and fast wet through.

Resins

Usually only orthophthalic and isophthalic polyester resins are used in spray-up. They are normally highly reactive to take full advantage of the process characteristics.



CRITICAL FACTORS

	RANGE	TYPICAL
SIZE	>2 m ² (20ft ²)	10 m ² (100ft ²)
PRODUCTION RATE (OF LAMINATE)	5 - 50 kg/hr (10 -100 Lb/hr)	20 kg/hr (40 Lb/hr).
PRODUCTION QUANTITY	5 - 5000	500
LABOUR CONTENT	MODERATE	
CAPITAL		
MACHINE	£10 - 20k	£15k
MOULD	£1000 - £30K	£1500

3.1.3 PROCESS DATA SHEET

COLD PRESS MOULDING

DESCRIPTION

A press moulding technique in which light duty tooling (low cost) is used. Hence low pressures and low temperatures are necessary. Therefore production rates are moderate, but capital expenditure is also moderate.

FIBRE PLACEMENT

The reinforcement mat is tailored to the size and shape of the mould it is then manually placed on the lower mould. Several layers may be applied depending on the thickness of the mould cavity to be filled. The reinforcement is allowed to overlap the pinch-off area of the mould.

MATRIX APPLICATION

As the process doesn't use heat to cure the resin system an accelerator is required in the mix. If the full resin system was batch mixed then the pot life would be unacceptable. Generally two batch mixes are made, one containing catalyst, the other containing accelerator. Sufficient from each batch is mixed together immediately prior to each moulding cycle. This is poured onto the reinforcement material within the mould.

WET THROUGH / WET OUT

The press is rapidly lowered thus closing the two halves of the mould. As the mould halves close the resin and reinforcement are compressed. The resin is pushed towards the perimeter of the mould, the pinch-off area. Because the reinforcement overlaps the pinch-off it is compressed more than within the mould. This restricts the flow of resin but allows the passage of air. Hence as the resin flows to the pinch-off a back pressure is created which ensures that the resin flows to all parts of the cavity.

CONSOLIDATION

The pinch-off zone on the mould can be as simple as a hard rubber strip 10-15 mm wide. This reduces the moulding thickness to about 50% at the perimeter. This simple device allows the generation of a back pressure with the resin and air to be expelled from the front of the moving resin boundary.

CONFORMATION

The shape of the component is a result of the cavity created by the two mould surfaces held in position by the pressure of the press. Typical pressures range from as low as 1 Bar up to 10 Bar. (On projected mould surface)

CURE

The process is effectively cold cure although the moulds are generally warmed to a modest temperature. The resin system is accelerated to achieve a reasonable cure cycle. A typical polyester cure time is 15 minutes. However the cure produces an exothermic reaction which heats the mould. Thus the amount of accelerator is progressively reduced after the first two or three mouldings, until steady state conditions are arrived at. A compromise is arrived at with the fastest cycle time without either product or mould degradation due to excessive temperature.

RELEASE

As for hand lay-up, but high temperature versions may be necessary to cope with the high exothermic reaction.

MATERIALS

Fibres

The reinforcement material must allow the flow of resin, not through the thickness but in-plane and over relatively large distances. Also the reinforcement must be capable of conformance to complex mould shapes and variations in thickness. These factors dictate the type of reinforcement which can be used. Continuous filament mat and needle mat (both glass fibre) are most common, but woven roving and multi-axial reinforcements (glass, carbon etc.) can also be used.

Resins

The most popular resin system is polyester due to its versatility and suitability to the process. However for more demanding applications epoxy or phenolic resins are occasionally used.

Other : Gel coat. See Hand lay-up. Tissue. See Hand lay-up.

CRITICAL FACTORS

	RANGE	TYPICAL
SIZE	0.5 m ² to 5 m ² (5ft ² - 50ft ²)	1 m ² (10ft ²)
PRODUCTION RATE (No MOULDINGS)	0.5 to 3 /hr.	2 /hr.
PRODUCTION QUANTITY	100 to 5000	500
LABOUR CONTENT	MODERATE	
CAPITAL	£20K to £60K	£40K

3.1.4 PROCESS DATA SHEET

RESIN TRANSFER MOULDING

DESCRIPTION

Reinforcement is placed on the bottom mould. The moulds are then closed and clamped together. Resin is then injected into the cavity under pressure. Cure rapidly takes place after which the moulds are opened and the product released.

FIBRE PLACEMENT

Reinforcement mat is placed onto the lower mould. It must fit the contours and perimeter of the mould accurately. Hence 'preformed' mat is often the preferred option.

MATRIX APPLICATION

The resin is machine-mixed immediately prior to it being injected, under pressure, into the mould cavity. The pressure at which the resin is injected is typically 5 Bar (70 psi).

WET THROUGH / WET OUT

The pressure from the injection machine forces the resin through the reinforcement. The surface coating (size) on the fibre must be capable of allowing the fibre to be wetted by the resin very quickly, before gelation of the resin starts.

CONSOLIDATION

A 'pinch-off' device is necessary at the perimeter of the mould to allow air to pass through but to restrict the flow of resin. Pinch-off details are similar to those employed in cold-press moulding. This ensures that a back pressure is created to ensure that the mould cavity is fully filled.

CONFORMATION

The mould surfaces are kept in the correct location by either clamping devices or a low pressure press. Injection pressures are not high. Nevertheless flimsy moulds will distort. Therefore to ensure that the correct thickness is maintained, the moulds must be fairly robust.

CURE

Resin systems are generally, but not essentially, cold cure. Because they are mixed and injected into the mould within seconds, they can be extremely reactive and consequently have very short gel and cure times.

RELEASE

High temperature release agents are necessary due to the high exothermic reaction inherent in the process. The use of GRP and low cost tooling methods don't lend themselves to mechanical part ejection devices. Consequently release tends to be a hand process and labour intensive.

MATERIALS

Fibres

Glass fibre is the dominant reinforcement as it's cost is more appropriate than other more costly materials. CFM is the most commonly used format. However CSM with thermodeformable binder, which allows the production of preformed reinforcement shapes, may also be used. Sprayed chopped roving preforms may also be used.

Resins

Polyester resin and epoxy resin are both candidate resin systems. The choice is dependent on the relative importance of cost or performance. Whichever is chosen, low viscosity and high reactivity are necessary characteristics.

Others

Gel coat. See Hand lay-up.

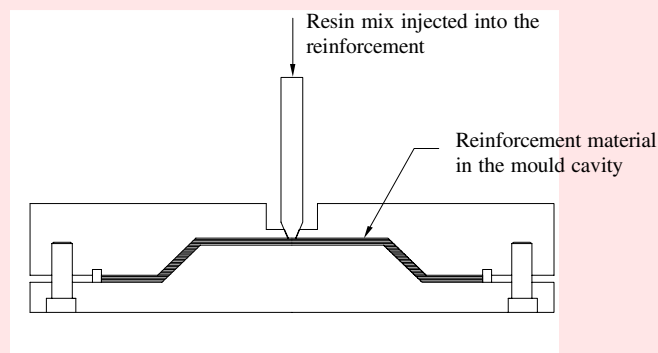
CRITICAL FACTORS

SIZE
PRODUCTION RATE (No MOULDINGS)
PRODUCTION QUANTITY
LABOUR CONTENT
CAPITAL

RANGE
0.2 m² to 10 m² (2-100ft²)
1/2 to 4 /hr.
500 - 5000
Medium to high
£10000 to £45000

TYPICAL
0.5 m² (5ft²)
3 /hr.
2000
£15000

Resin Transfer Moulding (RTM)



3.1.5 PROCESS DATA SHEET

AUTOClave/VACUUM BAG

DESCRIPTION

Layers of pre-impregnated fibre are applied to a mould and rolled. A rubber or plastic bag is placed over the lay-up and the air is removed by means of a vacuum pump. The mould is then placed in an oven, or an autoclave which applies further pressure and temperature to cure the resin.

The process is slow and laborious but produces excellent properties.

FIBRE PLACEMENT

Hand or machine placement of successive layers of prepreg. The layers are placed to a predetermined order and angle to achieve the laminate properties required. Computer controlled machines allow the precise placement of tapes of prepreg and eliminate problems associated with hand operations. Alternatively dry fibre, in any format may be used.

MATRIX APPLICATION

Incorporated in the prepreg. Or if dry reinforcement is used then resin mix is poured onto the fibre.

WET THROUGH / WET OUT

This has been achieved during the manufacture of the prepreg and is one of the benefits of the process. The material has been machine prepared in a controlled and precise manner thus assuring its quality.

CONSOLIDATION

This is achieved by the action of the vacuum and the applied pressure, typically 7 bar (100psi). The individual layers become fused and any excess resin is bled away. Some prepreg have the precise quantity of resin present which is required. More often there is an excess of resin to ensure good consolidation, this is removed by the use of a porous layer (bleed ply).

CONFORMATION

The applied pressure conforms the prepreg to the mould surface. The upper surface is a result of the material thickness and the pressure exerted on it by the rubber bag.

CURE

As a result of the applied heat (80°C to 200°C), either from the oven or the autoclave.

RELEASE

A special release film is applied to the each surface of the lay-up. It is porous to allow the passage of air and excess resin.

MATERIALS

Fibres

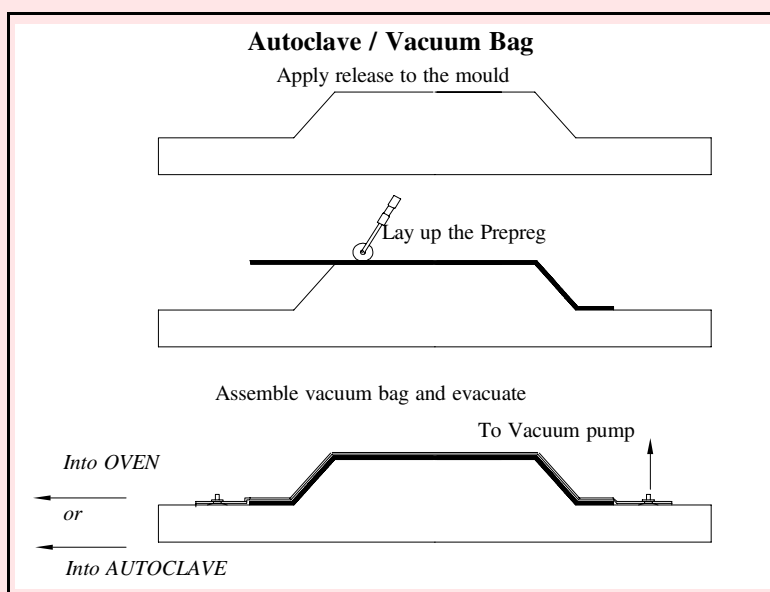
Carbon, glass and aramid fibre and prepreps of these fibres.

Resins

Almost exclusively epoxy resin. The process is justified by the excellent properties it produces. Hence the highest performance resin system is justified.

CRITICAL FACTORS

	RANGE	TYPICAL
SIZE	0.2 m ² to 100 m ² (2-1000ft ²)	2 m ² (20ft ²)
CYCLE TIME	1 hr. to 20 hr.	12 hr.
PRODUCTION QUANTITY	1 to 500	50
LABOUR CONTENT	MEDIUM	
CAPITAL	£50k to £500k	£200k



3.1.6 PROCESS DATA SHEET

HOT PRESS MOULDING

DESCRIPTION

Hot press moulding is a mass production method for the manufacture of composite components. A hydraulic press is used capable of applying a pressure of about 100 tonnes per m² (150 psi) of platen area. A matched metal tool is located between the platens. The cavity between the tool halves having been machined to produce the shape required. The tool is heated to about 130°C to 170°C either from the heated platens or directly (by cartridge heaters etc.). The polymer mix (thermoset) and reinforcement are placed in the tool, which is then rapidly closed. After 2 to 3 minutes cure is completed, the tool is opened and the component removed.

FIBRE PLACEMENT

Manual placement of either dry reinforcement or pre-impregnated reinforcement (sheet or dough, moulding compound or prepreg)

MATRIX APPLICATION

If the reinforcement isn't pre-impregnated then catalysed resin is poured onto the fibre. The pouring technique must avoid air entrapment. Hence it is preferable not to pour with a circular motion. Generally only 1/3 to 1/2 of the reinforcement is wetted at this stage.

WET THROUGH / WET OUT

Pre-impregnated materials are wet through and wet out at the pre-pegging stage.

With 'wet resin' technique, the closure of the die and the consequent hydraulic pressure forces the resin through the reinforcement, pushing a front of air to, and through, the pinch-off area.

CONSOLIDATION

The pinch off zone in the perimeter of the die cavity is large enough to allow air to pass through (0.05 - 0.25mm / 0.002 - 0.010 in) but restricts the flow of the much more viscous resin. Hence a pressure is generated which encourages the resin to flow to any remaining voids. Thus the whole cavity is filled with only a very small "flash" of resin passing through the pinch-off.

As this is very thin and without reinforcement, it is easily removed from the moulding after release from the die (deflash).

CONFORMATION

The applied pressure at closure of the die is maintained while cure takes place. The volume of resin in the die changes due to the chemistry of cure and thermal expansion effects. The applied pressure therefore maintains the shape of the component during the transition from liquid to solid.

CURE

The resin system, whether as a liquid or as a compound, contains a curing agent which is reasonably stable at room temperature and has an acceptable pot life. When it experiences the heat of the die (typically 130°C to 150°C) the cure reaction commences. The cure time is dependent on the type of resin, the level of curing agent used and the thickness of the component. Thick sections take a long time to heat through, plus

they can generate excessive exothermic temperature. Hence die temperature is generally lower for thick parts, therefore slower to mould.

RELEASE

Resins are very good adhesives. In order to prevent adhesion of the moulding to the die, release agents are incorporated into the resin mix and/or applied to the die surfaces. New dies are particularly prone to "stick-ups". With age they improve and are less likely to cause problems.

Typical release agents are described in Chapter 1.

MATERIALS

Compounds

Sheet moulding compound (SMC)

Dough moulding compound (DMC)

Bulk moulding compound (BMC)

These use polyester resin plus filler, catalyst, pigment, low profile additive etc.

Epoxy prepreg also may be compression moulded. This may have glass or carbon fibre as the reinforcement in uni-directional or bi-directional geometry.

Fibres

Continuous strand mat or chopped strand mat with insoluble binder.

Preforms produced a) by spraying chopped glass fibre and a binder onto a former of the required shape or b) by thermally deforming a CSM which has a thermoplastic binder.

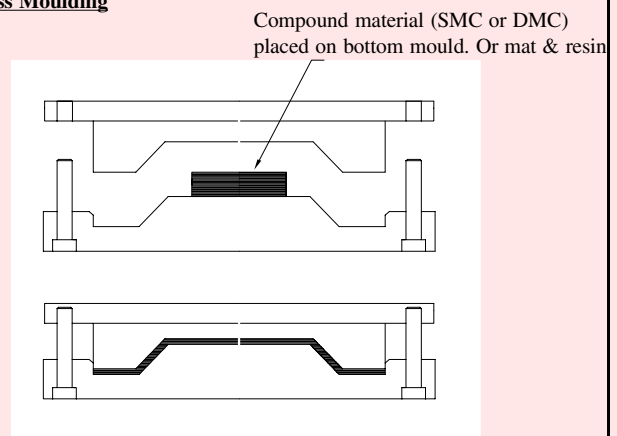
Resins

Wet moulding takes place with either polyester or epoxy resins using very similar mixes to those in compounds.

CRITICAL FACTORS

	RANGE	TYPICAL
SIZE	100 cm ² to 3m ² (15in ² to 30ft ²)	1/2 m ² (5ft ²)
CYCLE TIME	1 to 5 Minutes	3 Minutes
PRODUCTION QUANTITY	>5000	10000
LABOUR CONTENT	very low	
CAPITAL		
· PRESS	£75k to £500k	£150k
· TOOLS	£10k to £200k	£20k

Hot Press Moulding



DESCRIPTION

Continuous reinforcement is pulled through a device which applies the resin. The wetted fibre is then pulled on through a heated steel die which is the shape of the section to be produced. The die is heated to about 150°C which causes the resin to react, gel and cure. When the profile exits from the die it is at a high degree of cure. The profile is pulled by either reciprocating pullers or a caterpillar haul-off and it is then automatically cut to length with a flying saw.

FIBRE PLACEMENT

The precise positioning of the reinforcement materials prior to the die entrance is of paramount importance. It is achieved by a carefully engineered 'in-feed' system. This guides, locates, folds and tensions the various layers of reinforcing mat and uni-directional fibre. It also wipes excess resin from the reinforcement.

MATRIX APPLICATION

The resin is applied to the reinforcement either by the use of a dip tank or by injection. The dip tank approach is the most common. It consists of a tank containing the resin through which the reinforcement is pulled. The tank is replenished as necessary, to ensure that the process is continuous. The injection method is a cleaner option. The reinforcement is pulled through a fixed to the front of the die. The resin is injected under pressure into the cavity and thus it impregnates the reinforcement.

WET THROUGH / WET OUT

The time available for resin penetration and wet out of the fibre is dependent on the speed of the profile and the length of the resin tank or injection cavity. The process is aided by the physical working of the reinforcement by the use of bars which 'break' the reinforcement strands into their individual filaments.

CONSOLIDATION

The action of pulling the impregnated fibres into the die creates a hydraulic pressure which forces out any air which is present. For this to be effective the fibres must have been impregnated with a slight excess of resin.

CONFORMATION

The shape of the die determines the profile shape. But the quantities of reinforcement and resin mix are critical to ensure that the die is filled properly.

CURE

Resins systems must be highly reactive to cure in the available time. Machine speed, die temperature and resin reactivity are parameters which interact and must be balanced.

As the process is 'hot cure' an accelerator is not required. It is normal with polyesters to use more than one catalyst, each initiating at a different temperature. This spreads the reaction and thus reduces the exotherm temperature to a manageable level.

RELEASE

Release agents applied to the mould surface cannot be relied on as they would be very quickly worn away and therefore be inoperative. Hence it is necessary to include internal release agents in the resin mix.

MATERIALS**Fibres**

Glass, carbon and aramid fibres can be pultruded but the most common is glass fibre. This is a reflection of the applications rather than an intrinsic problem with the process. However the range of products available in glass fibre does help to ensure their dominance. The basic reinforcement geometry is uni-directional i.e. glass fibre 'roving' or carbon fibre 'tow'. This gives the longitudinal properties and allows the reinforcement to be pulled through the die. In order to achieve transverse performance either bi-directional or random reinforcement is needed e.g. woven roving or CFM respectively.

Resins

Polyester (isophthalic) is the most common matrix material. Vinylester is finding an important role in corrosion resistance applications. Urethane methacrylate has very good fire, smoke and toxicity performance. Epoxy is used in the higher performance applications and almost always with carbon fibre. Phenolic resins are being developed to make them suitable for pultrusion. The driving force is their excellent fire resistance.

Others

Tissue (Polyester or glass fibre)

CRITICAL FACTORS

	RANGE	TYPICAL
SIZE	As small as 3mm (1/8in) dia As large as 400mm (16in) deep * 1500mm (60in) wide	50 mm x 100 mm (2in x 4in)
PRODUCTION RATE	12 to 180 metres/hr (35 to 500 ft/hr)	45 m/hr (150 ft/hr)
PRODUCTION QUANTITY	5000 m (15000ft) to no limit	15000 m (50000ft)
LABOUR CONTENT	LOW	
CAPITAL		
MACHINE	£100k - £250k	£120k
TOOLS	£5k - 50k	£10k

Continued

PULTRUSION (Continued)

PULTREX PULTRUSION MACHINES

GENERAL DESCRIPTION

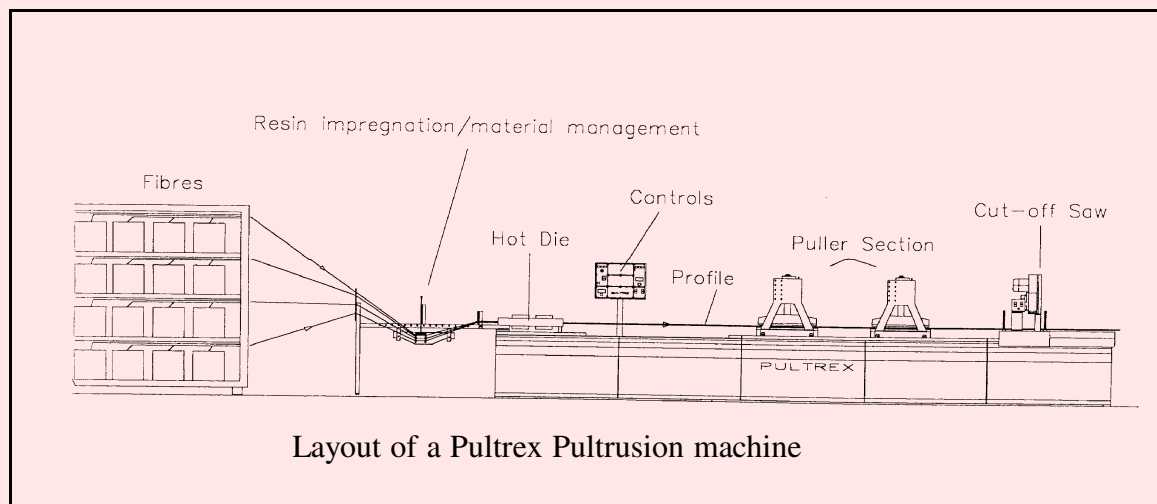
The PULTREX Px1000 - 12T is designed as a series of rigid structural stress relieved modules, each module being dedicated to a specific task. Modules are accurately aligned and assembled into a complete and self-contained unit capable of pulling very large unitary or multi-stream profiles.

The modules can be separated for the incorporation of ancillary equipment to allow a variety of in-line operations to be accomplished, such as the application of surface coatings, machining operations and crosshead extrusion of thermoplastic materials over the profile.

The four units used to assemble the standard machine are:-

- 1 Hot die bed module
- 2 Control module
- 3 Puller unit module
- 4 Cut off saw module

The PULTREX design allows the machine to be operated from either side, an important consideration when pulling very large profiles or multi-streams of smaller profiles. Production efficiency is enhanced when using several PULTREX machines as one operator can attend two machines.



PULTREX PULTRUSION MACHINES

CAPACITY CHART

MACHINE Reference	Px180-1T	Px250-3T	Px300-4T	Px300-6T	Px750-8T	Px1000-8T	Px1000-12T	Px1300-24T
PULLING FORCE kgf	1000	3000	4000	6000	8000	8000	12000	24000
PROFILE CLAMP FORCE								
per puller (kgf) @ 6.5 bar air pressure	3480	9400	11000	11000	22000	22000	33000	44000
per puller (kgf) @ 10.0 bar air pressure	5300	14400	16750	16750	33000	33000	50250	67000
standard clamping length (mm)	380	660	660	660	660	660	660	660
MAXIMUM PROFILE DIMENSIONS								
Width mm	180	250	300	300	750	1000	1000	1300
standard height mm	40	125	160	160	160	160	230	350
optional height mm			230	230	230/300	230/300	300	
PULLING SPEED								
Infinitely variable								
minimum - metres/min	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.06
maximum - metres/min	4.00	5.00	4.00	3.25	3.00	2.50	2.25	2.00
DIE HEATING ZONES								
Self-tune temperature controllers								
Standard	2	2	2	2	4	4	4	8
Option: Up to 12 zones on all machines								
UTILITIES - For Std. Machine								
Electrical - kva	13	15	18	20	30	30	35	40
Compressed air @ 6.5- 10 bar m3/min	0.02	0.02	0.025	0.025	0.025	0.025	0.025	0.035

PULTREX PULLWINDING MACHINES

Pultrex Pullwinding machines in conjunction with any standard Pultrusion machine provide a combination of conventional pultrusion and continuous filament winding. This allows high volume production of thin wall, high strength F.R.P. hollow profiles

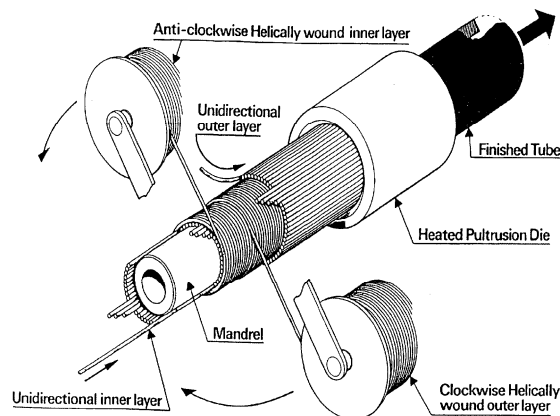
The Pultrex range of Pullwinding machines has been designed around Pultrex's 20 years of production experience in the Pultrusion industry. The machines are free-standing and have been ergonomically designed for simple operation, whilst offering sophisticated features unique to Pultrex machines

Standard Features include:

- Single (+ winding) or Twin winding heads (+ / - winding)
- Totally independent, fully closed loop, Microprocessor control
- On-line variable, digital pitch control
- Integral Die and mandrel location for precision wall thickness control
- Integral resin/fibre impregnation system included as standard
- Height adjustable to interface to any Pultrusion machine
- Fully guarded with safety interlocks.

PULTREX Pullwinding Machine Specification

Machine model reference	Pw 75-1-4	Pw 75-2-4	Pw 200-1-8	Pw 200-2-8	Pw 350-1-8	Pw 350-2-8
Number of Winding Heads	1	2	1	2	1	2
Max Profile Diameter-mm	75	75	200	200	350	350
Maximum Spool Size - mm	160	160	260	260	260	260
Maximum Spool Weight - kg	10	10	20	20	20	20
Number of Spools / Head	4	4	8	8	8	8
Total Number of Spools	4	8	8	16	8	16
Max. Head Rotation - r.p.m	180	180	100	100	80	80
Digital Winding Pitch Control						
Fine Increment @ 0.1 mm	1-99	1-99	1-99	1-99	1-99	1-99
Course Increment @ 1 mm	N/A	N/A	1-999	1-999	1-999	1-999
Number of resin Tanks	3	5	3	5	3	5
On-Line Tension Control	Optional	Optional	Optional	Optional	Optional	Optional
Utilities - For Std. Machine Electrical						
Electrical - Kva	2.5	2.5	3.3	3.3	5.8	5.8
Compressed air - @ 6.5 Bar m ³ /min	0.01	0.01	0.01	0.01	0.01	0.01
required with optional on-line tension control						



Schematic of Pulwinding variation to Pultrex pultrusion machines

DESCRIPTION

Produces a surface of revolution (cylinder, cone etc.). In it's simplest form Filament Winding consists of a rotating cylindrical mandrel upon which are wound reinforcing fibres which have been impregnated with resin. The fibre applicator traverses the length of the mandrel thus building up the laminate thickness. Variations include extra axes of movement to allow the winding of domed ends, spheres, conical shapes etc.

FIBRE PLACEMENT

Continuous reinforcement is placed and oriented on the mandrel surface by the position of the pay-out eye. In the most simple filament winding machine the pay out eye is fixed to the carriage and therefore can only traverse the length of the mandrel. Hence the angle at which it is placed is dependent on the rotational speed of the mandrel and the traverse rate of of the carriage.

The use of extra axes of movement (rotational or translational) allow the fibre to be placed on more complex shapes.

MATRIX APPLICATION

Pre-impregnated fibre may be used otherwise the resin is generally applied by an impregnation bath. The bath is mounted on the carriage. It has a set of parallel bars between which the reinforcement passes.

WET THROUGH / WET OUT

Passing the reinforcement between the bars in the resin bath spreads the fibre and allows the resin to penetrate the fibre bundle.

CONSOLIDATION

Tension is applied to the reinforcement as it is being wound onto the mandrel. This is achieved by the general friction in the system and by the application of tension to the reinforcement packages on the creel. This tension results in the reinforcement applying a pressure to the mandrel surface. This pressure effectively consolidates the laminate. Mat and woven products may be rolled when on the mandrel to further remove entrapped air.

CONFORMATION

The fibres conform to the mould surface by virtue of the winding tension. However on a frictionless surface the fibres will take the shortest route between two points on the surface (this is the geodesic path).

Therefore it is necessary to wind a geodesic path or to generate sufficient frictional force to keep the fibre in the chosen path. (Tacky resin or tacky pre-preg).

CURE

A 'cold cure' may be used if a non-prepreg system is used, but this creates a pot life problem in the resin bath. Normally heat is applied to the mandrel while it is still on the machine or the mandrel is removed and placed in an oven. Thus allowing further winding to take place.

RELEASE

After cure the component is removed from the mandrel either by collapsing the mandrel or by a mechanical puller device, typically hydraulic to generate sufficient force. Complex shapes may not allow the mandrel to be withdrawn. This problem may be overcome by the use of a collapsible mandrel or by producing the mandrel from a meltable material such as low melting point alloys or wax.

MATERIALS**Fibres**

Glass fibre roving, carbon fibre and aramid as rovings or yarns. Also woven tapes of these fibres.

Glass fibre and thermoplastic veils may be used on the mould surface and or as a finishing layer to produce resin rich corrosion barriers.

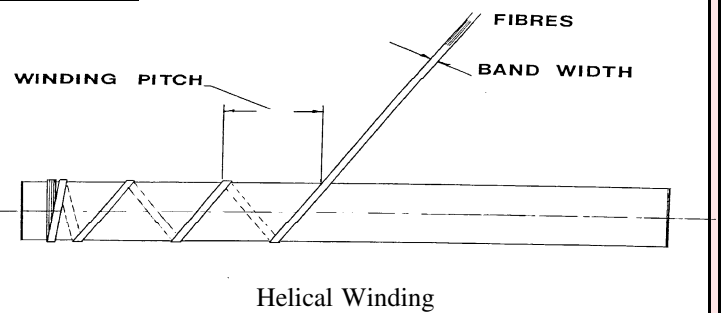
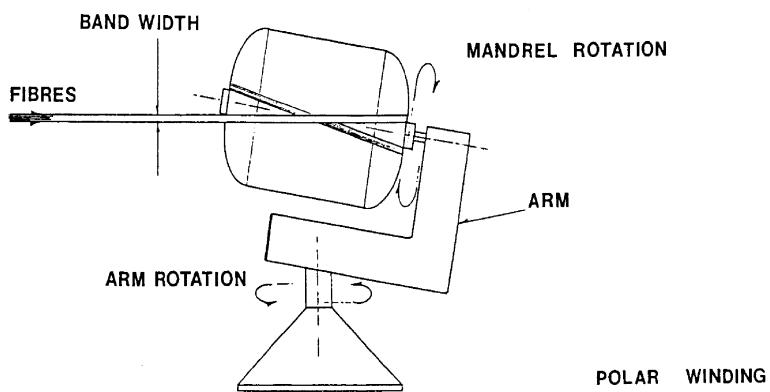
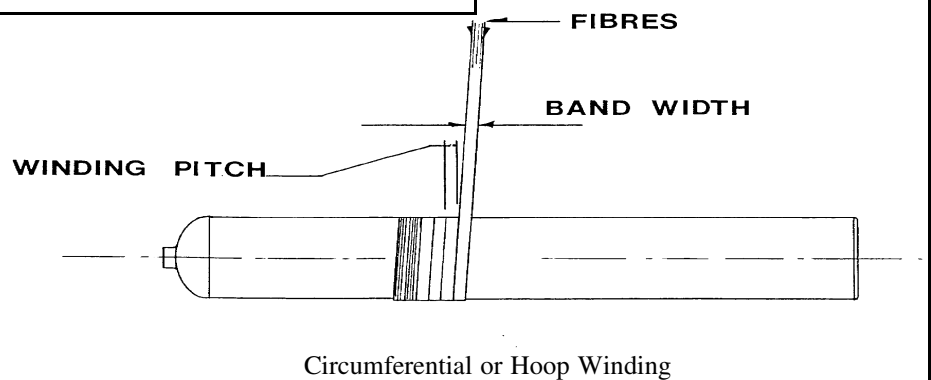
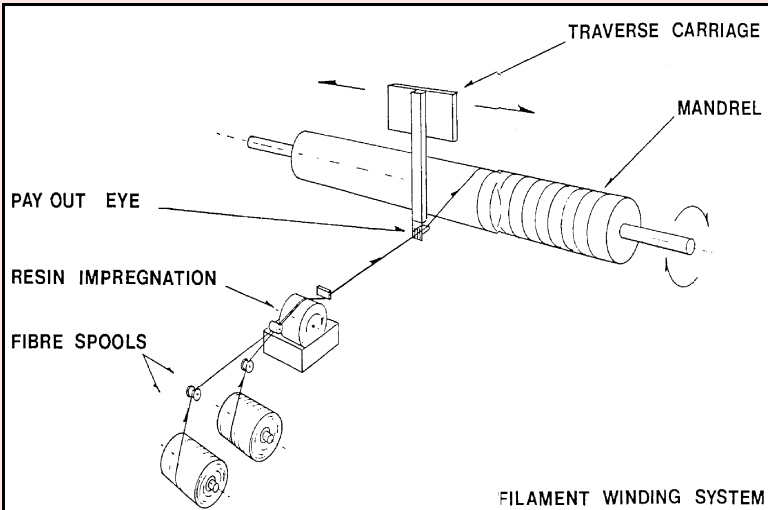
Resins

Epoxy resin is the most commonly used resin because the process lends itself to demanding applications which justify the use of epoxy. However any of the thermosets can, and are used commensurate with the application requirements.

CRITICAL FACTORS

	RANGE	TYPICAL
SIZE	20mm (3/4in) dia * 200 mm (8in) long to 5m (15ft) dia * 38m (100ft) long	300mm(12in) dia * 2m (6ft) long
CYCLE TIME	1 hr to 24 hr	4 hr
PRODUCTION QUANTITY	1 to 10000	50
LABOUR CONTENT	Medium	
CAPITAL	£10k to £500k	£100k

Filament Winding Options



Courtesy : Pultrex Ltd

Filament Winding

In order to exemplify filament winding a specific multi-axis filament winding machine is described in detail as follows:- The PULTREX MODWIND range of filament winding machines is a modular concept design reducing material and engineering design costs. This allows for great flexibility in selecting, winding length, diameter, number of controlled axes and number of spindles.

The machine is specified by :

- Number of controlled spindles
- Number of numerically controlled axes
- Maximum component diameter (mm)
- Maximum component length (mm)

Headstock and Drive Spindle

The headstock is a rigid rectangular steel box containing the main spindle(s) and servo drive motor.

To get maximum versatility, and allow for a range of mandrels of different inertias, the spindle drive is arranged so that it can have different speed ratios. Change of ratio is by fitting different sizes of drive pulleys/belts. These are easily accessible within the headstock.

Mandrel diameter ranges are:

500mm (20in)	1000mm (40in)
1500mm(60in)	2000 mm (80in)

Traverse Beam and Main Carriage

The traverse beam provides location for the hardened carriage ways and tailstock support. It allow for mandrel lengths of 2 to 10 metres, in 1 metre increments. Drive for the main carriage is by a precision machined rack and pinion. As the beam is of overhead configuration, it allows easy access for set-up and in process viewing of winding.

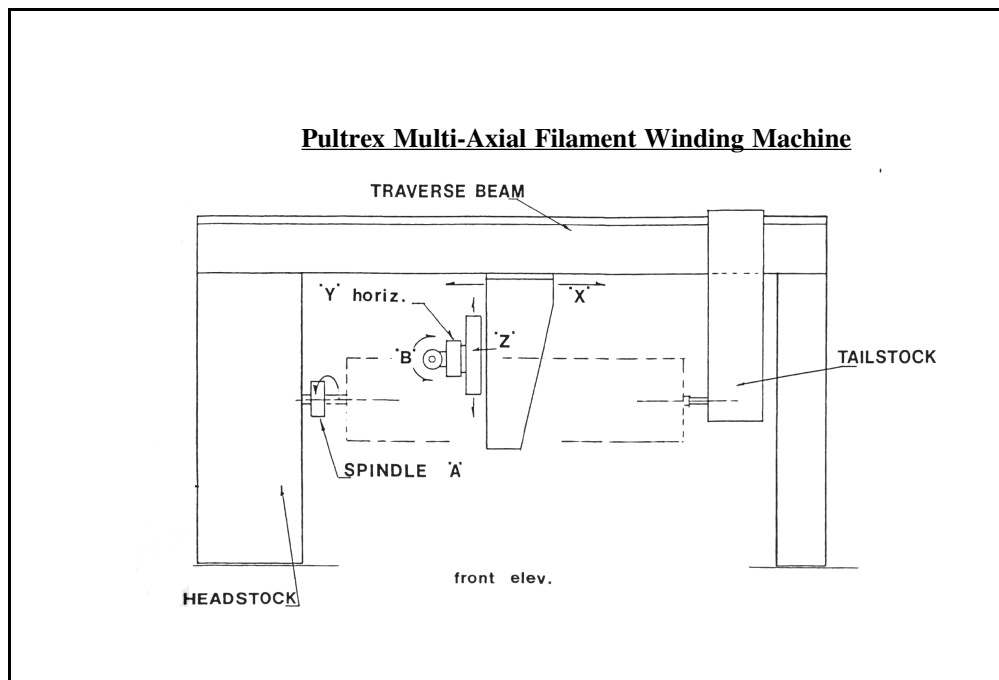
Tailstock and Beam Support

The tailstock is a steel fabrication. It has roller location on its top edge which runs on the top of the traverse beam. The tailstock has a horizontal quill that is adjusted by turning a handwheel. The movement of the tailstock is 125mm. The quill has a bearing mounted rotating centre for location to mandrels.

Carriage Assembly

Hardened ways are attached to the rigid main "X" carriage providing precision movement for the vertical "Z" axis. The "Z" carriage supports the horizontal "Y" axis. The "Y" axis is a rigid aluminium box section fitted with hardened ways running in the "Z" carriage locations.

The "Y" arm carries a rotating face plate, the "B" axis, driven through gearing and shafting mounted at the rear of the "Y" arm. Being hollow it allows fibres to pass through its centre of rotation. The face of the rotating plate has tapped holes to provide location for fibre guide systems. The "B" axis head is removable to permit the use of other fixed or driven devices. The yaw axis is vertical and located at the end of the "Y" arm. It supports the "B" axis when fitted. The Yaw motion is + or - 45 deg. in the horizontal plane and has a resolution of 0.01 degrees.



3.2 PROCESS CHARACTERISATION CHARTS

It is difficult to judge the relative merits of one process against another without an intimate knowledge of both. This problem is accentuated with composites due to the wide variety of options available. It is all too easy to decide on a particular process without having fully considered the range of possibilities. The following set of charts has been drawn up in an attempt to alleviate this problem. They compare in a graphic format the critical characteristics of the available processes. They are not intended to be precise but simply reasonable indications which will allow some processes to be set aside because they are unlikely to be suitable and others to be considered in more detail.

The parameters compared are :

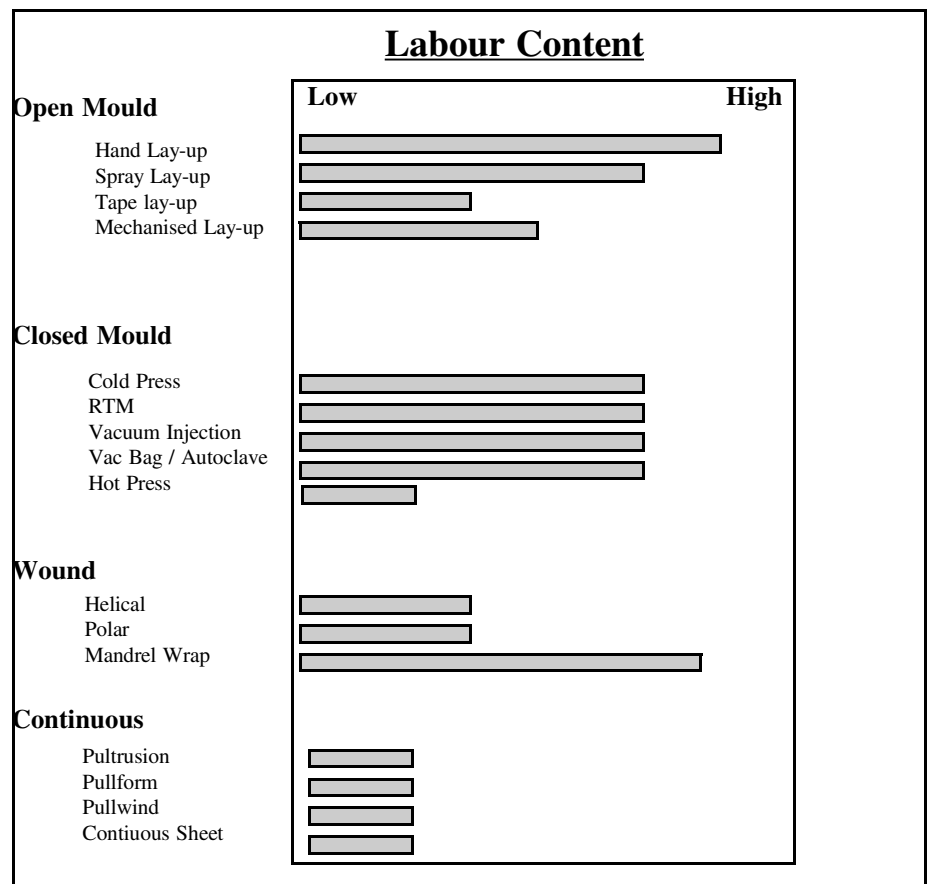
- **Labour content,**
- **Cycle time,**
- **Viable production quantity,**
- **Capital cost of equipment,**
- **Product surface area,**
- **Component shape.**

LABOUR CONTENT

3.2.1 LABOUR CONTENT

An indication of the labour content for each process relative to the amount of composite material produced is given in the chart.

The amount of labour required for a process is an important factor in the selection process. Those requiring high labour content tend also to require a higher level of skill. This is the case for Hand Lay-up and Mandrel Wrapping. Both require considerable skill and experience to ensure high quality work, quickly produced. Spray-up requires a similar degree of skill but its high deposition rate results in lower labour costs per kilogram of composite produced.



CYCLE TIME

3.2.2 CYCLE TIME

The chart compares the cycle times for the various processes on a Logarithmic scale. Hence for example, the cycle time for the production of a component by Spray-up can be anywhere from 50 minutes to 1000 minutes. The cycle time is taken to include all of the time that the mould is occupied. However it ignores the 'over night' time in the situation when a moulding could be removed from the mould at the end of a shift but for convenience is left until the next day.

Cycle times for several of the continuous processes are not given. By definition they do not have a cycle they run continuously at a particular rate. Pullforming has characteristics of both continuous and non-continuous processes and can be given a cycle time and a running speed.

	Cycle Time Minutes (log scale)			
	1	10	100	1000
Open Mould				
Hand Lay-up				
Spray Lay-up				
Tape lay-up				
Mechanised Lay-up				
Closed Mould				
Cold Press				
RTM				
Vacuum Injection				
Vacuum Bag				
Autoclave				
Hot Press				
Wound				
Helical				
Polar				
Mandrel Wrap				
Continuous				
Pultrusion	Not Applicable			
Pullform				
Pullwind	Not Applicable			
Continuous Sheet	Not Applicable			

VIABLE PRODUCTION QUANTITY

3.2.3 VIABLE PRODUCTION QUANTITY

The chart compares the viable production quantity on a logarithmic scale ranging from 1 off to greater than 1 million components off, for the discontinuous processes. For the continuous processes the scale is metres of product from 1 metre to greater than 1 million metres.

As may be seen the full range of production quantities can be accommodated by the available processes. There is an exception however. It is apparent that there isn't a viable production process for the production of short lengths of continuous profile in the range 1 metre to 5000 metres. This isn't strictly true because the continuous processes are perfectly capable of producing short runs, they simply become unacceptably expensive. But if there is no alternative process/material option they are the only choice.

	Viable Production Quantity						
	Units of Production						
	1	10	100	1000	10 ⁴	10 ⁵	10 ⁶
Open Mould							
Hand Lay-up							
Spray Lay-up							
Tape lay-up							
Mechanised Lay-up							
Closed Mould							
Cold Press							
RTM							
Vacuum Injection							
Vacuum Bag							
Autoclave							
Hot Press							
Wound							
Helical							
Polar							
Mandrel Wrap							
Continuous	Metres of Production						
	1	10	100	1000	10 ⁴	10 ⁵	10 ⁶
Pultrusion							>>>>
Pullform							>>>>
Pullwind							>>>>
Continuous Sheet							>>>>

CAPITAL COST OF EQUIPMENT.

3.2.4 CAPITAL COST OF EQUIPMENT.

The chart gives an indication of the capital costs to be expected for the individual processes. This shows both mould cost and equipment cost with both a range and a typical value. These values are intended to give guidance only and not to be taken too literally. Their benefit lies in giving the scale of cost rather than the absolute value.

	Capital Cost (£)					
	Mould Cost			Equipment Cost		
Open Mould	Min	Max	Typical	Min	Max	Typical
Hand Lay-up	100	20000	1000	0	0	0
Spray Lay-up	100	20000	1000	5000	10000	8000
Tape lay-up	500	5000	3000	20000	50000	30000
Mechanised Lay-up	1000	100000	50000	20000	50000	30000
Closed Mould						
Cold Press	500	3000	2000	5000	30000	15000
RTM	500	2000	1000	5000	10000	8000
Vacuum Injection	500	1000	1000			
Vacuum Bag	500	2000	1000	500	5000	1000
Autoclave	500	10000	5000	40000	500000	200000
Hot Press	5000	100000	15000	30000	250000	75000
Wound						
Helical	100	5000	1000	30000	200000	100000
Polar	300	10000	5000			20000
Mandrel Wrap	100	1000	500			
Continuous						
Pultrusion	1000	30000	6000	60000	250000	110000
Pullform	2000	50000	20000	100000	300000	200000
Pullwind	1000	5000	2000	100000	250000	150000
Continuous Sheet				100000	5*10 ⁶	1*10 ⁶

PRODUCT SURFACE AREA

3.2.5 PRODUCT SURFACE AREA

An indication of the size of component which is viable for each process is given in the chart. Hand Lay-up is probably the most versatile in this respect as it allows components to be made which can be as small as 0.1m²(1ft²) or as large as 1200 m². In reality these are not true limits but they represent economic boundaries which can be over stepped if the application so demands.

The continuous processes cannot be represented in this way as by definition the product could theoretically have an infinite surface area. However the maximum width that the continuous processes typically accommodate is probably 3m (10ft) for sheet and 1.5m (5ft) for pultrusion.

	Product Surface Area (m2) (1m ² = approx10ft ²)					
	0.1	1	10	100	1000	10000
Open Mould						
Hand Lay-up						>>>>
Spray Lay-up						>>>>
Tape lay-up						
Mechanised Lay-up						>>>>
Closed Mould						
Cold Press						
RTM						
Vacuum Injection						
Vacuum Bag						
Autoclave						
Hot Press						
Wound						
Helical						
Polar						
Mandrel Wrap						
Continuous						
Pultrusion	Not Applicable					
Pullform	Not Applicable					
Pullwind	Not Applicable					
Continuous Sheet	Not Applicable					

SHAPE CLASSIFICATION

3.2.6 SHAPE CLASSIFICATION

The design process is aided by the classification of components into particular shapes. This is an aid in the concept stage of the design process. It is also relevant to the question of production processes.

The shape classifications are not mutually exclusive, ie because a component is a surface of revolution does not exclude it from being a linear prism. For example a tube is a surface of revolution and also a linear prism (if it doesn't have a taper). It could also be considered as two dimensional and hence moulded by say hand lay-up. Therefore each shape classification is awarded crosses which represent the degree of relevance that the process has to produce the shape. The more crosses the more relevant is the process. For example the Hand lay-up process is most applicable to 2 dimensional shapes and surfaces of revolution (tanks). It is feasible although rare to produce linear or 3D shapes by HLU.

	Shape Classification			
	Linear Prismatic	Two Dimensional	Three Dimensional	Surface of Revolution
Open Mould				
Hand Lay-up	X	XXXX	X	XXXX
Spray Lay-up	X	XXXX	X	XXXX
Tape lay-up	X	XXXX	X	X
Mechanised Lay-up	X	XXXX	X	X
Closed Mould				
Cold Press	X	XXXX	X	
RTM	X	XXXX	X	
Vacuum Injection	X	XXXX	X	
Vacuum Bag	X	XXXX	X	
Autoclave	X	XXXX	X	
Hot Press	X	XXXX	XXXX	
Wound				
Helical	XX			XXXX
Polar				XXXX
Mandrel Wrap	XX			XXXX
Continuous				
Pultrusion	XXXX	XX		X
Pullform			XXXX	
Pullwind	XXXX			X
Continuous Sheet	XXXX	XX		

REINFORCING MATERIAL RELATED TO PROCESS

3.2.7 MATERIALS

The chart lists the range of reinforcement materials available and shows which material can be matched with which process.

Two types of material are shown : those which are simply the reinforcement itself and those which are compounds of the reinforcement and the resin mix. Three compounds are shown SMC, DMC and Prepreg. Details of these materials are given in Chapter 1. For each material the reinforcement geometry is given.

For example, chopped strand mat (CSM) has the notation 'ISO' this indicates that the reinforcement material is isotropic in-plane. '0 deg' indicates that the reinforcement material is uni-directional. '0,90' indicates that the reinforcement is bi-directional. '0,90,+/-45' indicates that the reinforcement material is multi-axial, in this case 4 axes but there may be only three.

The black boxes indicate that this is a primary material for the process. The grey boxes indicate that it is possible for the reinforcement material to be used but it rarely occurs in practice. Empty boxes indicate that the reinforcement material cannot be used with that process or it is extremely unlikely.

	REINFORCING MATERIAL RELATED TO PROCESS								
	CSM	CFM	Chopped Roving	Uni-directional	Woven	Multi-Axial	Needle Mat	SMC/ DMC	Prepreg
Open Mould	ISO	ISO	ISO	0 Deg	0,90	0,90,+/-45	0,90	ISO	0,90 0,90,+/-45
Hand Lay-up									
Spray Lay-up									
Tape lay-up									
Mechanised Lay-up									
Closed Mould									
Cold Press									
RTM									
Vacuum Injection									
Vacuum Bag									
Autoclave									
Hot Press									
Wound									
Helical									
Polar									
Mandrel Wrap									
Continuous									
Pultrusion									
Pullform									
Pullwind									
Continuous Sheet									

Check List for Choice of Production Process

1) **Shape**

Which shape classification(s) apply?

- Linear prism
- Two dimensional
- Three dimensional
- Surface of revolution

2) **Quantity**

What is the number of components required per annum?

What is the total number of components required?

2) **Size**

What is the physical size of the component?

3) **Properties**

What special properties are required?

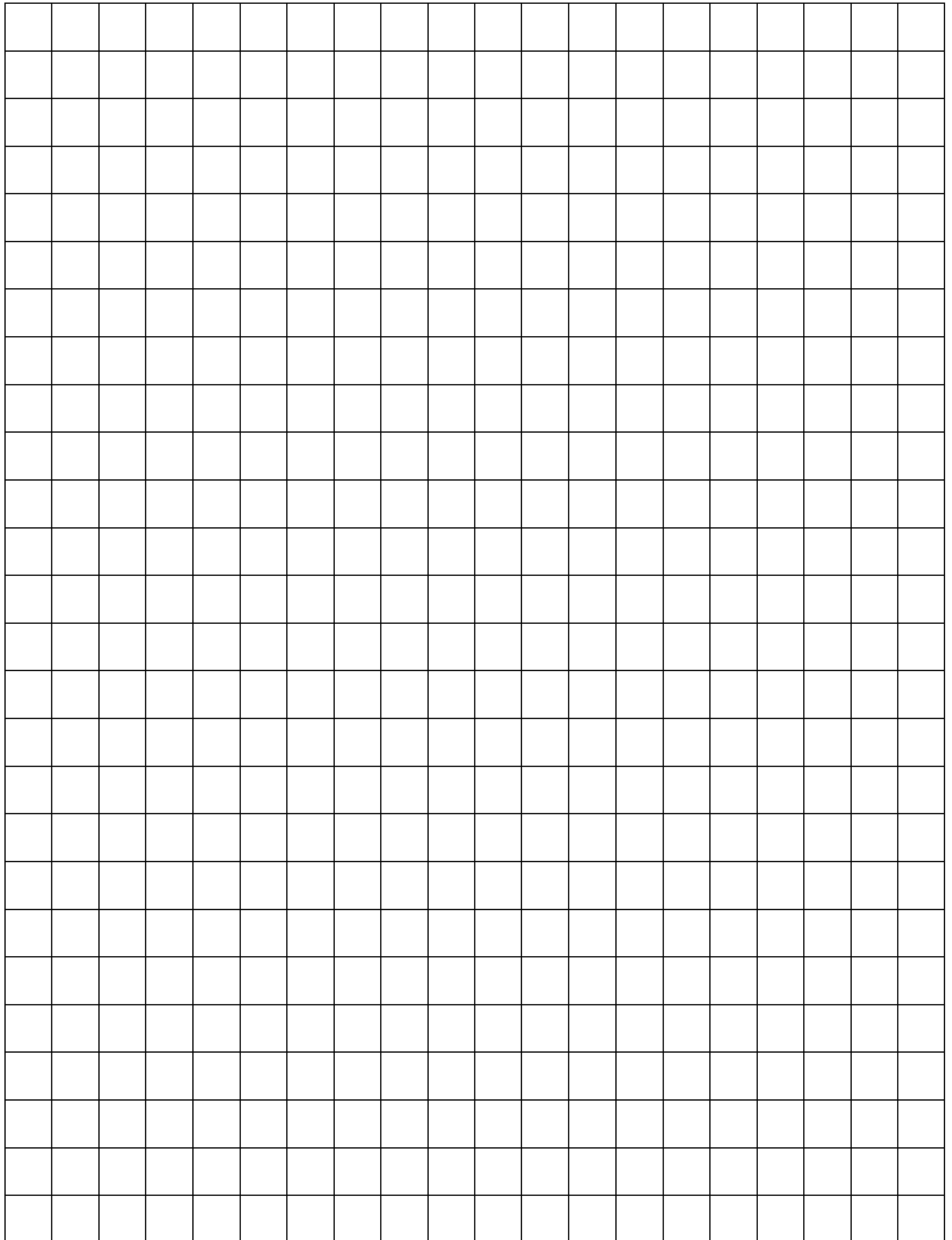
Mechanical performance - strength, stiffness

Fire

4) **Consolidation**

Is it appropriate to consolidate several small components into one large component?

Is it appropriate to breakdown the shape into a large number of clones?



4 CONSTRUCTION ANALYSIS

4.1 Principles

4.2 Types of Construction Calculations

- Surface area based
- Cross section based
- Profiles

4.3 Compressibility of Reinforcements

Unlike conventional materials, it is necessary with composites to determine the amount and type of fibre to be used. The designer may want to know the thickness of a laminate for a given amount of fibre and resin or he may know the thickness and want to know how much material must be used to achieve it.

The quantity of reinforcement, resin and the various other ingredients in the resin mix which are required to achieve a particular thickness is the subject of Construction Analysis. It isn't a scientific subject but very pragmatic. The concepts and equations which are used are simple and straight forward. They could easily be derived each time they are used. But this would be time consuming and open to error in spite of their simplicity.

Hence an attempt has been made to cover this topic in detail to allow calculations to be handled swiftly and accurately, however frequently they are required.

4.1 PRINCIPLES

MOULDING BEHAVIOR OF REINFORCEMENT

The behaviour of reinforcement materials during the moulding process has surprisingly little effect on these calculations with one or two exceptions.

Consider a 'roving' of glass fibre or a 'tow' of carbon fibre. These materials are supplied wound as a 'cheese'. In use they are unwound either from the inside of the core or from the outside, in which case the package (cheese) must rotate. The reinforcement strand consists of a collection of hundreds or thousands of individual filaments. The shape of the strand is the important characteristic, it is a flat tape 1 to 5 mm wide and a fraction of a millimetre thick. We can assume that it is a simple rectangular section when used in processes such as filament winding. We can also assume that it will conform to any complex section when used in processes such as pultrusion.

Two dimensional reinforcement Chopped strand Mat, Continuous Strand Mat, Woven roving etc have a natural thickness which can be compressed under moulding pressure. CFM may be compressed very considerably and Multi-axial fabrics hardly at all, but nevertheless they can all be compressed to some extent. The same applies to unidirectional reinforcement (rovings and tows), the space they take up is dependant on the amount of pressure applied. Hence we should not think of only one thickness being available from a particular reinforcement, but a range of thicknesses depending on the applied pressure. If the same pressure is applied each time then the same thickness will be achieved each time, if not then thickness will vary.

The exception to this rule is prepreg (a pre-impregnated compound of reinforcement and resin). The prepregging operation produces a compound at a similar pressure to the subsequent moulding process. Hence the moulded thickness is predetermined and effectively constant.

TEX

Tex is simply a measure of the mass per unit length of linear reinforcement measured in g/km. Hence a roving designated 2400 TEX has a mass of 2400 g/km. 2400 TEX is obviously 2.4 kTEX. This is less frequently used but is a more convenient unit for construction calculations.

In the USA the term YEILD is used rather than TEX. The YEILD of a roving is defined as Number of YARDS per lb. It is therefore a reciprocal of TEX.

The conversion equation is

$$\text{Tex (g/km)} * \text{Yield (yd/lb)} = 496000$$

Equation 4.1

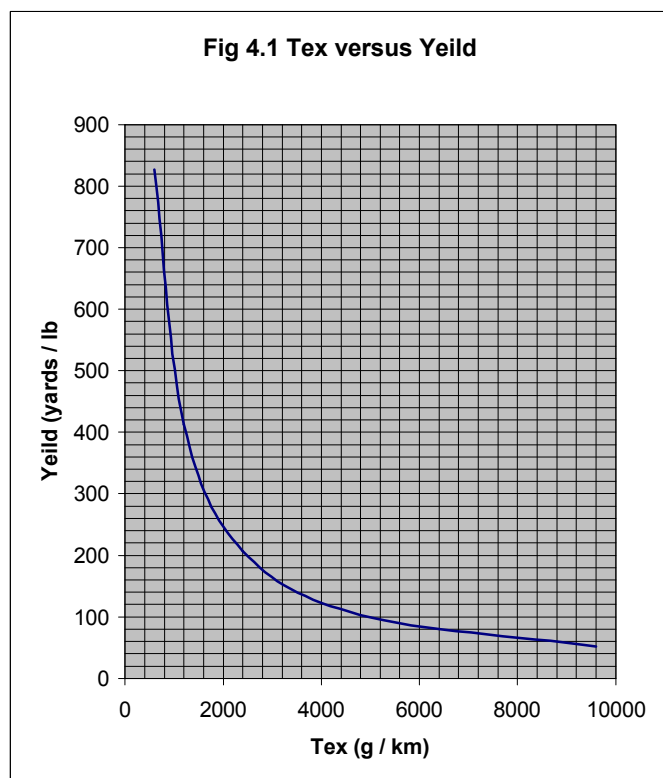
Table 4.1 and Fig 4.1 compare TEX values and YEILD for various standards available under the two systems.

Alternative systems which are still occasionally used with composites reinforcements are COUNT and DENIER.

COUNT is the number of 100 yd per lb.
ie 130's count is 13000 yd/lb

DENIER IS $\text{TEX} * 9$

TABLE 4.1 Tex versus Yeild			
Common Tex values used in Europe	Equivalent Yield value	Common Yield values used USA	Equivalent Tex value
600	827		
1200	413	450	1102
2400	207	225	2204
4800	103	113	4390
9600	52	56	8857



MASS FRACTION AND VOLUME FRACTION

Mass fraction of a reinforcement material or constituent in a composite is simply:

$$\text{Mass of constituent} / \text{Total mass of the composite}$$

Equation 4.2

Similarly, Volume fraction of a constituent =

$$\text{Vol of constituent} / \text{Total vol of composite}$$

Equation 4.3 (a)

or if a slice is taken through the composite then :

Volume fraction of a constituent =

$$\text{Cross sectional area of constituent} / \text{Total CSA}$$

Equation 4.3 (b)

If each constituent had the same density then Volume fraction and Mass fraction would be the same value. This is never the case and a choice must be made whether to perform construction calculations from the basis of Weight fractions or Volume fractions. It makes very little difference to the calculations but each has advantages from a practical stand point.

For instance in the hand Lay-up process the chopped strand mat to be used for a particular moulding is weighed and the amount of resin mix to be used arrived at by multiplying that figure by some known factor, typically a factor of two. This is very simple for the operator and easy to control.

Hence there is a Resin to glass ratio of 2 to 1. The total laminate will weigh 3 units of which the glass weighs 1 unit. The Mass fraction of the glass in the composite is therefore 1/3.

$$\text{RESIN} / \text{GLASS RATIO} = (1 / \text{Mf}) - 1$$

Equation 4.4

where Mf is the mass fraction of fibre.

The spray-up process is similar. When the spray machine operator is setting his machine he runs only glass for say 10 seconds and weighs it. He then runs resin only for 10 seconds which he also weighs. The resin mass is required to be some fixed ratio greater the glass (2.5/1 is typical) the spray gun is adjusted to achieve this.

The total mass of material is 3.5 parts of which the glass constitutes 1 part. Therefore the mass fraction of fibre is 1/3.5 which is about 28%.

As these processes are inherently tied to mass fractions it is sensible to make construction calculations on that basis. But there is another good reason for there use. In order to check the construction of a composite after it has been produced the simplest method is to burn off the resin in a furnace. If the composite is weighed before burning and the remaining glass weighed after, then the mass fraction can be calculated to check consistency. This is a very common quality assessment method which has variations to suit composites with non-combustible fillers or with carbon fibre which itself can lose mass in the furnace.

So why bother using anything other than mass fractions? Just as some processes find the use of mass fractions the most convenient option, other processes are more amenable to the use of volume fractions. The Pultrusion process is the most notable example. The process requires that the die is packed with sufficient reinforcement to fill the shape and that the volume remaining between the fibres is filled with resin mix. The density of the individual constituents is irrelevant, it is their volume which governs if the die is filled. Consequently with this type of process, construction calculations are much simpler in terms of volume fraction.

There is also a fundamental justification for the use of volume fractions. The performance characteristics of composites are a function of the relative quantities of the constituents. Eg strength and stiffness are both direct functions of how much reinforcement is in the composite. The measurement of how much reinforcement is present in a composite is by volume and not by mass.

The conversion between volume fraction and mass fraction is given in Equation 4.5 & 4.6 and fig 4.1

$$V_1 = \frac{M_1 / \delta_1}{M_1 / \delta_1 + M_2 / \delta_2 + M_3 / \delta_3}$$

Equation 4.5

$$M_1 = \frac{\delta_1 V_1}{\delta_1 V_1 + \delta_2 V_2 + \delta_3 V_3}$$

Equation 4.6

Where δ is the density of the constituent
 V is the volume fraction of the constituent
 M is the mass fraction of the constituent

Example 4.1

A carbon fibre laminate and a glass fibre laminate each have a fibre volume fraction of 60%. What is the mass fraction for each laminate?

Assume for the carbon a density of 1.79 g/cm³ for the glass 2.55 g/cm³ and for the resin 1.2 g/cm³.

First for the carbon fibre laminate:

from equation 4.6

$$\text{Mass fraction (Carbon)} = \frac{1.79 \times 0.6}{1.79 \times 0.6 + 1.2 \times 0.4}$$

$$= 69 \%$$

for the glass fibre laminate

$$\text{Mass fraction (Glass)} = \frac{2.55 \times 0.6}{2.55 \times 0.6 + 1.2 \times 0.4}$$

$$= 76 \%$$

Example 4.2

Find the volume fractions for the constituents of a laminate consisting of glass fibre, polyester resin and calcium carbonate filler with details shown in the table.

	Mass fraction	Density g/cm ³
Glass fibre	30%	2.55
Polyester resin	50%	1.2
Calcium carbonate	20%	2.7

from equation 4.5

$$V_f = \frac{0.3/2.55}{0.3/2.55 + 0.5/1.2 + 0.2/2.7}$$

$$= 19.3 \%$$

again from equation 4.5

$$V_r = \frac{0.5/1.2}{0.5/1.2 + 0.3/2.55 + 0.2/2.7}$$

$$= 68.5 \%$$

by difference the volume fraction of filler is :

$$100 - 19.3 - 68.5 = 12.2 \%$$

Volume Fraction Ranges

The amount of space that a reinforcement occupies is a function of its packing efficiency. This in turn is a function of its degree of alignment. Unidirectional reinforcement is highly aligned and therefore capable of being highly packed without degradation to the individual filaments. A typical volume fraction for unidirectional reinforcements is 65%.

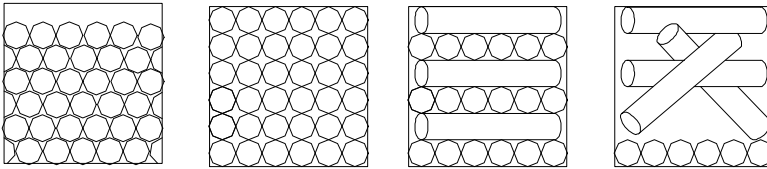
A bi-directional array or a random array can of course be produced by multi-layering unidirectional reinforcement each layer at a different angle, the fibre volume fraction in this case corresponds to unidirectional reinforcement.

Although random reinforcements are said to be random in the plane of the material, the reality may be significantly different. It is not unusual for random mat to have a degree of directionality. For some products this is often in the length direction of the roll but for others may be biased in the trans-

verse direction. The degree of bias is generally only about 5%.

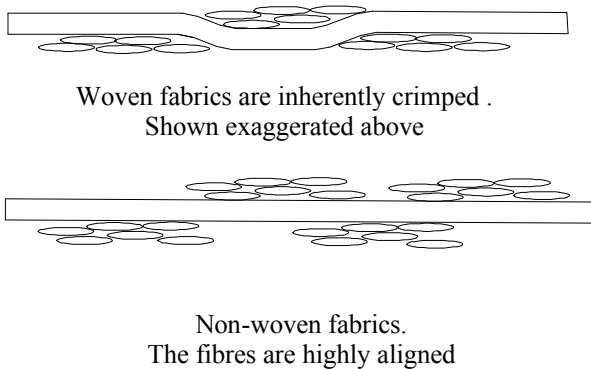
Similarly with bi-directional fabrics there is generally a degree of bias due to the inherent characteristics of textile processing. (See chapter 5). It is therefore good practice in the more demanding applications that chopped strand mat, continuous filament mat and bi-directional fabrics are laid-up with successive layers placed at 90 degrees to one another.

Fig 4.2 Effect of geometrical disarray of the reinforcement on packing efficiency.



Woven materials on the other hand, by the nature of the weaving process have some parts of the fibre slightly 'out of plane' as they pass over and under one another. This results in a slightly poorer packing efficiency and hence a lower volume fraction of fibres. A typical fibre volume fraction for woven products is perhaps 40%.

Fig 4.3 Comparison of Woven and Non-woven fabrics



On the other hand Non-woven fabrics (See BTI products in chapter 1) do not exhibit this problem.

Random mats have the poorest packing efficiency and therefore give a typical volume fraction of about 20%.

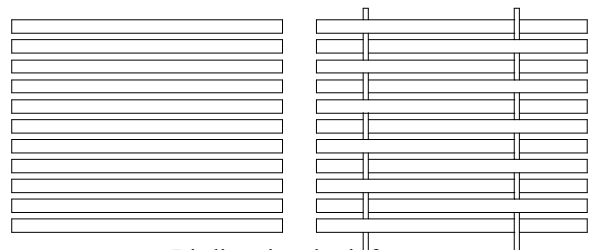
A low volume fraction of fibres should not be seen necessarily as a bad characteristic. For certain requirements the lowest volume fraction of fibres is the optimum. Random reinforcement also has the advantage that its properties are approximately equal in all directions.

Fig 4.4 shows the range of volume fractions available from the different types of reinforcement.

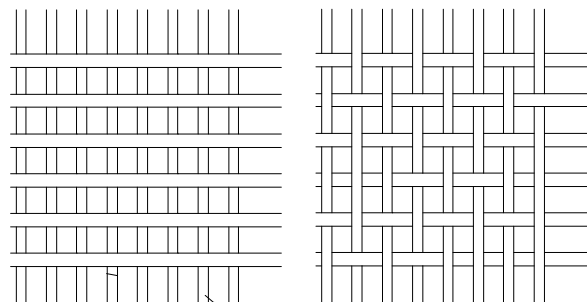
Fig 4.4 TYPICAL FIBRE VOLUME FRACTIONS

	APPROX RANGE %	TYPICAL %
Unidirectional reinforcement	50 - 70	65
Bi-directional reinforcement (Woven)	30 - 50	40
Random reinforcement (Mat)	10 - 30	20

Unidirectional reinforcements
Roving Fabric - Woven or non-woven



Bi-directional reinforcements
Non-woven Woven



Random Reinforcement

Chopped Strand Mat

Continuous Strand Mat

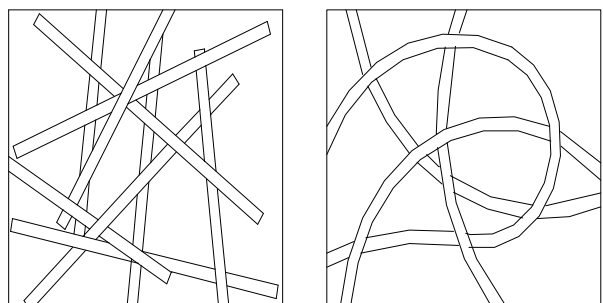


Fig 4.5 Conversion Volume Fraction to Mass Fraction

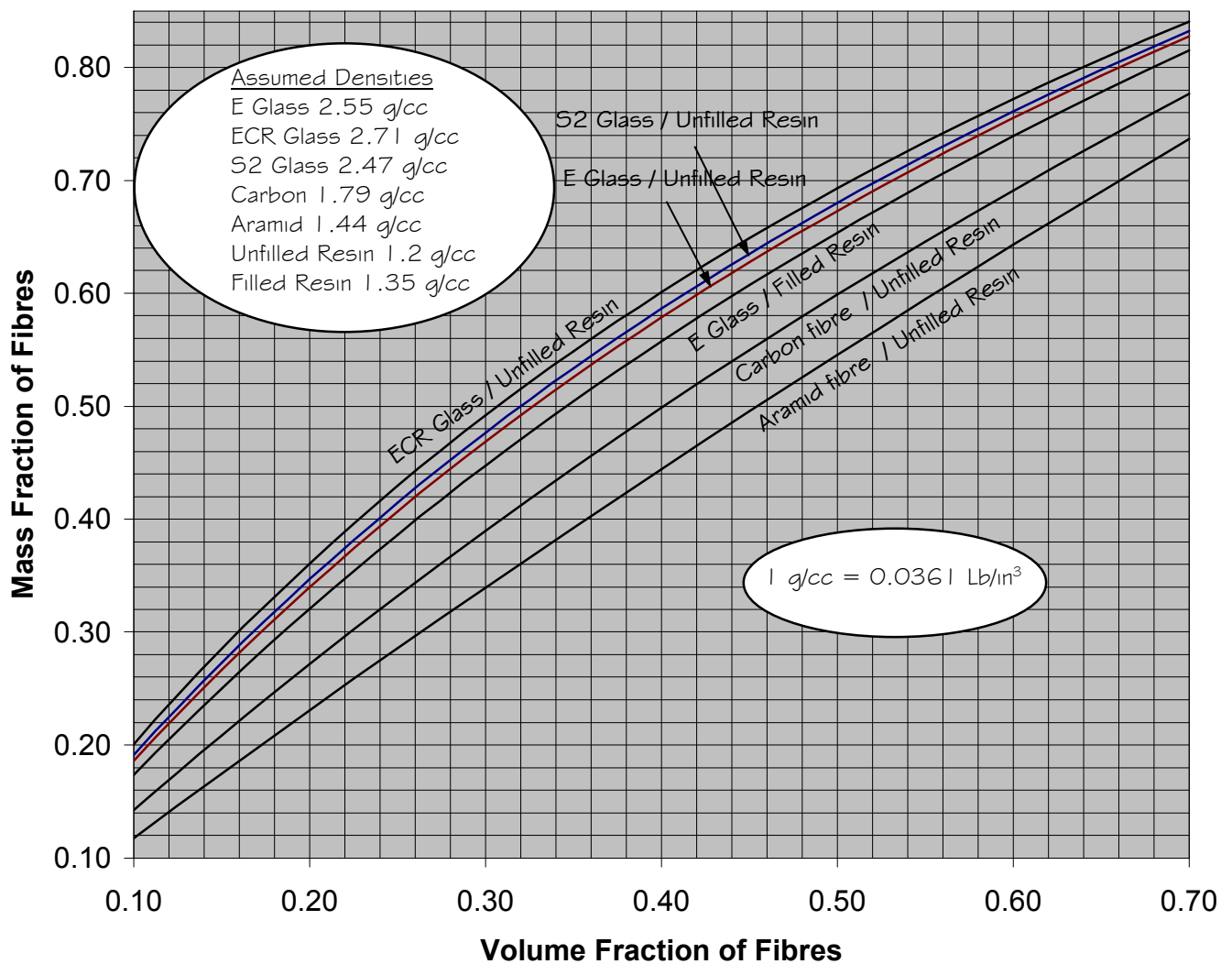


Fig 4.6 Laminate Density versus Volume Fraction

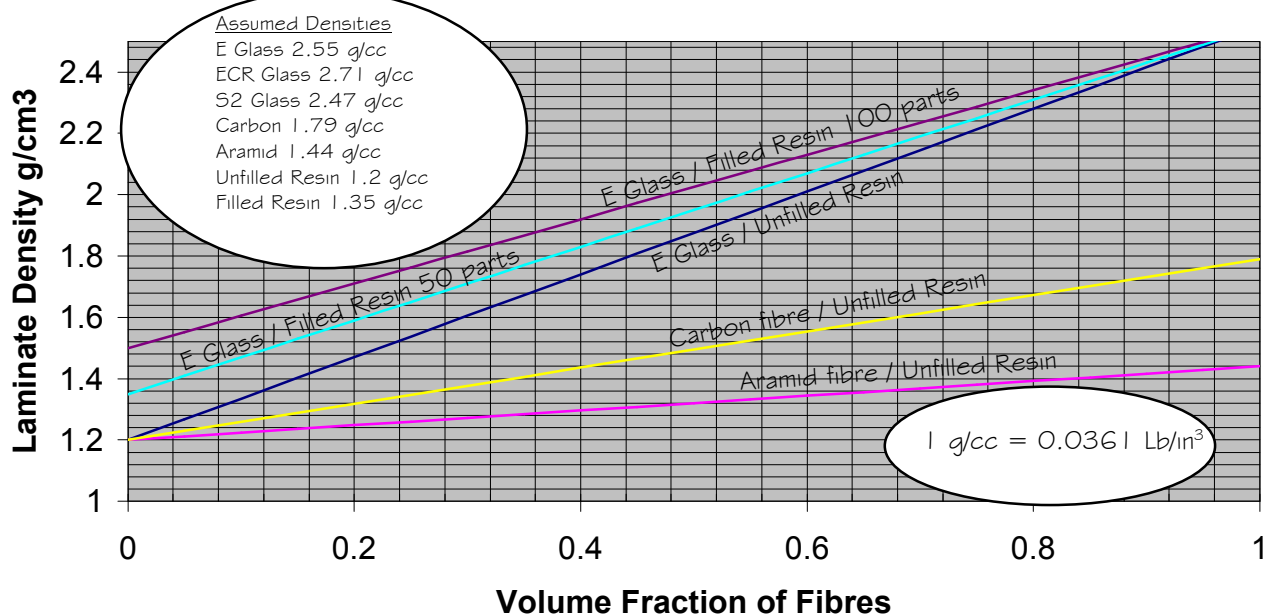


Fig 4.8 DENSITY OF CONSTITUENTS			
	CONSTITUENT	DENSITY	
		g/cm ³	Lb/in ³
Reinforcements			
	E glass Roving & Woven Roving	2.55	0.092
	E glass Chopped Strand Mat	2.55	0.092
	E glass Continuous Strand Mat	2.43	0.088
	Aramid Kevlar 49	1.45	0.052
	Aramid Twaron	1.44	0.052
	Carbon XAS	1.79	0.065
Resins			
	Polyester	1.11 - 1.25	0.04-0.045
	Polyester Class I fire retardant	1.50	0.054
	Vinyl ester	1.10 - 1.34	0.04-0.048
	Epoxy	1.13-1.23	0.041-0.044
	Urethane Methacrylate	1.12	0.04
	Phenolic		
Monomers			
	Styrene	0.91	0.033
	Methyl methacrylate	0.94	0.034
Catalysts and Hardeners			
	Trigonox 21C	0.99	0.036
	Trigonox C	1.04	0.038
	Perkadox 16	1.13	0.041
	Trigonox 29B50	0.97	0.035
	HY 905	1.24	0.045
	HY917	1.20	0.043
	DY070	1.00	0.036
	NL49ST (1%)	0.91	0.033

Fig 4.8 (continued) DENSITY OF CONSTITUENTS			
	CONSTITUENT	DENSITY	
		g/cm ³	Lb/in ³
Low profile additives			
	Range	0.92-1.03	0.033-0.037
Release agents			
	Ortholeum	0.99	0.036
	Zelec UN	0.99	0.036
	Zinc stearate	1.09	0.039
	Silcolube wax	1.02	0.037
	PAT 657C	0.86	0.031
Fillers & Fire retardant additives			
	Calcium carbonate	1.70	0.061
	Clay	2.60	0.094
	Microdol	2.85	0.103
	Aluminium Trihydrate	2.42	0.087
	Saytex	3.00	0.108
	Makteshim	1.70	0.061
Pigments			
	(Typical)	1.65	0.06

Table 4.9 RESIN MIX DENSITY, TABULAR CALCULATION

The following table may be used to calculate the density of a resin mix.

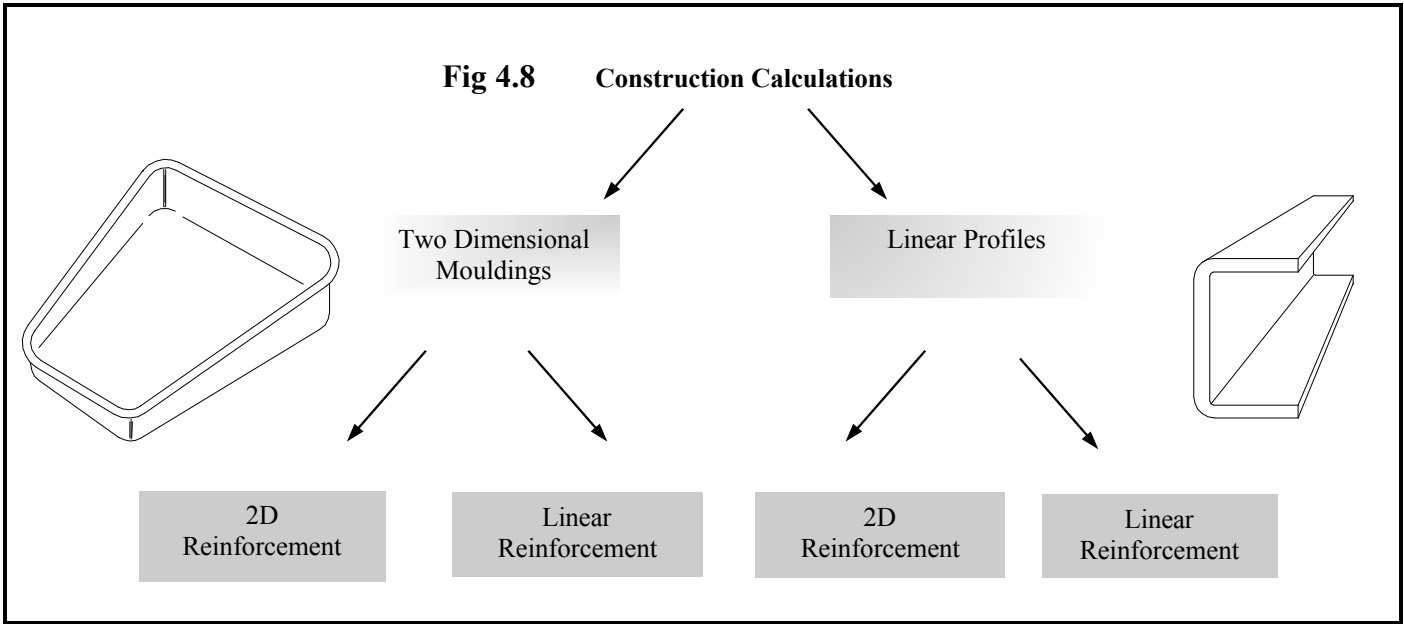
Column (C) is completed by dividing col (A) by col (B). The resin mix density is then the sum of col (A) divided by sum of col (C).

	(A)	(B)	(C)
CONSTITUENT	No PARTS	DENSITY (g/cm ³)	VOLUME (A/B)
RESIN	100	1.2	83.3
FILLER	30	2.6	11.5
CATALYST	1	1.0	1.0
ACCELERATOR	1	1.0	1.0
PIGMENT	5	1.65	3.03
TOTAL	137		99.83

$$\text{DENSITY OF RESIN MIX} = \text{SUM (A)} / \text{SUM (C)} = 137 / 99.83 = 1.37 \text{ g/cm}^3$$

NOTE If the resin mix does not use filler then it is often sufficiently accurate, and normal practice to assume the resin mix has the density of the pure resin.

4.2 TYPES OF CONSTRUCTION CALCULATION



Construction calculations conveniently fall into two categories depending on whether the shape of the component is two dimensional or a linear profile. The former requires SURFACE AREA calculations and the latter requires CROSS SECTIONAL AREA calculations.

It would be very convenient if only two dimensional reinforcements were used in two dimensional components and only linear reinforcements (rovings, tow etc) were used in linear profiles. Unfortunately this is not the case. Both types of reinforcement are used in both types of component.

Thus the layer of resin will have a thickness of :
 $1 \text{ kg/m}^2 / 1.2 \text{ g/cm}^3 = 0.83 \text{ mm}$

Similarly if a layer of chopped strand mat of 450 g/m^2 was able to be 'melted down' and poured into the same mould its thickness would be :

$$\frac{0.45 \text{ kg/m}^2}{2.55 \text{ g/cm}^3} = 0.18 \text{ mm}$$

Thus the total thickness may be calculated by the addition of the thicknesses attributable to each constituent and a laminate made from these constituents will have a thickness of :

$$0.83 + 0.18 \text{ mm} = 1.01 \text{ mm}$$

SURFACE AREA BASED CONSTRUCTION CALCULATIONS WITH 2-D REINFORCEMENT (e.g. mat or fabric)

Consider 1 kg of resin poured into a mould 1m by 1m. The thickness of the resin is given by the general equation :

$$\text{Thickness} = \frac{\text{Mass per unit area}}{\text{Density}}$$

Equation 4.7

The units which are commonly used in practice are inconsistent but they are convenient. They are : -

For simplicity the equation is used with the inconsistent units as

Metric system	Imperial system
mm	inches
kg/m^2	oz/ft^2
g/cm^3	Lb/in^3

by chance, no correction constant is required. In metric units it becomes :

$$\text{Thickness (mm)} = \frac{\text{Mass / unit area (kg/m}^2\text{)}}{\text{Density (g/cm}^3\text{)}}$$

Equation 4.8

$$\text{Thickness (in)} = \frac{1}{2304} \frac{\text{Mass / unit area (oz/ft}^2\text{)}}{\text{Density (Lb/in}^3\text{)}}$$

Equation 4.8 (Imperial)

Or in imperial units

Consider 1 oz of resin, of density 0.043 Lb/in^3 , poured into a mould 1ft by 1ft.

Using Equation 4.8 (Imperial)

The layer of resin will have a thickness of :

$$\text{Thickness (in)} = \frac{1}{2304} \frac{1 \text{ oz/ft}^2}{0.043 \text{ Lb/in}^3} = 0.01 \text{ in}$$

Similarly if a layer of chopped strand mat of 1.5 oz/ft^2 was able to be 'melted down' and poured into the same mould its thickness would be :

$$= \frac{1}{2304} \frac{1.5 \text{ oz/ft}^2}{0.092 \text{ Lb/in}^3} = 0.0071 \text{ in}$$

Thus the total thickness may be calculated by the addition of the thicknesses attributable to each constituent and a laminate made from these constituents will have a thickness of :

$$0.01 + 0.0071 = 0.0171 \text{ in}$$

Example 4.3

What will be the thickness of a laminate consisting of 2 layers of chopped strand mat of 450 g/m² if a resin to glass ratio of 2:1 is used?

From Equation 4.8

$$\begin{aligned} \text{The thickness attributable to the glass} \\ &= \text{Mass per m}^2 \text{ of glass (kg/m}^2\text{)} / \text{density of glass} \\ &= 2 \times 0.45 / 2.55 = 0.35 \text{ mm} \end{aligned}$$

The resin / glass ratio is 2/1, hence the amount of resin is :

$$2 \times 2 \times 0.45 \text{ kg/m}^2 = 1.8 \text{ kg/m}^2$$

The thickness attributable to the resin (assuming density of resin = 1.2 g/cm³)

$$= 1.8 \text{ kg} / 1.2 \text{ g/cm}^3 = 1.5 \text{ mm}$$

Hence total thickness = 0.35 + 1.5 = 1.85 mm

Example 4.3 Imperial

What will be the thickness of a laminate consisting of 2 layers of chopped strand mat of 1.5 oz/ft² if a resin to glass ratio of 2:1 is used ?

From Equation 4.8

$$\begin{aligned} \text{The thickness attributable to the glass} \\ &= \text{Weight per ft}^2 \text{ of glass (oz/ft}^2\text{)} / \text{density of glass} \times 2304 \\ &= 2 \times 1.5 / (0.092 \times 2304) \\ &= 0.0142 \text{ in} \end{aligned}$$

The resin / glass ratio is 2/1, hence the amount of resin is :

$$2 \times 2 \times 1.5 \text{ oz/ft}^2 = 6 \text{ oz/ft}^2$$

The thickness attributable to the resin (assuming density of resin = 0.043 Lb/in³)

$$= 6 \text{ oz/ft}^2 / 0.043 \text{ Lb/in}^3 / 2304 = .061 \text{ in}$$

Hence total thickness = 0.0142 + 0.0605 = 0.075 in

Laminate thickness generalises to the following equation

$$t_k = \frac{w_f}{d_f} + \frac{(1 - W_f) w_m}{W_f d_m}$$

Where: -	Metric system	Imperial system
t_k = Laminate thickness	mm	inches
w_f = mass of glass fibre w_m = mass of matrix resin	kg/m ²	oz/ft ²
\bar{a}_f = Density of glass fibre, \bar{a}_m = Density of matrix resin	g/cm ³	Lb/in ³
W_f = Mass fraction of glass fibre		

EXAMPLE 4.4

How can a thickness of 3 mm be achieved with a chopped strand mat laminate if the fibre content is to be 30 % by weight?

Chopped strand mat is available in a range of weights as shown in the table below. The attributable thickness for each has been calculated as in the previous examples and assuming a density for the glass of 2.55 g/cm³.

Thickness attributable to glass fibre reinforcement materials

Mass g/m ²	Attributable thickness (mm)
300	0.3/2.55 = 0.118 mm
450	0.45/2.55 = 0.176 mm
600	0.6/2.55 = 0.235 mm
900	0.9/2.55 = 0.353 mm

(Note, the attributable thickness is not the laminate thickness, it is the thickness that the glass fibre would have if it was 'melted' down)

A trial and error approach will be used. The reinforcement mass fraction is to be 30 %. Therefore if we choose the lightest of the reinforcements, 300 g/m², a laminate made from it will have a mass of: 300 / 0.3 = 1000 g/m²

The amount of resin used is 1000 - 300 = 700 g/m²

The thickness attributable to the resin, from Equation 4.8 is
0.7 / 1.2 = 0.583 mm

Hence the total thickness of a laminate from 300 g/m² glass reinforcement with a fibre weight fraction of 30 % is:

$$0.118 + 0.583 = 0.701 \text{ mm}$$

The number of layers we would require to achieve a thickness of 3 mm is
3 / 0.701 = 4.3

Hence we could use 4 or 5 layers. 4 layers would give a thickness of:
4 x 0.701 = 2.8 mm

(We could of course use 2 layers of 600 g/m² with exactly the same result) and 5 layers would give a thickness of:
5 x 0.701 = 3.5 mm

Now 300 g/m² is the smallest (generally available) building block so if we are restricted to the requirement of a 30 % mass fraction then the choice is between 2.8 and 3.5 mm. But we could choose the 2.8 mm option and add sufficient resin to bring the thickness up to 3mm. In which case what will be the fibre mass fraction? The thickness of resin that we need to make up is 3 mm - 2.8 mm = 0.2 mm

From Equation 4.8 :-

$$\text{Mass/unit area (Kg/m}^2\text{)} = \text{Thickness (mm)} \times \text{Density (g/cm}^3\text{)}$$

Hence 0.2 mm of resin thickness represents a mass per unit area of:
0.2 mm x 1.2 g/cm³ = 0.24 kg/m²

We would have used 700 g/m² of resin per layer at 30% mass fraction but we will now use an additional 240 g/m².

Hence amount of resin required = 700 x 4 + 240 = 3040 g/m² and the resulting fibre mass fraction (M_f) is simply:

$$\begin{aligned} &\text{Fibre mass} / \text{Total mass} \\ &= (4 \times 300) / (4 \times 300 + 3040) \\ &= 28.3 \% \end{aligned}$$

EXAMPLE 4.4 Imperial

How can a thickness of 1/8" be achieved with a chopped strand mat laminate if the fiber content is to be 30 % by weight ?

Chopped strand mat is available in a range of weights as shown in the table below. The attributable thickness for each has been calculated as in the previous examples and assuming a density for the glass of 0.092 Lb/in³ (2.55 g/cm³).

Thickness attributable to glass fibre reinforcement materials	
Mass oz/ft²	Attributable thickness (in)
1	$1/0.092/16/144 = 0.00471$ in
1 1/2	$1.5/0.092/16/144 = 0.00708$ in
2	$2/0.092/16/144 = 0.00942$ in
3	$3/0.092/16/144 = 0.01413$ in
(Note, the attributable thickness is not the laminate thickness, it is the thickness that the glass fibre would have if it was 'melted' down)	

A trial and error approach will be used. The reinforcement weight fraction is to be 30 %. Therefore if we choose the lightest of the reinforcements, 1 oz/ft², a laminate made from it will have a weight of: $1 / 0.3 = 3.33$ oz/ft²

Hence the amount of resin used is $3.33 - 1 = 2.3$ oz/ft²
The thickness attributable to the resin, from Equation 4.8 is
 $2.33/0.043/16/144 = 0.024$ in

Hence the total thickness of a laminate from 1 oz/ft² glass reinforcement with a fiber weight fraction of 30 % is
 $0.00471 + 0.024 = 0.0287$ in

The number of layers we would require to achieve a thickness of 1/8 in is : $0.125 / 0.0287 = 4.3$

Hence we could use 4 or 5 layers. 4 layers would give a thickness of $4 * 0.0287 = 0.115$ in

(We could of course use 2 layers of 2 oz/ft² with exactly the same result) and 5 layers would give a thickness of
 $5 * 0.0287 = 0.144$ in

Now 1 oz/ft² is the smallest (generally available) building block so if we are restricted to the requirement of a 30 % Weight fraction then the choice is between 0.115 and 0.144in. But we could choose the 0.115 option and add sufficient resin to bring the thickness up to 0.125 in. In which case what will be the fiber weight fraction? The thickness of resin that we need to make up is $0.125 - 0.115$ in = 0.010 in

From Equation 4.8, 0.010 in of resin thickness represents a weight per unit area of $0.010 \text{ in} * 0.043 * 16 * 144 = 0.99$ say 1 oz/ft²

We would have used 2.33 oz/ft² of resin per layer of 1oz mat at 30 % weight fraction but we will now use an additional 1 oz/ft².

Hence amount of resin required = $2.33 \text{ oz/ft}^2 * 4 + 1 \text{ oz/ft}^2 = 10.32 \text{ oz/ft}^2$ and the resulting fiber weight fraction (Wf) is simply
Fiber weight / Total weight
 $= (4 \text{ oz/ft}^2) / (4 \text{ oz/ft}^2 + 10.32 \text{ oz/ft}^2)$
 $= 28 \%$

EXAMPLE 4.5

A laminate consists of 3 layers of Chopped strand mat and 2 layers of Woven roving, see below. What will be the thickness?

1. 450 g/m² CSM with fibre mass fraction (Mf) of 0.2
2. 800 g/m² Woven roving with Mf of 0.35
3. 300 g/m² CSM with Mf of 0.2
4. 800 g/m² Woven roving with Mf of 0.35
5. 450 g/m² CSM with Mf of 0.2

Using a tabular approach but the same basic equations.

Layer Type	Fibre Mass kg/m ²	Mass Fraction %	Layer Mass kg/m ² (Eq 4.2)	Resin Mass kg/m ²	Thickness (mm) attributable to :-		
					Fibre (Eq 4.7)	Resin (Eq 4.7)	Total (mm)
CSM	0.45	20	0.45/0.2 = 2.25	2.25-0.45 = 1.8	0.45/2.55 = 0.18	1.8/1.2 = 1.5	1.68
WR	0.8	35	0.8/0.35 = 2.29	2.29-0.8 = 1.49	0.8/2.55 = 0.31	1.49/1.2 = 1.24	1.55
CSM	0.3	20	0.3/0.2 = 1.5	1.5-0.3 = 1.2	0.3/2.55 = 0.12	1.2/1.2 = 1.0	1.12
WR	0.8	35	0.8/0.35 = 2.29	2.29-0.8 = 1.49	0.8/2.55 = 0.31	1.49/1.2 = 1.24	1.55
CSM	0.45	20	0.45/0.2 = 2.25	2.25-0.45 = 1.8	0.45/2.55 = 0.18	1.8/1.2 = 1.5	1.68
TOTAL	2.8		10.58		1.1	6.48	7.58

Hence the total thickness of the laminate is 7.58 mm and it will weigh 10.58 kg/m².

If the Resin / Glass ratio is known rather than fibre mass fraction then column (4) in the table isn't needed. The calculation is simpler. The resin mass is found by multiplying the fibre mass by the Resin / Glass ratio.

EXAMPLE 4.5 Imperial

A laminate consists of 3 layers of Chopped strand mat and 2 layers of Woven roving, see below. What will be the thickness?

1. 1.5 oz/ft² CSM with fiber weight fraction (Wf) of 0.2
2. 24 oz/yd² (2.67 oz/ft²) Woven roving with Wf of 0.35
3. 1.5 oz/ft² CSM with Wf of 0.2
4. 24 oz/yd² (2.67 oz/ft²) Woven roving with Wf of 0.35
5. 1.5 oz/ft² CSM with Wf of 0.2

Using a tabular approach but the same basic equations.

Layer Type	Fibre Mass oz/ft ²	Mass Fraction %	Layer Mass oz/ft ² (Eq 4.2)	Resin Mass oz/ft ²	Thickness (in) attributable to :-		
					Fibre (Eq 4.7)	Resin (Eq 4.7)	Total (in)
CSM	1.5	20	1.5/0.2 = 7.5	7.5-1.5 = 6	1.5/0.092/2304 = 0.0071	6/0.043/2304 = 0.061	0.0681
WR	2.67	35	2.67/0.35 = 7.63	7.63-2.67 = 4.96	2.67/0.092/2304 = 0.0126	4.96/0.043/2304 = 0.05	0.0626
CSM	1	20	1.0/0.2 = 5.0	5.0-1.0 = 4	1.0/0.092/2304 = 0.0047	4/0.043/2304 = 0.04	0.0447
WR	2.67	35	2.67/0.35 = 7.63	7.63-2.67 = 4.96	2.67/0.092/2304 = 0.0126	4.96/0.043/2304 = 0.05	0.0626
CSM	1.5	20	1.5/0.2 = 7.5	7.5-1.5 = 6	1.5/0.092/2304 = 0.0071	6/0.043/2304 = 0.061	0.0681
TOTAL	9.34		35.26	25.92	0.044	0.262	0.306

Hence the total thickness of the laminate is 0.306 inches and it will weigh 35.26 oz/ft².

SURFACE AREA CALCULATIONS WITH *LINEAR* REINFORCEMENT

The fundamental equations for these calculations are :

Laminate thickness (mm) =

$$\frac{\text{fibre mass (kg/m}^2\text{)}}{\text{fibre density (g/cm}^3\text{)} * V_f} \quad \text{Equation 4.9}$$

Mass/unit length (kTex) =

$$\text{Mass/unit area (g/m}^2\text{)} * \text{width (m)} \quad \text{Equation 4.10}$$

Or in Imperial units: -

Laminate thickness (in) =

$$\frac{\text{fibre mass (oz/ft}^2\text{)}}{2304 * \text{fibre density (Lb/in}^3\text{)} * V_f}$$

Equation 4.9 (Imperial)

Yield (yd/Lb) =

$$\frac{64 * \text{width (in)}}{\text{Mass/unit area (oz/ft}^2\text{)}}$$

Equation 4.10 (Imperial)

Example 4.6

Say we want to cover the surface of a cylinder 1/2m long and 1m circumference, with unidirectional roving laminate to a thickness of 5 mm. How many ends of 4800 Tex roving will be required at a volume fraction of 60%.

A convenient method is to calculate first the mass/m² required of fibre, then convert this to mass / unit length. Then calculate how many ends of roving this requires.

$$\begin{aligned} \text{from Equation 4.9 Fibre mass (kg/m}^2\text{)} &= \\ \text{fibre density (g/cm}^3\text{)} * V_f * \text{Laminate thickness} &= \\ = 2.55 * 0.6 * 5 &= 7.65 \text{ kg/m}^2 \end{aligned}$$

$$\begin{aligned} \text{From equation 4.10 Mass/unit length (kTex)} &= \\ \text{Mass/unit area (g/m}^2\text{)} * \text{width (m)} &= \end{aligned}$$

$$= 7650 \text{ (g/m}^2\text{)} * 0.5 \text{ (m)} = 3825 \text{ kTex}$$

$$\begin{aligned} \text{Therefore the number of ends of 4800 Tex roving is :} &= \\ 3825 \text{ kTex} / 4.8 \text{ kTex} &= 797 \text{ ends} \end{aligned}$$

Or in Imperial units

Say length = 20", circumference = 40" and thickness = 0.2"

How many ends of 103 yield roving will be required at a volume fraction of 60% ?

from Equation 4.9

$$\begin{aligned} \text{Fiber mass (oz/ft}^2\text{)} &= \text{f (Lb/in}^3\text{)} * V_f * t \text{ (in)} * 2304 \\ &= 0.092 * 0.6 * 0.2 * 2304 \\ &= 25.4 \text{ oz/ft}^2 \end{aligned}$$

From equation 4.10

$$\text{Yield (yd/Lb)} = 64 \text{ width (in)} / \text{Mass/unit area (oz/ft}^2\text{)}$$

$$= 64 / 20 \text{ in} / 25.4 \text{ oz/ft}^2$$

$$= 0.1258 \text{ yd/Lb}$$

Therefore the number of ends of 103 yield roving is :

$$\begin{aligned} 103 \text{ yd/Lb} / 0.1258 \text{ yd/Lb} &= \\ = 819 \text{ ends} \end{aligned}$$

CROSS SECTIONAL AREA BASED CONSTRUCTION CALCULATIONS

CROSS SECTIONAL AREA CALCULATIONS WITH *LINEAR* REINFORCEMENT.

'Linear' reinforcements are those measured by the mass of per unit length rather than per unit area.

So Roving, Tow and Yarn are classified as linear reinforcements. Tex (g/km) is the Metric unit of measurement and Yield (yd/Lb) is the Imperial unit

When the construction calculation is concerned with cross sectional area rather than surface area then it is generally more convenient to work with volume fractions of the constituents rather than mass fractions.

The cross sectional area of any constituent is given by the equation :

$$\text{Cross sectional area (mm}^2\text{)} = \frac{\text{Linear Mass (kTex)}}{\text{Density (g/cm}^3\text{)}}$$

Equation 4.11

Or in Imperial Units

$$\begin{aligned} \text{Cross sectional area (in}^2\text{)} &= \\ = 1 / \{36 * \text{Yield (yd/Lb)} * \text{Density (Lb/in}^3\text{)}\} \end{aligned}$$

Equation 4.11 Imperial

(Inconsistent units and Linear mass are discussed earlier.)

Example 4.7

Find the cross sectional area of a single E glass roving of linear mass 2400 Tex. The density of E glass is 2.55 g/cm³.

From equation 4.11

$$\begin{aligned} \text{CSA} &= \frac{2.4 \text{ kTex}}{2.55 \text{ g/cm}^3} \\ &= 0.94 \text{ mm}^2 \end{aligned}$$

Example 4.7 (Imperial Units)

Find the cross sectional area of a single E glass roving of 207 yield. The density of E glass is 0.092 Lb/in³.

from equation 4.11

$$\text{CSA (in}^2\text{)} = 1 / \{36 * 207 * 0.092 \text{ Lb/in}^3\} = 0.00146 \text{ in}^2$$

Example 4.8

Find the cross sectional area of 10 Tows of carbon fibre each of 800 Tex (620 yield).

From table 4.3 Density of carbon fibre = 1.79 g/cm³ (0.065 Lb/in³)

$$\begin{aligned} \text{From equation 4.11 Cross sectional area} &= \frac{10 * 0.8 \text{ kTex}}{1.79 \text{ g/cm}^3} \\ &= 4.47 \text{ mm}^2 \end{aligned}$$

Or in Imperial Units

Total yield = 620 yd/Lb / 10 ends = 62 yd/lb

$$\begin{aligned} \text{Cross sectional area (in}^2\text{)} &= \\ = 1 / \{36 * \text{Yield (yd/Lb)} * \text{Density (Lb/in}^3\text{)}\} &= \\ = 1 / \{36 * 62 * 0.065\} &= \\ = 0.00689 \text{ in}^2 \end{aligned}$$

(Note: divide yield by number of ends to get total yield)

Example 4.9

Say in example 4.7 the fibre is encapsulated in resin so that the volume fraction of fibre (Vf) is 60%. What will be the cross sectional area of the composite?

From example 4.7 the cross sectional area of the fibre is 0.94 mm²

From equation 4.3(b)

$$\begin{aligned}\text{Cross sectional area (composite)} &= \frac{\text{Cross sectional area (fibre)}}{\text{Fibre Volume fraction}} \\ &= 0.94 / 0.6 = 1.57 \text{ mm}^2\end{aligned}$$

In Imperial units

From example 4.7 the cross sectional area of the fibre is 0.00146 in²

From equation 4.3(b)

$$\begin{aligned}\text{Cross sectional area (composite)} &= \frac{0.00146 \text{ in}^2}{0.6} \\ &= 0.0024 \text{ in}^2\end{aligned}$$

Example 4.10

A section shape of 10 mm by 20 mm is to be filled with E glass fibre and resin with a fibre volume fraction of 60 %. How many ends of 2400 Tex roving will be required?

$$\text{Total cross section area} = 10 \times 20 = 200 \text{ mm}^2$$

From equation 4.3(b)

$$\begin{aligned}\text{Fibre cross sectional area} &= \text{Laminate cross sectional area} \times V_f \\ &= 200 \times 0.6 = 120 \text{ mm}^2\end{aligned}$$

From equation 4.11

$$\begin{aligned}\text{Linear mass (kTex)} &= \text{Fibre cross sectional area} \times \text{Density} \\ &= 120 \text{ mm}^2 \times 2.55 \text{ g/cm}^3 \\ &= 306 \text{ kTex}\end{aligned}$$

The linear mass of the rovings to be used is 2400 tex then number of rovings required is :

$$306000 \text{ Tex} / 2400 \text{ Tex} = 127 \text{ Ends of roving}$$

Example 4.10 Imperial

A section shape of 0.4 in by 0.8 in is to be filled with E glass fiber and resin with a fiber volume fraction of 60 %. How many ends of 207 yield roving will be required ?

$$\text{Total cross section area} = 0.4 \times 0.8 = 0.32 \text{ in}^2$$

From equation 4.3(b)

$$\begin{aligned}\text{Fiber cross section area} &= \text{Laminate cross section area} \times V_f \\ &= 0.32 \times 0.6 = 0.192 \text{ in}^2\end{aligned}$$

From equation 4.11

$$\begin{aligned}\text{Yield} &= 1 / \{36 \times \text{area (in}^2) \times \text{Density}\} \\ &= 1 / \{36 \times 0.192 \times 0.092\} = 1.57 \text{ yd/Lb}\end{aligned}$$

The linear weight of the rovings to be used is 207 yield then number of rovings required is:

$$207 \text{ yd/Lb} / 1.57 \text{ yd/Lb} = 131 \text{ Ends of roving}$$

Example 4.11

How many tows of XAS carbon fibre would be required to fill the same shape at 60 % fibre volume fraction ?

The same cross sectional area of fibre will be required i.e. 120 mm² . Assuming that the density of the fibre is 1.79 g/cm³ then from equation 4.11

$$\text{Linear mass of fibre (kTex)} = 1.79 \times 120 = 215 \text{ kTex}$$

Say the linear mass of the carbon tow is 800 Tex then

$$\text{Number ends of carbon tow} =$$

$$215 \text{ KTex} / 0.8 \text{ kTex} = 269 \text{ ends}$$

Or in Imperial Units

Example 4.11 Imperial

How many tows of XAS graphite fiber would be required to fill the same shape at 60% fiber volume fraction ?

$$\text{Cross sectional area to be filled} = 0.4 \times 0.8 = 0.32 \text{ in}^2$$

$$\text{At 60\% volume fraction} = 0.32 \times 0.6 = 0.192 \text{ in}^2$$

Assuming that the density of the carbon fiber is = 1.79 g/cm³ (0.065 Lb/in³)

then from Equation 4.11 Imperial the total yield required is

$$\begin{aligned}\text{Yield (yd/Lb)} &= \\ 1 / \{36 \times \text{Cross sectional area (in}^2) \times \text{Density (Lb/in}^3)\} & \\ &= 2.22 \text{ (yd/Lb)}\end{aligned}$$

Say the yield of the graphite tow is 620 yd/Lb then the number ends of graphite tows =

$$= 620 / 2.22 = 279 \text{ ends}$$

CROSS SECTIONAL AREA CALCULATIONS WITH TWO DIMENSIONAL REINFORCEMENT

Two dimensional reinforcement (CSM, CFM woven roving etc) is specified by its mass per unit area. Therefore when these materials are to be used it is sensible to use mass per unit area as the basis for construction calculations.

The basic equation is :

$$\text{Thickness of laminate (mm)} = \frac{\text{fibre mass kg/m}^2}{\text{fibre density} \times V_f} \quad \text{equation 4.9}$$

Or Imperial

$$\text{Laminate thickness (in)} = \frac{\text{fibre mass (oz/ft}^2\text{)}}{2304 \times \text{fibre density (Lb/in}^3\text{)} \times V_f}$$

Example 4.12

What mass of E glass CFM is required to fill a cavity 10 mm deep if the fibre volume fraction is to be 25 %?

Rearranging the equation

$$\begin{aligned} \text{Mass of fibre kg/m}^2 &= \text{laminate thickness} \times \text{fibre density} \times V_f \\ &= 10 \times 2.55 \times 0.25 = 6.37 \text{ kg/m}^2 \end{aligned}$$

Now CFM is commercially available as :-
300, 450 and 600 g/m².

Therefore the nearest combination to 6.37 kg/m² is:
10 layers of 600 g/m² plus 1 layer of 300 g/m² giving a total of 6.3 kg/m².

Example 4.12 Imperial

What weight of E glass CFM is required to fill a cavity 0.4 in deep if fiber volume fraction is to be 25 % ?

From equation 4.9

$$\text{Mass of fibre (oz/ft}^2\text{)} = 2304 \times \text{fibre density (Lb/in}^3\text{)} \times V_f \times \text{Thickness (in)}$$

$$2304 \times 0.092 \times 0.25 \times 0.4 = 21.2 \text{ oz/ft}^2$$

Now CFM is available as 1, 1.5, 2 oz/ft².

Therefore the nearest combination to 21.2 oz/ft² is:
10 layers of 2 oz/ft² plus 1 layer of 1 oz/ft² giving a total of 21.0 oz/ft².

Example 4.13

What will be the fibre volume fraction if 2 layers of 800 g/m² woven roving is compression moulded to a thickness of 2mm?

$$\begin{aligned} \text{Laminate thickness (tk)} &= 2 \text{ mm} \\ \text{Fibre mass} &= 2 \times 800 = 1.6 \text{ kg/m}^2 \\ \text{Volume fraction of fibres (Vf)} &= ? \end{aligned}$$

From equation 4.9

$$\begin{aligned} V_f &= \frac{\text{Mass of fibre kg/m}^2}{\text{Thickness of laminate (mm)} \times \text{fibre density}} \\ &= 1.6 / (2 \times 2.55) = 0.313 \\ &= 31.3 \% \end{aligned}$$

Example 4.13 Imperial

What will be the fiber volume fraction if 2 layers of 24 oz/ yd² woven roving is compression molded to a thickness of 0.08 in?

$$\begin{aligned} \text{Laminate thickness} &= 0.08 \text{ in} \\ \text{Fiber mass} &= 2 \times 24 / 9 = 5.33 \text{ oz/ft}^2 \\ \text{Volume fraction of fibers (Vf)} &= ? \end{aligned}$$

From equation 4.9 Imperial

$$\begin{aligned} V_f &= \frac{\text{Mass of fibre (oz/ft}^2\text{)}}{2304 \times \text{Thickness of laminate (mm)} \times \text{fibre density}} \\ &= 5.33 / (2304 \times 0.08 \times 0.092) = 0.313 \\ &= 31.3 \% \end{aligned}$$

SUMMARY OF EQUATIONS FOR CONSTRUCTION ANALYSIS

BASIC EQUATIONS

$$\text{Tex (g/km)} * \text{Yield (yd/lb)} = 496000 \quad \text{Equation 4.1}$$

$$\begin{aligned} \text{Mass fraction of a constituent} \\ = \frac{\text{Mass of constituent}}{\text{Total mass of the composite}} \end{aligned} \quad \text{Equation 4.2}$$

$$\begin{aligned} \text{Volume fraction of a constituent} \\ = \frac{\text{Volume of constituent}}{\text{Total volume of the composite}} \end{aligned} \quad \text{Equation 4.3(a)}$$

or

$$\begin{aligned} \text{Volume fraction of a constituent} \\ = \frac{\text{Cross sectional area of the constituent}}{\text{Total CSA}} \end{aligned} \quad \text{Equation 4.3(b)}$$

$$\text{Resin / Glass Ratio} = (1 / M_f) - 1 \quad \text{Equation 4.4}$$

Conversion Mass fraction to and from Volume fraction

$$V_1 = \frac{\frac{M_1}{d_1}}{\frac{M_1}{d_1} + \frac{M_2}{d_2} + \frac{M_3}{d_3} + \text{etc}} \quad \text{Equation 4.5}$$

$$M_1 = \frac{d_1 V_1}{d_1 V_1 + d_2 V_2 + d_3 V_3} \quad \text{Equation 4.6}$$

Where

δ is the density of the constituent
 V is the volume fraction of the constituent
 M is the mass fraction of the constituent

Laminate density (δ_{lam})

$$\delta_{\text{Lam}} = d_1 V_1 + d_2 V_2 + d_3 V_3$$

General equation for Laminate thickness

$$t_k = \frac{w_f}{d_f} + \frac{(1 - W_f) w_m}{W_f d_m}$$

Where: -	Metric system	Imperial system
t_k = Laminate thickness	mm	inches
w_f = mass of glass fibre w_m = mass of matrix resin	kg/m ²	oz/ft ²
d_f = Density of glass fibre, d_m = Density of matrix resin	g/cm ³	Lb/in ³
W_f = Mass fraction of glass fibre		

SURFACE CALCULATIONS

$$\begin{aligned} \text{Thickness} &= \text{Mass per unit area} / \text{Density} \\ &(\text{Any consistent units}) \end{aligned} \quad \text{Equation 4.7}$$

$$\begin{aligned} \text{Thickness attributable to a constituent (mm)} &= \\ &\frac{\text{Mass / unit area (kg/m}^2\text{)}}{\text{Density (g/cm}^3\text{)}} \end{aligned} \quad \text{Equation 4.8}$$

$$\begin{aligned} \text{Thickness (in)} &= \frac{1}{2304} \frac{\text{Mass / unit area (oz/ft}^2\text{)}}{\text{Density (Lb/in}^3\text{)}} \\ &\text{Equation 4.8 (Imperial)} \end{aligned}$$

$$\begin{aligned} \text{Laminate thickness (mm)} &= \frac{\text{fibre mass (kg/m}^2\text{)}}{\text{fibre density (g/cm}^3\text{)} \times V_f} \\ &\text{Equation 4.9} \end{aligned}$$

$$\begin{aligned} \text{Laminate thickness (in)} &= \frac{\text{fibre mass (oz/ft}^2\text{)}}{2304 \times \text{fibre density (Lb/in}^3\text{)} \times V_f} \\ &\text{Equation 4.9 (Imperial)} \end{aligned}$$

$$\begin{aligned} \text{Mass/unit length (kTex)} &= \text{Mass/unit area (g/m}^2\text{)} \times \text{width (m)} \\ &\text{Equation 4.10} \end{aligned}$$

$$\begin{aligned} \text{Yield (yd/Lb)} &= \frac{64 \times \text{width (in)}}{\text{Mass/unit area (oz/ft}^2\text{)}} \\ &\text{Equation 4.10 (Imperial)} \end{aligned}$$

LINEAR CALCULATIONS

$$\begin{aligned} \text{Cross sectional area (mm}^2\text{)} \\ &= \text{Linear Mass (kTex)} / \text{Density (g/cm}^3\text{)} \end{aligned} \quad \text{Equation 4.11}$$

or in alternative units

$$\begin{aligned} \text{Cross sectional area (cm}^2\text{)} &= \\ &\text{Mass per unit length (Tex)} / \text{Density (g/cm}^3\text{)} \end{aligned}$$

$$\begin{aligned} \text{Cross sectional area (in}^2\text{)} \\ &= 1 / \{36 \times \text{Yield (yd/Lb)} \times \text{Density (Lb/in}^3\text{)}\} \\ &\text{Equation 4.11 Imperial} \end{aligned}$$

$$\begin{aligned} \text{Thickness of laminate mm} &= \frac{\text{fibre mass kg/m}^2}{\text{fibre density} \times V_f} \\ &\text{Equation 4.12} \end{aligned}$$

GENERAL CALCULATIONS

$$\begin{aligned} \text{Profile volume (cm}^3\text{/m)} \\ &= \text{Profile cross sectional area (cm}^2\text{)} \times 100 \\ &= \text{Profile cross sectional area (mm}^2\text{)} \\ &\text{Equation 4.13} \end{aligned}$$

To convert between linear and surface units equation 4.14 is used.

$$\begin{aligned} \text{Mass/unit area (g/m}^2\text{)} \times \text{width (m)} &= \text{Mass/unit length (kTex)} \\ &\text{Equation 4.14} \end{aligned}$$

$$\begin{aligned} \text{Mass/unit area (oz/ft}^2\text{)} \times \text{width (ft)} / 48 &= \\ \text{Mass/unit length (Lb/yd)} &= 1/\text{yield} \\ &\text{Equation 4.14 Imperial} \end{aligned}$$

$$\text{Profile cost (p/mm}^2\text{/m)} = p / \text{cm}^3 \quad \text{Equation 4.15}$$

$$\begin{aligned} \text{Profile cost (£/kg)} &= \frac{\text{Profile cost (p/mm}^2\text{/m)} \times 10}{\text{Density (g/cm}^3\text{)}} \\ &\text{Equation 4.16} \end{aligned}$$

CONSTRUCTION CALCULATIONS - PROFILES

Fig 4.9 is used to determine the amount of reinforcement required to fill the die cross section of pultruded profiles.

1. The die cross sectional area is entered.
2. Appropriate values are entered in columns (a) to (d) and (f). This allows column (e) to be calculated.
3. The local volume fraction, for each material is selected from Fig 4.3 (using $\sqrt{P} = 1.25$, unless information is available to the contrary). This is entered into column (h), allowing columns (i) and (j) to be calculated.
4. The sum of the layer cross sectional areas is then com-

pared with the CSA of the profile. The reinforcement layers or weights are adjusted to give 100% die fill.

It also allows the approximate Young's modulus of the profile to be estimated.

To estimate Young's modulus of the profile:

1. Enter column (k), the fibre modulus, for each layer.
2. Column (l) is an efficiency factor (beta) which depends on the directionality of the fibres in the particular layer. Values for beta are given in Chapter 5.
3. Hence column (m) can be completed (the moduli of individual layers) the sum of which is a reasonable estimate of Young's Modulus of the profile.

Fig 4.9 to determine reinforcement to fill cross section of pultruded profile

Section shape: Channel section 10 cm wide, 5 cm deep, 0.5 cm thick METRIC TABLE														
Section Cross sectional area (CSA) (cm ²) = 10 cm ²														
Layer	Type	Rovings		Mat or Fabric		Fibre				Layer CSA mm ²	Fibre Global Vf *	Fibre Modulus GPa	β ** Reinforcement Efficiency	Profile Young's Modulus GPa
		Tex g/km or mg/m	No. Ends	Mass g/m ²	Effective Width m	weight g/m	Density g/cc	Volume cc/m	Local Volume Fraction ***					
		a	b	c	d	e	f	g	h	i	j	k	l	m
						a x b/1000 or c x d		e/f		g/h	g/csa/100			j x k x l
1	Roving	4800	113			542.4	2.55	213	0.62	3.43	0.21	70	1	14.89
2	CFM 2 layers			1200	0.3	360	2.55	141	0.28	5.04	0.14	70	0.375	3.71
3	UD Carbon fabric			600	0.3	180	1.8	100	0.66	1.52	0.1	230	1	23
4														
Total						1082.4		454		9.99				41.60
Percentage die fill % = Sum col (i) / CSA x 100 = 99.88 %														

Section shape: Channel section 4 in wide, 2 in deep, 0.2 in thick IMPERIAL TABLE														
Section Cross sectional area (CSA) (in ²) = 1.6														
Layer	Type	Rovings		Mat or Fabric		Fibre				Layer CSA in ²	Fibre Global Vf *	Fibre Modulus Msi	β ** Reinforcement Efficiency	Profile Young's Modulus Msi
		Yield yd/Lb	No. Ends	Mass oz/ft ²	Effective Width ft	weight Lb/ft	Density Lb/in ³	Volume in ³ /ft	Local Volume Fraction ***					
		a	b	c	d	e	f	g	h	i	j	k	l	m
						b/a/3 or c x d /16		e/f		g/h/12	g/CSA/12			j x k x l
1	Roving	103	108			0.350	0.092	3.8	0.62	0.51	0.198	10	1	1.98
2	CFM 2 layers			4	1	0.25	0.088	2.8	0.28	0.85	0.148	10	0.375	0.55
3	UD Carbon fabric			2	1	0.125	0.065	1.92	0.66	0.24	0.100	33	1	3.305
4														
Total						0.725		8.56		1.60				5.84
Percentage die fill % = Sum col (i) / CSA x 100 = 99.93 %														

* Global Volume fraction of fibre is volume of fibre in the layer relative to the total volume.

** Reinforcement efficiency (β) is a measure of the degree of fibre alignment (see property prediction).

*** See Fig 4.3.

COMPRESSIBILITY OF REINFORCEMENT MATERIALS

Construction calculations are straight forward if the same type of reinforcement is to be used throughout the laminate. A knowledge of the densities of the resin and the fibre allows the thickness of the laminate to be calculated as has been shown earlier.

However with some processes, particularly pultrusion, it is common practice to use several types of material in one laminate. The thickness of each layer and hence its position in the laminate can only be predicted by a knowledge of the amount to which each layer of reinforcement material compresses under load. An empirical model has been developed which is pragmatic and representative of typical reinforcing materials. Ref 1

Reinforcement materials of different types used in the same laminate are analogous to a series of compression springs each of different length and different spring rate. In order to determine the thickness of each layer (which is equivalent to the length of each compression spring in series) it is necessary to characterise the load / deflection response of each material. (Equivalent to the 'rate' of the spring).

The situation is complicated for two reasons. Reinforcement materials don't behave linearly. Also the unloaded thickness of a layer of reinforcement material is very difficult to define.

In order to characterise reinforcement materials, a range of trials were carried out in which each was subjected to a compressive load. The resulting deformation was measured from which the volume fraction of fibres was calculated.

If the square root of pressure is plotted against fibre volume fraction then a reasonable approximation of a straight line is generated over the range of practical values. This gives a simple equation which is straightforward to manipulate.

General equations for a variety of reinforcement materials is given in TABLE 4.7 and shown graphically in fig 4.3.

TABLE 4.7
CHARACTERISTIC EQUATIONS FOR COMPRESSIBILITY
OF TYPICAL REINFORCING MATERIALS

	Equations 4.17 (a-g)	
E Glass Continuous Strand Mat	$V_f \% = 8.56 + 15.49\sqrt{P}$	(a)
E Glass Chopped Strand Mat	$V_f \% = 20 + 14.69\sqrt{P}$	(b)
E Glass Roving	$V_f \% = 32 + 23.96\sqrt{P}$	(c)
E Glass Woven Fabric	$V_f \% = 40 + 14.37\sqrt{P}$	(d)
Kevlar Fabric	$V_f \% = 47 + 16.29\sqrt{P}$	(e)
Unidirectional Carbon Cloth	$V_f \% = 34 + 25.55\sqrt{P}$	(f)
+/-45 Carbon Fibre Fabric	$V_f \% = 35 + 16.29\sqrt{P}$	(g)

The thickness of laminates moulded under a particular pressure can thus be predicted if the effect of the matrix viscosity is negligible relative to the compressibility of the reinforcement. This is the case for instance with vacuum moulded laminates where a vacuum is applied to the dry reinforcement to 'pull' the resin through it. But it isn't applicable to SMC and DMC where the matrix viscosity is very high.

Example 4.14

What thickness will chopped strand mat compress to when subjected to a vacuum of 0.9 Bar?

This fibre volume fraction can be read directly from the graph in Fig 4.3 or more accurately calculated from equation 4.17 (b). From the graph the fibre volume fraction for CSM at a pressure of 0.9 Bar is about 34 %.

Alternatively by calculation :

for E Glass Chopped Strand Mat

$$\begin{aligned} V_f &= 20 + 14.69 \sqrt{P} \\ \text{therefore } V_f &= 20 + 14.69 \sqrt{0.9} \\ &= 33.9 \% \end{aligned}$$

The pultrusion process is particularly applicable to this technique. The constant factor in the construction analysis of a pultrudate, is the pressure exerted within the die of the dry reinforcement. This applies even when using more than one type of reinforcing material.

The characteristic equations are general for both mass/m² of reinforcement and number of layers of reinforcement.

The analogy with compression springs is that it is irrelevant how the length of a spring is made up. One long spring may be used or several shorter springs of different lengths may be used to make up the same length. As long as the same total length is achieved and similar springs are used then the same load / deflection response will be achieved.

It is therefore irrelevant how a reinforcement pack is made up for a particular material type. One heavy layer may be used or several layers, possibly of different mass, may be used. In each case the same total load / deformation response results.

The graphs shown in fig 4.3 may be employed to determine the effect on reinforcement pressure of an increase in fibre volume fraction, mass / m² of reinforcement and number of layers of reinforcement.

The thickness of reinforcing materials, particularly of woven products, is a characteristic often quoted in product information sheets. It is obviously desirable to know the thickness of a material but the definition of thickness is not simple. Thickness is not defined as an absolute value, it is defined relative to a particular load. This is only of value if we want to work at that load. If not then the data is valueless.

However the technique described here allows two alternatives. Either the 'zero load' thickness can be determined. It is the

intercept value from the graph of volume fraction versus root pressure. Alternatively the reinforcement material can be fully characterised by defining its volume fraction / pressure response in the form, $V_f = K_1 + K_2 \times \sqrt{P}$, as used in equation 4.13.

Example 4.15

A Laminate is to be produced by compressing reinforcement between two 300 mm square plattens with a load of 1.5 tonnes. What will be the total thickness of the laminate?

The reinforcement consists of the following construction :

- A) 1 layer of 600 g/m² Chopped strand mat
- B) 1 layer of 900 g/m² Woven roving
- C) 1 layer of 450 g/m² Chopped strand mat

Assuming that the compressibility of the reinforcement remains substantially the same when it has been impregnated with resin. (Note, this is not the case with compounds: SMC, DMC, Prepreg)

The applied pressure is

$$\begin{aligned} & 1.5 / (300 * 300) \text{ Tonnes} / \text{mm}^2 \\ & = 1500 * 9.8 / (300 * 300) \text{ N/mm}^2 \\ & = 0.163 \text{ N/mm}^2 \\ & = 10 * 0.163 \text{ Bar} = 1.63 \text{ Bar} \end{aligned}$$

From fig 4.3 at $\sqrt{1.63 \text{ Bar}}$ (1.27) the fibre volume fraction is approximately 58 % for woven roving and 38% for chopped strand mat.

The thickness for each layer using equation 4.12 is therefore:

$$\begin{aligned} \text{Thickness layer A)} \\ & = 0.6 \text{ kg/m}^2 / 2.55 \text{ g/cm}^3 / 0.38 \\ & = 0.62 \text{ mm} \end{aligned}$$

$$\begin{aligned} \text{Thickness layer B)} \\ & = 0.9 \text{ kg/m}^2 / 2.55 \text{ g/cm}^3 / 0.58 \\ & = 0.61 \text{ mm} \end{aligned}$$

$$\begin{aligned} \text{Thickness layer C)} \\ & = 0.45 \text{ kg/m}^2 / 2.55 \text{ g/cm}^3 / 0.38 \\ & = 0.46 \text{ mm} \end{aligned}$$

$$\text{Total thickness of the laminate} = 1.69 \text{ mm}$$

Example 4.16

What extra moulding pressure will be required increase the volume fraction of a woven fabric laminate from 50 % to 55%?

It may be seen from Fig 4.3 that to increase volume fraction from 50 to 55 % requires an increase moulding pressure from about 1/2 Bar to about 1 Bar.

or by calculation using equation 4.17(d)

For E Glass Woven Fabric

$$V_f \% = 40 + 14.37 \sqrt{P}$$

$$\begin{aligned} \text{therefore } P &= ((V_f \% - 40) / 14.37)^2 \\ \text{therefore at 50 \% Volume fraction} \end{aligned}$$

$$P = ((50-40)/14.37)^2 = 0.48 \text{ Bar}$$

$$\begin{aligned} \text{and at 55\% } P &= ((55-40)/14.37)^2 \\ &= 1.09 \text{ Bar} \end{aligned}$$

which represents an increase of 127 % in pressure.

Fig 4.11 Compressibility of Reinforcement Materials

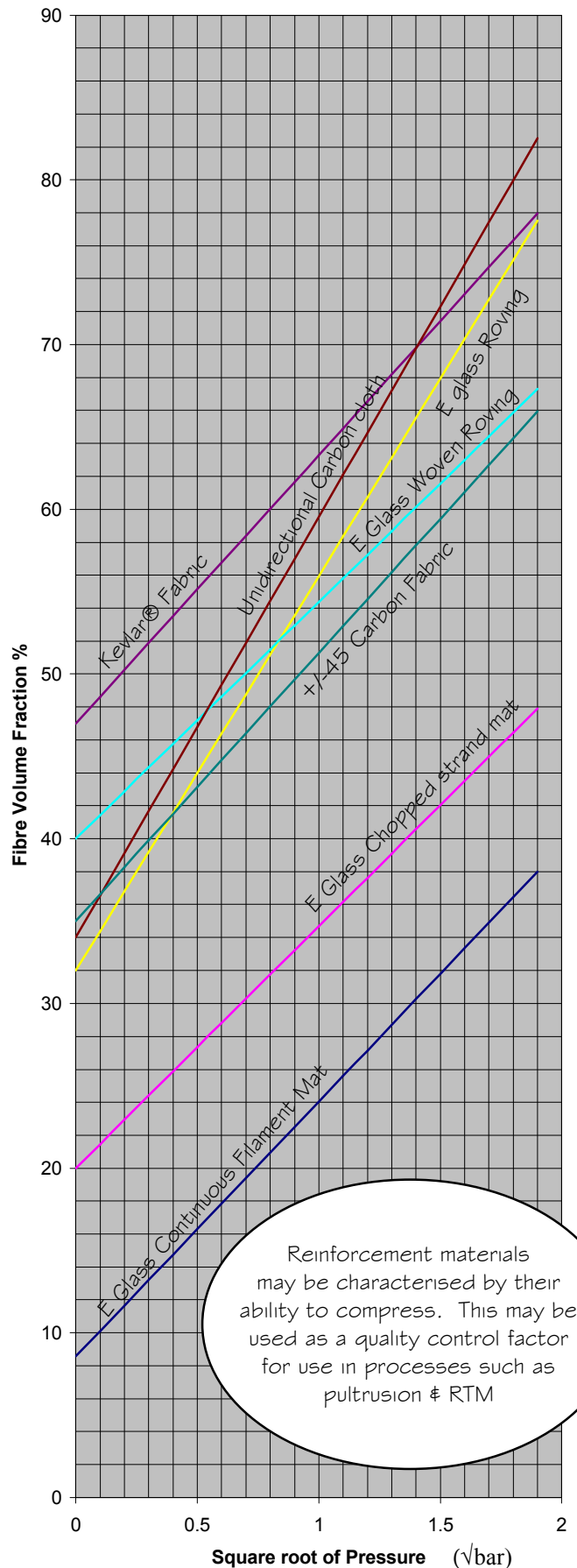


Table 4.12 Thickness of E glass Laminates																								
Density fibre 2.55																								
Density resin mix 1.20																								
Mf = Mass fraction of Fibre		Example. The thickness of a 450 g/m2 , 30% wf laminate is 1.05 mm																						
Vf = Volume fraction of Fibre																								
Fibre	Mass g/m2	100	200	300	450	500	550	600	750	800	900	1000	1050	1200	1350	1500	1650	1800	1950	2100	2250	2400	2550	2700
Mf	Vf	LAMINATE THICKNESS (mm)																						
0.25	0.136	0.29	0.58	0.87	1.30	1.45	1.59	1.74	2.17	2.31	2.60	2.89	3.04	3.47	3.90	4.34	4.77	5.21	5.64	6.07	6.51	6.94	7.38	7.81
0.26	0.142	0.28	0.55	0.83	1.24	1.38	1.52	1.66	2.07	2.21	2.49	2.76	2.90	3.32	3.73	4.15	4.56	4.98	5.39	5.80	6.22	6.63	7.05	7.46
0.27	0.148	0.26	0.53	0.79	1.19	1.32	1.45	1.59	1.98	2.12	2.38	2.65	2.78	3.17	3.57	3.97	4.36	4.76	5.16	5.56	5.95	6.35	6.75	7.14
0.28	0.155	0.25	0.51	0.76	1.14	1.27	1.39	1.52	1.90	2.03	2.28	2.54	2.66	3.04	3.42	3.80	4.18	4.56	4.94	5.32	5.70	6.08	6.46	6.84
0.29	0.161	0.24	0.49	0.73	1.09	1.22	1.34	1.46	1.82	1.95	2.19	2.43	2.55	2.92	3.28	3.65	4.01	4.38	4.74	5.11	5.47	5.84	6.20	6.57
0.30	0.168	0.23	0.47	0.70	1.05	1.17	1.29	1.40	1.75	1.87	2.10	2.34	2.45	2.80	3.15	3.50	3.86	4.21	4.56	4.91	5.26	5.61	5.96	6.31
0.31	0.175	0.22	0.45	0.67	1.01	1.12	1.24	1.35	1.69	1.80	2.02	2.25	2.36	2.70	3.03	3.37	3.71	4.04	4.38	4.72	5.06	5.39	5.73	6.07
0.32	0.181	0.22	0.43	0.65	0.97	1.08	1.19	1.30	1.62	1.73	1.95	2.16	2.27	2.60	2.92	3.24	3.57	3.89	4.22	4.54	4.87	5.19	5.52	5.84
0.33	0.188	0.21	0.42	0.63	0.94	1.04	1.15	1.25	1.56	1.67	1.88	2.08	2.19	2.50	2.81	3.13	3.44	3.75	4.06	4.38	4.69	5.00	5.31	5.63
0.34	0.195	0.20	0.40	0.60	0.90	1.00	1.11	1.21	1.51	1.61	1.81	2.01	2.11	2.41	2.71	3.01	3.32	3.62	3.92	4.22	4.52	4.82	5.13	5.43
0.35	0.202	0.19	0.39	0.58	0.87	0.97	1.07	1.16	1.45	1.55	1.75	1.94	2.04	2.33	2.62	2.91	3.20	3.49	3.78	4.07	4.36	4.66	4.95	5.24
0.36	0.209	0.19	0.37	0.56	0.84	0.94	1.03	1.12	1.41	1.50	1.69	1.87	1.97	2.25	2.53	2.81	3.09	3.37	3.65	3.93	4.22	4.50	4.78	5.06
0.37	0.217	0.18	0.36	0.54	0.81	0.91	1.00	1.09	1.36	1.45	1.63	1.81	1.90	2.17	2.44	2.72	2.99	3.26	3.53	3.80	4.07	4.35	4.62	4.89
0.38	0.224	0.18	0.35	0.53	0.79	0.88	0.96	1.05	1.31	1.40	1.58	1.75	1.84	2.10	2.36	2.63	2.89	3.15	3.42	3.68	3.94	4.20	4.47	4.73
0.39	0.231	0.17	0.34	0.51	0.76	0.85	0.93	1.02	1.27	1.36	1.53	1.70	1.78	2.03	2.29	2.54	2.80	3.05	3.31	3.56	3.82	4.07	4.32	4.58
0.40	0.239	0.16	0.33	0.49	0.74	0.82	0.90	0.99	1.23	1.31	1.48	1.64	1.72	1.97	2.22	2.46	2.71	2.96	3.20	3.45	3.69	3.94	4.19	4.43
0.41	0.246	0.16	0.32	0.48	0.72	0.80	0.88	0.95	1.19	1.27	1.43	1.59	1.67	1.91	2.15	2.39	2.63	2.86	3.10	3.34	3.58	3.82	4.06	4.30
0.42	0.254	0.15	0.31	0.46	0.69	0.77	0.85	0.93	1.16	1.23	1.39	1.54	1.62	1.85	2.08	2.31	2.55	2.78	3.01	3.24	3.47	3.70	3.93	4.17
0.43	0.262	0.15	0.30	0.45	0.67	0.75	0.82	0.90	1.12	1.20	1.35	1.50	1.57	1.80	2.02	2.25	2.47	2.69	2.92	3.14	3.37	3.59	3.82	4.04
0.44	0.270	0.15	0.29	0.44	0.65	0.73	0.80	0.87	1.09	1.16	1.31	1.45	1.53	1.74	1.96	2.18	2.40	2.61	2.83	3.05	3.27	3.49	3.70	3.92
0.45	0.278	0.14	0.28	0.42	0.63	0.71	0.78	0.85	1.06	1.13	1.27	1.41	1.48	1.69	1.90	2.12	2.33	2.54	2.75	2.96	3.17	3.39	3.60	3.81
0.46	0.286	0.14	0.27	0.41	0.62	0.69	0.75	0.82	1.03	1.10	1.23	1.37	1.44	1.64	1.85	2.06	2.26	2.47	2.67	2.88	3.08	3.29	3.49	3.70
0.47	0.294	0.13	0.27	0.40	0.60	0.67	0.73	0.80	1.00	1.07	1.20	1.33	1.40	1.60	1.80	2.00	2.20	2.40	2.60	2.80	3.00	3.20	3.40	3.60
0.48	0.303	0.13	0.26	0.39	0.58	0.65	0.71	0.78	0.97	1.04	1.17	1.29	1.36	1.55	1.75	1.94	2.14	2.33	2.53	2.72	2.91	3.11	3.30	3.50
0.49	0.311	0.13	0.25	0.38	0.57	0.63	0.69	0.76	0.94	1.01	1.13	1.26	1.32	1.51	1.70	1.89	2.08	2.27	2.46	2.64	2.83	3.02	3.21	3.40
0.50	0.320	0.12	0.25	0.37	0.55	0.61	0.67	0.74	0.92	0.98	1.10	1.23	1.29	1.47	1.65	1.84	2.02	2.21	2.39	2.57	2.76	2.94	3.13	3.31
0.51	0.329	0.12	0.24	0.36	0.54	0.60	0.66	0.72	0.89	0.95	1.07	1.19	1.25	1.43	1.61	1.79	1.97	2.15	2.33	2.50	2.68	2.86	3.04	3.22
0.52	0.338	0.12	0.23	0.35	0.52	0.58	0.64	0.70	0.87	0.93	1.05	1.16	1.22	1.39	1.57	1.74	1.92	2.09	2.26	2.44	2.61	2.79	2.96	3.14
0.53	0.347	0.11	0.23	0.34	0.51	0.57	0.62	0.68	0.85	0.90	1.02	1.13	1.19	1.36	1.53	1.70	1.87	2.04	2.21	2.38	2.55	2.71	2.88	3.05
0.54	0.356	0.11	0.22	0.33	0.50	0.55	0.61	0.66	0.83	0.88	0.99	1.10	1.16	1.32	1.49	1.65	1.82	1.98	2.15	2.31	2.48	2.64	2.81	2.98
0.55	0.365	0.11	0.21	0.32	0.48	0.54	0.59	0.64	0.81	0.86	0.97	1.07	1.13	1.29	1.45	1.61	1.77	1.93	2.09	2.26	2.42	2.58	2.74	2.90
0.56	0.375	0.10	0.21	0.31	0.47	0.52	0.58	0.63	0.79	0.84	0.94	1.05	1.10	1.26	1.41	1.57	1.73	1.88	2.04	2.20	2.36	2.51	2.67	2.83
0.57	0.384	0.10	0.20	0.31	0.46	0.51	0.56	0.61	0.77	0.82	0.92	1.02	1.07	1.22	1.38	1.53	1.68	1.84	1.99	2.14	2.30	2.45	2.60	2.76
0.58	0.394	0.10	0.20	0.30	0.45	0.50	0.55	0.60	0.75	0.80	0.90	1.00	1.05	1.19	1.34	1.49	1.64	1.79	1.94	2.09	2.24	2.39	2.54	2.69
0.59	0.404	0.10	0.19	0.29	0.44	0.49	0.53	0.58	0.73	0.78	0.87	0.97	1.02	1.17	1.31	1.46	1.60	1.75	1.89	2.04	2.19	2.33	2.48	2.62
0.60	0.414	0.09	0.19	0.28	0.43	0.47	0.52	0.57	0.71	0.76	0.85	0.95	1.00	1.14	1.28	1.42	1.56	1.71	1.85	1.99	2.13	2.27	2.42	2.56
0.61	0.424	0.09	0.18	0.28	0.42	0.46	0.51	0.55	0.69	0.74	0.83	0.92	0.97	1.11	1.25	1.39	1.53	1.66	1.80	1.94	2.08	2.22	2.36	2.50
0.62	0.434	0.09	0.18	0.27	0.41	0.45	0.50	0.54	0.68	0.72	0.81	0.90	0.95	1.08	1.22	1.35	1.49	1.63	1.76	1.90	2.03	2.17	2.30	2.44
0.63	0.445	0.09	0.18	0.26	0.40	0.44	0.48	0.53	0.66	0.71	0.79	0.88	0.93	1.06	1.19	1.32	1.45	1.59	1.72	1.85	1.98	2.12	2.25	2.38
0.64	0.456	0.09	0.17	0.26	0.39	0.43	0.47	0.52	0.65	0.69	0.77	0.86	0.90	1.03	1.16	1.29	1.42	1.55	1.68	1.81	1.94	2.07	2.20	2.32
0.65	0.466	0.08	0.17	0.25	0.38	0.42	0.46	0.50	0.63	0.67	0.76	0.84	0.88	1.01	1.14	1.26	1.39	1.51	1.64	1.77	1.89	2.02	2.14	2.27
0.66	0.477	0.08	0.16	0.25	0.37	0.41	0.45	0.49	0.62	0.66	0.74	0.82	0.86	0.99	1.11	1.23	1.36	1.48	1.60	1.73	1.85	1.97	2.09	2.22
0.67	0.489	0.08	0.16	0.24	0.36	0.40	0.44	0.48	0.60	0.64	0.72	0.80	0.84	0.96	1.08	1.20	1.32	1.44	1.57	1.69	1.81	1.93	2.05	2.17
0.68	0.500	0.08	0.16	0.24	0.35	0.39	0.43	0.47	0.59	0.63	0.71	0.78	0.82	0.94	1.06	1.18	1.29	1.41	1.53	1.65	1.76	1.88	2.00	2.12
0.69	0.512	0.08	0.15	0.23	0.34	0.38	0.42	0.46	0.57	0.61	0.69	0.77	0.80	0.92	1.03	1.15	1.26	1.38	1.49	1.61	1.72	1.84	1.95	2.07
0.70	0.523	0.07	0.15	0.22	0.34	0.37	0.41	0.45	0.56															

Table 4.13 Thickness of Carbon Laminates

Density fibre	1.79																							
Density resin mix	1.20																							
Mf= Mass fraction of Fibre		Example. The thickness of a 800 g/m2 , 69% wf (60% Vf) laminate is 1.05 mm																						
Vf= Volume fraction of Fibre																								
Fibre Mass g/m2		100	200	300	450	500	550	600	750	800	900	1000	1050	1200	1350	1500	1650	1800	1950	2100	2250	2400	2550	2700
Mf	Vf	LAMINATE THICKNESS (mm)																						
0.25	0.183	0.31	0.61	0.92	1.38	1.53	1.68	1.84	2.29	2.45	2.75	3.06	3.21	3.67	4.13	4.59	5.05	5.51	5.96	6.42	6.88	7.34	7.80	8.26
0.26	0.191	0.29	0.59	0.88	1.32	1.47	1.61	1.76	2.20	2.34	2.64	2.93	3.08	3.52	3.96	4.40	4.84	5.27	5.71	6.15	6.59	7.03	7.47	7.91
0.27	0.199	0.28	0.56	0.84	1.27	1.41	1.55	1.69	2.11	2.25	2.53	2.81	2.95	3.37	3.80	4.22	4.64	5.06	5.48	5.90	6.33	6.75	7.17	7.59
0.28	0.207	0.27	0.54	0.81	1.22	1.35	1.49	1.62	2.03	2.16	2.43	2.70	2.84	3.24	3.65	4.05	4.46	4.86	5.27	5.67	6.08	6.48	6.89	7.29
0.29	0.215	0.26	0.52	0.78	1.17	1.30	1.43	1.56	1.95	2.08	2.34	2.60	2.73	3.12	3.51	3.90	4.29	4.68	5.07	5.46	5.85	6.24	6.63	7.02
0.30	0.223	0.25	0.50	0.75	1.13	1.25	1.38	1.50	1.88	2.00	2.25	2.50	2.63	3.00	3.38	3.75	4.13	4.51	4.88	5.26	5.63	6.01	6.38	6.76
0.31	0.231	0.24	0.48	0.72	1.09	1.21	1.33	1.45	1.81	1.93	2.17	2.41	2.53	2.90	3.26	3.62	3.98	4.34	4.71	5.07	5.43	5.79	6.15	6.52
0.32	0.240	0.23	0.47	0.70	1.05	1.16	1.28	1.40	1.75	1.86	2.10	2.33	2.45	2.80	3.14	3.49	3.84	4.19	4.54	4.89	5.24	5.59	5.94	6.29
0.33	0.248	0.23	0.45	0.68	1.01	1.13	1.24	1.35	1.69	1.80	2.03	2.25	2.36	2.70	3.04	3.38	3.71	4.05	4.39	4.73	5.06	5.40	5.74	6.08
0.34	0.257	0.22	0.44	0.65	0.98	1.09	1.20	1.31	1.63	1.74	1.96	2.18	2.29	2.61	2.94	3.26	3.59	3.92	4.24	4.57	4.90	5.22	5.55	5.88
0.35	0.265	0.21	0.42	0.63	0.95	1.05	1.16	1.26	1.58	1.69	1.90	2.11	2.21	2.53	2.84	3.16	3.48	3.79	4.11	4.42	4.74	5.06	5.37	5.69
0.36	0.274	0.20	0.41	0.61	0.92	1.02	1.12	1.22	1.53	1.63	1.84	2.04	2.14	2.45	2.75	3.06	3.37	3.67	3.98	4.28	4.59	4.90	5.20	5.51
0.37	0.282	0.20	0.40	0.59	0.89	0.99	1.09	1.19	1.48	1.58	1.78	1.98	2.08	2.37	2.67	2.97	3.26	3.56	3.86	4.15	4.45	4.75	5.04	5.34
0.38	0.291	0.19	0.38	0.58	0.86	0.96	1.06	1.15	1.44	1.53	1.73	1.92	2.01	2.30	2.59	2.88	3.17	3.45	3.74	4.03	4.32	4.60	4.89	5.18
0.39	0.300	0.19	0.37	0.56	0.84	0.93	1.02	1.12	1.40	1.49	1.68	1.86	1.96	2.23	2.51	2.79	3.07	3.35	3.63	3.91	4.19	4.47	4.75	5.03
0.40	0.309	0.18	0.36	0.54	0.81	0.90	0.99	1.09	1.36	1.45	1.63	1.81	1.90	2.17	2.44	2.71	2.98	3.26	3.53	3.80	4.07	4.34	4.61	4.88
0.41	0.318	0.18	0.35	0.53	0.79	0.88	0.97	1.05	1.32	1.41	1.58	1.76	1.85	2.11	2.37	2.64	2.90	3.16	3.43	3.69	3.96	4.22	4.48	4.75
0.42	0.327	0.17	0.34	0.51	0.77	0.85	0.94	1.03	1.28	1.37	1.54	1.71	1.79	2.05	2.31	2.56	2.82	3.08	3.33	3.59	3.85	4.10	4.36	4.62
0.43	0.336	0.17	0.33	0.50	0.75	0.83	0.91	1.00	1.25	1.33	1.50	1.66	1.75	2.00	2.25	2.49	2.74	2.99	3.24	3.49	3.74	3.99	4.24	4.49
0.44	0.345	0.16	0.32	0.49	0.73	0.81	0.89	0.97	1.21	1.30	1.46	1.62	1.70	1.94	2.19	2.43	2.67	2.91	3.16	3.40	3.64	3.89	4.13	4.37
0.45	0.354	0.16	0.32	0.47	0.71	0.79	0.87	0.95	1.18	1.26	1.42	1.58	1.66	1.89	2.13	2.37	2.60	2.84	3.08	3.31	3.55	3.79	4.02	4.26
0.46	0.363	0.15	0.31	0.46	0.69	0.77	0.85	0.92	1.15	1.23	1.38	1.54	1.61	1.84	2.07	2.31	2.54	2.77	3.00	3.23	3.46	3.69	3.92	4.15
0.47	0.373	0.15	0.30	0.45	0.67	0.75	0.82	0.90	1.12	1.20	1.35	1.50	1.57	1.80	2.02	2.25	2.47	2.70	2.92	3.15	3.37	3.60	3.82	4.05
0.48	0.382	0.15	0.29	0.44	0.66	0.73	0.80	0.88	1.10	1.17	1.32	1.46	1.53	1.75	1.97	2.19	2.41	2.63	2.85	3.07	3.29	3.51	3.73	3.95
0.49	0.392	0.14	0.29	0.43	0.64	0.71	0.78	0.86	1.07	1.14	1.28	1.43	1.50	1.71	1.93	2.14	2.35	2.57	2.78	2.99	3.21	3.42	3.64	3.85
0.50	0.401	0.14	0.28	0.42	0.63	0.70	0.77	0.84	1.04	1.11	1.25	1.39	1.46	1.67	1.88	2.09	2.30	2.51	2.71	2.92	3.13	3.34	3.55	3.76
0.51	0.411	0.14	0.27	0.41	0.61	0.68	0.75	0.82	1.02	1.09	1.22	1.36	1.43	1.63	1.84	2.04	2.24	2.45	2.65	2.85	3.06	3.26	3.47	3.67
0.52	0.421	0.13	0.27	0.40	0.60	0.66	0.73	0.80	1.00	1.06	1.20	1.33	1.39	1.59	1.79	1.99	2.19	2.39	2.59	2.79	2.99	3.19	3.39	3.59
0.53	0.431	0.13	0.26	0.39	0.58	0.65	0.71	0.78	0.97	1.04	1.17	1.30	1.36	1.56	1.75	1.95	2.14	2.34	2.53	2.73	2.92	3.11	3.31	3.50
0.54	0.440	0.13	0.25	0.38	0.57	0.63	0.70	0.76	0.95	1.01	1.14	1.27	1.33	1.52	1.71	1.90	2.09	2.28	2.47	2.66	2.85	3.04	3.23	3.43
0.55	0.450	0.12	0.25	0.37	0.56	0.62	0.68	0.74	0.93	0.99	1.12	1.24	1.30	1.49	1.67	1.86	2.05	2.23	2.42	2.61	2.79	2.98	3.16	3.35
0.56	0.460	0.12	0.24	0.36	0.55	0.61	0.67	0.73	0.91	0.97	1.09	1.21	1.27	1.46	1.64	1.82	2.00	2.18	2.37	2.55	2.73	2.91	3.09	3.28
0.57	0.471	0.12	0.24	0.36	0.53	0.59	0.65	0.71	0.89	0.95	1.07	1.19	1.25	1.42	1.60	1.78	1.96	2.14	2.32	2.49	2.67	2.85	3.03	3.21
0.58	0.481	0.12	0.23	0.35	0.52	0.58	0.64	0.70	0.87	0.93	1.05	1.16	1.22	1.39	1.57	1.74	1.92	2.09	2.27	2.44	2.61	2.79	2.96	3.14
0.59	0.491	0.11	0.23	0.34	0.51	0.57	0.63	0.68	0.85	0.91	1.02	1.14	1.19	1.37	1.54	1.71	1.88	2.05	2.22	2.39	2.56	2.73	2.90	3.07
0.60	0.501	0.11	0.22	0.33	0.50	0.56	0.61	0.67	0.84	0.89	1.00	1.11	1.17	1.34	1.50	1.67	1.84	2.01	2.17	2.34	2.51	2.67	2.84	3.01
0.61	0.512	0.11	0.22	0.33	0.49	0.55	0.60	0.65	0.82	0.87	0.98	1.09	1.15	1.31	1.47	1.64	1.80	1.96	2.13	2.29	2.46	2.62	2.78	2.95
0.62	0.522	0.11	0.21	0.32	0.48	0.53	0.59	0.64	0.80	0.86	0.96	1.07	1.12	1.28	1.44	1.60	1.76	1.92	2.09	2.25	2.41	2.57	2.73	2.89
0.63	0.533	0.10	0.21	0.31	0.47	0.52	0.58	0.63	0.79	0.84	0.94	1.05	1.10	1.26	1.41	1.57	1.73	1.89	2.04	2.20	2.36	2.52	2.67	2.83
0.64	0.544	0.10	0.21	0.31	0.46	0.51	0.57	0.62	0.77	0.82	0.92	1.03	1.08	1.23	1.39	1.54	1.70	1.85	2.00	2.16	2.31	2.47	2.62	2.77
0.65	0.555	0.10	0.20	0.30	0.45	0.50	0.55	0.60	0.76	0.81	0.91	1.01	1.06	1.21	1.36	1.51	1.66	1.81	1.96	2.12	2.27	2.42	2.57	2.72
0.66	0.565	0.10	0.20	0.30	0.44	0.49	0.54	0.59	0.74	0.79	0.89	0.99	1.04	1.19	1.33	1.48	1.63	1.78	1.93	2.07	2.22	2.37	2.52	2.67
0.67	0.576	0.10	0.19	0.29	0.44	0.48	0.53	0.58	0.73	0.78	0.87	0.97	1.02	1.16	1.31	1.45	1.60	1.74	1.89	2.04	2.18	2.33	2.47	2.62
0.68	0.588	0.10	0.19	0.29	0.43	0.48	0.52	0.57	0.71	0.76	0.86	0.95	1.00	1.14	1.28	1.43	1.57	1.71	1.85	2.00	2.14	2.28	2.42	2.57
0.69	0.599	0.09	0.19	0.28	0.42	0.47	0.51																	

Table 4.14 Thickness of Kevlar Laminates

Density fibre		1.44																						
Density resin mix		1.20																						
Mf = Mass fraction of Fibre		Example. The thickness of a 800 g/m2, 70% wf (66% vf) laminate is 0.84 mm																						
Vf = Volume fraction of Fibre																								
Fibre	Mass g/m2	100	200	300	450	500	550	600	750	800	900	1000	1050	1200	1350	1500	1650	1800	1950	2100	2250	2400	2550	2700
Mf	Vf	LAMINATE THICKNESS (mm)																						
0.25	0.217	0.32	0.64	0.96	1.44	1.60	1.76	1.92	2.40	2.56	2.88	3.19	3.35	3.83	4.31	4.79	5.27	5.75	6.23	6.71	7.19	7.67	8.15	8.63
0.26	0.226	0.31	0.61	0.92	1.38	1.53	1.69	1.84	2.30	2.45	2.76	3.07	3.22	3.68	4.14	4.60	5.06	5.52	5.98	6.44	6.90	7.36	7.82	8.28
0.27	0.236	0.29	0.59	0.88	1.33	1.47	1.62	1.77	2.21	2.36	2.65	2.95	3.09	3.54	3.98	4.42	4.86	5.31	5.75	6.19	6.63	7.07	7.52	7.96
0.28	0.245	0.28	0.57	0.85	1.28	1.42	1.56	1.70	2.13	2.27	2.55	2.84	2.98	3.40	3.83	4.26	4.68	5.11	5.53	5.96	6.38	6.81	7.24	7.66
0.29	0.254	0.27	0.55	0.82	1.23	1.37	1.50	1.64	2.05	2.19	2.46	2.73	2.87	3.28	3.69	4.10	4.51	4.92	5.33	5.74	6.15	6.56	6.97	7.38
0.30	0.263	0.26	0.53	0.79	1.19	1.32	1.45	1.58	1.98	2.11	2.38	2.64	2.77	3.17	3.56	3.96	4.35	4.75	5.15	5.54	5.94	6.33	6.73	7.13
0.31	0.272	0.25	0.51	0.76	1.15	1.27	1.40	1.53	1.91	2.04	2.29	2.55	2.68	3.06	3.44	3.82	4.21	4.59	4.97	5.35	5.74	6.12	6.50	6.88
0.32	0.282	0.25	0.49	0.74	1.11	1.23	1.36	1.48	1.85	1.97	2.22	2.47	2.59	2.96	3.33	3.70	4.07	4.44	4.81	5.18	5.55	5.92	6.29	6.66
0.33	0.291	0.24	0.48	0.72	1.07	1.19	1.31	1.43	1.79	1.91	2.15	2.39	2.51	2.86	3.22	3.58	3.94	4.30	4.65	5.01	5.37	5.73	6.09	6.44
0.34	0.300	0.23	0.46	0.69	1.04	1.16	1.27	1.39	1.73	1.85	2.08	2.31	2.43	2.77	3.12	3.47	3.81	4.16	4.51	4.86	5.20	5.55	5.90	6.24
0.35	0.310	0.22	0.45	0.67	1.01	1.12	1.23	1.35	1.68	1.79	2.02	2.24	2.35	2.69	3.03	3.36	3.70	4.04	4.37	4.71	5.04	5.38	5.72	6.05
0.36	0.319	0.22	0.44	0.65	0.98	1.09	1.20	1.31	1.63	1.74	1.96	2.18	2.28	2.61	2.94	3.26	3.59	3.92	4.24	4.57	4.90	5.22	5.55	5.88
0.37	0.329	0.21	0.42	0.63	0.95	1.06	1.16	1.27	1.59	1.69	1.90	2.11	2.22	2.54	2.85	3.17	3.49	3.80	4.12	4.44	4.76	5.07	5.39	5.71
0.38	0.338	0.21	0.41	0.62	0.92	1.03	1.13	1.23	1.54	1.64	1.85	2.05	2.16	2.46	2.77	3.08	3.39	3.70	4.01	4.31	4.62	4.93	5.24	5.55
0.39	0.348	0.20	0.40	0.60	0.90	1.00	1.10	1.20	1.50	1.60	1.80	2.00	2.10	2.40	2.70	3.00	3.30	3.60	3.90	4.20	4.50	4.79	5.09	5.39
0.40	0.357	0.19	0.39	0.58	0.88	0.97	1.07	1.17	1.46	1.56	1.75	1.94	2.04	2.33	2.63	2.92	3.21	3.50	3.79	4.08	4.38	4.67	4.96	5.25
0.41	0.367	0.19	0.38	0.57	0.85	0.95	1.04	1.14	1.42	1.51	1.70	1.89	1.99	2.27	2.56	2.84	3.12	3.41	3.69	3.98	4.26	4.54	4.83	5.11
0.42	0.376	0.18	0.37	0.55	0.83	0.92	1.01	1.11	1.38	1.48	1.66	1.85	1.94	2.21	2.49	2.77	3.04	3.32	3.60	3.88	4.15	4.43	4.71	4.98
0.43	0.386	0.18	0.36	0.54	0.81	0.90	0.99	1.08	1.35	1.44	1.62	1.80	1.89	2.16	2.43	2.70	2.97	3.24	3.51	3.78	4.05	4.32	4.59	4.86
0.44	0.396	0.18	0.35	0.53	0.79	0.88	0.97	1.05	1.32	1.40	1.58	1.76	1.84	2.11	2.37	2.63	2.90	3.16	3.42	3.69	3.95	4.21	4.48	4.74
0.45	0.405	0.17	0.34	0.51	0.77	0.86	0.94	1.03	1.28	1.37	1.54	1.71	1.80	2.06	2.31	2.57	2.83	3.08	3.34	3.60	3.85	4.11	4.37	4.63
0.46	0.415	0.17	0.33	0.50	0.75	0.84	0.92	1.00	1.25	1.34	1.51	1.67	1.76	2.01	2.26	2.51	2.76	3.01	3.26	3.51	3.76	4.01	4.27	4.52
0.47	0.425	0.16	0.33	0.49	0.74	0.82	0.90	0.98	1.23	1.31	1.47	1.63	1.72	1.96	2.21	2.45	2.70	2.94	3.19	3.43	3.68	3.92	4.17	4.41
0.48	0.435	0.16	0.32	0.48	0.72	0.80	0.88	0.96	1.20	1.28	1.44	1.60	1.68	1.92	2.16	2.40	2.64	2.88	3.11	3.35	3.59	3.83	4.07	4.31
0.49	0.445	0.16	0.31	0.47	0.70	0.78	0.86	0.94	1.17	1.25	1.41	1.56	1.64	1.87	2.11	2.34	2.58	2.81	3.05	3.28	3.51	3.75	3.98	4.22
0.50	0.455	0.15	0.31	0.46	0.69	0.76	0.84	0.92	1.15	1.22	1.38	1.53	1.60	1.83	2.06	2.29	2.52	2.75	2.98	3.21	3.44	3.67	3.90	4.13
0.51	0.464	0.15	0.30	0.45	0.67	0.75	0.82	0.90	1.12	1.20	1.35	1.50	1.57	1.79	2.02	2.24	2.47	2.69	2.92	3.14	3.36	3.59	3.81	4.04
0.52	0.474	0.15	0.29	0.44	0.66	0.73	0.81	0.88	1.10	1.17	1.32	1.46	1.54	1.76	1.98	2.20	2.42	2.63	2.85	3.07	3.29	3.51	3.73	3.95
0.53	0.484	0.14	0.29	0.43	0.65	0.72	0.79	0.86	1.08	1.15	1.29	1.43	1.51	1.72	1.94	2.15	2.37	2.58	2.80	3.01	3.23	3.44	3.66	3.87
0.54	0.495	0.14	0.28	0.42	0.63	0.70	0.77	0.84	1.05	1.12	1.26	1.40	1.47	1.69	1.90	2.11	2.32	2.53	2.74	2.95	3.16	3.37	3.58	3.79
0.55	0.505	0.14	0.28	0.41	0.62	0.69	0.76	0.83	1.03	1.10	1.24	1.38	1.45	1.65	1.86	2.06	2.27	2.48	2.68	2.89	3.10	3.30	3.51	3.72
0.56	0.515	0.13	0.27	0.40	0.61	0.67	0.74	0.81	1.01	1.08	1.21	1.35	1.42	1.62	1.82	2.02	2.23	2.43	2.63	2.83	3.04	3.24	3.44	3.64
0.57	0.525	0.13	0.26	0.40	0.60	0.66	0.73	0.79	0.99	1.06	1.19	1.32	1.39	1.59	1.79	1.98	2.18	2.38	2.58	2.78	2.98	3.18	3.37	3.57
0.58	0.535	0.13	0.26	0.39	0.58	0.65	0.71	0.78	0.97	1.04	1.17	1.30	1.36	1.56	1.75	1.95	2.14	2.34	2.53	2.73	2.92	3.11	3.31	3.50
0.59	0.545	0.13	0.25	0.38	0.57	0.64	0.70	0.76	0.96	1.02	1.15	1.27	1.34	1.53	1.72	1.91	2.10	2.29	2.48	2.67	2.87	3.06	3.25	3.44
0.60	0.556	0.13	0.25	0.38	0.56	0.63	0.69	0.75	0.94	1.00	1.13	1.25	1.31	1.50	1.69	1.88	2.06	2.25	2.44	2.63	2.81	3.00	3.19	3.38
0.61	0.566	0.12	0.25	0.37	0.55	0.61	0.67	0.74	0.92	0.98	1.10	1.23	1.29	1.47	1.66	1.84	2.02	2.21	2.39	2.58	2.76	2.95	3.13	3.31
0.62	0.576	0.12	0.24	0.36	0.54	0.60	0.66	0.72	0.90	0.96	1.08	1.21	1.27	1.45	1.63	1.81	1.99	2.17	2.35	2.53	2.71	2.89	3.07	3.25
0.63	0.587	0.12	0.24	0.36	0.53	0.59	0.65	0.71	0.89	0.95	1.07	1.18	1.24	1.42	1.60	1.78	1.95	2.13	2.31	2.49	2.66	2.84	3.02	3.20
0.64	0.597	0.12	0.23	0.35	0.52	0.58	0.64	0.70	0.87	0.93	1.05	1.16	1.22	1.40	1.57	1.74	1.92	2.09	2.27	2.44	2.62	2.79	2.97	3.14
0.65	0.607	0.11	0.23	0.34	0.51	0.57	0.63	0.69	0.86	0.91	1.03	1.14	1.20	1.37	1.54	1.71	1.89	2.06	2.23	2.40	2.57	2.74	2.92	3.09
0.66	0.618	0.11	0.22	0.34	0.51	0.56	0.62	0.67	0.84	0.90	1.01	1.12	1.18	1.35	1.52	1.69	1.85	2.02	2.19	2.36	2.53	2.70	2.87	3.03
0.67	0.629	0.11	0.22	0.33	0.50	0.55	0.61	0.66	0.83	0.88	0.99	1.10	1.16	1.33	1.49	1.66	1.82	1.99	2.15	2.32	2.49	2.65	2.82	2.98
0.68	0.639	0.11	0.22	0.33	0.49	0.54	0.60	0.65	0.81	0.87	0.98	1.09	1.14	1.30	1.47	1.63	1.79	1.96	2.12	2.28	2.44	2.61	2.77	2.93
0.69	0.650	0.11	0.21	0.32	0.48	0.53	0.59	0.64	0.80	0.86	0.96	1.07	1.12	1.28	1.44	1.60	1.76	1.92	2.08	2.24	2.40	2.57	2.73	2.89
0.70	0.660	0.11	0.21	0.32	0.47	0.53	0.58	0.63	0.79	0.84	0.95	1.05	1.10											

Fig 4.12 Imperial Thickness of E glass Laminates

Density resin mix 0.043 Lb/in³

Mf = Mass fraction of Fibre

Density fibre 0.092 Lb/in³

Vf = Volume fraction of Fibre

Example. The thickness of a 1.5 oz/ft², 30% wf laminate is 42.4 mil = 0.0424 inches

Fibre Mass oz/ft ²		0.25	0.5	1.0	1.5	2	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
Mf	Vf	LAMINATE THICKNESS (mil) 1 mil = 0.001 inches																	
0.25	0.135	8.7	17.5	35.0	52.5	70.0	87.5	105	122	140	157	175	192	210	227	245	262	280	297
0.26	0.141	8.4	16.7	33.4	50.2	66.9	83.6	100	117	134	151	167	184	201	217	234	251	268	284
0.27	0.147	8.0	16.0	32.0	48.0	64.0	80.0	96.0	112	128	144	160	176	192	208	224	240	256	272
0.28	0.154	7.7	15.3	30.7	46.0	61.3	76.7	92.0	107	123	138	153	169	184	199	215	230	245	261
0.29	0.160	7.4	14.7	29.4	44.1	58.9	73.6	88.3	103	118	132	147	162	177	191	206	221	235	250
0.30	0.167	7.1	14.1	28.3	42.4	56.5	70.7	84.8	98.9	113	127	141	155	170	184	198	212	226	240
0.31	0.174	6.8	13.6	27.2	40.8	54.4	68.0	81.6	95.1	109	122	136	150	163	177	190	204	217	231
0.32	0.180	6.5	13.1	26.2	39.3	52.3	65.4	78.5	91.6	105	118	131	144	157	170	183	196	209	222
0.33	0.187	6.3	12.6	25.2	37.8	50.4	63.0	75.6	88.2	101	113	126	139	151	164	176	189	202	214
0.34	0.194	6.1	12.2	24.3	36.5	48.6	60.8	72.9	85.1	97.2	109	122	134	146	158	170	182	194	207
0.35	0.201	5.9	11.7	23.5	35.2	46.9	58.7	70.4	82.1	93.9	106	117	129	141	153	164	176	188	199
0.36	0.208	5.7	11.3	22.7	34.0	45.3	56.7	68.0	79.3	90.6	102	113	125	136	147	159	170	181	193
0.37	0.215	5.5	11.0	21.9	32.9	43.8	54.8	65.7	76.7	87.6	98.6	110	120	131	142	153	164	175	186
0.38	0.223	5.3	10.6	21.2	31.8	42.4	53.0	63.6	74.2	84.7	95.3	106	117	127	138	148	159	169	180
0.39	0.230	5.1	10.3	20.5	30.8	41.0	51.3	61.5	71.8	82.0	92.3	103	113	123	133	144	154	164	174
0.40	0.238	5.0	9.9	19.9	29.8	39.7	49.6	59.6	69.5	79.4	89.4	99.3	109	119	129	139	149	159	169
0.41	0.245	4.8	9.6	19.2	28.9	38.5	48.1	57.7	67.3	77.0	86.6	96.2	106	115	125	135	144	154	164
0.42	0.253	4.7	9.3	18.7	28.0	37.3	46.6	56.0	65.3	74.6	84.0	93.3	103	112	121	131	140	149	159
0.43	0.261	4.5	9.0	18.1	27.1	36.2	45.2	54.3	63.3	72.4	81.4	90.5	100	109	118	127	136	145	154
0.44	0.269	4.4	8.8	17.6	26.3	35.1	43.9	52.7	61.5	70.3	79.0	87.8	96.6	105	114	123	132	141	149
0.45	0.277	4.3	8.5	17.1	25.6	34.1	42.6	51.2	59.7	68.2	76.7	85.3	93.8	102	111	119	128	136	145
0.46	0.285	4.1	8.3	16.6	24.9	33.1	41.4	49.7	58.0	66.3	74.6	82.8	91.1	99.4	108	116	124	133	141
0.47	0.293	4.0	8.0	16.1	24.1	32.2	40.2	48.3	56.3	64.4	72.4	80.5	88.5	96.6	105	113	121	129	137
0.48	0.301	3.9	7.8	15.7	23.5	31.3	39.1	47.0	54.8	62.6	70.4	78.3	86.1	93.9	102	110	117	125	133
0.49	0.310	3.8	7.6	15.2	22.8	30.4	38.1	45.7	53.3	60.9	68.5	76.1	83.7	91.3	99	107	114	122	129
0.50	0.319	3.7	7.4	14.8	22.2	29.6	37.0	44.4	51.8	59.2	66.7	74.1	81.5	88.9	96.3	104	111	118	126
0.51	0.327	3.6	7.2	14.4	21.6	28.8	36.0	43.2	50.5	57.7	64.9	72.1	79.3	86.5	93.7	101	108	115	123
0.52	0.336	3.5	7.0	14.0	21.1	28.1	35.1	42.1	49.1	56.1	63.2	70.2	77.2	84.2	91.2	98.2	105	112	119
0.53	0.345	3.4	6.8	13.7	20.5	27.3	34.2	41.0	47.8	54.7	61.5	68.3	75.2	82.0	88.8	95.7	103	109	116
0.54	0.354	3.3	6.7	13.3	20.0	26.6	33.3	39.9	46.6	53.3	59.9	66.6	73.2	79.9	86.6	93.2	100	107	113
0.55	0.364	3.2	6.5	13.0	19.5	26.0	32.4	38.9	45.4	51.9	58.4	64.9	71.4	77.9	84.3	90.8	97.3	103.8	110.3
0.56	0.373	3.2	6.3	12.6	19.0	25.3	31.6	37.9	44.3	50.6	56.9	63.2	69.6	75.9	82.2	88.5	94.9	101.2	107.5
0.57	0.383	3.1	6.2	12.3	18.5	24.7	30.8	37.0	43.2	49.3	55.5	61.7	67.8	74.0	80.2	86.3	92.5	98.7	104.8
0.58	0.392	3.0	6.0	12.0	18.0	24.1	30.1	36.1	42.1	48.1	54.1	60.1	66.1	72.2	78.2	84.2	90.2	96.2	102.2
0.59	0.402	2.9	5.9	11.7	17.6	23.5	29.3	35.2	41.1	46.9	52.8	58.7	64.5	70.4	76.3	82.1	88.0	93.9	99.7
0.60	0.412	2.9	5.7	11.4	17.2	22.9	28.6	34.3	40.1	45.8	51.5	57.2	63.0	68.7	74.4	80.1	85.9	91.6	97.3
0.61	0.422	2.8	5.6	11.2	16.8	22.3	27.9	33.5	39.1	44.7	50.3	55.9	61.4	67.0	72.6	78.2	83.8	89.4	95.0
0.62	0.433	2.7	5.5	10.9	16.4	21.8	27.3	32.7	38.2	43.6	49.1	54.5	60.0	65.4	70.9	76.3	81.8	87.2	92.7
0.63	0.443	2.7	5.3	10.6	16.0	21.3	26.6	31.9	37.3	42.6	47.9	53.2	58.6	63.9	69.2	74.5	79.8	85.2	90.5
0.64	0.454	2.6	5.2	10.4	15.6	20.8	26.0	31.2	36.4	41.6	46.8	52.0	57.2	62.4	67.6	72.8	78.0	83.2	88.4
0.65	0.465	2.5	5.1	10.2	15.2	20.3	25.4	30.5	35.5	40.6	45.7	50.8	55.8	60.9	66.0	71.1	76.1	81.2	86.3
0.66	0.476	2.5	5.0	9.9	14.9	19.8	24.8	29.8	34.7	39.7	44.6	49.6	54.5	59.5	64.5	69.4	74.4	79.3	84.3
0.67	0.487	2.4	4.8	9.7	14.5	19.4	24.2	29.1	33.9	38.8	43.6	48.4	53.3	58.1	63.0	67.8	72.7	77.5	82.4
0.68	0.498	2.4	4.7	9.5	14.2	18.9	23.7	28.4	33.1	37.9	42.6	47.3	52.1	56.8	61.5	66.3	71.0	75.7	80.5
0.69	0.510	2.3	4.6	9.3	13.9	18.5	23.1	27.8	32.4	37.0	41.6	46.3	50.9	55.5	60.1	64.8	69.4	74.0	78.6
0.70	0.522	2.3	4.5	9.0	13.6	18.1	22.6	27.1	31.7	36.2	40.7	45.2	49.7	54.3	58.8	63.3	67.8	72.3	76.9
0.71	0.534	2.2	4.4	8.8	13.3	17.7	22.1	26.5	30.9	35.4	39.8	44.2	48.6	53.0	57.5	61.9	66.3	70.7	75.1
0.72	0.546	2.2	4.3	8.6	13.0	17.3	21.6	25.9	30.3	34.6	38.9	43.2	47.5	51.9	56.2	60.5	64.8	69.1	73.5
0.73	0.558	2.1	4.2	8.5	12.7	16.9	21.1	25.4	29.6	33.8	38.0	42.3	46.5	50.7	54.9	59.2	63.4	67.6	71.8
0.74	0.571	2.1	4.1	8.3	12.4	16.5	20.7	24.8	28.9	33.1	37.2	41.3	45.5	49.6	53.7	57.8	62.0	66.1	70.2
0.75	0.584	2.0	4.0	8.1	12.1	16.2	20.2	24.2	28.3	32.3	36.4	40.4	44.5	48.5	52.5	56.6	60.6	64.7	68.7
0.76	0.597	2.0	4.0	7.9	11.9	15.8	19.8	23.7	27.7	31.6	35.6	39.5	43.5	47.4	51.4	55.3	59.3	63.2	67.2
0.77	0.610	1.9	3.9	7.7	11.6	15.5	19.3	23.2	27.1	30.9	34.8	38.7	42.5	46.4	50.3	54.1	58.0	61.9	65.7
0.78	0.624	1.9	3.8	7.6	11.3	15.1	18.9	22.7	26.5	30.3	34.0	37.8	41.6	45.4	49.2	53.0	56.7	60.5	64.3
0.79	0.637	1.9	3.7	7.4	11.1	14.8	18.5	22.2	25.9	29.6	33.3	37.0	40.7	44.4	48.1	51.8	55.5	59.2	62.9
0.80	0.652	1.8	3.6	7.2	10.9	14.5	18.1	21.7	25.3	29.0	32.6	36.2	39.8	43.4	47.1	50.7	54.3	57.9	61.5

Fig 4.13 Imperial Thickness of Carbon Fibre Laminates

Density fibre 0.065 Lb/in³

Density resin mix 0.043 Lb/in³

Mf = Mass fraction of Fibre

Vf = Volume fraction of Fibre

Example. The thickness of a 2 oz/ft², 40% wf laminate is 43.6 mil = 0.0436 inches

Fibre Mass oz/ft ²		0.25	0.5	1.0	1.5	2	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
Mf	Vf	LAMINATE THICKNESS (mil) 1 mil = 0.001 inches																	
0.25	0.181	9.2	18.5	37.0	55.4	73.9	92.4	111	129	148	166	185	203	222	240	259	277	296	314
0.26	0.189	8.9	17.7	35.4	53.1	70.8	88.5	106	124	142	159	177	195	212	230	248	266	283	301
0.27	0.197	8.5	17.0	34.0	51.0	67.9	84.9	101.9	119	136	153	170	187	204	221	238	255	272	289
0.28	0.205	8.2	16.3	32.6	48.9	65.3	81.6	97.9	114	131	147	163	179	196	212	228	245	261	277
0.29	0.213	7.8	15.7	31.4	47.1	62.8	78.5	94.2	110	126	141	157	173	188	204	220	235	251	267
0.30	0.221	7.6	15.1	30.2	45.3	60.5	75.6	90.7	105.8	121	136	151	166	181	196	212	227	242	257
0.31	0.229	7.3	14.6	29.1	43.7	58.3	72.9	87.4	102.0	117	131	146	160	175	189	204	219	233	248
0.32	0.237	7.0	14.1	28.1	42.2	56.3	70.3	84.4	98.4	113	127	141	155	169	183	197	211	225	239
0.33	0.246	6.8	13.6	27.2	40.8	54.3	67.9	81.5	95.1	109	122	136	149	163	177	190	204	217	231
0.34	0.254	6.6	13.1	26.3	39.4	52.5	65.7	78.8	91.9	105.1	118	131	144	158	171	184	197	210	223
0.35	0.263	6.4	12.7	25.4	38.1	50.8	63.6	76.3	89.0	101.7	114	127	140	153	165	178	191	203	216
0.36	0.271	6.2	12.3	24.6	36.9	49.2	61.6	73.9	86.2	98.5	111	123	135	148	160	172	185	197	209
0.37	0.280	6.0	11.9	23.9	35.8	47.7	59.7	71.6	83.5	95.5	107.4	119	131	143	155	167	179	191	203
0.38	0.288	5.8	11.6	23.1	34.7	46.3	57.9	69.4	81.0	92.6	104.2	116	127	139	150	162	174	185	197
0.39	0.297	5.6	11.2	22.5	33.7	44.9	56.2	67.4	78.6	89.9	101.1	112	124	135	146	157	168	180	191
0.40	0.306	5.5	10.9	21.8	32.7	43.6	54.5	65.5	76.4	87.3	98.2	109.1	120	131	142	153	164	175	185
0.41	0.315	5.3	10.6	21.2	31.8	42.4	53.0	63.6	74.2	84.8	95.4	106.0	117	127	138	148	159	170	180
0.42	0.324	5.2	10.3	20.6	30.9	41.2	51.5	61.8	72.2	82.5	92.8	103.1	113	124	134	144	155	165	175
0.43	0.333	5.0	10.0	20.1	30.1	40.1	50.1	60.2	70.2	80.2	90.3	100.3	110	120	130	140	150	160	170
0.44	0.342	4.9	9.8	19.5	29.3	39.0	48.8	58.6	68.3	78.1	87.9	97.6	107.4	117	127	137	146	156	166
0.45	0.351	4.8	9.5	19.0	28.5	38.0	47.5	57.0	66.5	76.1	85.6	95.1	104.6	114	124	133	143	152	162
0.46	0.360	4.6	9.3	18.5	27.8	37.1	46.3	55.6	64.8	74.1	83.4	92.6	101.9	111.2	120	130	139	148	157
0.47	0.370	4.5	9.0	18.1	27.1	36.1	45.1	54.2	63.2	72.2	81.3	90.3	99.3	108.4	117	126	135	144	154
0.48	0.379	4.4	8.8	17.6	26.4	35.2	44.0	52.8	61.6	70.4	79.3	88.1	96.9	105.7	114	123	132	141	150
0.49	0.389	4.3	8.6	17.2	25.8	34.4	43.0	51.5	60.1	68.7	77.3	85.9	94.5	103.1	112	120	129	137	146
0.50	0.398	4.2	8.4	16.8	25.2	33.5	41.9	50.3	58.7	67.1	75.5	83.9	92.2	100.6	109.0	117	126	134	143
0.51	0.408	4.1	8.2	16.4	24.6	32.8	40.9	49.1	57.3	65.5	73.7	81.9	90.1	98.3	106.4	115	123	131	139
0.52	0.417	4.0	8.0	16.0	24.0	32.0	40.0	48.0	56.0	64.0	72.0	80.0	88.0	96.0	104.0	112.0	120	128	136
0.53	0.427	3.9	7.8	15.6	23.4	31.3	39.1	46.9	54.7	62.5	70.3	78.1	86.0	93.8	101.6	109.4	117	125	133
0.54	0.437	3.8	7.6	15.3	22.9	30.6	38.2	45.8	53.5	61.1	68.7	76.4	84.0	91.7	99.3	106.9	115	122	130
0.55	0.447	3.7	7.5	14.9	22.4	29.9	37.3	44.8	52.3	59.7	67.2	74.7	82.1	89.6	97.1	104.6	112.0	119.5	127.0
0.56	0.457	3.7	7.3	14.6	21.9	29.2	36.5	43.8	51.1	58.4	65.7	73.0	80.3	87.6	95.0	102.3	109.6	116.9	124.2
0.57	0.467	3.6	7.1	14.3	21.4	28.6	35.7	42.9	50.0	57.2	64.3	71.5	78.6	85.8	92.9	100.0	107.2	114.3	121.5
0.58	0.477	3.5	7.0	14.0	21.0	28.0	35.0	42.0	49.0	55.9	62.9	69.9	76.9	83.9	90.9	97.9	104.9	111.9	118.9
0.59	0.488	3.4	6.8	13.7	20.5	27.4	34.2	41.1	47.9	54.8	61.6	68.5	75.3	82.1	89.0	95.8	102.7	109.5	116.4
0.60	0.498	3.4	6.7	13.4	20.1	26.8	33.5	40.2	46.9	53.6	60.3	67.0	73.7	80.4	87.1	93.8	100.5	107.3	114.0
0.61	0.509	3.3	6.6	13.1	19.7	26.3	32.8	39.4	46.0	52.5	59.1	65.7	72.2	78.8	85.3	91.9	98.5	105.0	111.6
0.62	0.519	3.2	6.4	12.9	19.3	25.7	32.2	38.6	45.0	51.5	57.9	64.3	70.8	77.2	83.6	90.0	96.5	102.9	109.3
0.63	0.530	3.2	6.3	12.6	18.9	25.2	31.5	37.8	44.1	50.4	56.7	63.0	69.3	75.6	81.9	88.2	94.5	100.8	107.1
0.64	0.540	3.1	6.2	12.4	18.5	24.7	30.9	37.1	43.2	49.4	55.6	61.8	68.0	74.1	80.3	86.5	92.7	98.8	105.0
0.65	0.551	3.0	6.1	12.1	18.2	24.2	30.3	36.3	42.4	48.4	54.5	60.6	66.6	72.7	78.7	84.8	90.8	96.9	103.0
0.66	0.562	3.0	5.9	11.9	17.8	23.8	29.7	35.6	41.6	47.5	53.4	59.4	65.3	71.3	77.2	83.1	89.1	95.0	101.0
0.67	0.573	2.9	5.8	11.6	17.5	23.3	29.1	34.9	40.8	46.6	52.4	58.2	64.1	69.9	75.7	81.5	87.4	93.2	99.0
0.68	0.584	2.9	5.7	11.4	17.1	22.9	28.6	34.3	40.0	45.7	51.4	57.1	62.9	68.6	74.3	80.0	85.7	91.4	97.1
0.69	0.596	2.8	5.6	11.2	16.8	22.4	28.0	33.6	39.2	44.8	50.5	56.1	61.7	67.3	72.9	78.5	84.1	89.7	95.3
0.70	0.607	2.8	5.5	11.0	16.5	22.0	27.5	33.0	38.5	44.0	49.5	55.0	60.5	66.0	71.5	77.0	82.5	88.0	93.5
0.71	0.618	2.7	5.4	10.8	16.2	21.6	27.0	32.4	37.8	43.2	48.6	54.0	59.4	64.8	70.2	75.6	81.0	86.4	91.8
0.72	0.630	2.7	5.3	10.6	15.9	21.2	26.5	31.8	37.1	42.4	47.7	53.0	58.3	63.6	68.9	74.2	79.5	84.8	90.1
0.73	0.641	2.6	5.2	10.4	15.6	20.8	26.0	31.2	36.4	41.6	46.8	52.1	57.3	62.5	67.7	72.9	78.1	83.3	88.5
0.74	0.653	2.6	5.1	10.2	15.3	20.4	25.6	30.7	35.8	40.9	46.0	51.1	56.2	61.3	66.5	71.6	76.7	81.8	86.9
0.75	0.665	2.5	5.0	10.0	15.1	20.1	25.1	30.1	35.1	40.2	45.2	50.2	55.2	60.3	65.3	70.3	75.3	80.3	85.4
0.76	0.677	2.5	4.9	9.9	14.8	19.7	24.7	29.6	34.5	39.5	44.4	49.3	54.3	59.2	64.1	69.1	74.0	78.9	83.9
0.77	0.689	2.4	4.8	9.7	14.5	19.4	24.2	29.1	33.9	38.8	43.6	48.5	53.3	58.2	63.0	67.8	72.7	77.5	82.4
0.78	0.701	2.4	4.8	9.5	14.3	19.0	23.8	28.6	33.3	38.1	42.9	47.6	52.4	57.1	61.9	66.7	71.4	76.2	81.0
0.79	0.713	2.3	4.7	9.4	14.0	18.7	23.4	28.1	32.8	37.4	42.1	46.8	51.5	56.2	60.8	65.5	70.2	74.9	79.6
0.80	0.726	2.3	4.6	9.2	13.8	18.4	23.0	27.6	32.2	36.8	41.4	46.0	50.6	55.2	59.8	64.4	69.0	73.6	78.2

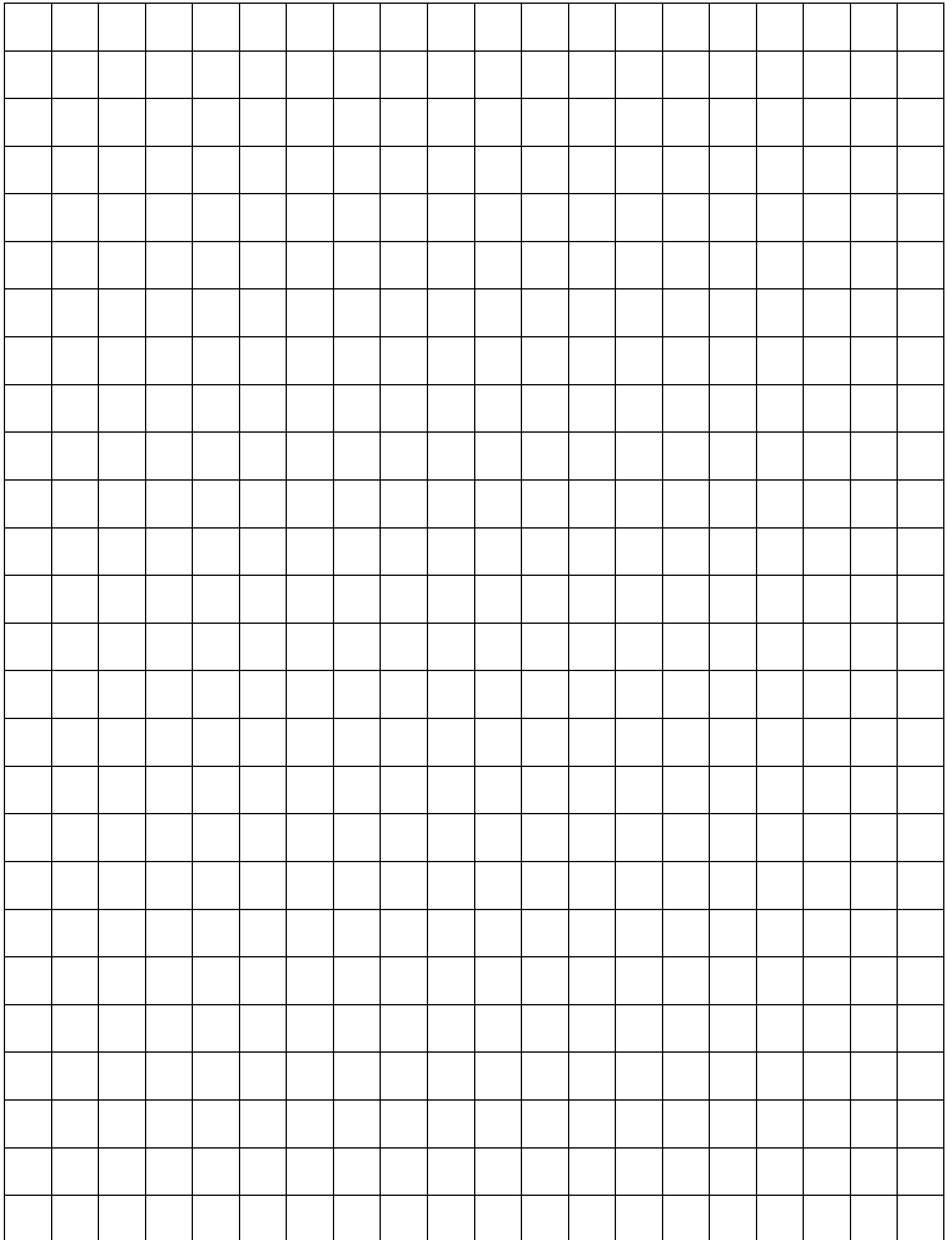
Fig 4.14 Imperial Thickness of Aramid Fibre LaminatesDensity resin mix 0.043 Lb/in³

Mf = Mass fraction of Fibre

Density fibre 0.052 Lb/in³Example. The thickness of a 1.5 oz/ft², 30% wf laminate is 42.4 mil = 0.0424 inches

Vf = Volume fraction of Fibre

Fibre Mass oz/ft ²		0.25	0.5	1.0	1.5	2	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
Mf	Vf	LAMINATE THICKNESS (mil) 1 mil = 0.001 inches																	
0.25	0.216	9.7	19.3	38.6	57.9	77.3	96.6	116	135	155	174	193	212	232	251	270	290	309	328
0.26	0.225	9.3	18.5	37.1	55.6	74.1	92.7	111	130	148	167	185	204	222	241	260	278	297	315
0.27	0.234	8.9	17.8	35.6	53.5	71.3	89.1	106.9	125	143	160	178	196	214	232	249	267	285	303
0.28	0.243	8.6	17.2	34.3	51.5	68.6	85.8	102.9	120	137	154	172	189	206	223	240	257	274	292
0.29	0.252	8.3	16.5	33.1	49.6	66.1	82.6	99.2	116	132	149	165	182	198	215	231	248	264	281
0.30	0.262	8.0	15.9	31.9	47.8	63.8	79.7	95.7	111.6	128	144	159	175	191	207	223	239	255	271
0.31	0.271	7.7	15.4	30.8	46.2	61.6	77.0	92.4	107.8	123	139	154	169	185	200	216	231	247	262
0.32	0.280	7.4	14.9	29.8	44.7	59.6	74.5	89.4	104.3	119	134	149	164	179	194	209	223	238	253
0.33	0.289	7.2	14.4	28.8	43.3	57.7	72.1	86.5	100.9	115	130	144	159	173	187	202	216	231	245
0.34	0.299	7.0	14.0	27.9	41.9	55.9	69.9	83.8	97.8	111.8	126	140	154	168	182	196	210	224	237
0.35	0.308	6.8	13.5	27.1	40.6	54.2	67.7	81.3	94.8	108.4	122	135	149	163	176	190	203	217	230
0.36	0.317	6.6	13.1	26.3	39.4	52.6	65.7	78.9	92.0	105.2	118	131	145	158	171	184	197	210	223
0.37	0.327	6.4	12.8	25.5	38.3	51.1	63.8	76.6	89.4	102.1	114.9	128	140	153	166	179	191	204	217
0.38	0.336	6.2	12.4	24.8	37.2	49.6	62.0	74.4	86.9	99.3	111.7	124	136	149	161	174	186	199	211
0.39	0.346	6.0	12.1	24.1	36.2	48.3	60.3	72.4	84.5	96.5	108.6	121	133	145	157	169	181	193	205
0.40	0.355	5.9	11.7	23.5	35.2	47.0	58.7	70.5	82.2	93.9	105.7	117.4	129	141	153	164	176	188	200
0.41	0.365	5.7	11.4	22.9	34.3	45.7	57.2	68.6	80.1	91.5	102.9	114.4	126	137	149	160	172	183	194
0.42	0.375	5.6	11.1	22.3	33.4	44.6	55.7	66.9	78.0	89.1	100.3	111.4	123	134	145	156	167	178	189
0.43	0.384	5.4	10.9	21.7	32.6	43.5	54.3	65.2	76.0	86.9	97.8	108.6	119	130	141	152	163	174	185
0.44	0.394	5.3	10.6	21.2	31.8	42.4	53.0	63.6	74.2	84.8	95.4	106.0	116.6	127	138	148	159	170	180
0.45	0.404	5.2	10.3	20.7	31.0	41.4	51.7	62.1	72.4	82.7	93.1	103.4	113.8	124	134	145	155	165	176
0.46	0.413	5.0	10.1	20.2	30.3	40.4	50.5	60.6	70.7	80.8	90.9	101.0	111.1	121.2	131	141	151	162	172
0.47	0.423	4.9	9.9	19.7	29.6	39.5	49.3	59.2	69.1	78.9	88.8	98.6	108.5	118.4	128	138	148	158	168
0.48	0.433	4.8	9.6	19.3	28.9	38.6	48.2	57.8	67.5	77.1	86.8	96.4	106.0	115.7	125	135	145	154	164
0.49	0.443	4.7	9.4	18.9	28.3	37.7	47.1	56.6	66.0	75.4	84.8	94.3	103.7	113.1	123	132	141	151	160
0.50	0.453	4.6	9.2	18.4	27.7	36.9	46.1	55.3	64.5	73.8	83.0	92.2	101.4	110.6	119.9	129	138	148	157
0.51	0.463	4.5	9.0	18.0	27.1	36.1	45.1	54.1	63.2	72.2	81.2	90.2	99.2	108.3	117.3	126	135	144	153
0.52	0.473	4.4	8.8	17.7	26.5	35.3	44.2	53.0	61.8	70.7	79.5	88.3	97.2	106.0	114.8	123.6	132	141	150
0.53	0.483	4.3	8.6	17.3	25.9	34.6	43.2	51.9	60.5	69.2	77.8	86.5	95.1	103.8	112.4	121.1	130	138	147
0.54	0.493	4.2	8.5	16.9	25.4	33.9	42.4	50.8	59.3	67.8	76.3	84.7	93.2	101.7	110.1	118.6	127	136	144
0.55	0.503	4.2	8.3	16.6	24.9	33.2	41.5	49.8	58.1	66.4	74.7	83.0	91.3	99.6	107.9	116.2	124.5	132.8	141.1
0.56	0.513	4.1	8.1	16.3	24.4	32.6	40.7	48.8	57.0	65.1	73.2	81.4	89.5	97.7	105.8	113.9	122.1	130.2	138.4
0.57	0.523	4.0	8.0	16.0	23.9	31.9	39.9	47.9	55.9	63.8	71.8	79.8	87.8	95.8	103.7	111.7	119.7	127.7	135.7
0.58	0.533	3.9	7.8	15.7	23.5	31.3	39.1	47.0	54.8	62.6	70.5	78.3	86.1	93.9	101.8	109.6	117.4	125.2	133.1
0.59	0.543	3.8	7.7	15.4	23.0	30.7	38.4	46.1	53.8	61.4	69.1	76.8	84.5	92.2	99.8	107.5	115.2	122.9	130.6
0.60	0.554	3.8	7.5	15.1	22.6	30.2	37.7	45.2	52.8	60.3	67.8	75.4	82.9	90.5	98.0	105.5	113.1	120.6	128.1
0.61	0.564	3.7	7.4	14.8	22.2	29.6	37.0	44.4	51.8	59.2	66.6	74.0	81.4	88.8	96.2	103.6	111.0	118.4	125.8
0.62	0.574	3.6	7.3	14.5	21.8	29.1	36.3	43.6	50.9	58.1	65.4	72.7	79.9	87.2	94.5	101.7	109.0	116.3	123.5
0.63	0.585	3.6	7.1	14.3	21.4	28.5	35.7	42.8	50.0	57.1	64.2	71.4	78.5	85.6	92.8	99.9	107.1	114.2	121.3
0.64	0.595	3.5	7.0	14.0	21.0	28.0	35.1	42.1	49.1	56.1	63.1	70.1	77.1	84.1	91.2	98.2	105.2	112.2	119.2
0.65	0.606	3.4	6.9	13.8	20.7	27.6	34.5	41.3	48.2	55.1	62.0	68.9	75.8	82.7	89.6	96.5	103.4	110.3	117.1
0.66	0.616	3.4	6.8	13.5	20.3	27.1	33.9	40.6	47.4	54.2	61.0	67.7	74.5	81.3	88.1	94.8	101.6	108.4	115.1
0.67	0.627	3.3	6.7	13.3	20.0	26.6	33.3	40.0	46.6	53.3	59.9	66.6	73.3	79.9	86.6	93.2	99.9	106.5	113.2
0.68	0.637	3.3	6.5	13.1	19.6	26.2	32.7	39.3	45.8	52.4	58.9	65.5	72.0	78.6	85.1	91.7	98.2	104.8	111.3
0.69	0.648	3.2	6.4	12.9	19.3	25.8	32.2	38.6	45.1	51.5	58.0	64.4	70.8	77.3	83.7	90.2	96.6	103.1	109.5
0.70	0.659	3.2	6.3	12.7	19.0	25.3	31.7	38.0	44.4	50.7	57.0	63.4	69.7	76.0	82.4	88.7	95.0	101.4	107.7
0.71	0.669	3.1	6.2	12.5	18.7	24.9	31.2	37.4	43.6	49.9	56.1	62.3	68.6	74.8	81.1	87.3	93.5	99.8	106.0
0.72	0.680	3.1	6.1	12.3	18.4	24.5	30.7	36.8	43.0	49.1	55.2	61.4	67.5	73.6	79.8	85.9	92.0	98.2	104.3
0.73	0.691	3.0	6.0	12.1	18.1	24.2	30.2	36.2	42.3	48.3	54.4	60.4	66.4	72.5	78.5	84.6	90.6	96.6	102.7
0.74	0.702	3.0	5.9	11.9	17.8	23.8	29.7	35.7	41.6	47.6	53.5	59.5	65.4	71.4	77.3	83.3	89.2	95.1	101.1
0.75	0.713	2.9	5.9	11.7	17.6	23.4	29.3	35.1	41.0	46.8	52.7	58.6	64.4	70.3	76.1	82.0	87.8	93.7	99.5
0.76	0.724	2.9	5.8	11.5	17.3	23.1	28.8	34.6	40.4	46.1	51.9	57.7	63.4	69.2	75.0	80.7	86.5	92.3	98.0
0.77	0.735	2.8	5.7	11.4	17.0	22.7	28.4	34.1	39.8	45.4	51.1	56.8	62.5	68.2	73.9	79.5	85.2	90.9	96.6
0.78	0.746	2.8	5.6	11.2	16.8	22.4	28.0	33.6	39.2	44.8	50.4	56.0	61.6	67.2	72.8	78.4	84.0	89.5	95.1
0.79	0.757	2.8	5.5	11.0	16.5	22.1	27.6	33.1	38.6	44.1	49.6	55.1	60.7	66.2	71.7	77.2	82.7	88.2	93.8
0.80	0.768	2.7	5.4	10.9	16.3	21.7	27.2	32.6	38.0	43.5	48.9	54.4	59.8	65.2	70.7	76.1	81.5	87.0	92.4

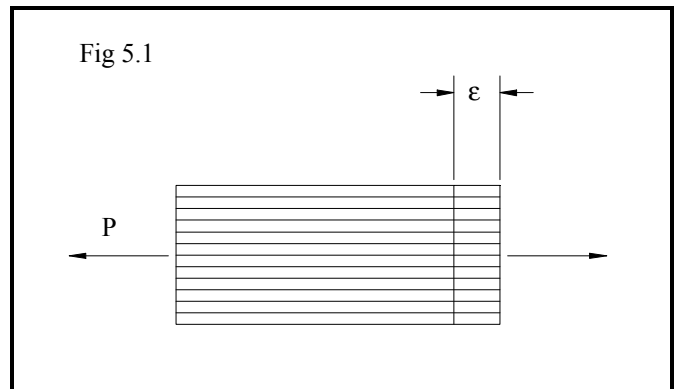


5 PROPERTY PREDICTION

Mechanics of Reinforcement

The stress / strain characteristics of composites are different to most metals and plastics. Short term testing gives a linear stress / strain curve and there is no yield. Design of composites is usually carried out on the basis of ultimate strength (with appropriate design factors), whereas with steel, for instance, design is usually based on the yield strength.

Consider a unidirectional composite, as shown in Fig 5.1 subjected to a load P .



If pure elastic deformation is assumed then:

Strain in the matrix = strain in the fibres.

$$\text{i.e. } \epsilon_m = \epsilon_f$$

Now $E = \sigma / \epsilon$

$$\text{therefore } \sigma_m / E_m = \sigma_f / E_f$$

$$\text{or } \sigma_f / \sigma_m = E_f / E_m$$

where

σ = stress

σ = stress at failure (strength)

E = elastic Modulus

Suffix m = matrix

Suffix f = fibre

In words, we could say that the stress in each material is determined by its modulus of elasticity. The higher modulus material will have a high stress put into it and the low modulus material will have only a low stress. Therefore, to reinforce a low strength material it must be matched with a material which has a higher modulus of elasticity. The high modulus will impart high stress into the stronger material and therefore reduce the stress in the weaker material. It is thus desirable to match as closely as possible the ratios:

$$\sigma_f / E_f \text{ and } \sigma_m / E_m$$

However, in practice this is often not too critical. For instance, if the fibres are considerably stronger than the matrix,
(Continued on page 5.2)

(Continued from page 5.1)

say 10 times stronger, then a mismatch in the properties, which under utilises the strength of the matrix is, in fact, only wasting a relatively small amount. Obviously, this problem is also less significant in composites which have a large volume of fibres.

When we say that these two ratios should be matched, we are in fact saying the two values of strain to failure (ϵ_f and ϵ_m) should be compatible. The strain to failure of the matrix should preferably be equal to, or exceed, the strain to failure of the fibres. Glass fibres have an elastic modulus 20 times greater than polyester resin they consequently carry 20 times the stress and are therefore able to utilise their high strength.

Tensile modulus of the composite

Consider again Fig.5.1 The load required to strain the composite =

$$P = \sigma_k A_k$$

where

A_k = cross sectional area of the composite

σ_k = stress in the composite. This load consists of the load carried by the fibres (P_f) and the load carried by Matrix (P_m).

$$\text{i.e. } P = P_f + P_m$$

$$\text{but } P_f = \sigma_f A_f \\ P_m = \sigma_m A_m$$

$$\text{therefore } P = \sigma_f A_f + \sigma_m A_m \\ = \sigma_k A_k$$

$$(\text{Now } \sigma = E \epsilon)$$

$$\text{therefore } E_f \epsilon A_f + E_m \epsilon A_m = E_k \epsilon A_k$$

$$\text{i.e. } E_k = E_f A_f / A_k + E_m A_m / A_k$$

$$\text{Now the ratio } A_f / A_k = \frac{\text{cross sectional area of fibres}}{\text{cross sectional area of composite}}$$

which is volume fraction of fibres (V_f)

$$\text{similarly } A_m / A_k = \frac{\text{cross sectional area of matrix}}{\text{cross sectional area of composite}}$$

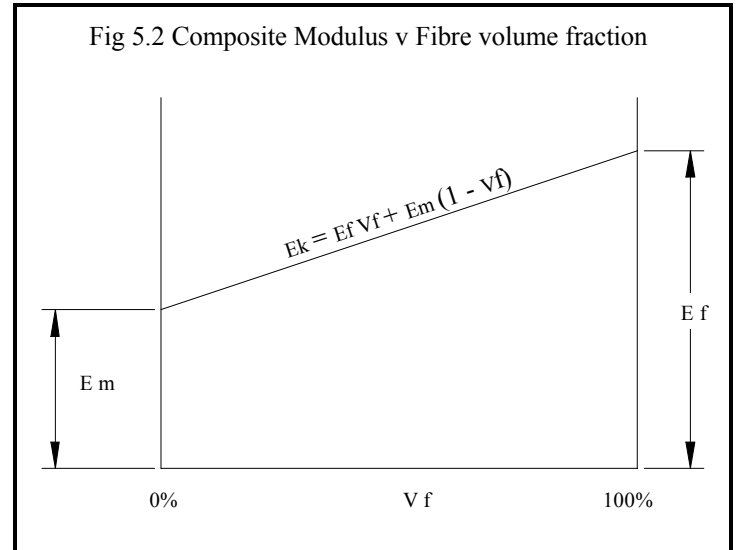
which is the volume fraction of matrix (V_m)

$$\text{therefore } E_k = E_f V_f + E_m V_m$$

$$\text{and of course } V_f = (1 - V_m)$$

$$\text{therefore } E_k = E_f V_f + E_m (1 - V_f) \quad \text{Equation 5.1}$$

This is an example of a rule of mixtures equation. In this case, although not perfect, it predicts, to a generally acceptable level of accuracy, the composite modulus. It is, of course, simply the equation of the graph shown in Fig.5.2.



Example

A composite consists of a matrix of epoxy resin of tensile modulus 3.5 GPa and glass fibres of tensile modulus 76 GPa laid in one direction.

Predict the composite's tensile modulus according to the law of mixtures if the volume fraction of fibres is 30%.

$$E_m = 3.5 \text{ GPa} \\ E_f = 76 \text{ GPa} \\ V_f = 0.3$$

Hence the modulus of the composite in the direction of the fibres is: -

$$E_k = 76 \times 0.3 + 3.5 \times (1 - 0.3) \\ \therefore E_k = 25.25 \text{ GPa}$$

Or in Imperial units

$$\text{Modulus of the resin } (E_m) = 0.5 \text{ Msi} \\ \text{Modulus of the fibres } (E_f) = 11 \text{ Msi} \\ \text{Fibre volume fraction } (V_f) = 0.3$$

Hence the modulus of the composite in the direction of the fibres is: -

$$E_k = 11 \times 0.3 + 0.5 \times (1 - 0.3) \\ \therefore E_k = 3.65 \text{ Msi}$$

Msi and psi are shorthand for imperial units.
Msi = psi $\times 10^6$.
psi = lb/in²

Composite strength

With suitable selection of fibre and matrix, a high percentage of the stress in a composite can be transferred to the fibres, even though they may represent only a low fraction of the total volume of material. To predict the actual strength of the composite is difficult. Assume that the composite is unidirectional and that there is perfect bond between fibres and matrix. The rule of mixtures is a possible model of the strength behaviour of the composite. In which case :-

$$\underline{\sigma}_k = \underline{\sigma}_f V_f + \underline{\sigma}_m V_m \quad \text{-- equation 5.2}$$

where

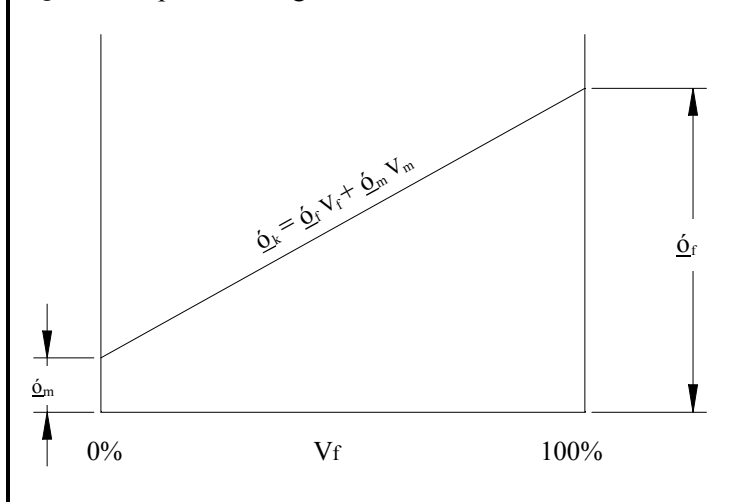
$\underline{\sigma}_k$ = strength of the composite

$\underline{\sigma}_f$ = strength of the fibres

$\underline{\sigma}_m$ = strength of the matrix

This may be represented graphically as in Fig. 5.3
However, this is shown to be a poor model if the stress/strain diagrams for the constituents are investigated.

Fig 5.3 Composite strength versus Fibre Volume Fraction



Consider Fig. 5.4 which shows the stress/strain curves for a fibre and a matrix, each of which obey Hooke's law up to failure.

ϵ_f = strain in fibres at failure

σ_m^1 = stress in *matrix* when the *fibres* fail

σ_f^1 = stress in the *fibres* when the *matrix* fails.

It can be seen from this that the composite fails although the matrix is not carrying its maximum stress i.e. the fibres have a lower strain to failure than the matrix, they fail at ϵ_f . At that level of strain the matrix has only achieved a stress level of σ_m^1 .

Fig 5.4 Fibre failure strain < Matrix failure strain

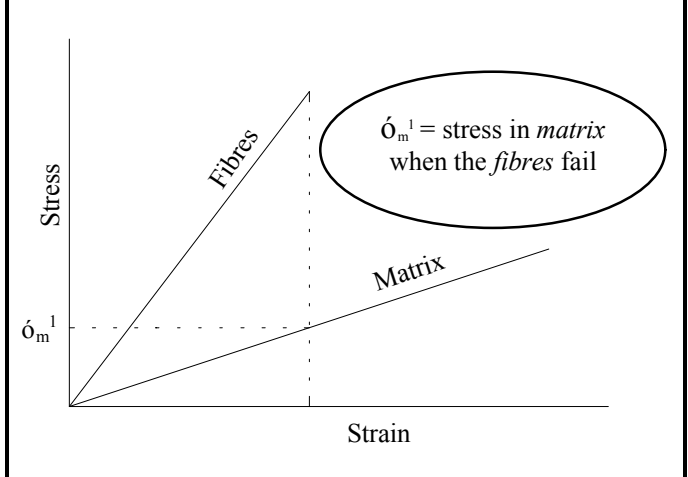


Fig. 5.5 shows another case, this time the matrix fails at a lower level of strain than the fibres. Therefore, we could modify the Law of Mixtures equation by replacing $\underline{\sigma}_f$ by $E_f \epsilon$, and $\underline{\sigma}_m$ by $E_m \epsilon$ so that the composite's strength is:

$$\underline{\sigma}_k = E_f \epsilon V_f + E_m \epsilon V_m$$

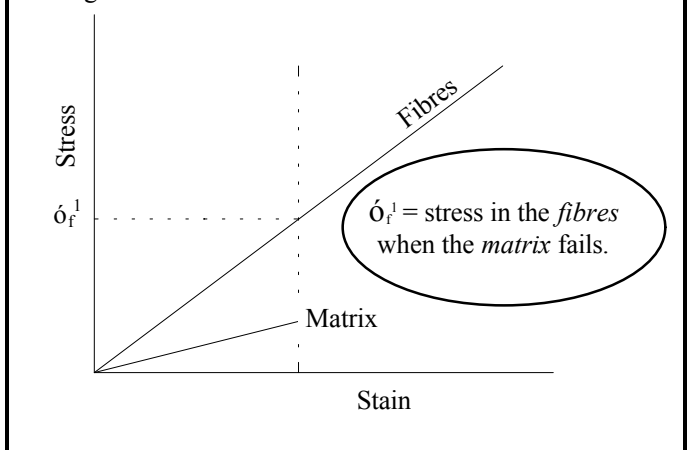
where ϵ = strain to failure of the matrix or the fibres, whichever is lower.

However, that is only for fibre / matrices which obeys Hooke's law up to failure (perfectly elastic). Very often the stress/strain response of the matrix is non-linear then the equation for composite strength is modified to:

$$\underline{\sigma}_k = \underline{\sigma}_f V_f + \sigma_m^1 V_m \quad \text{- if the fibres fail first}$$

$$\text{or} \quad \underline{\sigma}_k = \sigma_f^1 V_f + \underline{\sigma}_m V_m \quad \text{- if the matrix fails first.}$$

Fig 5.5 Matrix failure strain < Fibre failure strain



From this it can be seen that there are several ways of defining the strength of a composite. They are :-

- At failure of the matrix
- At failure of the fibres
- At maximum load carrying capacity

Under different circumstances each of these definitions and others may be valid.

(Continued on page 5.4)

(Continued from page 5.3)

From this it can be seen that there are several ways of defining the strength of a composite. They are:-

- At failure of the matrix
- At failure of the fibres
- At maximum load carrying capacity

Under different circumstances each of these definitions and others may be valid. For instance, consider a unidirectional composite which has a stress/strain diagram for its constituents as in Fig. 5.6 If the fibre content is very low then the strength of the composite is mainly attributable to that of the matrix.

When the strain level reaches the strain to failure of the matrix it fails and the load is transferred to the fibres which, because they are few in number, cannot support that load and immediately fail catastrophically,

$$\text{i.e. } \underline{\sigma}_k = \underline{\sigma}_f' V_f + \underline{\sigma}_m V_m$$

Again consider Fig 5.6. If now the fibre content is high then the failure of the matrix is hardly noticed. The small load (relative to the fibres) that it carries, is transferred to the fibres, but it is insignificant. The composite continues to carry load up to the failure strain of the fibres (theoretically) and the strength of the composite is:-

$$\underline{\sigma}_k = \underline{\sigma}_f V_f$$

This is a much simplified situation because the matrix would no longer have transferred stress from fibre to fibre and therefore failure would have been initiated earlier. Note: It would often be deemed that failure had occurred at the matrix strain to failure even though load carrying capacity was almost unaffected.

Now consider again a unidirectional composite which has a very low fibre content but stress / strain curves as shown in Fig 5.7. Failure occurs in the fibres at a level of strain well below the strain to failure of the matrix. However, because there is only a low volume fraction of fibres present in the composite the load carrying capacity is almost unaffected.

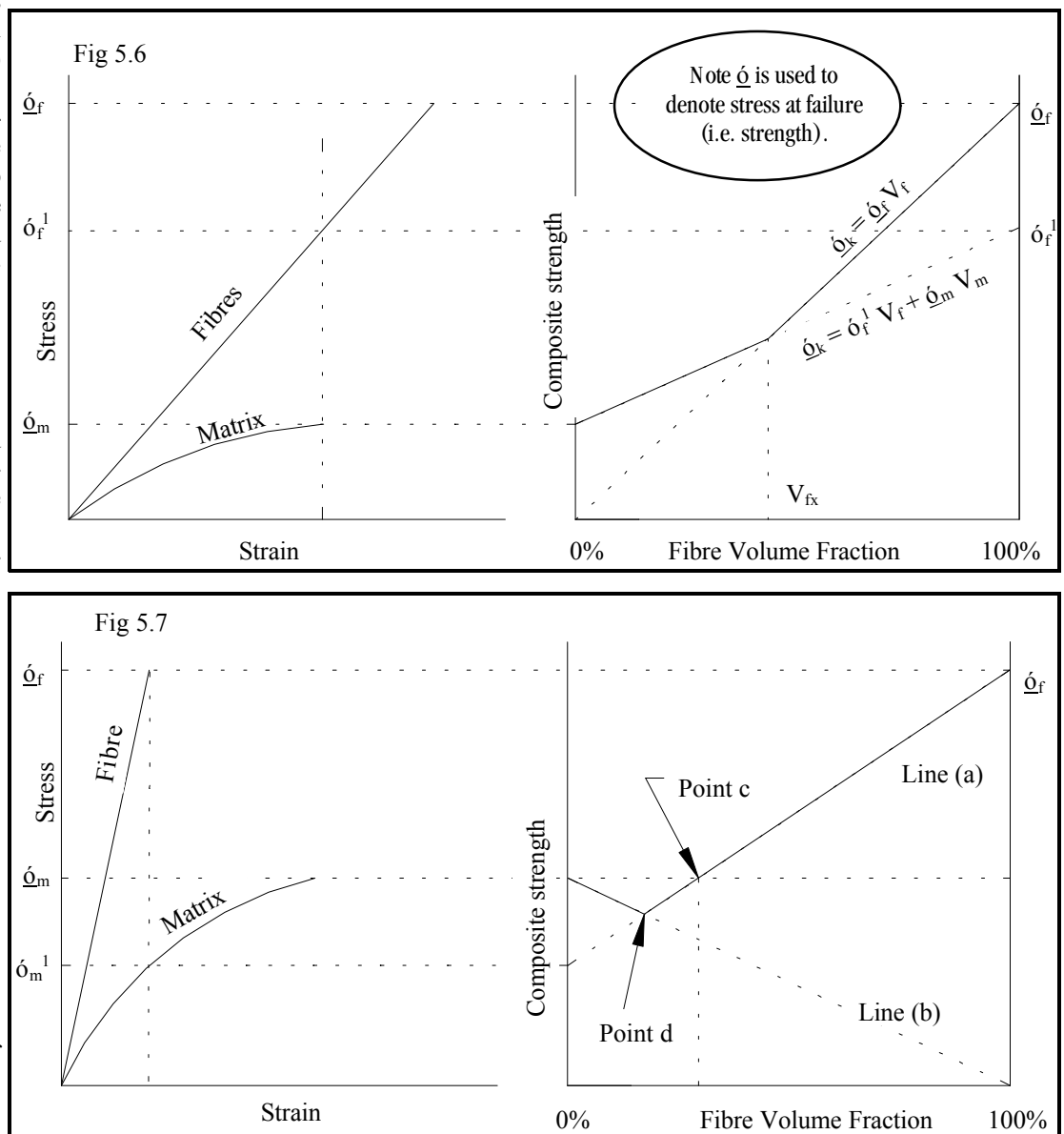
The composite continues to carry load up to failure strain of the matrix. In this case, because only a small quantity of fibres is present in the composite, its strength is in fact reduced. The fibres act, after failure, as holes in the matrix and

consequently give a lower strength. Therefore up to a certain level, the addition of fibres reduces the strength of the composite.

Consider again the stress/strain diagram in Fig 5.7 but this time assume that the fibre content is high. Again, the fibres will fail first but, because there is a large proportion of them and because of the high modulus, they are carrying the major portion of the load. At their failure, that load is immediately transferred to the matrix which is incapable of carrying it and immediate failure occurs. There is, therefore, a critical value for the fibre content, below which the composite has a lower strength than the matrix alone. Line (a) represents the equation in Fig 5.7.

$$\underline{\sigma}_k = \underline{\sigma}_f V_f + \underline{\sigma}_m' V_m$$

and is of course the simple law of mixtures equation with the modified term for matrix stress



i.e. $\underline{\sigma}_m' =$ stress in **matrix** at the failure of the **fibres**.

Line (b) represents the equation:-

$$\underline{\sigma}_k = \underline{\sigma}_m V_m$$

and is true for that range of fibre contents where the addition of fibres detracts from strength of the matrix alone.

(Continued on page 5.5)

(Continued from page 5.4)

Point C on the graph is known as $V_{f \text{ crit}}$. That is the critical volume fraction below which the strength of the composite is less than that of the matrix. Point D is $V_{f \text{ min}}$, the volume fraction for which the composite strength is a minimum. $V_{f \text{ min}}$ is found by equating the two equations for σ_c

$$\text{i.e. } \sigma_f V_f + \sigma_m V_m = \sigma_c V_m$$

Similarly $V_{f \text{ crit}}$ can be found by equating

$$\sigma_c = \sigma_f V_f + \sigma_m V_m$$

$$\text{therefore } V_{f \text{ min}} = \frac{\sigma_m - \sigma_m^1}{\sigma_f + \sigma_m - \sigma_m^1}$$

Prediction of elastic properties

The main difference between design using composite materials and design using other materials is that the designer does not just select the most suitable material from a fairly small range. He is able to design the material itself to have the particular properties which he wants. This facility greatly enhances the versatility of design available and when used to the full can enable the designer to produce highly competitive designs. The properties of composites may be predicted with reasonable accuracy by two methods. (a) extrapolation from empirical data (b) the use of mathematical models. Figs 6.16 and 6.17 have been drawn from empirical data. In B.S. 4994 a term is used which is the parallel of ultimate strength it is the ultimate tensile unit strength (U.T.U.S.) in which the strength of the material is measured not simply in terms of **load per cross sectional area** but in terms of **load per width per mass of reinforcement**. The units for which are: - N/mm per kg/m² of glass fibre.

Conservative values of U.T.U.S. for glass fibre / polyester are given in the table.

Ultimate Tensile Unit Strength		
Type of Glass fibre Reinforcement	N/mm width per kg/m ² of glass fibre	Lb/in width per oz/ft ² of glass fibre
Random (e.g. Chopped strand mat)	200	349
Bi-directional (e.g. Woven Roving)	250	436
Unidirectional	500	872

Similarly, elastic modulus may be quoted in the same units. This is known as the extensibility and the values generally used are shown in the table below.

Extensibility		
Type of Glass fibre Reinforcement	N/mm width per kg/m ² of glass fibre	Lb/in width per oz/ft ² of glass fibre
Random (e.g. Chopped strand mat)	14000	24400
Bi-directional (e.g. Woven Roving)	16000	27900
Unidirectional	28000	48800

Property Prediction using mathematical models

Reinforcement efficiency factors

The tensile modulus may be predicted for unidirectional composites using the Law of Mixtures as shown in the section on the mechanics of reinforcing action. This is a very simple and convenient mathematical model.

$$\text{i.e. } E_k = E_f V_f + E_m V_m$$

It may be modified to suit composites other than unidirectional:

$$E_k = \beta E_f V_f + E_m V_m \quad \text{Equn 5.3}$$

E_k = tensile modulus of the composite

E_f = tensile modulus of the fibres

E_m = tensile modulus of the matrix

V_f = volume fraction of fibres

V_m = volume fraction of matrix

β = efficiency factor of the reinforcement. See the table below (Ref. 2).

Reinforcement Arrangement	β = efficiency factor of the reinforcement
Unidirectional composites	$\beta = 1$
Bi-directional composites (woven roving)	$\beta = 5$
Random in-plane composites (CSM)	$\beta = 0.375$
Random in space composites (DMC)	$\beta = 0.2$

Example

To estimate the tensile modulus (E) of a glass fibre/polyester laminate which consists of 33% by weight chopped strand mat.

Say E for glass fibre = 69 GPa

and E for polyester resin = 3.5 GPa

Now $W_f = 0.33$ but V_f is required.

From equation 4.5

$$V_f = \frac{M_f / \delta_f}{M_f / \delta_f + M_m / \delta_m}$$

If $\delta_f = 2.56 \text{ Mg/m}^3$ and $\delta_m = 1.12 \text{ Mg/m}^3$ then from the above equation $V_f = 0.19$.

$$E_k = 0.375 \times 69 \times 0.19 + 3.5 \times 0.81$$

Or using imperial units

Say E for glass fibre = 10 Msi and E for resin = 0.5 Msi

Now $M_f = 0.33$ but V_f is required.

If $\delta_f = 0.092 \text{ Lb/in}^3$ and $\delta_m = 0.043 \text{ Lb/in}^3$

then again using equation 4.5 produces $V_f = 0.19$

$$E_k = 0.375 \times 10 \times 0.19 + 0.5 \times 0.81$$

$$= 1.12 \text{ Msi}$$

Tensile modulus Multi axial laminate

It has been shown that if the model of a random laminate (chopped strand mat / polyester for instance) is assumed to consist of many layers each unidirectional but with pseudo isotropic orientation, then the modulus in any direction is given by :-

$$E_k = 3/8 E_L + 5/8 E_T \quad \text{-- equation 5.5}$$

Where

E_L = Longitudinal modulus of the assumed unidirectional layer

E_T = Transverse modulus of the assumed unidirectional layer.

Example

Estimate the tensile modulus of the laminate: -chopped strand mat / polyester resin,

Assume $V_f = 19\%$

$E_f = 69 \text{ GPa}$ and

$E_m = 3.5 \text{ GPa}$

In the model each layer of unidirectional material is assumed to have the same glass content as the whole laminate therefore there are assumed to be a very large number of unidirectional layers each with $V_f = 0.19$. The modulus of each of these may be estimated from

$$E_L = E_f \cdot V_f + E_m \cdot V_m$$

$$= 69 \times 0.19 + 3.5 \times 0.81$$

$$\therefore E_L = 15.9 \text{ MN/m}^2$$

Now E_T approximates to E_m if the fibre volume fraction is less than about 20% (for glass fibre).

$$\therefore \text{assume } E_T = E_m = 3.5 \text{ GPa}$$

$$\text{then } E_k = 3/8 \times 15.9 + 5/8 \times 3.5$$

$$\therefore E_k = 8.15 \text{ MN/m}^2$$

This result may be compared with the rule of mixtures with an efficiency factor which predicts a value of 7.7 GPa and the empirical extensibility data in chapter 6 which gives a value of about 6 GPa. The latter is generally considered to be conservative.

Or using imperial units

Say $E_f = 10 \text{ Msi}$ and $E_m = 0.5 \text{ Msi}$

$$E_L = E_f \cdot V_f + E_m \cdot V_m$$

$$= 10 \times 0.19 + 0.5 \times 0.81 = 2.3 \text{ Msi}$$

$$\text{assume } E_T = E_m = 0.5 \text{ Msi}$$

$$\text{therefore } E_k = 3/8 \times 2.3 + 5/8 \times 0.5$$

$$\therefore E_k = 1.18 \text{ Msi}$$

This result may be compared with the rule of mixtures with an efficiency factor which predicts a value of 1.12 Msi and the empirical extensibility data in chapter 6 which gives a value of about 0.87 Msi. The latter is generally considered to be conservative.

Msi and psi are shorthand for imperial units.
Msi = psi $\times 10^6$
psi = lb/in²

Transverse modulus

The transverse modulus may be predicted from several models, two of which are shown below: Ref. (3)

$$E_T = \frac{E_f E_m}{E_m V_f + E_f V_m} \quad \text{-- equation 5.6}$$

or

$$E_t = 2[1 - \nu_f + (\nu_f - \nu_m)V_m] \times \left[\frac{k_f(2k_m + G_m) - G_m(k_f - k_m)V_m}{(2k_m + G_m) + 2(k_f - k_m)V_m} \right] \quad \text{-- equation 5.7}$$

where $k_f = E_f / \{2(1 - \nu_f)\}$

$k_m = E_m / \{2(1 - \nu_m)\}$

$G_f = E_f / \{2(1 + \nu_f)\}$

$G_m = E_m / 2 \{ (1 + \nu_m) \}$

and E_T = transverse modulus

E_f = modulus of the fibres

E_m = modulus of the matrix

ν_f = Poisson's ratio for the fibres

ν_m = Poisson's ratio for the matrix

V_f = volume fraction of fibres

V_m = volume fraction of matrix

Prediction of Poisson's ratio

A reasonable prediction of Poisson's ratio for unidirectional composites can be made from:

Longitudinal Poisson's ratio

$$\mu_{LT} = V_f \mu_f + V_m \mu_m \quad \text{-- equation 5.8}$$

and transverse Poissons ratio

$$\mu_{TL} = \mu_{LT} E_T / E_L \quad \text{-- equation 5.9}$$

where V_f = volume fraction of fibres

V_m = volume fraction of matrix

μ_f = Poisson's ratio of the fibres

μ_m = Poisson's ratio of the matrix

E_L = longitudinal modulus

E_T = transverse modulus

Example

If $V_f = 0.6$, $\mu_f = 0.22$ and $\mu_m = 0.33$

$$\begin{aligned} \text{then } \mu_{LT} &= 0.6 \times 0.22 + (1 - 0.6) \times 0.33 \\ &= 0.26 \end{aligned}$$

Prediction of shear modulus

For unidirectional composites an expression for the shear modulus is:

$$G_{LT} = G_m \left[\frac{\frac{G_f}{G_m} (1 + V_f) + V_m}{\frac{G_f}{G_m} V_m + 1 + V_f} \right] \quad \text{-- equation 5.10 -- Ref. (3)}$$

where G_m = shear modulus of the matrix

G_f = shear modulus of the fibres

V_f = volume fraction of fibres

V_m = volume fraction of matrix

Normally G_m would be given by: -

$$G_m = \frac{E_m}{2(1 + \nu_m)} \quad \text{-- equation 5.11}$$

However, in the case, which can occur with resin, that the compressive modulus and the tensile modulus are different then:

$$G_m = \frac{E_{mt} E_{mc}}{E_{mt} (1 + \mu_{mc}) + E_{mc} (1 + \mu_{mt})} \quad \text{-- equation 5.12 -- (Ref 4)}$$

where,

E_{mt} & E_{mc} are tensile and compressive matrix moduli respectively.

μ_{mt} , μ_{mc} are tensile and compressive matrix Poissons' ratio respectively

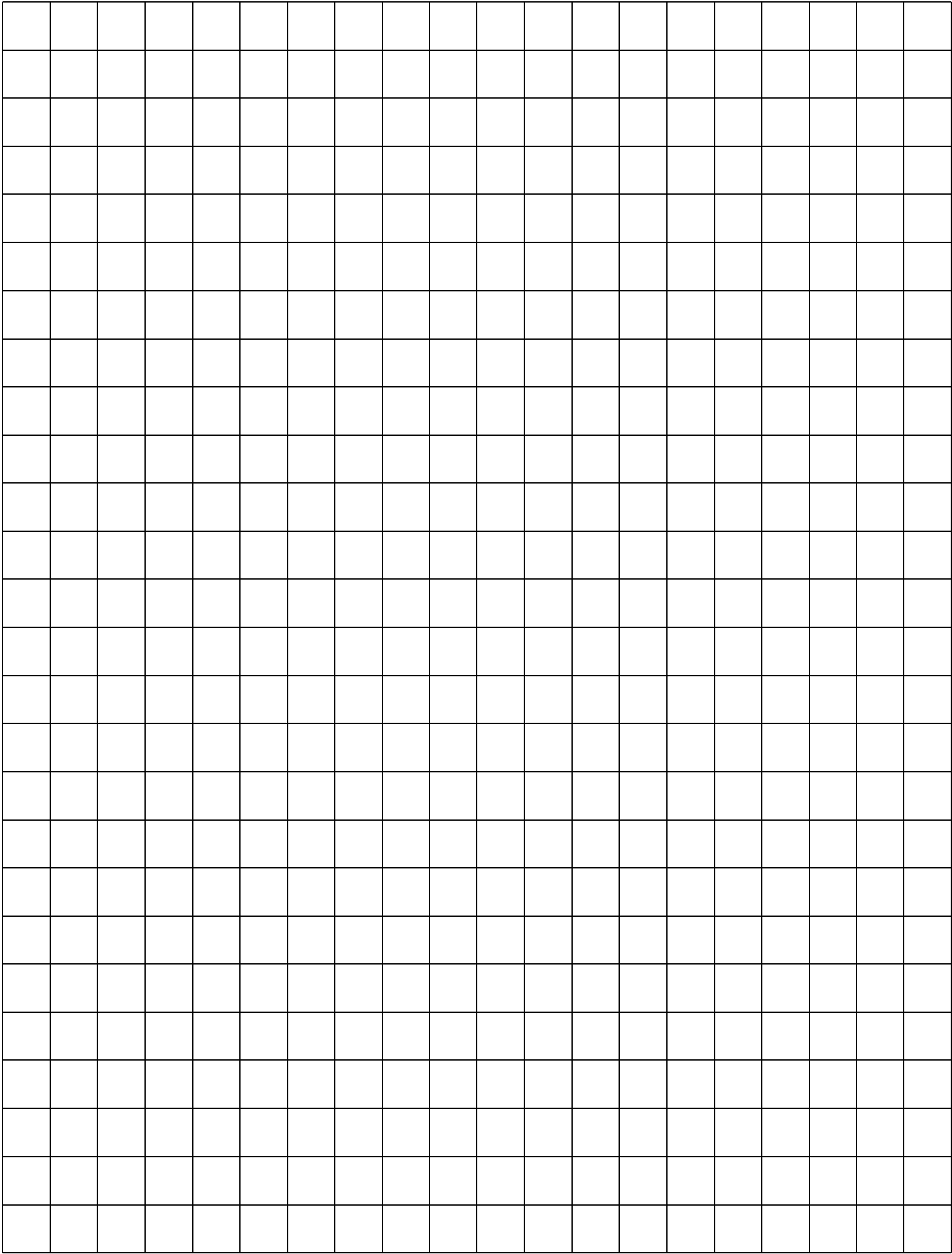
References

1 BS 4994 "Design and Construction of Vessels and Tanks in Reinforced Plastics." 1987

2 Krenchel "Fibre Orientation" Akademisk Forlag, Copenhagen.

3 Calcote Lee R "The Analysis of Laminated Composite Structures" Van Nostrand Reinhold

4 Lubin G "Handbook of Fibreglass and Advanced Plastics Composites" Van Nostrand Reinhold



6 Design of Composites

Design Process

Unit Property Based Design

Multi-layer Laminates in Flexure

Sandwich Construction

Data Sheets

Design of Pultrusions & Section Properties

Top Hat Shapes - Section Properties

References

6.1 The Design Process

The design process consists of several iterative stages, which result, hopefully, in the designer reaching a satisfactory solution to his problem. It is shown schematically in Fig 6.1.

Although in principle the design process remains the same, in practice different activities dominate depending whether the design process is primarily 'selective' or whether the intention is to produce an optimum such that the lowest possible cost or weight has been achieved. There are techniques available which allow this to be carried out efficiently.

Selective design requires the same activities but the design brief stipulates or implies a particular area of search. Once a solution has been found very little or no attempt is made to optimise it. This is the case when designing with standard structural elements, 'I' beams for example. Particular sizes are available from which to select. Therefore there is no opportunity to refine or optimise. This provides rapid economic solutions to common engineering problems.

Composite structural elements are available as standard pultrusions in the form of Box beams, Angles, Channels etc.

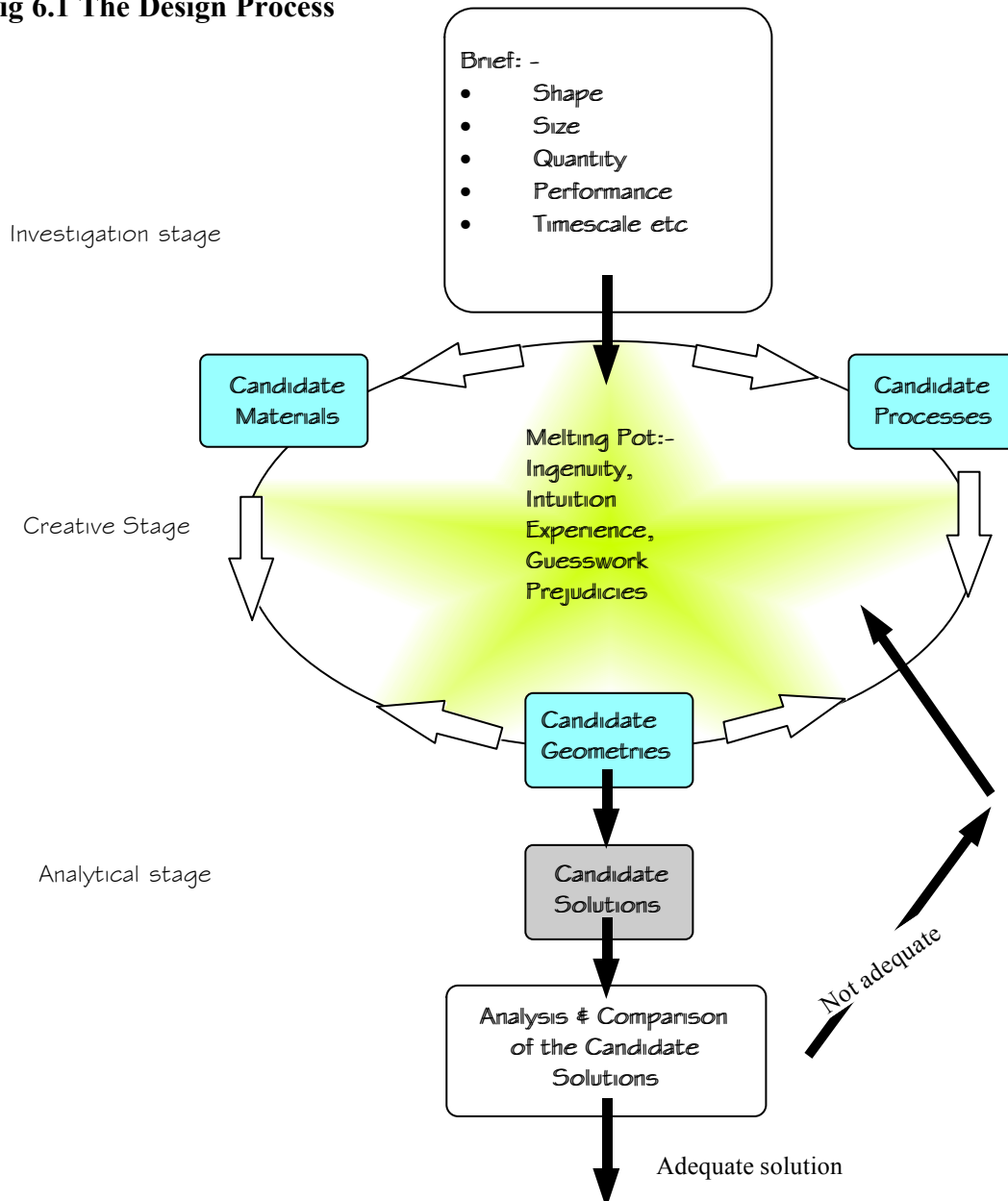
The properties and performance are known thus allowing structural analysis to be carried out. Hence designs may be made on a selective basis from these 'off-the-shelf' composites.

On the other hand, composites in general and pultrusions in particular may be 'tailor made' for a particular design brief and allowing an optimised design to be achieved.

In the case of optimum design of composites not only is the geometry (shape) designed but also the material itself. Material design and geometry cannot be solved in isolation. Candidate solutions are analysed and compared. The process is iterated until the optimum solution is found.

The analysis of composite materials is discussed in detail elsewhere and in various references, notably Ref 6.6 which is concerned with classical laminate analysis. This is a powerful tool for the analysis of composite materials including those which are pultruded. It allows materials to be modelled consisting of multi-layers of differing fibre reinforcements at any angle. The elastic properties may be predicted and with the application of a failure criterion, the failure can be predicted.

Fig 6.1 The Design Process



6.2 Design- Unit Properties Based

The strength and stiffness of a composite are a function of the amount of reinforcement present rather than thickness of laminate.

e.g. If two laminates are made each from 1 layer of 600 g/m² CSM but with different resin amounts of resin say 2/1 resin / glass and 3/1 resin / glass ratio. They will have different thickness' (About 1.5 mm and about 1.8 mm respectively). But the tensile load which they can carry will be much the same. Tensile strength is load to failure per width per thickness. As they have different thicknesses (due to the different amounts of resin present) they will have different tensile strengths but the same load carrying capacity.

Similarly under a given tensile load they will each extend the same amount but will have quite different tensile modulus values. Hence it is convenient for the design of some composite structures, those dominated by tensile loads, for the designer to use unit properties rather than the commonly used moduli or strengths. However, in calculations such as stability under external pressure, unit modulus is not sufficient and the normally defined modulus values are calculated and used.

This approach is used in Ref 1 (British Standard 4994, "Specification for design and construction of vessels and tanks in reinforced plastics").

Whereas the units for ultimate tensile strength (UTS) and tensile modulus are N/mm². The units for both Ultimate Tensile Unit Strength (UTUS.) and Unit Modulus are: -

N/mm width per kg/m² of glass.

The Standard does not include the use of imperial units but UTUS and Unit Modulus units translate from metric to imperial as: -

Lb/in width per oz/ft² of glass.

Ultimate tensile unit strength: (U) (N/mm per Kg/m² glass)

This is the strength of a constituent layer of laminate, expressed as force per unit width per unit weight of the reinforcement. This value is obtained from the failure load in a tensile test.

Unit Modulus: (X) N/mm width per kg/m² glass)

This is the ratio of the load per unit width to the strain. It is obtained from the measured load and strain in a tensile test. BS4994 specifies requirements for the design, materials, construction, inspection, testing and erection of vessels and tanks in reinforced plastics, consisting of a polyester, epoxy or furane resin system reinforced with glass-fibres, manufactured by the wet lay-up process. Constructions both with and without a liner of thermoplastics are included. Filament winding is included to a limited extent.

Values for UTUS and Unit Modulus are given on page 5.5 & 6.14.

The standard requires that calculations are carried out for both stress in the laminate and strain, the construction used is that which is greatest.

Hence the design criterion employed is either *Load limited* or *Strain limited*.

The procedure is :

A. Load limited design

1. Determine circumferential unit load $Q = \frac{PD}{2}$

2. Determine design factor, K

3. Determine $U_L = \frac{UTUS}{K}$

4. Calculate mass of material $= \frac{Q_c}{U}$

B. Strain limited design

1 Determine $\epsilon = 0.1\epsilon_R$ or $\epsilon = 0.2\%$ whichever is least

2 Calculate $U_s = X_s \epsilon$

where X_s is extensibility of the material.

3. Calculate mass of material $= \frac{Q_c}{U_s}$

Mass of material required is whichever is the greater of the two. The procedure is shown in the following example.

Example 6.1

Design of a vertical cylindrical storage tank

To determine the construction required for the cylindrical section of a vertical cylindrical storage tank to BS 4994.

The vessel is a storage tank with a fully supported base. The cylindrical portion of the vessel is 1000 mm dia. The height of the cylinder is 3400 mm. The capacity is 2000 litre and the s.g. of the contents is 1.4.

Other details :

Design pressure : Fully flooded plus 0.5 barG

Design temperature 70°C

Construction : The vessel is Celmar lined and will be produced by hand lay using CSM with a 30% mass fraction of fibre. The Heat distortion temperature of the resin is at least 90°C. Strain to failure of the resin system $\geq 1.5\%$

The Cylinder of the vessel

Consider the Design factors (9.2.2 Ref 1)

k1 Manufacturing method (9.2.2 table 6 Ref 1)

As the vessel will be produced by hand lay k1 = **1.5**

k2 Chemical environment (App E.2 method A Ref 1)

The vessel has a thermoplastic liner and therefore k2 = **1.2** (1.5)

k3 Relating to Temperature

The resin HDT > 90°C. Hence k3 = **1.25** (1.1) (9.2.2 Fig 1 Ref 1)

k4 Cyclic loading

The vessel is required to be loaded to its design capacity less than 10,000 times. Hence k4 = **1.4** (1.1) (9.2.2 Fig 2 1)

k5 curing procedure

The vessel will not be post cured at elevated temperature and will operate above 45°C. Hence k5 = **1.5** (1.2) (9.2.2 e Ref 1)

Design factor K

$K = 3 \ k_1 \ k_2 \ k_3 \ k_4 \ k_5$ (9.2.2 eq 1)

Therefore $K = 3 \times 1.5 \times 1.2 \times 1.25 \times 1.4 \times 1.5 = 14.18$

(Continued on page 6.4)

(Continued from page 6.3)

The remainder of the calculation is laid out to allow easy comparison between the metric & imperial versions.

Allowable Unit Loadings (See page 5.5)

Load limited allowable unit loading

$$u \text{ for chopped strand mat laminates} = 200 \text{ N/mm per kg/m}^2$$

$$U_L = u/K \quad (\text{Eq 2 Ref 1})$$

$$= 200/14.18 = 14.1 \text{ N/mm per kg/m}^2$$

Strain Limited Allowable Unit Loading

Strain to failure of the resin system $\geq 1.5\%$

Strain allowable \leq smaller of $0.1\epsilon_r$ or 0.2%

Hence max allowable strain $\hat{\epsilon} = 0.15\%$ (9.2.4 Ref 1)

Unit modulus for CSM, $X = 14000 \text{ N/mm}^2 \text{ per kg/m}^2$
(See page 5.5)

Then Strain limited allowable unit loading =

$$U_s = X \cdot \epsilon \quad (\text{Eq 3 Ref 1})$$

Hence $U_s = 14000 \times 0.0015 = 21 \text{ N/mm per kg/m}^2 \text{ CSM}$

U_L is smaller than U_s therefore Design unit loading =

$$U_L = 14.1 \text{ N/mm per kg/m}^2$$

Design pressure

The most onerous case is a static head of 3040 mm and the density of the contents = 1.4 and applied pressure of 0.5 barG. Therefore pressure due to the head = $3040 \times 9.8/1E6 \times 1$

$$= 0.042 \text{ N/mm}^2$$

Applied pressure = 0.5 barG = 0.05 N/mm}^2

$$\text{Total} = 0.092 \text{ N/mm}^2$$

Unit Loads

Maximum circumferential Unit load ($Q_{\phi i}$)

$$Q_{\phi i} = p D_i / 2 \quad (14.2 \text{ Ref 1})$$

where p is the total pressure. = 0.092 N/mm^2

D_i = internal diameter = 1000 mm

$$Q_{\phi i} = 0.092 \times 1000 / 2 = 46 \text{ N/mm}$$

Mass of CSM required for max unit loading

Proposed construction is:-

3.6 kg/m² Chopped strand mat with 30% glass content

$$U_{\text{lam}} = 3.6 \times 14.1 = 50.76 > 46$$

Therefore the proposed construction suitable.

Thickness Metric

The laminate thickness (mm) (Chapter 4) is given by:

$$t_k = \frac{w_f}{d_f} + \frac{(1 - W_f) w_r}{W_f d_r}$$

w_f = mass of glass fibre (kg/m²), d_f = Density of glass (2.55 g/cc),

w_r = mass of resin (kg/m²), d_r = Density of resin (1.2g/cc)

W_f = Mass fraction of glass fibre = 30%

$$t_k = 3.6/2.55 + (1-0.3)/0.3 \times 3.6/1.2 = 8.4 \text{ mm}$$

Therefore laminate thickness required = 8.4 mm

Example 6.1 (Imperial version)

To determine the construction required for the cylindrical section of the vertical cylindrical storage tank in example 6.1 but using the Imperial units rather than metric.

The cylindrical portion of the vessel is 40 in dia by 10 ft high.

The density of the contents is 0.05 Lb/in³ (1.4g/cc).

Design pressure : Fully flooded plus 7.25 psi

The Design factor is determined as in the metric approach

Therefore $K = 14.18$

Allowable Unit Loadings (See page 5.5)

Load limited allowable unit loading

$$u \text{ for chopped strand mat laminates} = 349 \text{ Lb/in per oz per ft}^2$$

$$U_L = u/K = 349 / 14.18$$

$$= 24.6 \text{ Lb/in per oz/ft}^2$$

Strain Limited Allowable Unit Loading

Strain to failure of the resin system $\geq 1.5\%$

Strain allowable \leq smaller of $0.1\epsilon_r$ or 0.2%

Hence max allowable strain $\hat{\epsilon} = 0.15\%$

Unit modulus for CSM, $X = 24400 \text{ Lb/in per oz per ft}^2$
(See page 5.5)

Then Strain limited allowable unit loading =

$$U_s = X \cdot \epsilon$$

Hence $U_s = 24400 \times 0.0015 = 36.6 \text{ Lb/in per oz per ft}^2 \text{ CSM}$

U_L is smaller than U_s therefore Design unit loading =

$$U_L = 24.6 \text{ Lb/in per oz/ft}^2$$

Design pressure

The most onerous case is a static head of 10 ft and the density of the contents = 0.05 Lb/in³ and applied pressure of 7.25 psi.

Therefore pressure due to the head = 120×0.05

$$= 6.0 \text{ psi}$$

Applied pressure of 7.25 psi

$$\text{Total} = 13.25 \text{ psi}$$

Unit Loads

Maximum circumferential Unit load $Q_{\phi i} =$

$$Q_{\phi i} = p D_i / 2$$

where p is the total pressure. = 13.25 psi

D_i = internal diameter = 40 in

$$Q_{\phi i} = 13.25 \times 40 / 2 = 265 \text{ Lb/in}$$

Mass of CSM required for max unit loading

Proposed Construction:-

12 oz/ft² Chopped strand mat 30 % glass content by weight

$$U_{\text{lam}} = 12 \times 24.6 = 295 > 265$$

Therefore the proposed construction is suitable..

Thickness - Imperial

The laminate thickness (in) (Chapter 4) is given by:

$$t_k = \left[\frac{w_f}{d_f} + \frac{(1 - W_f) w_r}{W_f d_r} \right] / 2304$$

w_f = mass glass fibre (oz/ft²), d_f = Density glass (0.092 lb/in³)

w_r = mass resin (oz/ft²), d_r = Density of resin (0.043lb/in³)

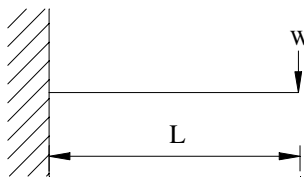
W_f = Mass fraction of glass fibre = 30%

$$t_k = [12/0.092 + (1-0.3)/0.3 \times 12/0.043] / 2304 = 0.34$$

Therefore laminate thickness required = 0.34 in

Fig 6.3 Deflection and Stress in Beams of Uniform Section

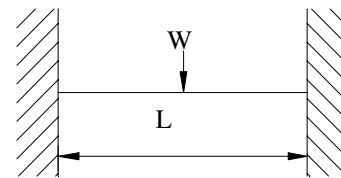
Fixed at one end loaded at other



$$\text{Deflection at end} = \frac{WL^3}{3EI}$$

$$\text{Stress at support} = \frac{WLy}{I}$$

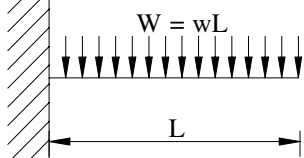
Fixed at the ends loaded at centre



$$\text{Deflection at centre} = \frac{WL^3}{192EI}$$

$$\text{Stress at centre} = \frac{WLy}{8I}$$

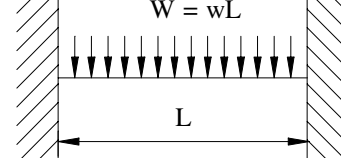
Fixed at one end loaded uniformly



$$\text{Deflection at end} = \frac{WL^3}{8EI}$$

$$\text{Stress at support} = \frac{WLy}{2I}$$

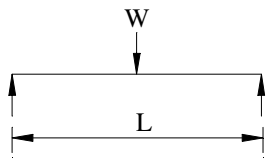
Fixed at the ends loaded uniformly



$$\text{Deflection at centre} = \frac{WL^3}{384EI}$$

$$\text{Stress at centre} = \frac{WLy}{12I}$$

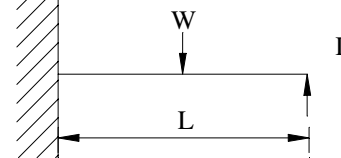
Supported at the ends loaded at the centre



$$\text{Deflection at centre} = \frac{WL^3}{48EI}$$

$$\text{Stress at centre} = \frac{WLy}{4I}$$

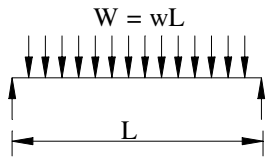
Fixed at one end, supported at the other



$$\text{Deflection(Max)} = \frac{WL^3}{107EI}$$

$$\text{Stress at fixed end} = \frac{3WLy}{16I}$$

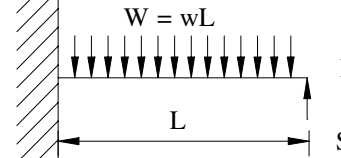
Supported at the ends loaded uniformly



$$\text{Deflection at centre} = \frac{5WL^3}{384EI}$$

$$\text{Stress at centre} = \frac{WLy}{8I}$$

Fixed at one end, supported at the other



$$\text{Deflection(Max)} = \frac{WL^3}{185EI}$$

$$\text{Stress at fixed end} = \frac{WLy}{8I}$$

W = Total load on beam

L = Effective length of beam

I = Second moment of area of beam cross section

y = Distance from neutral axis

E = Elastic modulus in bending of the beam about the relevant axis

Fig 6.4 Section Properties - Common shapes

Position of neutral axis (y mm)	D/2	D/2	D/2	D/2	D/2	D/2	D/2
Area (A mm ²)	BD - bd	bD + Bd	BD	(BD - bd)	$\pi D^2/4$	$\pi (D^2 - d^2)/4$	B(D - d)
Section modulus (Z mm ³)	$(BD^3 - bd^3) / 6D$	$(bD^3 + Bd^3) / 6D$	$BD^2 / 6$	$(BD^3 - bd^3) / 6D$	$\pi D^3/32$	$\pi (D^4 - d^4)/32D$	$B(D^3 - d^3) / 6D$
Second Moment of area (mm ⁴)	$(BD^3 - bd^3) / 12$	$(bD^3 + Bd^3) / 12$	$BD^3 / 12$	$(BD^3 - bd^3) / 12$	$\pi D^4/64$	$\pi (D^4 - d^4)/64$ or $\pi D^3t/8$ for thin tubes	$B(D^3 - d^3) / 12$

Multi layer laminates in flexure

A common problem in the design of composites is the analysis of laminates made up from layers of different materials. The two dominant requirements in design are:

- to determine the flexural rigidity of the composite and
- the strength of the composite.

Fig 6.5

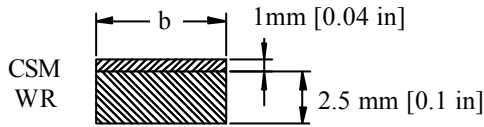
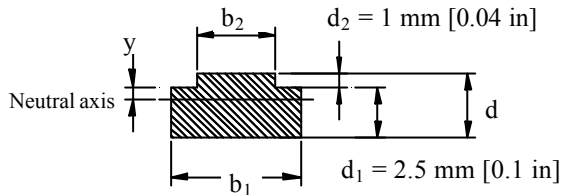


Fig 6.6



$$E = 15 \text{ GPa [2.2 Msi]}$$

A simple strength of materials approach is as follows: A typical combination of materials is chopped strand mat and woven roving.

Example 6.2

Say a laminate consists of simply a thickness of each as in Fig. 6.5 (note a "thickness" may be made up from several layers of that material).

$$\begin{aligned} \text{Say } E_{\text{CSM}} &= 7500 \text{ MN/m}^2 \text{ [1.1 Msi]} \\ \text{and } E_{\text{WR}} &= 15000 \text{ MN/m}^2 \text{ [2.2 Msi]} \end{aligned}$$

The flexural rigidity of the section may be found by the "equivalent section" technique. In this method the theoretical section shape is changed whereby the thickness of each layer stays the same but the width is determined by the elastic modulus of the layer.

$$\text{Assume } b_1 \text{ has unit width then } b_2 = b_1 \times 7500 / 15000$$

$$[\text{Imperial } b_2 = b_1 \times 1.1 / 2.2]$$

The 2nd moment of area of the section may then be calculated. For instance, if the material is assumed to be all woven roving then, the equivalent section of Fig. 6.5 would be as shown in Fig. 6.6. The position of the neutral axis, the second moment of area and hence the flexural rigidity can be calculated thus :

$$y = d - \frac{d^2 b_2 + d_1^2 (b_1 - b_2)}{2(b_1 d_1 + b_2 d_2)}$$

-- equation 6.1

$$= \frac{3.5 - (3.5^2 \times 0.5 + 2.5^2 (0.5))}{2(1 \times 2.5 + 0.5 \times 1)}$$

$$= 1.96 \text{ mm}$$

$$I = \frac{1}{3} (b_2 y^3 + b_1 (d - y)^3 - (b_1 - b_2) (d - y - d_1)^3)$$

-- equation 6.2

$$I = \frac{1}{3} \{ 0.5 y^3 + 1(3.5 - y)^3 - (0.5)(3.5 - y - 2.5)^3 \}$$

$$= 2.62 \text{ mm}^4$$

i.e. The second moment of area of the "equivalent section" is 2.62 mm^4 .

$$\begin{aligned} \text{Therefore the flexural rigidity (EI) of the actual section} \\ &= 2.62 \times 15000 \text{ Nmm}^2 \\ &= 39300 \text{ Nmm}^2. \end{aligned}$$

Or in imperial units

$$\begin{aligned} y &= 0.14 - (0.14^2 \times 0.5 + 0.1^2 (0.5)) \\ &= 2(1 \times 0.1 + 0.5 \times 0.04) \\ &= 0.078 \text{ in} \end{aligned}$$

$$I = \frac{1}{3} \{ 0.5 y^3 + 1(0.14 - y)^3 - (0.5)(0.14 - y - 0.1)^3 \}$$

$$= 0.000168 \text{ in}^4$$

$$\begin{aligned} \text{The flexural rigidity (EI) of the actual section} \\ &= 1.68\text{E-4} \times 2.2\text{E6 Lb.in}^2 \\ &= 370 \text{ Lb.in}^2 \end{aligned}$$

The second part of the problem is strength. If the laminate is subjected to a bending moment, what will be the stress distribution in the laminate and how will it fail?

Consider Fig. 6.7

The stress at any distance C from the neutral axis is

$$\sigma = \frac{M_b C E_c}{EI}$$

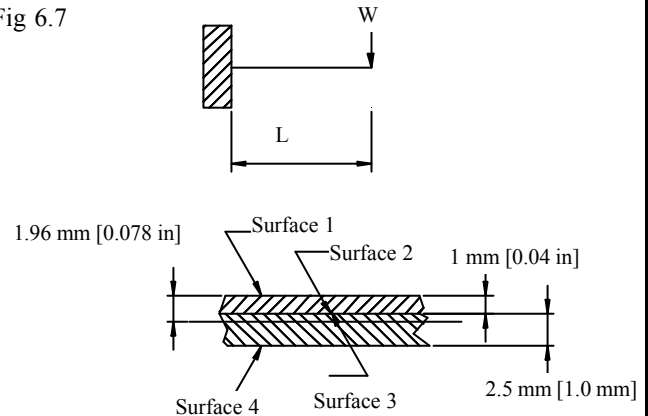
where M_b = the applied bending moment

C = distance from the neutral axis

E_c = Elastic modulus of the material at position C

EI = overall flexural rigidity

Fig 6.7



$$\begin{aligned} \text{Hence at position (1)} \quad \sigma_1 &= \frac{M_b \times 1.96 \times 7500}{39300} \\ \text{See Fig.6.7} \quad &= 0.374 M_b \text{ N/mm}^2 \end{aligned}$$

$$\begin{aligned} \text{at position (2)} \quad \sigma_2 &= \frac{M_b (1.96 - 1) \times 7500}{39300} \\ &= 0.183 M_b \text{ N/mm}^2 \end{aligned}$$

$$\begin{aligned} \text{at position (3)} \quad \sigma_3 &= \frac{M_b (1.96 - 1) \times 15000}{39300} \\ &= 0.366 M_b \text{ N/mm}^2 \end{aligned}$$

$$\begin{aligned} \text{at position (4)} \quad \sigma_4 &= \frac{M_b (3.5 - 1.96) \times 15000}{39300} \\ &= 0.589 M_b \text{ N/mm}^2 \end{aligned}$$

It can be seen that the maximum stress is at position (4). This is not necessarily the most likely failure position, because at position (4) the material is woven roving which has higher

strength than chopped strand mat.

Say the chopped strand mat ultimate strength (tensile or compressive) (σ_{ultCSM}) = 100MN/m² and the woven roving ultimate strength, tensile or compressive (σ_{ultWR}) = 280MN/m² then equating stress and strength (σ and σ_{ult}) find the bending moment at which failure occurs (M_b) thus:

$\sigma_1 = \sigma_{ultCSM}$ hence $0.374M_b = 100$ therefore $M_b = 267$ Nmm

$\sigma_2 = \sigma_{ultCSM}$ hence $0.183M_b = 100$ therefore $M_b = 546$ Nmm

$\sigma_3 = \sigma_{ultWR}$ hence $0.366M_b = 280$ therefore $M_b = 765$ Nmm

$\sigma_4 = \sigma_{ultWR}$ hence $0.589M_b = 280$ therefore $M_b = 475$ Nmm

It can be seen that initial failure occurs at position (1) i.e. the outer face of the chopped strand mat layer. When a bending moment of 267 Nmm is reached. Note, it has been assumed that tensile strength and compressive strength are equal. This is not necessarily so, in which case the direction of bend would alter the conditions. i.e. whether the critical positions were subjected to tensile or compressive loads.

Or in imperial units

Hence at position (1) $\sigma_1 = \frac{M_b \times 0.078 \times 1.1E6}{370}$
See Fig.6.7 $= 232 M_b \text{ Lb/in}^2$

at position (2) $\sigma_2 = \frac{M_b (0.078 - 0.04) \times 1.1E6}{370}$
 $= 113 M_b \text{ Lb/in}^2$

at position (3) $\sigma_3 = \frac{M_b (0.078 - 0.04) \times 2.2E6}{370}$
 $= 226 M_b \text{ Lb/in}^2$

at position (4) $\sigma_4 = \frac{M_b (0.14 - 0.078) \times 2.2E6}{370}$
 $= 369 M_b \text{ Lb/in}^2$

It can be seen that the maximum stress is at position (4). This is not necessarily the most likely failure position, because at position (4) the material is woven roving which has higher strength than chopped strand mat.

Say the chopped strand mat ultimate strength (tensile or compressive) (σ_{ultCSM}) = 14500 Lb/in² and the woven roving ultimate strength, tensile or compressive (σ_{ultWR}) = 40000 Lb/in² then equating stress and strength (σ and σ_{ult}) find the bending moment at which failure occurs (M_b) thus:

$\sigma_1 = \sigma_{ultCSM}$ hence $232M_b = 14500$ therefore $M_b = 62.5$ Lb.in

$\sigma_2 = \sigma_{ultCSM}$ hence $113M_b = 14500$ therefore $M_b = 128$ Lb.in

$\sigma_3 = \sigma_{ultWR}$ hence $226M_b = 40000$ therefore $M_b = 177$ Lb.in

$\sigma_4 = \sigma_{ultWR}$ hence $369M_b = 40000$ therefore $M_b = 108$ Lb.in

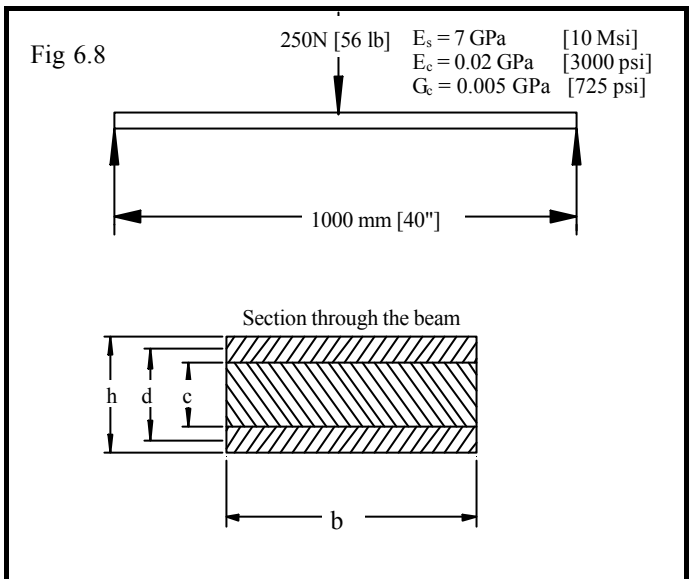
It can be seen that initial failure occurs at position (1) i.e. the outer face of the chopped strand mat layer, when a bending moment of 62.5 Lb.in is reached.

Note, it has been assumed that tensile strength and compressive strength are equal. This is not necessarily so, in which case the direction of bend would alter the conditions. i.e. whether the critical positions were subjected to tensile or compressive loads.

Sandwich Beams

Sandwich construction is an extremely effective method of producing stiff, light and economical composites structures when used in the right application and in the right manner. The following equations will assist with the less complex situations and should illustrate some of the problems which exist when designing sandwich structures. They are generally used to improve the flexural rigidity of a panel or beam in terms of cost, or weight.

The use of composites in this manner is extremely efficient Consider Fig: 6.8. Various expressions may be used to determine the flexural rigidity of sandwich structures. Each has its own particular limitations.



Equation 6.3 ignores the flexural rigidity of the core, which is a reasonable assumption for many of the foam cores which are in common use, but would not be acceptable for those core materials such as balsa which itself has appreciable flexural rigidity.

$$\text{flexural rigidity } D = \frac{E_s \cdot b(h^3 - c^3)}{12}$$

-- equation 6.3

where E_s = skin modulus

b = width of the beam

If the flexural rigidity of the core is included then the expression becomes:

$$D = \frac{E_s \cdot b \cdot t^3}{6} + \frac{E_s \cdot b \cdot t \cdot d^2}{2} + \frac{E_c \cdot b \cdot c^3}{12}$$

-- equation 6.4.

The first two terms are an alternative arrangement of equation 6.3. The third term relates to the flexural rigidity of the core. E_s and E_c are the elastic moduli of skins and core respectively. The first term in the above expression may be ignored if the skins are thin. The third may be ignored if the bending stiffness of the core is small.

Consequently, a reasonable approximation under the right conditions is:

$$D = \frac{E_s \cdot b \cdot t \cdot d^2}{2}$$

Equation 6.5

(Continued on page 6.8)

(Continued from page 6.7)

Therefore, use equation 6.4 if the core has appreciable stiffness and the skins are thick.

Use equation 6.3 if the skins are again thick but the core has negligible rigidity.

Use equation 6.5 if the skins are thin and the core has negligible rigidity.

Very often the designer is able to ignore shear deflections but, unfortunately sandwich structures are particularly prone to this problem and shear deflections must be determined. For a simply supported sandwich beam with a load W in the centre the deflection due to shear is given by:

$$\delta_{\text{shear}} = \frac{W L c}{4 b d^2 G}$$

and for simple support with a uniformly distributed load of w /unit length

$$\delta_{\text{shear}} = \frac{w L^2 c}{8 b d^2 G}$$

where L = span

G = shear modulus of the core.

Example 6.3

Determine the total deflection of the sandwich beam shown in Fig. 6.9. Using the more rigorous expression for flexural rigidity (D).

$$D = \frac{E_s b t^3}{6} + \frac{E_s b t d^2}{2} + \frac{E_c b c^3}{12}$$

$$= \frac{7000 \times 100 \times 3^3}{6} + \frac{7000 \times 100 \times 3 \times 28^2}{2} + \frac{20 \times 100 \times 25^3}{12}$$

$$= 3.15 \times 10^6 + 823 \times 10^6 + 2.6 \times 10^6$$

$$\therefore D = 828 \text{ N.m}^2$$

Note in this case the middle term of the expression alone gives an answer with less than 1% error.

Now total deflection =

deflection due to bending plus deflection due to shear.

$$= \frac{W L^3}{48 D} + \frac{W L c}{4 b d^2 G}$$

$$= \frac{250 \times 1000^3}{48 \times 828 \times 10^6} + \frac{250 \times 1000 \times 25}{4 \times 100 \times 28^2 \times 5}$$

$$= 6.29 + 3.99$$

Therefore Total deflection = 10.28mm.

Example 6.3 [Imperial]

$$D = \frac{1E6 \times 4 \times 1/8^3}{6} + \frac{1E6 \times 4 \times 1/8 \times 1.125^2}{2} + \frac{3000 \times 4 \times 1^3}{12}$$

$$= 1302 + 316E3 + 1000$$

$$\therefore D = 319E3 \text{ Lb.in}^2$$

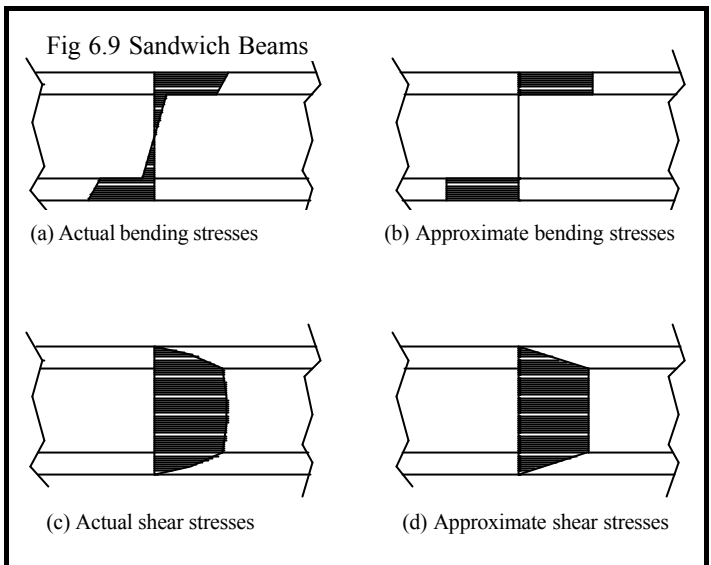
$$\text{Total deflection} = \frac{56 \times 40^3}{48 \times 319E3} + \frac{56 \times 40 \times 1}{4 \times 4 \times 1.125^2 \times 725}$$

$$= 0.23 + 0.15$$

Therefore Total deflection = 0.38 in.

Stresses in sandwich beams

The actual bending stresses in sandwich beams are illustrated in Fig. 6.9a. But it is reasonable to assume that the core carries none of the bending stress and that the skins have a constant stress through their thickness. Hence the bending stresses may be assumed to be as is shown in Fig. 6.9b.



The actual shear stresses in a sandwich beam are as shown in Fig. 6.9c. But it is reasonable to assume that the stresses are as shown in Fig. 6.9d. The actual bending stress in the skins is given by:

$$\sigma_s = \frac{M E_s h}{2D}$$

equation 6.8

but if equation 6.5 is used for D then :

$$\sigma_s = \frac{M h}{b t d^2}$$

equation 6.9

Where M is the applied bending moment.

The actual shear stress in the core, τ_c is given by

$$\tau_c = \frac{Q \{ E_s t d/2 + E_c/2 (c^2/4 - y^2) \}}{D}$$

equation 6.10

where y is any distance from the neutral axis and Q is the shear force. If, however, E_c is assumed to be zero and equation 6.5 is again taken for D , then the shear stress in the core is

$$\tau_c = \frac{Q}{b d}$$

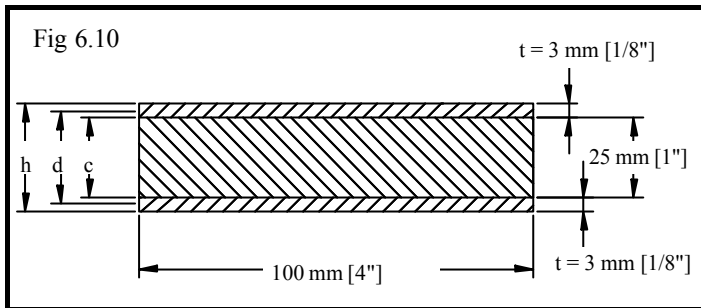
Equation 6.11

Example

Determine the bending stress in the skin and the shear stress in the core for the beam illustrated in the previous example (and see fig 6.10)

The bending stress in the skins is:

$$\sigma_s = \frac{M h}{b t d^2}$$



$$M = 250/2 \times 1000/2 \text{ N mm}$$

$$h = 31 \text{ mm [1.25"]}, b = 100 \text{ mm [4"]},$$

$$t = 3 \text{ mm [1/8"]}, d = 28 \text{ mm [1.125"]}$$

$$\text{Therefore } \sigma_s = \frac{250 \times 1000 \times 31}{2 \times 2 \times 100 \times 3 \times 28^2}$$

$$= 8.24 \text{ N/mm}^2$$

$$\text{the shear stress in the core } \tau_c = \frac{250}{2 \times 100 \times 28}$$

$$= 0.045 \text{ N/mm}^2$$

Or in Imperial Units

$$M = 56/2 \times 40/2 \text{ lbf. in}$$

$$\text{Therefore } \sigma_s = \frac{56 \times 40 \times 1.25}{2 \times 2 \times 4 \times 0.125 \times 1.125}$$

$$= 1106 \text{ Lbf/in}^2$$

$$\text{the shear stress in the core } \hat{\tau}_c = \frac{56}{2 \times 4 \times 1.125}$$

$$= 6.2 \text{ Lbf/in}^2$$

Flexural Rigidity of Sandwich Beams with CSM skins

Figures 6.11 and 6.12 plot the flexural rigidity of sandwich beams with chopped strand mat laminate skins of

various thickness'. Fig 6.11 is an enlargement of the area below the scale of Fig 6.12. The stiffness of the core material is assumed to be negligible.

Fig 6.11

Flexural Rigidity of Sandwich Beams
Chopped strand mat / Polyester at 2/1 resin/g lass

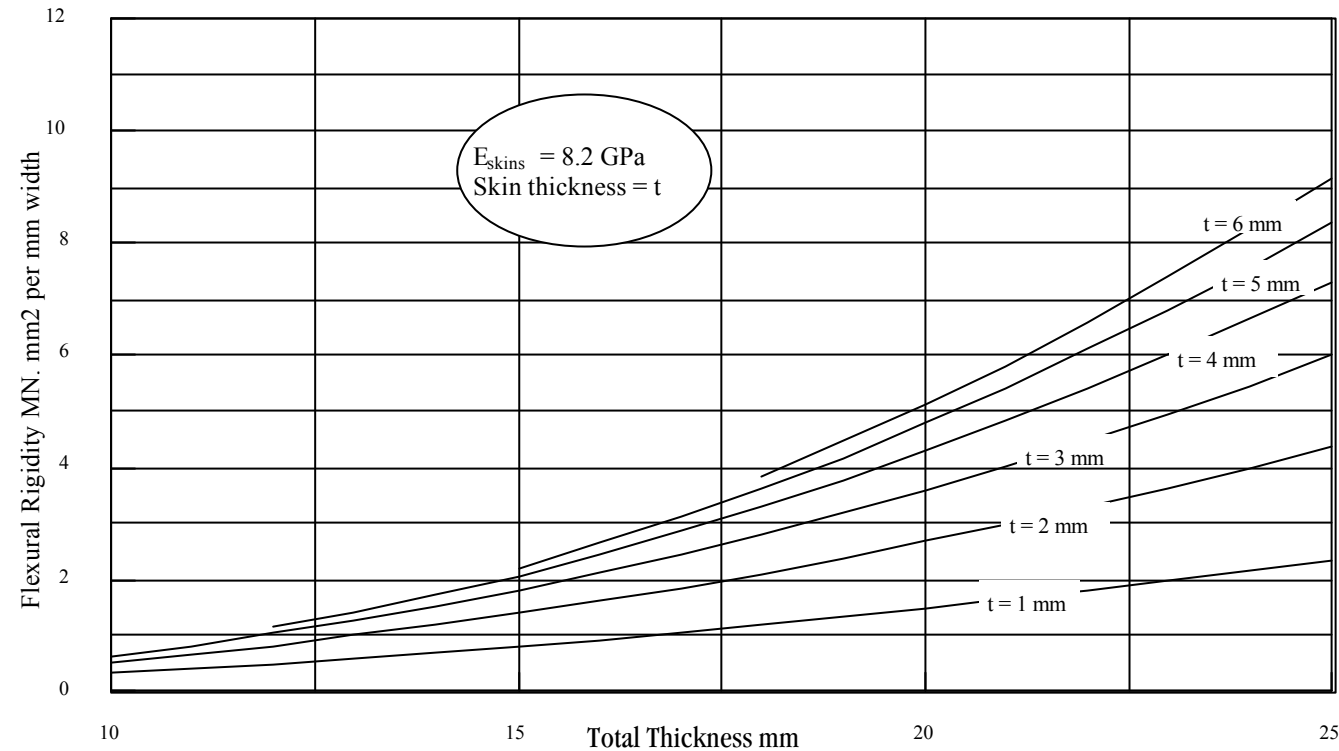
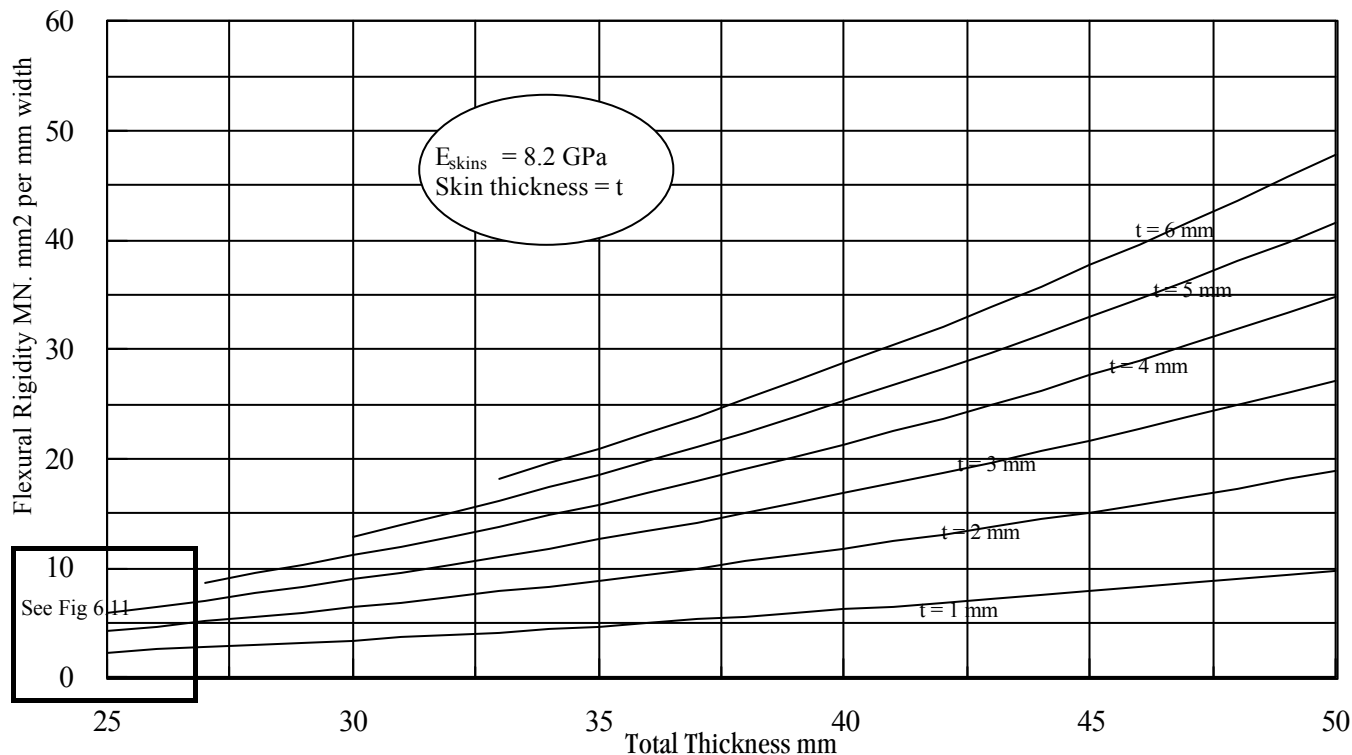


Fig 6.12

Flexural Rigidity of Sandwich Beams
Chopped strand mat / Polyester at 2/1 resin/g lass



Flexural Rigidity of Sandwich Beams with WR skins

Figures 6.13 and 6.14 plot the flexural rigidity of sandwich beams with Woven Roving laminate skins of

various thickness'. Fig 6.13 is an enlargement of the area below the scale of Fig 6.14.

The stiffness of the core material is assumed to be negligible.

Fig 6.13

Flexural Rigidity of Sandwich Beams

Woven Roving / Polyester at 1/1 resin / glass

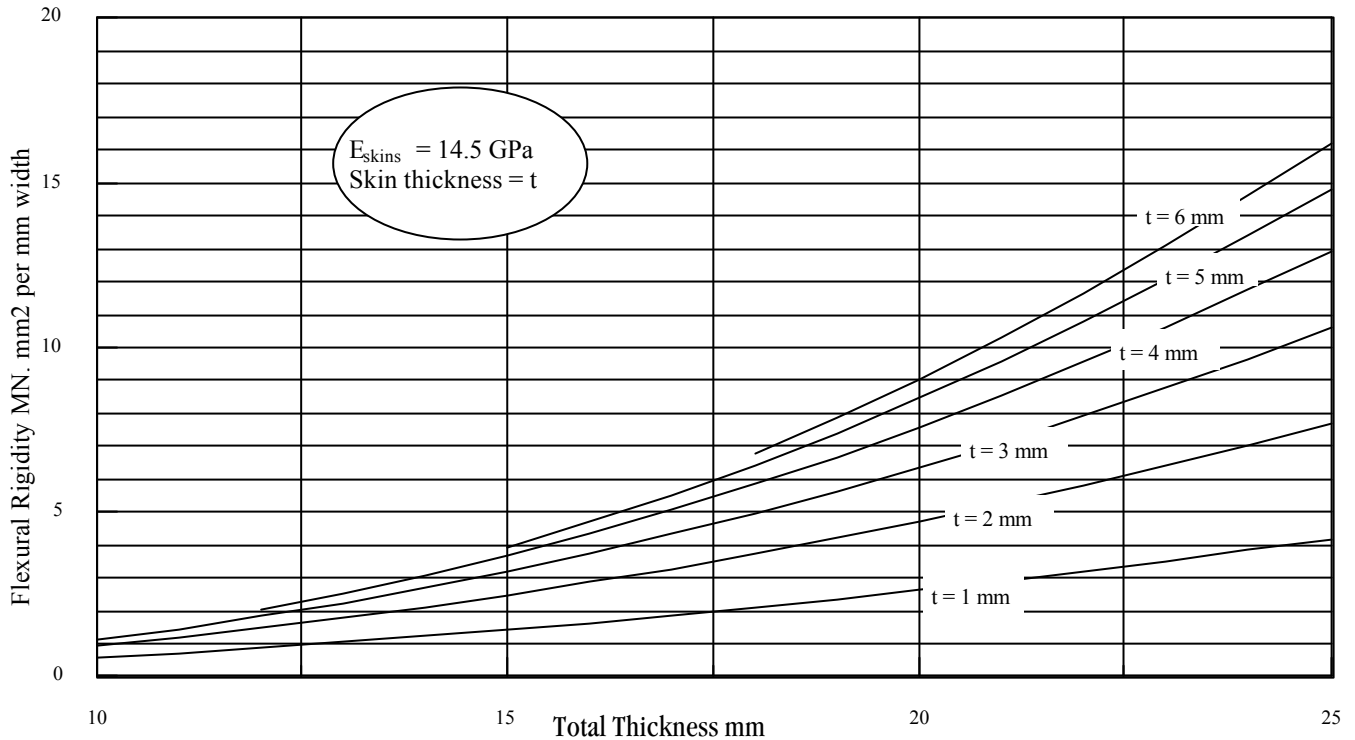
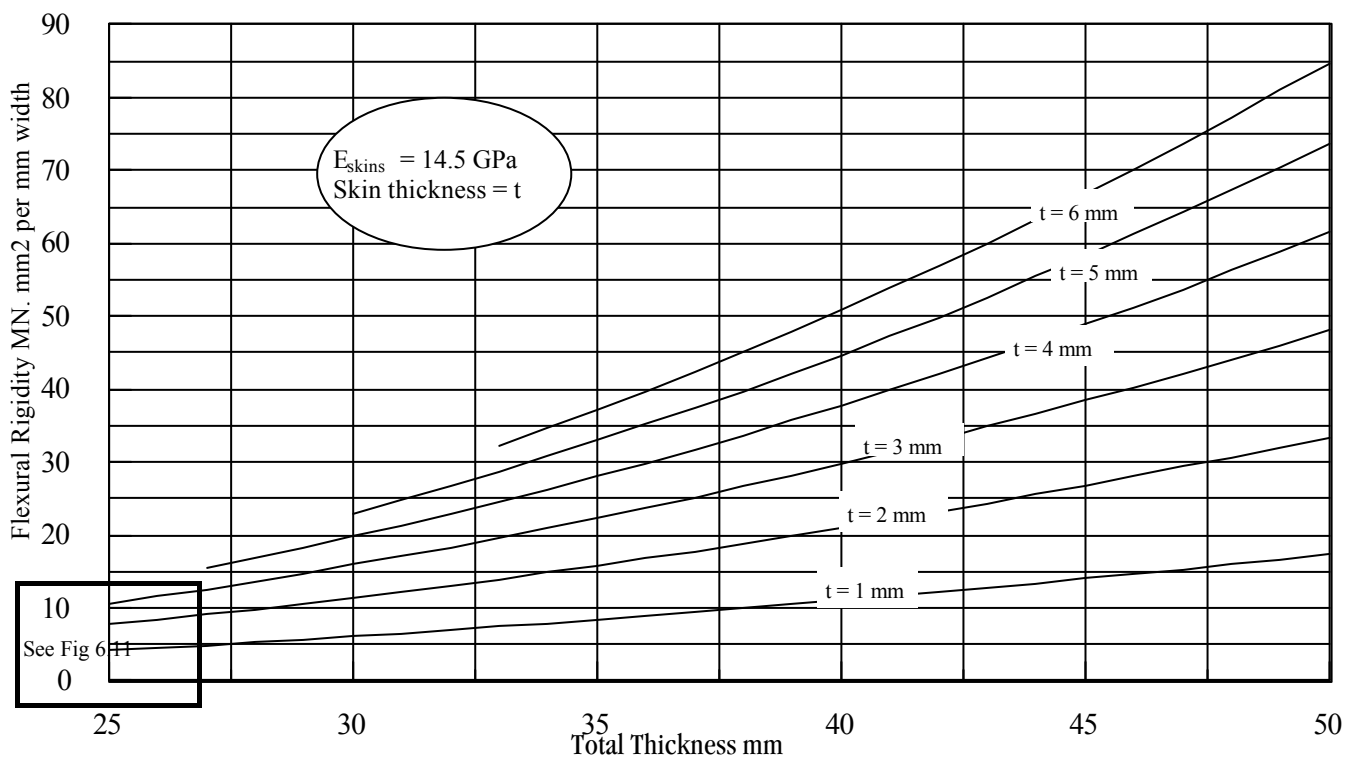


Fig 6.14

Flexural Rigidity of Sandwich Beams

Woven Roving / Polyester at 1/1 resin / glass



Flexural Rigidity of Sandwich Beams with CSM skins

Figures 6.11 (Imperial) and 6.12 (Imperial) plot the flexural rigidity of sandwich beams with chopped strand mat laminate skins of various thickness'.
The stiffness of the core material is assumed to be negligible.

Fig 6.11 (Imperial) is an enlargement of the area below the scale of Fig 6.12 (Imperial).
The stiffness of the core material is assumed to be negligible.

Fig 6.11 (Imperial)

Flexural Rigidity of Sandwich Beams Chopped Strand Mat / Polyester

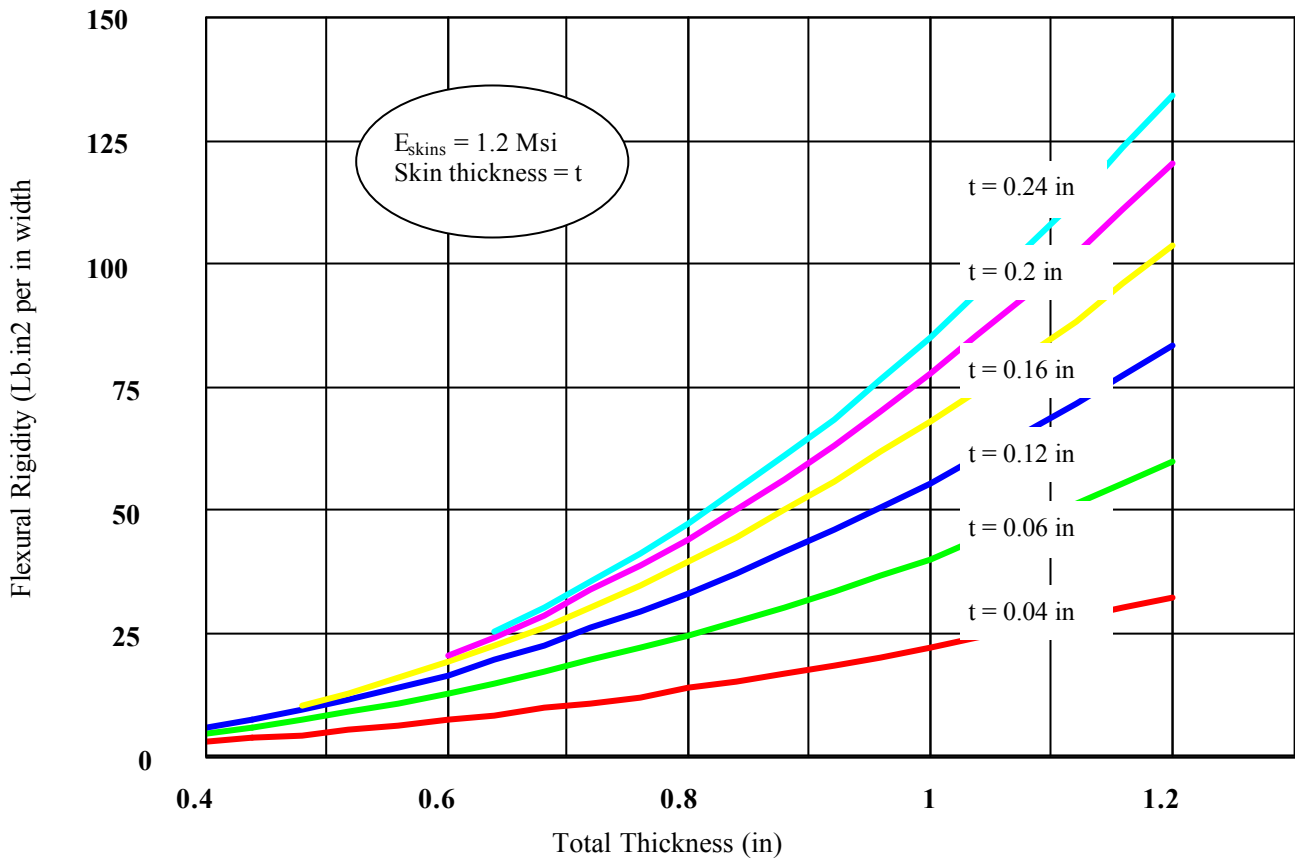
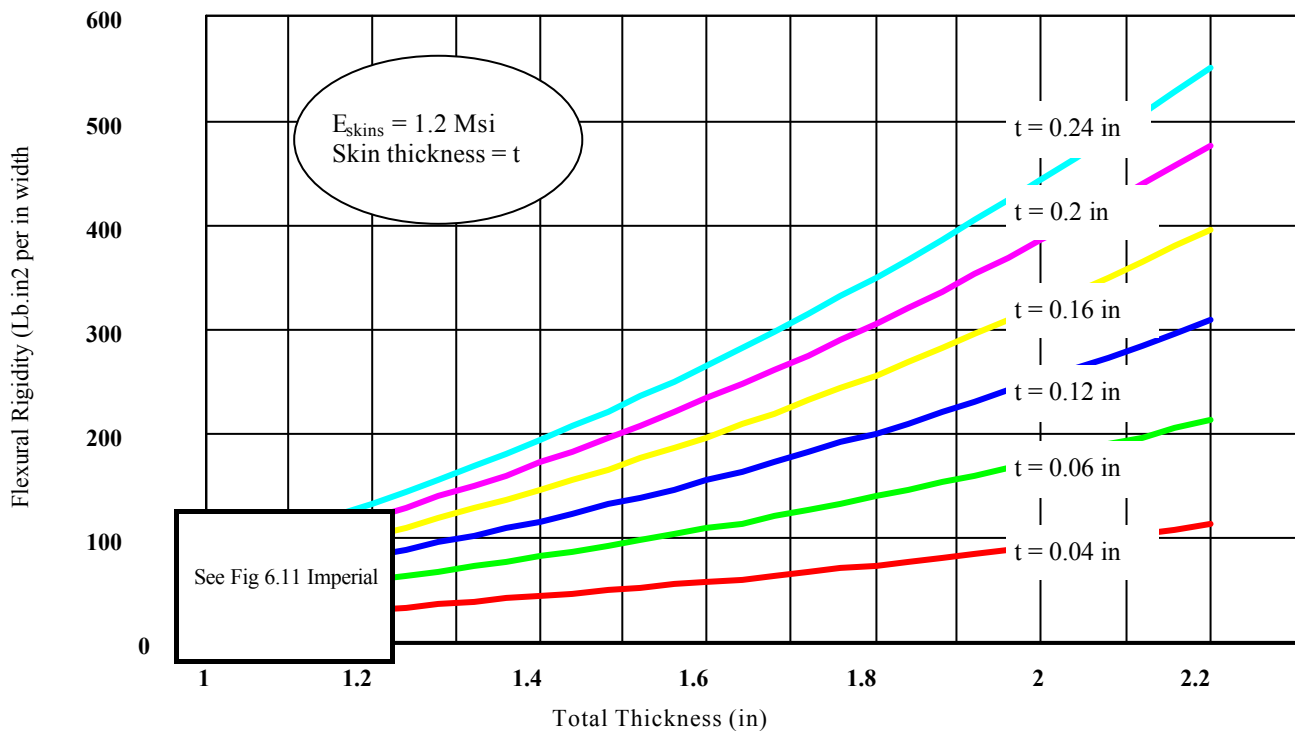


Fig 6.12 (Imperial)

Flexural Rigidity of Sandwich Beams Chopped Strand Mat / Polyester



Flexural Rigidity of Sandwich Beams with WR skins

Figures 6.13 (Imperial) and 6.14 (Imperial) plot the flexural rigidity of sandwich beams with Woven Roving laminate skins of various thickness'. Fig 6.13 (Imperial) is an enlargement of

the area below the scale of Fig 6.14 (Imperial) .

The stiffness of the core material is assumed to be negligible.

Fig 6.13 (Imperial)

**Flexural Rigidity of Sandwich Beams
Woven Roving/ Polyester**

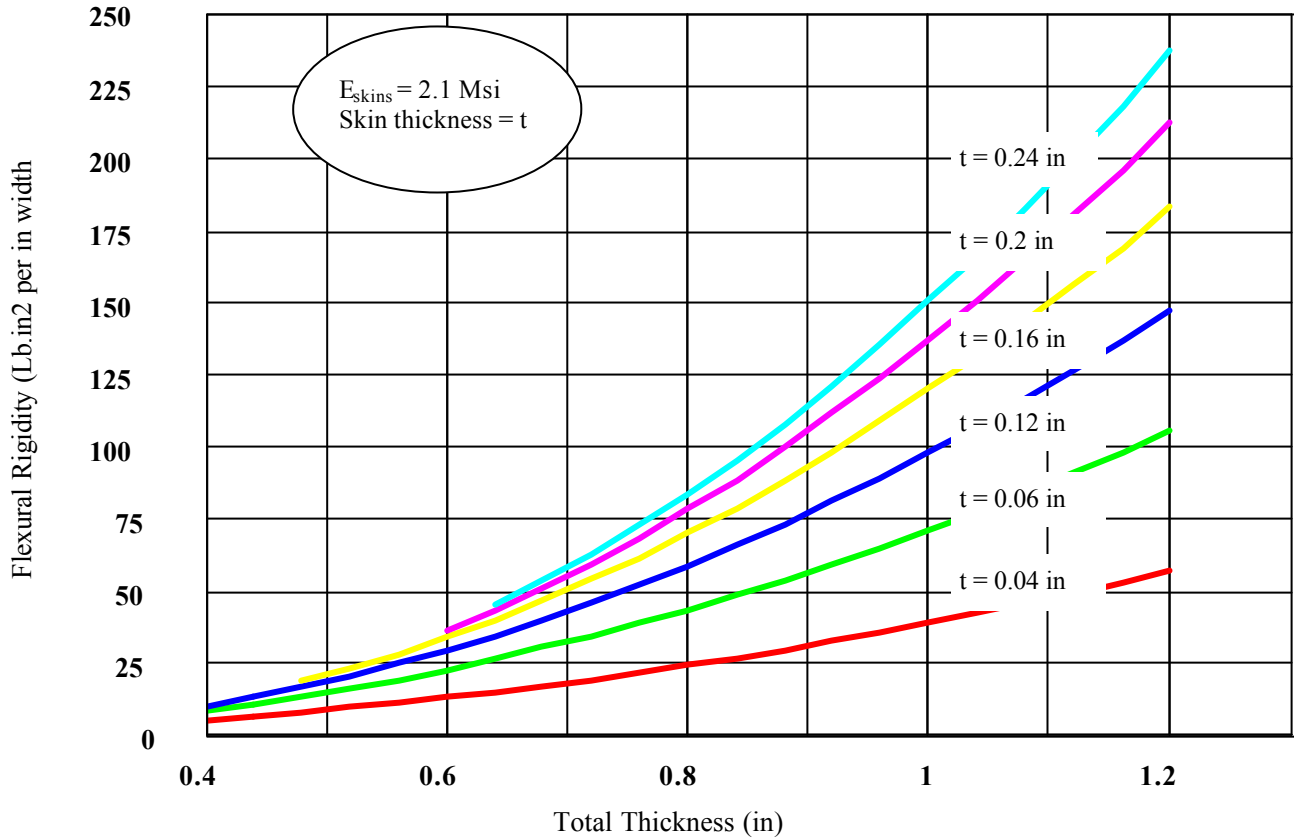


Fig 6.14 (Imperial)

**Flexural Rigidity of Sandwich Beams
Woven Roving/ Polyester**

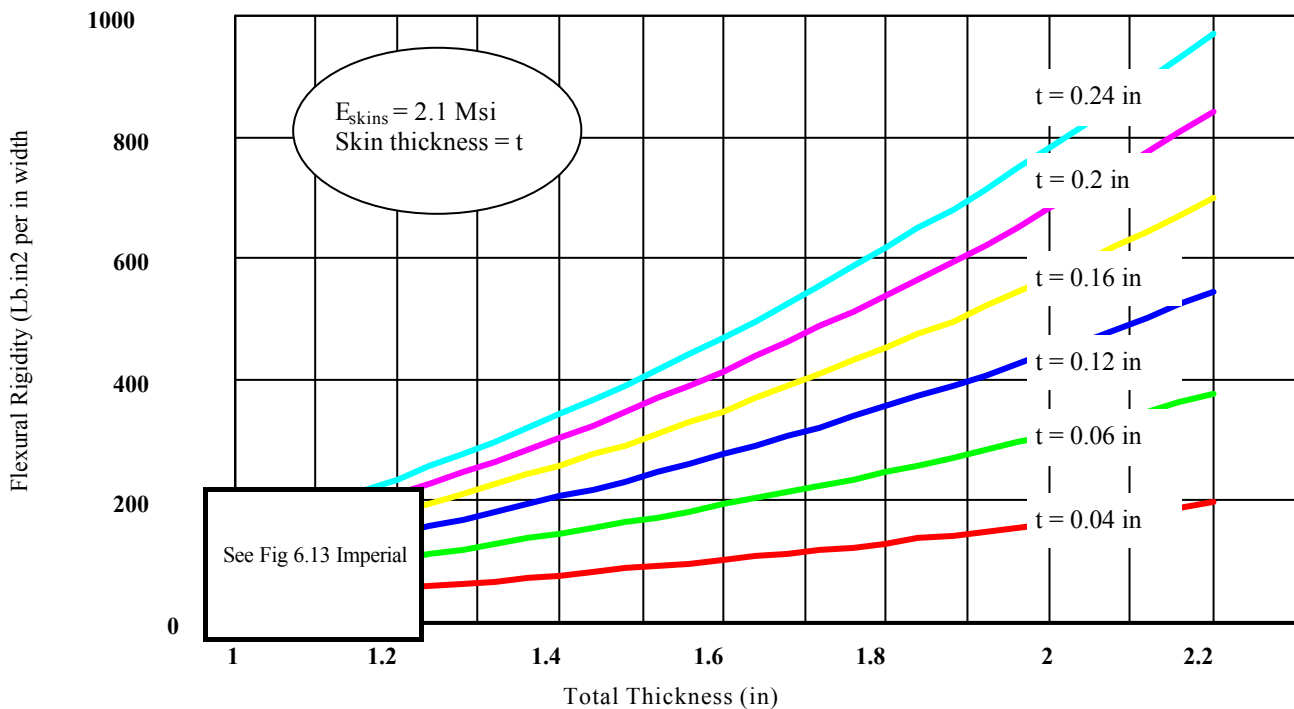


Fig 6.15 Data extracted from Literature- Mean values				VF %	WF % (R/G)	Modulus Values								Poisson's	
						TENSILE		COMPRESSIVE		SHEAR		FLEXURAL		Ratio	
						LONG	TRANS	LONG	TRANS	LONG	TRANS	LONG	TRANS	LONG	TRANS
						GPa	GPa	GPa	GPa	GPa	GPa	GPa	GPa	12	21
	GLASS FIBRE LAMINATES	RESIN	FIBRE												
1	CSM	ISOPH	E GLASS	20.2	35	9.33	9.33					9.59	9.59		
2	CSM	SB 406PA	E GLASS	18.43	32.45							9.1	9.1		
3	CSM	SB 406PA	E GLASS	22.5	38.2							10.56	10.56		
4	CSM	POLYESTER	E GLASS	12		6.5									
5	CSM	POLYESTER	E GLASS	17		7.8						7.3			
6	CSM	POLYESTER	E GLASS	20		8.6									
7	CSM	POLYESTER	E GLASS	20.5		8.9									
8	CSM	POLYESTER	E GLASS	20.5		9.05						8			
9	CSM	POLYESTER	E GLASS	20		9.1						8.25			
10	CSM	POLYESTER	E GLASS	25		9.9						9.8			
11	CSM	POLYESTER	E GLASS	19.5		10.05									
12	CSM	POLYESTER	E GLASS	13.5		7.8						6.3			
13	CSM	POLYESTER	E GLASS	14											
14															
15	CSM	POLYESTER	E GLASS	19	2:1	8.1		8.1				6.7			
16	WR/CSM	POLYESTER	E GLASS	26.5	1.3:1	11.72		11.93				9.5			
17	WR	POLYESTER	E GLASS	32	1:1	15.8		18				13.4			
18	UD/CSM	POLYESTER	E GLASS	27.7	1.2:1	21									
19															
20	RESIN - Cast	BIP837	E GLASS	ZERO		3.21	3.21	3.22	3.22					0.36	
21	Unidirectional 0 deg	BIP837	E GLASS	27		19.23		16.13		3.3		16.42		0.294	
22	Unidirectional 0 deg	BIP837	E GLASS	39		24.38		23.26		2.6		23.18		0.276	
23	Unidirectional 0 deg	BIP837	E GLASS	46		27.66		26.32		2.8		26.49		0.276	
24	Unidirectional 0 deg	BIP837	E GLASS	57		32.79		32.79		3.6		32.37		0.27	
25	Unidirectional 0 deg	BIP837	E GLASS	64		41		40		4		40.56		0.257	
26	Unidirectional 0 deg	EPOXY	E GLASS	45		38.6	8.27			4.14				0.26	
27															
28	Unidirectional 0 deg	BIP837	E GLASS	27		19.23		16.13		3.3		16.42		0.294	
29	Unidirectional 30 deg	BIP837	E GLASS	27		8.70		9.38						0.6	
30	Unidirectional 45 deg	BIP837	E GLASS	27		8		7.69						0.32	
31	Unidirectional 60 deg	BIP837	E GLASS	27		4.76		5.5						0.27	
32	Unidirectional 90 deg	BIP837	E GLASS	27		5.5		6						0.07	
33															
34	Unidirectional 0 deg	BIP837	E GLASS	27		19.23		16.13		3.3		16.423		0.294	
35	CROSS PLY 0,90,90,0	BIP837	E GLASS	27		15.15		18.75						0.1	
36	ANGLE PLY +/-45	BIP837	E GLASS	27		6.25		8.07						0.37	
37	MULTI DIR 0,45,-45,-45,45,0	BIP837	E GLASS	46		17.79		16.67						0.31	
38															
39	CARBON FIBRE LAMINATES														
40	Unidirectional 0 deg	EPOXY	TYPE A	62.5		112	10			5		122		0.33	0.032
41	Unidirectional 0 deg	EPOXY 3501-5A	AS	66		138	8.96			7.1				0.3	
42	Unidirectional 0 deg	EPOXY 3601	T300	60		132	10	123	10	5					
43	Unidirectional 0 deg	EPOXY 976	T300	66		157	9	167	13	7				0.228	0.0133
44	Unidirectional 0 deg	EPOXY XD927	XAS 3000	60		131									
45	Unidirectional 0 deg	EPOXY N5208	T300	70		181	10.3			7.17				0.28	
46	Unidirectional 0 deg	EPOXY	H-IM6	66		203	11.2			8.4				0.32	
47															
48	0,+/-45,90	EPOXY 3620	T300	60											
49															
50	0,90 5s SATIN	EPOXY XD927	XAS 3000	60		84	72								
51	0,90 2*2 TWILL	EPOXY XD927	XAS 3000	60		74	73								
52															
53	KEVLAR FIBRE LAMINATES														
55	Unidirectional 0 deg	EPOXY	K49	60		76	5.5			2.3				0.34	
56	Unidirectional 0 deg	EPOXY	K49	60		76	5.51			1.86				0.34	
59															
60	0,90	ISOPHTH	K49	48.4	53	26						23.8			
61	0,90	ISOPHTH	K49 SIZED	50	55	26		16.3				23.4			
62															

	Strength Values								Ref	Notes
	TENSILE		COMPRESSIVE		ILSS	SHEAR	FLEXURAL			
	LONG	TRANS	LONG	TRANS	LONG	FRENGT	LONG	TRANS		
	MPa	MPa	MPa	MPa	MPa	MPa	MPa	MPa		
1	125	125					161	161	18	<div>Note</div> <div>To convert GPa to Msi multiply GPa by 0.145038</div> <div>To convert MPa to psi multiply MPa by 1.45038</div> <div>Because: -</div> <div>1GPa = 1000 MPa</div> <div>But 1MPa = 1N/mm² = 1MN/m² = 145.038 psi</div> <div>So 1GPa = 1000 x 145.038 psi = 145038 psi</div>
2									7	
3									7	
4	70						155		8	
5	90						190		8	
6	105						190		8	
7	108						210		8	
8							228		8	
9									8	
10							258		8	
11							210		8	
12	75								8	
13	87						160		8	
14										
15	108		150		7		190		9	
16	186		145		10		280		9	
17	250		190		9		285		9	
18	460		240		12				9	
19										
20	51	51	94	94					10	
21	420		241		42.93		337		10	
22	571		317		41.54		556		10	
23	616		330		43.98		637		10	
24	725		398		41.35		686		10	
25	858		385		38.86		815		10	
26	1062	31	610	118		72			6	
27										
28	420		241		42.93		337		10	Repeated for comparison
29	89		139						10	
30	60		117						10	
31	39		100						10	
32	30		87						10	
33										
34	420		241		42.93		337		10	Repeated for comparison
35	303		194						10	
36	77		110						10	
37	327		183						10	
38										
39										
40	1700	58			82		2000		11	
41	1448	51.7	1448	206.9		93.1			12	
42	1630	60	1500	270	110	100			13	
43	1517	49	1593	253		112.41			14	
44	1203				72		1381		15	
45	1500	40	1500	246		68			6	
46	3500	56	1540	150		98			6	
47										
48	554		660						13	
49										
50	791	822			58		1020	1005	15	
51	630	678			57		882	912	15	
52										
53										
55	1400	12	235	53		34			6	
56	1240		275		48				16	
59										
60	420		115		15-20		255		17	
61	420		115		12.8		255		9	
62										

Note

To convert GPa to Msi multiply GPa by 0.145038

To convert MPa to psi multiply MPa by 145.038

Because: -

1GPa = 1000 MPa

But 1MPa = 1N/mm² = 1MN/m² = 145.038 psi

So 1GPa = 1000 x 145.038 psi = 145038 psi = 0.145038 Msi

Data derive from Unit property values

“Unit” Property values called for in BS 4994 and BS6464 (Ref 6.2) have been used to determine design data in conventional units for chopped strand mat laminates in Fig 6.17 and for Woven Roving laminates in Fig 6.18. The basic data from which these have been derived is given in Fig 6.16.

Fig 6.16 Design Data - Unit Property Values			UTUS		Unit Modulus		Lap Shear Strength	
E Glass Laminates - Polyester or Vinyl ester			N/mm per kg/m ² glass	Lb/in per oz/ft ² glass	N/mm per kg/m ² glass	Lb/in per oz/ft ² glass	N/mm ²	Lb/in ²
Type of Reinforcement								
Chopped strand mat			200	349	14000	24416	7	1015
Woven Roving cloth	Square woven		250	436	16000	27904	6	870
	Low Bias*	Major dir	430	750	23000	40112	6	870
		Minor dir	90	157	10000	17440	6	870
	High Bias**	Major dir	450	785	25000	43600	6	870
Continuous Roving			500	872	28000	48832	6	870

* Low Bias = less than 5.1. to 1 ratio of reinforcement in the two directions ** High Bias = 5.1 to 1 or greater

Fig 6.17 Lower bound properties of E glass CSM laminates at various glass contents							
Laminate :		CSM	CSM	CSM	CSM	CSM	CSM
Density of resin	g/cc	1.2	1.2	1.2	1.2	1.2	1.2
Density of glass	g/cc	2.55	2.55	2.55	2.55	2.55	2.55
Resin /glass ratio by weight		1.855	2	2.25	2.5	2.75	3
Weight fraction %	%	35.03	33.33	30.77	28.57	26.67	25.00
Volume Fraction Fibre %	%	20.24	19.05	17.30	15.84	14.61	13.56
Laminate Thickness for 1 kg/m ² glass (mm)		1.94	2.06	2.27	2.48	2.68	2.89
Tensile strength	N/mm ²	103	97	88	81	75	69
Compressive strength	N/mm ²	103	97	88	81	75	69
Shear strength (In-plane) (80% Tensile) (Ref 3 Table 4.1)	N/mm ²	83	78	71	65	60	55
Lap shear strength	N/mm ²	7	7	7	7	7	7
Tensile Modulus	N/mm ²	7224	6800	6175	5655	5216	4841
Compressive Modulus	N/mm ²	7224	6800	6175	5655	5216	4841
Poisson's Ratio (Ref 4)		0.33	0.33	0.33	0.33	0.33	0.33
Shear Modulus (in-plane) Classical iso eqn	N/mm ²	2716	2556	2321	2126	1961	1820

Fig 6.18 Lower bound properties of E glass Woven Roving laminates at various glass contents							
Laminate :		WR	WR	WR	WR	WR	WR
Density of resin	g/cc	1.2	1.2	1.2	1.2	1.2	1.2
Density of glass	g/cc	2.55	2.55	2.55	2.55	2.55	2.55
Resin /glass ratio (by weight)		0.85	1	1.15	1.3	1.5	1.65
Weight fraction Fibre %	%	54.1	50.0	46.5	43.5	40.0	37.7
Volume Fraction Fibre %	%	35.6	32.0	29.0	26.6	23.9	22.2
Laminate Thickness for 1 kg/m ² glass (mm)		1.10	1.23	1.35	1.48	1.64	1.77
Tensile strength	N/mm ²	227	204	185	169	152	141
Compressive strength	N/mm ²	227	204	185	169	152	141
Shear strength (In-plane)	N/mm ²	66*					
Lap shear strength	N/mm ²	870	870	870	870	870	870
Tensile Modulus	N/mm ²	14540	13060	11850	10840	9740	9050
Compressive Modulus	N/mm ²	14540	13060	11850	10840	9740	9050
Poisson's Ratio		-	0.24	-	-	-	-
Shear Modulus (in-plane)	N/mm ²	2020*	0	0	0	0	0
* Ref 5							

Fig 6.17 (Imperial) Lower bound properties of E glass CSM laminates at various glass contents

Laminate :		CSM	CSM	CSM	CSM	CSM	CSM
Density of resin	Lb/in ³	0.043	0.043	0.043	0.043	0.043	0.043
Density of glass	Lb/in ³	0.092	0.092	0.092	0.092	0.092	0.092
Resin /glass ratio by weight		1.855	2	2.25	2.5	2.75	3
Weight fraction %	%	35.03	33.33	30.77	28.57	26.67	25.00
Volume Fraction Fibre %	%	20.24	19.05	17.30	15.84	14.61	13.56
Laminate Thickness for 1 oz/ft ² glass (in)		0.023	0.025	0.027	0.030	0.032	0.035
Tensile strength	Ksi	14.98	14.10	12.80	11.73	10.82	10.04
Compressive strength	Ksi	14.98	14.10	12.80	11.73	10.82	10.04
Shear strength (In-plane) (80% Tensile) (Ref 3 Table 4.1)	Ksi	11.98	11.28	10.24	9.38	8.65	8.03
Lap shear strength	psi	1015	1015	1015	1015	1015	1015
Tensile Modulus	Ksi	1048	986	896	820	757	702
Compressive Modulus	Ksi	1048	986	896	820	757	702
Poisson's Ratio (Ref 4)		0.33	0.33	0.33	0.33	0.33	0.33
Shear Modulus (in-plane) (Classical iso eqn)	Ksi	394	371	337	308	284	264

Fig 6.18 (Imperial) Lower bound properties of E glass Woven Roving laminates at various glass contents

Laminate :		WR	WR	WR	WR	WR	WR
Density of resin	Lb/in ³	0.043	0.043	0.043	0.043	0.043	0.043
Density of glass	Lb/in ³	0.092	0.092	0.092	0.092	0.092	0.092
Resin /glass ratio (by weight)		0.85	1	1.15	1.3	1.5	1.65
Weight fraction Fibre %	%	54.1	50.0	46.5	43.5	40.0	37.7
Volume Fraction Fibre %	%	35.5	31.9	28.9	26.4	23.8	22.1
Laminate Thickness for 1oz/ft ² glass (in)		0.013	0.015	0.016	0.018	0.020	0.021
Tensile strength	Ksi	32.8	29.4	26.7	24.4	22	20.4
Compressive strength	Ksi	32.8	29.4	26.7	24.4	22	20.4
Shear strength (In-plane)	Ksi	9.6*					
Lap shear strength	psi	870	870	870	870	870	870
Tensile Modulus	Ksi	2100	1884	1709	1564	1405	1306
Compressive Modulus	Ksi	2100	1884	1709	1564	1405	1306
Poisson's Ratio		-	0.24	-	-	-	-
Shear Modulus (in-plane)	Ksi	293*					
* Ref 5							

Data on DERA KANE® laminates

The data are intended to highlight the property differences existing between the various families of DERA KANE resins.

Specific values listed for a particular resin represent typical properties for other members of the resin family.

Typical properties, not to be construed as specifications

Laminate Thickness - 6mm

Laminate construction - V/M/M/Wr/M/Wr/M

V - std. 0.25mm corrosion grade C-glass veil, M - Chopped strand Mat

of 450 g/m², Wr - Woven roving Glass, Glass Content - 40%

Laminates of this type can be expected to be produced with a Coefficient of Variation of less than 10%. If the design value was required to be the mean value less two standard deviations. C of V = Standard Dev / mean.

Then Design value = Mean - 2*(C of V * Mean).

For example the mean Flexural strength at room temperature of 411-45 could be specified in the purchase requirement as 204 MPa.

Hence the design value = 204 - 2*(0.1 * 204) = 163 MPa.

Fig 6.19 Hand Lay-up DERA KANE* Epoxy Vinyl Ester Resin Laminates at Elevated Temperatures

	ASTM	DERAKANE Grade											
	D3299	411-45		441-400		8084		470-36		510A		510N	
	FLEXURAL STRENGTH												
	MPa	MPa	Ksi	MPa	Ksi	MPa	Ksi	MPa	Ksi	MPa	Ksi	MPa	Ksi
Room Temp	131	204	29.6	199	28.9	194	28.1	165	23.9	164	23.8	172	24.9
66°F		197	28.6	194	28.1	158	22.9	---	---	164	23.8	165	23.9
93°F		189	27.4	169	24.5	127	18.4	169	24.5	165	23.9	177	25.7
107°F		101	14.6	159	23.1	81	11.7	----	----	145	21.0	168	24.4
121°F		34	4.9	85	12.3	30	4.4	166	24.1	83	12.0	127	18.4
135°F		----	----	30	4.4	----	----	----	----	----	----	----	----
149°F		22	3.2	----	----	----	----	145	21.0	----	----	----	----
163°F		----	----	----	----	----	----	83	12.0	----	----	----	----
177°F		----	----	----	----	----	----	55	8.0	----	----	----	----
	FLEXURAL MODULUS												
		GPa	Ksi	GPa	Ksi	GPa	Ksi	GPa	Ksi	GPa	Ksi	GPa	Ksi
Room Temp	5.5	7.1	1030	7.9	1146	7.8	1131	8.6	1247	7.6	1102	7.9	1146
66°F		7	1015	7.6	1102	5.7	827	----	----	7.6	1102	7.6	1102
93°F		5.9	856	6.6	957	4.6	667	8.1	1175	6.2	899	7	1015
107°F		3.4	493	6.1	885	3.4	493	----	----	5.7	827	6.6	957
121°F		1.6	232	4.1	595	1.6	232	7.3	1059	4	580	6.3	914
135°F		----	----	1.4	203	----	----	----	----	----	----	----	----
149°F		1.6	232	----	----	----	----	5.7	827	----	----	----	----
163°F								4.2	609	--	----	--	----
177°F								3.6	522	--	----	--	----
	TENSILE STRENGTH												
		MPa	Ksi	MPa	Ksi	MPa	Ksi	MPa	Ksi	MPa	Ksi	MPa	Ksi
Room Temp	83	143	20.7	148	21.5	198	28.7	124	18.0	113	16.4	145	21.0
66°F		173	25.1	193	28.0	188	27.3	---	---	126	18.3	154	22.3
93°F		150	21.8	161	23.4	170	24.7	128	18.6	134	19.4	152	22.0
107°F		125	18.1	165	23.9	146	21.2	----	----	128	18.6	136	19.7
121°F		81	11.7	190	27.6	141	20.5	130	18.9	117	17.0	114	16.5
135°F		----	----	151	21.9	----	----	----	----	----	----	----	----
149°F		53	7.7	----	----	----	----	117	17.0	----	----	----	----
163°F		----	----	----	----	----	----	99	14.4	----	----	----	----
177°F		----	----	----	----	----	----	76	11.0	----	----	----	----
	TENSILE MODULUS												
		GPa	Ksi	GPa	Ksi	GPa	Ksi	GPa	Ksi	GPa	Ksi	GPa	Ksi
Room Temp		12	1740	9.2	1334	9.9	1436	11.4	1653	10.3	1494	9.5	1378
66°F		12.5	1813	8.9	1291	10.1	1465	----	----	11.7	1697	10.4	1508
93°F		10.3	1494	9.2	1334	9.7	1407	11.8	1711	9	1305	10.5	1523
107°F		7.7	1117	9	1305	8.1	1175	----	----	8.7	1262	10.1	1465
121°F		5.2	754	8.3	1204	6.5	943	11.8	1711	8.3	1204	9.1	1320
135°F		----	----	8.4	1218	----	----	----	----	----	----	----	----
149°F		----	----	----	----	----	----	7.2	1044	----	----	----	----
163°F								6.3	914	--	----	--	----
177°F								5	725	--	----	--	----

**Fig 6.20 Mean value data for unidirectional 'E' glass / Derakane* Composites
Produced by Filament winding and Compression mouldng.**

Physical property	Units		Test Method ASTM-	Derakane®* 411-45		Derakane® 470-36		Derakane® 510-A40		Derakane® 8084	
	Metric	Impe- rial		Metric	Imp	Metric	Imp	Metric	Imp	Metric	Imp
Glass Content (wt %)			Burn Off	69.3		70		65.3		68.1	
Glass Content (vol %)			Burn Off	49.7		51.6		49.5		48.1	
Specific Gravity			D792	1.85		1.84		2		1.87	
Longitudinal Tensile Stress	(MPa)	(Ksi)	D3039	872	126	771	112	860	125	829	120
Modulus	(GPa)	(Msi)		37.7	5.47	39.4	5.71	38.4	5.57	39	5.66
Elongation	(%)			2.42		2.02		2.29		2.16	
Poisson's Ratio				0.3		0.3		0.27		0.27	
Transverse Tensile Stress	(MPa)	(Ksi)	D3039	33.6	4.87	35.5	5.15	46.1	6.69	42.9	6.22
Modulus	(GPa)	(Msi)		10.3	1.49	10.6	1.54	9.7	1.41	8.3	1.2
Longitudinal Compressive Stress	(MPa)	(Ksi)	<1>	605	87.7	925	134	779	113	760	110
Modulus	(GPa)	(Msi)		35.4	5.13	37.6	5.45	37.6	5.45	36.5	5.29
Transverse Compressive Stress	(MPa)	(Ksi)	<1>	129	18.7	163	23.6	129	18.7	112	16.2
Modulus	(GPa)	(Msi)		9.4	1.36	10.2	1.48	11.2	1.62	7.9	1.15
Longitudinal Flexural Stress	(MPa)	(Ksi)	D790	1244	180	1356	197	1248	181	1180	171
Modulus	(GPa)	(Msi)		38.5	5.58	37.2	5.40	37.6	5.45	38.6	5.59
Transverse Flexural Stress	(MPa)	(Ksi)	D790	73.1	10.6	47.6	6.9	72.4	10.5	88.9	12.9
Modulus	(GPa)	(Msi)		9	1.3	9.6	1.39	9.4	1.36	9	1.3
In Plane Shear Stress	(MPa)	(Ksi)	<2>	139	20.1	109	15.8	155	22.5	133	19.3
Modulus	(GPa)	(Msi)		4.1	0.59	4.3	0.62	5.1	0.74	3.9	0.57
Inter laminar Shear Stress	(MPa)	(Ksi)	D2344	66.9	9.7	71.7	10.4	68.3	9.9	58.6	8.5
Interfacial Shear Stress	(MPa)	(Ksi)	<3>	79.3	11.5	80.7	11.7	70.3	10.2	77.2	11.2
Longitudinal CLTE	10 ⁶ / °C	10 ⁶ / °F	E381	8.7	4.8	6	3.3	7.9	4.4	6.8	3.8
Transverse CLTE	10 ⁶ / °C	10 ⁶ / °F	E381	35.2	19.5	29.3	16.3	30.6	17	41	22.8
<div> <div><1>IITRI Compressive Test</div> <div><2> Iosipescu Shear test</div> </div> <div> <div><3> Compressive Micro debond Test</div> <div>* Trade mark of Dow Chemical Company</div> </div>											

Fig 6.22 Low Temperature properties of DERAKANE* 411-45 resin / E glass CSM and WR Laminate

Mean values at temperature of:				
Temperature		75°F / 23.9°C	-45°F / -42.8°C	
Tensile strength	N/mm ²	214	200	
	Ksi	31	29	
Tensile Modulus	N/mm ²	13100	15200	
	Msi	1.9	2.2	
Flexural Strength	N/mm ²	228	276	
	Ksi	33	40	
Flexural Modulus	N/mm ²	8280	8970	
	Msi	1.2	1.3	
Laminate Construction : - M/Wr/M/Wr/M M - Chopped Strand Mat- 450 g/m ² Wr - woven Roving - 800 g/m ²		Ref:- Chemical Resistance & Engineering Guide- form 125-00043-594 SMG * Trade mark of Dow Chemical Company		

Epoxy Prepreg

Prepreg is a ready to mould compound of reinforcement fibres and resin in the form of a sheet. The resin is cured to a partial state (the “B” stage) before supply to the moulder. Final cure is achieved with heat and pressure.

Resins used for prepreg include epoxy, polyester, phenolic, polyimide and some high performance thermoplastics. The most commonly used reinforcement fibre for prepregs is carbon but glass, aramid and boron fibres are also used.

The following tables are a small selection of mean value data for epoxy prepreg laminates of glass or carbon fibre. The data is by courtesy of Advanced Composites Group

Laminates of this type can be expected to be produced with a Coefficient of Variation (C of V) of less than 4%.

If the design value was required to be the mean value less two standard deviations.

$$(C \text{ of } V = \text{Standard Deviation} / \text{mean}).$$

Then Design value = Mean - 2(C of V x Mean).

For example from Fig 6.23 the Flexural strength at 22°C of Woven T300 /Epoxy could be specified in the purchase requirement as a Mean value of 1100 MPa. with Max C of V of 4%.

Hence the design value would be: -

$$1100 - 2(0.04 \times 1100) = 1012 \text{ MPa.}$$

Fig 6.23 Mean values for Graphite / Epoxy UD laminate

Laminate :				
Resin System	ACG LTM 25			
Reinforcement	T300 UD Prepreg 0° configuration			
Volume Fraction Fibre	60 %			
Cure	24 hour @ 140°F/60°C Autoclave			
				After 2 hr boil
		RT Dry	122°F/ 50°C Dry	72°F/ 22°C
Tensile strength		-	-	-
Compressive strength		-	-	-
Inter lamina Shear strength	MPa	89	67	84
	Ksi	12.9	9.7	12.2
Flexural strength	MPa	1800	1600	1540
	Ksi	261	232	223
Tensile Modulus		-	-	-
Flexural Modulus	GPa	119	133	118
	Msi	17.3	19.3	17.1

Fig 6.24 Mean values for Graphite / Epoxy Woven laminate

Laminate :				
Resin System	ACG MT8E			
Reinforcement	T300 280 g/m2 (3k) 4*4 Twill 0°/90° configuration			
Volume Fraction Fibre		55 %		
Cure		1 hour @ 248°F/120°C		
				After 2 hr boil
		72°F/ 22 °C	176°F/ 80°C	72°F/ 22°C
Tensile strength		-	-	-
Compressive strength		-	-	-
Inter lamina Shear strength	MPa	72	46	
	Ksi	10.4	6.7	-
Flexural strength	MPa	1100	690	
	Ksi	160	100	-
Tensile Modulus		-	-	-
Flexural Modulus	GPa	60	59	
	Msi	8.7	8.6	-

Fig 6.25 Mean values for Graphite / Epoxy Woven laminate

Laminate :					
Resin System	ACG MT9F				
Reinforcement	T800 200 g/m2 (6k) 2*2 Twill 0°/90° configuration				
Volume Fraction Fiber	55%				
Cure	1 hour @ 248°F/120°C				
					After 24 hr boil
		72°F/ 22°C	176°F /80°C	266°F/ 130°C	266°F/ 130 °C
Tensile strength	MPa	850			
	Ksi	123	-		-
Compressive strength	MPa	760			
	Ksi	110	-		-
Inter lamina Shear strength	MPa	70	65	40	30
	Ksi	10.2	9.4	5.8	4.4
Flexural strength	MPa	1200	1050	64	64
	Ksi	174	152	131	107
Tensile Modulus	GPa	80			
	Msi	11.6	-	-	-
Flexural Modulus	GPa	65	65	64	64
	Msi	9.4	9.4	9.3	9.3

Fig 6.26 Mean values for Graphite / Epoxy UD laminate				
Laminate :				
Resin System	ACG MT8E			
Reinforcement	T700 UD Prepreg 0° configuration			
Volume Fraction Fiber	60 %			
Cure	1 hour @ 248°F/120°C			
				After 2 hr boil
		72°F/ 22°C	176°F/ 80°C	72°F/ 22°C
Tensile strength	MPa	1726	-	-
	Ksi	250	-	-
Compressive strength	MPa	-	-	-
	Ksi	-	-	-
Inter lamina Shear strength	MPa	80	50	67
	Ksi	12	7.3	9.7
Flexural strength	MPa	1700	107	-
	Ksi	247	155	-
Tensile Modulus	GPa	121	-	-
	Msi	17.5	-	-
Flexural Modulus	GPa	124	125	-
	Msi	18.0	18.1	-

Fig 6.27 Mean values for Epoxy/E Glass Woven laminate				
Laminate :				
Resin System	ACG LTM25			
Reinforcement	E Glass 300 g/m2 8 Harness satin , Fibres 0°,90°			
Volume Fraction Fibre	55 %			
Cure	24 hour @ 140°F/60°C Autoclave			
				After 2 hr boil
		72°F/ 22°C	122°F/ 50°C	72°F/ 22°C
Tensile strength	MPa	-	-	-
	Ksi	-	-	-
Compressive strength	MPa	-	-	-
	Ksi	-	-	-
Interlamina Shear strength	MPa	53	47	36
	Ksi	7.7	6.8	5.2
Flexural strength	MPa	780	630	430
	Ksi	113	91	62
Tensile Modulus	GPa	-	-	-
	Msi	-	-	-
Flexural Modulus	GPa	26	23	27
	Msi	3.8	3.3	3.9

Fibreforce is a leader in pultrusion technology in Europe and has many years experience in the pultrusion industry, it is the largest UK manufacturer, with production facilities at its head office in Runcorn and at its Southern office at Clacton - on - Sea.

Quality Assurance

A quality assurance system that conforms to the ISO 9000 series of international standards operates throughout the company with BS EN ISO 9002 certification being maintained at Runcorn.

Fibreforce is an approved supplier to British Aerospace & British Gas.

Pultruded composites from Fibreforce offer a real alternative to traditional materials such as steel, aluminium, plastics and wood.

Lightweight but extremely strong, Fibreforce pultrusions will not rot or rust, have excellent electrical and thermal insulation properties and are highly resistant to chemical or atmospheric corrosion.

As one of the world's leading suppliers of fibre reinforced composites, Fibreforce stock a wide range of solid, hollow or open sided profiles suitable for all standard applications. All profiles can be easily fabricated using bolts, rivets or adhesive bonding.

The Fibreforce pultrusion process produces profiles with exceptional strength, toughness and consistency. Pultrusions offer a number of advantages over traditional materials such as steel, aluminium and timber, and their use is increasing across a wide range of applications and industries.

The almost infinite variety of possible profiles allows a high degree of design freedom. Tailored properties such as strength, stiffness, weight, and colour can be engineered by product design at the early stages of product development.

Benefits Of Fibreforce Pultrusions

- Exceptional Strength
- Weight Advantage Over Metal
- Good Corrosion Resistance
- Maintenance Free
- Low Thermal Conductivity
- Effective Electrical Insulation
- Antistatic
- Electromagnetic Transparency
- Promotes Part Consolidation
- Excellent Dimensional Stability And Accuracy
- Good High And Low Temperature Performance
- Excellent Fire Properties

[See reference section for contact details](#)

Products Available From Fibreforce

Both standard and custom profiles are available from Fibreforce

FORCE 800

The FORCE 800 series from Fibreforce is a range of structural profiles specially selected for their engineering properties and designed to provide the optimum performance for each application. All profiles are held in stock at Fibreforce and are available for immediate despatch.

Typical Mechanical Properties

	Units	Longitudinal	Transverse
Tensile Strength	MN/m2	300	55
Compressive Strength	MN/m2	200	100
Compressive Modulus	GN/m2	17	7
Shear Strength	MN/m2	60	60
Shear Modulus	GN/m2	3	3
Flexural Strength	MN/m2	300	100
Flexural Modulus	GN/m2	12	5

Custom Pultrusions

Pultrusion is a technique for the continuous manufacture of fibre reinforced composite profiles. By incorporating glass, carbon, aramid and other high performance fibres into a range of high performance resins, physical properties can be achieved to meet the needs of engineers in a wide variety of applications.

A custom pultrusion is a pultruded product custom designed to meet the requirements of the specification for a particular application.

The Profile

Shape

Profiles can be solid, hollow or open sided - virtually any constant cross section can be pultruded. Pultrusion is a continuous moulding process producing straight cut lengths of sections - the lengths being determined by transport constraints. Profiles can also be supplied coiled.

Reinforcements

Typical reinforcements used are glass fibre and carbon in rovings and to achieve the required physical characteristics it is possible to vary the type, form, location and quantity of reinforcements used in the profile.

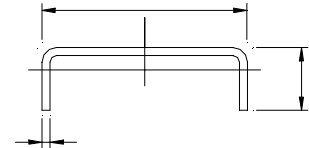
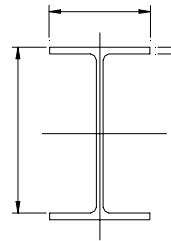
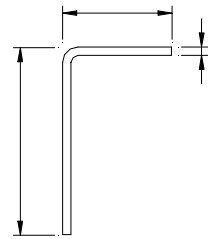
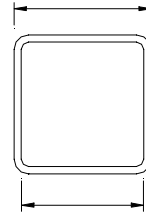
Resin System

Existing resin systems (polyester, vinyl ester, epoxy and modar) can be modified or special resins used to ensure that the profile can operate within the required environment.

Design

Design of both composite and profile is computer assisted to ensure maximum performance with minimum cost. Control of production equipment is by sophisticated production engineering techniques and all products are manufactured in accordance with ISO 9002.

Angle	Force 815	25 mm x 25 mm x 3 mm
	Force 814	50 mm x 50 mm x 6 mm
	Force 813	50 mm x 75 mm x 8 mm
	Force 812	75 mm x 75 mm x 4 mm
Box	Force 824	38 mm x 38 mm x 3 mm
	Force 823	44 mm x 44 mm x 6 mm
	Force 822	51 mm x 51 mm x 3.2 mm
	Force 820	100 mm x 100 mm x 4 mm
Channel	Force 821	51 mm x 51 mm x 38 id
	Force 819	75 mm x 25 mm x 5 mm
	Force 808	100 mm x 40 mm x 5 mm
	Force 831	200 mm x 60 mm x 8 mm
I Beam	Force 807	200 mm x 50 mm x 10 mm
	Force 818	102 mm x 51 mm x 6.35 mm
	Force 817	150 mm x 150 mm x 10 mm
	Force 816	200 mm x 200 mm x 10 mm
Special	Force 811	Tube 38 mm od x 33 mm id
	Force 810	Rung 34 mm od x 25 mm id
	Force 809	Kerb Angle 38 x 26 x 6.35

**Fig 6.28 Force 800 Engineering Properties**

SECTION	PROFILE	Area (mm ²)	WT (g/m)	ELong (GPa)	IYY (mm ⁴)	IXX (mm ⁴)	y' (mm)	x' (mm)
Angle	25x25x3	141	257	17.2	8.19 x 10 ³	8.19 x 10 ³	7.36	7.36
Angle	50x50x6	547	1018	17.2	126 x 10 ³	131 x 10 ³	14.70	14.70
Angle	75x50x8	905	1618	17.2	180 x 10 ³	504 x 10 ³	25.47	12.97
Angle	75x75x4	571	1012	17.2	318 x 10 ³	318 x 10 ³	20.40	20.40
Channel	73x25x5	574	1092	17.2	411x10 ³	29.2x10 ³	7.06	
Channel	100x40x5	850	1503	17.2	1.21 x 10 ⁶	119 x 10 ³	10.74	
Channel	200x60x8	2360	4050	17.2	12.3 x 10 ⁶	671 x 10 ³	14.56	
Channel	200x50x10	2777	5021	17.2	13.7 x 10 ⁶	427 x 10 ³	12.17	
I-Beam	102x51x6.35	1210	2262	17.2	141 x 10 ³	1.84 x 10 ⁶		
I-Beam	150x150x10	4382	7335	17.2	5.61 x 10 ⁶	16.8 x 10 ⁶		
I-Beam	200x200x10	5882	9935	17.2	13.3 x 10 ⁶	41.6 x 10 ⁶		
Box	38x38x3	416	748	17.2	84.5 x 10 ³			
Box	44x44x6	912	1704	17.2	225 x 10 ³			
Box	51x51x3.2	602	1051	17.2	227 x 10 ³			
Box	100x100x4	1536	2729	17.2	2.36 x 10 ⁶			
Tube	38x33	298	508	17.2	47.0 x 10 ³			
Rung	34x25	343	614	17.2	37.3 x 10 ³			
Kerb	38x25x6.35	673	1229	17.2				
Special	51x51x38dia	1432	2527	17.2	446 x 10 ³			

DESIGN CONSIDERATIONS WITH PULTRUSION

Performance criteria determine whether a standard structural element will be a suitable solution for a particular design brief. If not, then a custom shape must be designed. The geometrical shape of a pultrudate is a function of the performance required in service and the restrictions imposed by the production process. The critical aspects of pultrudate geometry are; thickness, radii, overall size, number of cavities and location of the reinforcement layers.

Thickness

Thick sections require longer time for the heat of the die to penetrate and therefore run more slowly than thin sections. It is therefore desirable to keep wall thickness to a minimum commensurate with achieving the required structural properties. The thickness range which is pultrudable is from 1mm to 50mm or more. However a more practical range is from 2mm to 20mm.

Radii

As a general rule **corner radii** should be as large as is feasible in order to avoid stress concentrations. This is not always possible particularly if a tooling split line occurs at the radius. In which case a sharp corner cannot be avoided. Thickness should be kept constant throughout the radius otherwise the reinforcement pack needs local modification. An acceptable minimum internal radius is 1.5 mm and external radius of : wall thickness plus internal radius.

Overall size

The maximum size which can be pultruded is of course dictated by the dimensions and the pulling capacity of the machine available. Pultrusion machines in common use vary from as small as 125 mm by 40 mm with a **pulling force** of 500 kg, to 1000 mm by 165 mm with a pulling force of 15 tonnes. There is therefore considerable scope for the design of small solid sections at one end of the scale, to very large hollow sections, at the other.

Cavities

Hollow profiles are possible and in fact common in pultrusion. They are very efficient structures but they do present production problems, particularly if there are multi-cavities. If hollow profiles can be avoided without detriment to performance, then do so. Otherwise minimise the number of cavities, the fewer there are the better. Hollow profiles often require overlapping reinforcement. Hence thickness changes may be necessary to accommodate the excess material.

Structural considerations

Glass fibre pultrusions have a significantly lower tensile modulus than steel or aluminium. This results in the design procedure being concerned initially with the deflection limits and only subsequently with the strength requirements which are generally found to be satisfactory.

The relatively **low modulus** of **glass fibre** pultrusions also requires that buckling characteristics be assessed a little more critically than would be the case with a steel component which have an abundance of stiffness relative to strength.

Carbon fibre pultrusions on the other hand have a **high modulus**, of the same order as steel, thus buckling is a less significant problem.

The **shear stiffness** of composite materials is relatively low. This can give rise to **deflections** in beams **due to shear** which are appreciable, possibly of similar magnitude to those due to bending. Therefore it is essential to calculate these deflections to ensure they are insignificant or taken into account. This is particularly important with deep sections and short spans.

Composites do not exhibit a yield zone in their stress/strain response. Therefore 'local yielding' cannot be relied upon to solve certain design problems, as is the case with steel design. **Stress concentrations**, perhaps due to misalignment of elements, cannot be left to yield as might be the practice with steelwork. The stress will remain in place and may result in premature failure. The lack of a yield zone in composites is easily accommodated by for example the use of large washers with bolted connections to allow local stresses to be spread more evenly.

If the matrix resin in a composite does not have sufficient '**strain to failure**' available then microcracking may occur at a level substantially below the ultimate strength of the component. This allows the ingress of the environment which, if it is particularly aggressive to the fibre, can result in premature failure. Hence the use of composite materials in aggressive environments such as chemical plant has prompted the assessment of strain limited design methods. These recognise that although a structure may be designed adequately within stress limitations, it may be subject to strains which are not acceptable. A strain limitation which is applied in BS4994 (which is concerned with the design of GRP Tanks and Vessels) is a maximum of 0.2%. This has been demonstrated to be a reasonable level for chemical plant.

For contact details see Reference Section

Standard pultruded structural elements

Standard pultruded structural elements produced by **Creative Pultrusions Inc** are shown in the tables. Performance characteristics and data on these profiles are given in Figs 6.29 & 6.30 allowing structural analysis to be carried out on a 'Strength of materials' basis. As when designing with metals,

wood, etc, for global analysis, pultruded materials and elements are assumed to be homogeneous. This allows the conventional engineering formulae to be used to interpolate test results to the particular design problem.

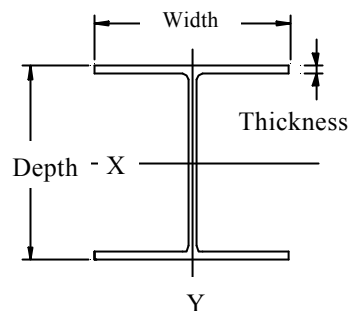
Fig 6.29		Series 1500 & 1525		Series 1625	
Properties of Pultruded Shapes Creative Pultrusions Inc		Mat + Roving 40 to 45% glass		Mat + Roving 40 to 45% glass	
Coupon values	Units	Long	Trans	Long	Trans
Tensile Strength	MPa	207	48	259	69
Tensile Modulus	GPa	17.2	5.5	20.7	6.9
Flexural Strength	MPa	207	69	259	97
Flexural Modulus	GPa	11.0	5.5	13.8	6.9
Izod Impact	ft.lb./in.	28	4	30	5
Compressive Strength	MPa	207	103	259	138
Compressive Modulus	GPa	17.2	6.9	17.2	8.3
Barcol Hardness	-	50	-	50	50
Shear Strength	MPa	38	38	48	41
Density	g/cc	1.61-1.75		1.61-1.75	
Coeff thermal expans	°C	5.2×10^{-6}	-	5.2×10^{-6}	-
Water Absorption	Max. %	0.6	-	0.5	-
Full Section Tests					
Modulus of Elasticity	GPa	17	-	19	-
Tensile Strength	MPa	138	-	172	-
Compressive Strength	MPa	138	-	172	-

Fig 6.29 (Imperial)		Series 1500 & 1525		Series 1625	
Properties of Pultruded Shapes Creative Pultrusions Inc		Mat + Roving 40 to 45% glass		Mat + Roving 40 to 45% glass	
Coupon values	Units	Long	Trans	Long	Trans
Tensile Strength	Ksi	30	7	37.5	10
Tensile Modulus	Msi	2.5	0.8	3	1
Flexural Strength	Ksi	30	10	37.5	14
Flexural Modulus	Msi	1.6	0.8	2	1
Izod Impact	ft.lb/in	28	4	30	5
Compressive Strength	Ksi	30	15	37.5	20
Compressive Modulus	Msi	2.5	1	2.5	1.2
Barcol Hardness	-	50	-	50	50
Shear Strength	Ksi	5.5	5.5	7	6
Density	lb/in ³	0.058 - 0.062		0.058 - 0.062	
Coeffic. thermal expans	/°C	5.2×10^{-6}	-	5.2×10^{-6}	-
Water Absorption	Max. %	0.6	-	0.5	-
Full Section Tests					
Modulus of Elasticity	Msi	2.5	-	2.8	-
Tensile Strength	Ksi	20	-	25	-
Compressive Strength	Ksi	20	-	25	-

Fig 6.30 Roving reinforced Pultrusions Creative Pultrusions			
Property Coupon values	Unit	65 to 70%	70 to 75%
		Glass (1)	Glass (2)
Tensile Strength	MPa	690	828
	Ksi	100	120
Tensile Modulus	GPa	41	45
	Msi	6	6.5
Flexural Strength	MPa	690	828
	Ksi	100	120
Flexural Modulus	GPa	690	828
	Ksi	100	120
Compressive Strength	MPa	414	483
	Ksi	60	70
Izod Impact Strength	ft.-lbs./in.	40	40
Barcol Hardness	-	40	40
Water Absorption	Maximum %	0.25	0.25
Density	g/cc	2	2
Coefficient of Thermal Expansion	°C	5.2×10^{-6}	5.2×10^{-6}
(1) Hollow rounds reinforced with roving only			
(2) Standard round rods and bars			

Fig 6.31 Wide Flange Beams

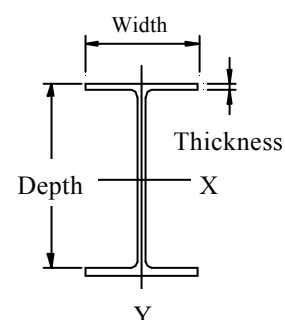
					XX Axis			YY Axis		
Depth	Width	T'ness	A	W	I	Z	r	I	Z	r
mm	mm	mm	mm ²	kg/m	mm ⁴ *10 ⁶	mm ³ *10 ³	mm	mm ⁴ *10 ⁶	mm ³ *10 ³	mm
76.2	76.2	6.35	1374	2.30	1.32	34.58	30.99	0.47	12.29	18.47
101.6	101.6	6.35	1863	3.13	3.30	65.06	42.16	1.11	21.96	24.51
152.4	152.4	6.35	2832	4.73	11.77	154.53	64.52	3.75	49.16	36.58
152.4	152.4	9.53	4181	7.01	16.72	219.59	63.50	5.63	73.74	36.83
203.2	203.2	9.53	5632	9.28	41.28	406.40	85.85	13.33	131.26	48.77
203.2	203.2	12.70	7426	12.46	52.89	520.45	84.58	17.79	175.18	49.02
254	254	9.53	7081	11.92	82.76	650.57	108.20	26.03	204.84	60.71
254	254	12.70	9390	15.73	106.64	839.02	107.19	34.72	272.84	60.96
304.8	304.8	12.70	11297	19.02	188.43	1237.22	128.78	59.98	393.29	73.15


Fig 6.31 (Imperial) Wide Flange Beams

					XX Axis			YY Axis		
Depth	Width	T'ness	A	W	I	Z	r	I	Z	r
in	in	in	in ²	Lb/ft	in ⁴	in ³	in	in ⁴	in ³	in
3	3	0.25	2.13	1.548	3.17	2.11	1.22	1.128	0.75	0.727
4	4	0.25	2.89	2.1	7.94	3.97	1.66	2.67	1.34	0.965
6	6	0.25	4.39	3.18	28.28	9.43	2.54	9	3	1.44
6	6	0.375	6.48	4.71	40.17	13.4	2.5	13.52	4.5	1.45
8	8	0.375	8.73	6.23	99.18	24.8	3.38	32.03	8.01	1.92
8	8	0.5	11.51	8.37	127.1	31.76	3.33	42.74	10.69	1.93
10	10	0.375	10.98	8.01	198.8	39.7	4.26	62.54	12.5	2.39
10	10	0.5	14.55	10.57	256.2	51.2	4.22	83.42	16.65	2.4
12	12	0.5	17.51	12.78	452.7	75.5	5.07	144.1	24	2.88

Fig 6.32 I Beams

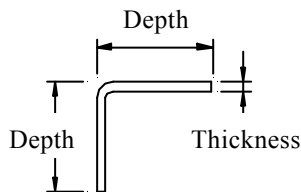
					XX Axis			YY Axis		
Depth	Width	T'ness	A	W	I	Z	r	I	Z	r
mm	mm	mm	mm ²	kg/m	mm ⁴ *10 ⁶	mm ³ *10 ³	mm	mm ⁴ *10 ⁶	mm ³ *10 ³	mm
76.2	38.1	6.35	890	1.59	0.73	19.2	28.7	0.06	3.13	8.18
101.6	50.8	6.35	1219	2.07	1.83	36.1	39.1	0.16	6.36	10.80
152.4	76.2	6.35	1858	3.13	6.63	87.2	59.9	0.47	12.37	15.95
152.4	76.2	9.53	2729	4.55	9.28	121.8	58.7	0.71	18.68	16.26
203.2	101.6	9.53	3694	6.13	23.08	227.0	79.3	1.68	33.04	21.34
203.2	101.6	12.70	4845	8.13	29.39	289.0	78.2	2.25	44.41	21.59
254	127	9.53	4661	7.78	46.48	365.9	99.8	3.27	51.46	26.42
254	127	12.70	6135	10.22	59.72	470.3	99.1	4.38	69.15	26.92
304.8	152.4	12.70	7426	12.74	105.8	693.2	119.4	7.54	99.14	32.00


Fig 6.32 (Imperial) I Beams

					XX Axis			YY Axis		
Depth	Width	T'ness	A	W	I	Z	r	I	Z	r
in	in	in	in ²	Lb/ft	in ⁴	in ³	in	in ⁴	in ³	in
3	1.5	0.25	1.38	1.068	1.75	1.17	1.13	0.143	0.191	0.322
4	2	0.25	1.89	1.39	4.4	2.2	1.54	0.388	0.388	0.425
6	3	0.25	2.88	2.1	15.92	5.32	2.36	1.13	0.755	0.628
6	3	0.375	4.23	3.06	22.3	7.43	2.31	1.71	1.14	0.64
8	4	0.375	5.725	4.12	55.45	13.85	3.12	4.03	2.016	0.84
8	4	0.5	7.51	5.46	70.62	17.65	3.08	5.41	2.71	0.85
10	5	0.375	7.225	5.23	111.7	22.33	3.93	7.854	3.14	1.04
10	5	0.5	9.51	6.87	143.5	28.7	3.9	10.51	4.22	1.06
12	6	0.5	11.51	8.56	254.1	42.3	4.7	18.11	6.05	1.26

Fig 6.33 Angles - Equal

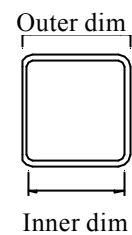
Depth	T ^{ness}	A	W	I	Z	r	x
mm	mm	mm ²	kg/m	mm ⁴ *10 ⁶	mm ³ *10 ³	mm	mm
25.4	3.18	143	0.23	0.0087	0.48	7.62	7.37
25.4	6.35	282	0.49	0.015	0.84	7.11	8.13
31.75	3.18	184	0.33	0.017	0.75	9.40	8.89
31.75	4.75	271	0.47	0.025	1.11	9.40	9.40
38.1	3.18	224	0.38	0.031	1.11	11.43	10.41
38.1	4.75	331	0.56	0.045	1.64	11.43	11.18
38.1	6.35	434	0.77	0.056	2.13	11.18	11.68
50.8	4.75	452	0.78	0.112	3.11	15.49	14.22
50.8	6.35	595	1.02	0.142	3.93	15.24	14.73
76.2	6.35	918	1.55	0.491	8.85	23.11	20.83
76.2	9.53	1346	2.27	0.708	13.11	22.86	22.10
101.6	6.35	1241	2.10	1.224	16.39	31.24	27.18
101.6	9.53	1830	3.15	1.773	24.25	30.99	28.45
127	9.53	2325	4.02	2.439	25.40	32.51	30.73
127	12.70	3065	5.30	3.101	32.28	31.75	30.48
152.4	9.53	2798	4.72	6.181	55.39	46.99	40.64
152.4	12.70	3689	6.24	8.067	73.09	46.74	42.16

**Fig 6.33 (Imperial) Angles - Equal**

Depth	Thick-ness	A	W	I	Z	r	xy
in	in	in ²	Lb/ft	in ⁴	in ³	in	in
1	0.125	0.222	0.157	0.021	0.029	0.3	0.29
1	0.25	0.4375	0.328	0.035	0.051	0.28	0.32
1.25	0.125	0.285	0.22	0.042	0.046	0.37	0.35
1.25	0.187	0.42	0.318	0.059	0.068	0.37	0.37
1.5	0.125	0.347	0.257	0.074	0.068	0.45	0.41
1.5	0.187	0.513	0.378	0.107	0.1	0.45	0.44
1.5	0.25	0.673	0.518	0.135	0.13	0.44	0.46
2	0.187	0.701	0.527	0.27	0.19	0.61	0.56
2	0.25	0.923	0.687	0.34	0.24	0.6	0.58
3	0.25	1.423	1.04	1.18	0.54	0.91	0.82
3	0.375	2.087	1.528	1.7	0.8	0.9	0.87
4	0.25	1.923	1.41	2.94	1	1.23	1.07
4	0.375	2.837	2.12	4.26	1.48	1.22	1.12
5	0.375	3.604	2.703	5.86	1.55	1.28	1.21
5	0.5	4.75	3.562	7.45	1.97	1.25	1.2
6	0.375	4.337	3.175	14.85	3.38	1.85	1.6
6	0.5	5.718	4.19	19.38	4.46	1.84	1.66

Fig 6.34 Square tubes

O.D	I.D	T ^{ness}	A	W	I	Z	r
mm	mm	mm	mm ²	kg/m	mm ⁴ *10 ⁶	mm ³ *10 ³	mm
25.4	19.1	3.2	278	0.47	0.024	1.87	9.1
38.1	31.8	3.2	439	0.80	0.091	4.79	14.3
38.1	25.4	6.4	802	1.35	0.14	7.41	13.2
44.5	38.1	3.2	520	0.87	0.15	6.75	16.9
44.5	31.8	6.4	963	1.64	0.24	10.83	15.8
50.8	44.5	3.2	601	1.03	0.23	9.03	19.5
50.8	41.3	4.7	819	1.42	0.28	10.95	18.4
50.8	38.1	6.4	1125	1.90	0.38	14.93	18.4
76.2	69.9	3.2	923	1.56	0.83	21.68	29.8
76.2	63.5	6.4	1770	2.99	1.45	38.18	28.6
104.8	95.3	4.7	1935	3.35	2.71	38.02	38.1

**Fig 6.34 (Imperial) Square tubes**

Outer	Inner	T ^{ness}	A	W	I	S	r
in	in	in	in ²	lb. /ft.	in ²	in ³	in
1	0.75	0.125	0.431	0.318	0.057	0.114	0.36
1.5	1.25	0.125	0.681	0.54	0.219	0.292	0.564
1.5	1.00	0.25	1.243	0.91	0.339	0.452	0.521
1.75	1.5	0.125	0.806	0.586	0.36	0.412	0.667
1.75	1.25	0.25	1.493	1.104	0.579	0.661	0.623
2	1.75	0.125	0.931	0.692	0.551	0.551	0.766
2	1.625	0.187	1.27	0.953	0.668	0.668	0.726
2	1.5	0.25	1.743	1.274	0.911	0.911	0.725
3	2.75	0.125	1.431	1.05	1.984	1.323	1.175
3	2.5	0.25	2.743	2.01	3.495	2.33	1.125
4.125	3.75	0.187	3	2.248	6.5	2.32	1.5

Fig 6.35 Angles - Unequal

					XX Axis			YY Axis		
Depth	Width	Thickness	A	W	I	Z	r	I	Z	r
mm	mm	mm	mm ²	kg/m	mm ⁴ *10 ⁶	mm ³ *10 ³	mm	mm ⁴ *10 ⁶	mm ³ *10 ³	mm
50.8	25.4	3.18	245	0.42	0.07	1.97	16.26	0.017	0.66	8.64
50.8	38.1	3.18	271	0.47	0.07	2.05	16.28	0.035	1.23	11.43
50.8	38.1	4.75	413	0.71	0.10	2.98	16.05	0.050	1.77	11.18
50.8	38.1	6.35	525	0.91	0.13	3.87	15.82	0.063	2.28	10.97
76.2	50.8	4.75	582	1.01	0.35	6.80	24.54	0.128	3.28	14.81
76.2	50.8	6.35	768	1.33	0.45	8.88	24.31	0.163	4.26	14.58
101.6	76.2	6.35	1090	1.88	1.15	16.39	32.51	0.566	9.83	22.86
101.6	76.2	9.53	1600	2.77	1.65	23.93	32.00	0.799	14.19	22.35
127	101.6	9.53	2129	3.68	3.25	37.69	40.64	1.33	21.30	27.94
127	101.6	12.70	2710	4.69	4.16	50.80	40.13	1.75	26.22	27.94
152.4	101.6	9.53	2329	3.99	5.62	54.41	49.02	2.04	26.22	29.72
152.4	101.6	12.70	3065	5.30	7.24	70.96	48.51	2.61	34.09	29.21
152.4	127	9.53	2710	4.69	6.66	63.91	48.77	2.37	31.14	29.46
152.4	127	12.70	3387	6.22	8.32	83.57	49.53	2.96	45.88	29.46

Fig 6.35 (Imperial) Angles - Unequal

					XX Axis			YY Axis		
Depth	Width	Thickness	A	W	I	Z	r	I	Z	r
in	in	in	mm ²	lb/ft	in ⁴	in ³	in	in ⁴	in ³	in
2	1	0.125	0.38	0.285	0.16	0.12	0.64	0.042	0.04	0.34
2	1.5	0.125	0.42	0.315	0.173	0.125	0.641	0.085	0.075	0.45
2	1.5	0.187	0.64	0.48	0.248	0.182	0.632	0.12	0.108	0.44
2	1.5	0.25	0.813	0.61	0.316	0.236	0.623	0.151	0.139	0.432
3	2	0.187	0.902	0.676	0.842	0.415	0.966	0.307	0.2	0.583
3	2	0.25	1.19	0.893	1.09	0.542	0.957	0.392	0.26	0.574
4	3	0.25	1.69	1.265	2.77	1	1.28	1.36	0.6	0.9
4	3	0.375	2.48	1.86	3.96	1.46	1.26	1.92	0.866	0.88
5	4	0.375	3.3	2.475	7.8	2.3	1.6	3.2	1.3	1.1
5	4	0.5	4.2	3.15	10	3.1	1.58	4.2	1.6	1.1
6	4	0.375	3.61	2.68	13.5	3.32	1.93	4.9	1.6	1.17
6	4	0.5	4.75	3.56	17.4	4.33	1.91	6.27	2.08	1.15
6	5	0.375	4.2	3.15	16	3.9	1.92	5.7	1.9	1.16
6	5	0.5	5.25	4.18	20	5.1	1.95	7.1	2.8	1.16

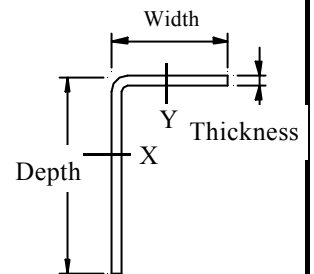
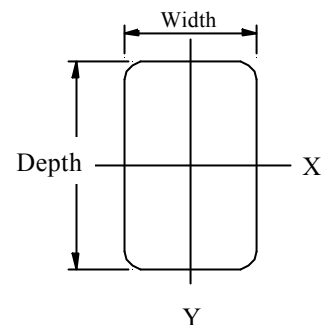


Fig 6.36 Solid Bars

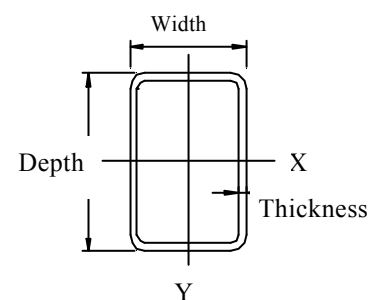
				XX Axis			YY Axis		
Depth	Width	A	W	I	Z	r	I	Z	r
mm	mm	mm ²	kg/m	mm ⁴ *10 ⁶	mm ³ *10 ³	mm	mm ⁴ *10 ⁶	mm ³ *10 ³	mm
25.4	12.7	323	0.60	0.017	1.38	7.34	0.004	0.69	3.66
31.75	19.05	605	1.12	0.051	3.20	9.17	0.018	1.92	5.51
25.4	25.4	645	1.19	0.035	2.74	7.34	0.035	2.74	7.34
31.75	31.75	1005	1.86	0.084	5.34	9.17	0.084	5.34	9.17
38.1	38.1	1452	2.68	0.176	9.24	11.00	0.176	9.24	11.00

**Fig 6.36 (Imperial) Solid Bars**

				XX Axis			YY Axis		
Depth	Width	A	W	I	Z	r	I	Z	r
in	in	in ²	Lb/ft	in ⁴	in ³	in	in ⁴	in ³	in
1	0.5	0.50	0.40	0.042	0.084	0.289	0.0104	0.042	0.144
1.25	0.75	0.94	0.75	0.122	0.195	0.361	0.044	0.117	0.217
1	1	1.00	0.80	0.083	0.167	0.289	0.083	0.167	0.289
1.25	1.25	1.56	1.25	0.203	0.326	0.361	0.203	0.326	0.361
1.5	1.5	2.25	1.80	0.422	0.564	0.433	0.422	0.564	0.433

Fig 6.37 Rectangular Tubes

					XX Axis		YY Axis		No of Internal Webs
Depth	Width	Wall	A	W	I	Z	I	Z	
mm	mm	mm	mm ²	kg/m	mm ⁴ *10 ⁶	mm ³ *10 ³	mm ⁴ *10 ⁶	mm ³ *10 ³	
31.8	19.1	3.2	323	0.52	0.050	3.11	0.025	1.80	0
63.5	38.1	2.3	548	0.91	0.258	6.55	0.133	5.24	0
63.5	38.1	3.2	606	1.04	0.32	10.00	0.142	4.92	0
127.0	50.8	4.7	1542	3.35	2.87	45.06	0.666	26.22	1
152.4	50.8	3.2	1419	2.68	3.41	50.80	0.583	22.94	2
152.4	50.8	4.7	1806	3.72	4.58	60.63	0.791	31.14	2
152.4	101.6	4.7	2258	4.46	7.33	96.68	3.871	77.02	2
203.2	25.4	2.3	1419	2.53	1.66	44.25	0.125	4.59	2
228.6	25.4	3.2	1548	2.98	6.24	55.22	0.137	4.92	2
304.8	19.1	3.2	2065	3.57	13.32	95.04	0.083	6.55	4

**Fig 6.37 (Imperial) Rectangular Tubes**

					XX Axis		YY Axis		No of Internal Webs
Depth	Width	Wall	A	W	I	S	I	Z	
in	in	in	in ²	lb. /ft.	in ²	in ³	mm ⁴ *10 ⁶	mm ³ *10 ³	
1.25	0.75	0.125	0.5	0.35	0.12	0.19	0.06	0.11	0
2.5	1.5	0.09	0.85	0.61	0.62	0.4	0.32	0.32	0
2.5	1.5	0.125	0.94	0.7	0.77	0.61	0.34	0.3	0
5	2	0.187	2.39	2.25	6.9	2.75	1.6	1.6	1
6	2	0.125	2.2	1.8	8.2	3.1	1.4	1.4	2
6	2	0.187	2.8	2.5	11	3.7	1.9	1.9	2
6	4	0.187	3.5	3	17.6	5.9	9.3	4.7	2
8	1	0.09	2.2	1.7	4	2.7	0.3	0.28	2
9	1	0.125	2.4	2	15	3.37	0.33	0.3	2
12	0.75	0.125	3.2	2.4	32	5.8	0.2	0.4	4

Fig 6.38 Channels

					XX Axis			YY Axis		
Depth	Width	Thickness	A	W	I	Z	r	I	Z	r
mm	mm	mm	mm ²	kg/m	mm ⁴ *10 ⁶	mm ³ *10 ³	mm	mm ⁴ *10 ⁶	mm ³ *10 ³	mm
50.8	14.28	3.2	232	0.38	0.07	2.95	18.03	0.003	0.31	3.78
76.2	22.23	6.35	686	1.12	0.48	12.62	26.42	0.023	1.48	5.84
76.2	25.4	4.76	558	0.95	0.37	10.65	25.40	0.020	1.31	5.08
76.2	25.4	6.35	726	1.09	0.46	12.29	25.65	0.022	1.47	5.33
76.2	38.1	6.35	887	1.36	0.67	18.03	29.72	0.083	3.44	10.41
101.6	28.58	6.35	927	1.54	1.19	23.60	35.56	0.053	2.52	7.62
101.6	44.45	4.75	860	1.73	1.58	31.14	38.10	0.133	4.59	11.18
152.4	41.28	6.35	1411	2.45	4.25	55.72	54.86	0.179	5.67	11.56
152.4	42.88	9.53	2087	3.47	6.04	79.31	54.10	0.273	8.65	11.48
203.2	55.55	6.35	1915	3.31	10.50	106.52	74.17	0.308	6.72	12.67
203.2	55.55	9.53	2812	4.79	14.88	146.50	72.90	0.637	15.13	15.09
254	69.85	12.7	4677	8.10	38.49	319.06	90.68	1.390	26.38	17.53

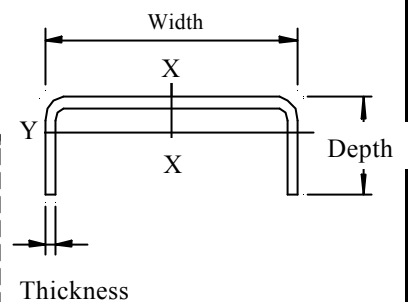


Fig 6.38 (Imperial) Channels

					XX Axis			YY Axis		
Depth	Width	Thickness	A	W	I	Z	r	I	Z	r
in	in	in	in ²	Lb/ft	in ⁴	in ³	in	in ⁴	in ³	in
2	0.562	0.126	0.344	0.258	0.18	0.18	0.71	0.0079	0.019	0.149
3	0.875	0.250	1.005	0.75	1.153	0.77	1.04	0.0563	0.0906	0.23
3	1.00	0.187	0.85	0.64	0.9	0.65	1.00	0.049	0.08	0.20
3	1.00	0.250	0.98	0.735	1.1	0.75	1.01	0.0520	0.09	0.21
3	1.50	0.250	1.22	0.915	1.6	1.1	1.17	0.20	0.21	0.41
4	1.125	0.250	1.38	1.035	2.87	1.44	1.40	0.1270	0.154	0.3
4	1.750	0.187	1.55	1.163	3.8	1.9	1.50	0.32	0.28	0.44
6	1.625	0.250	2.13	1.648	10.22	3.4	2.16	0.43	0.346	0.455
6	1.688	0.375	3.10	2.33	14.52	4.84	2.13	0.656	0.528	0.452
8	2.187	0.250	2.97	2.227	25.22	6.5	2.92	0.74	0.41	0.499
8	2.187	0.375	4.23	3.218	35.75	8.94	2.87	1.53	0.923	0.594
10	2.750	0.500	7.25	5.44	92.48	19.47	3.57	3.34	1.61	0.69

Fig 6.39 (Imperial) Solid Rounds

d	A	W	I	Z	r
mm	mm ²	kg/m	mm ⁴ x 10 ⁴	mm ³ x 10 ³	mm
4.75	18.1	0.033	0.000025	0.010	1.19
6.35	31.6	0.065	0.000083	0.026	1.59
7.54	44.5	0.082	0.00016	0.043	1.88
7.94	49.7	0.101	0.00021	0.052	1.98
9.53	71.0	0.146	0.00042	0.087	2.38
10.32	83.2	0.155	0.00054	0.108	2.57
11.11	96.8	0.198	0.00083	0.149	2.77
12.70	126.5	0.259	0.00125	0.197	3.18
15.88	198	0.406	0.00291	0.367	3.97
19.05	285	0.582	0.00666	0.696	4.75
20.64	334	0.685	0.00874	0.864	5.16
22.23	388	0.795	0.012	1.088	5.56
25.40	506	1.037	0.020	1.606	6.35
31.75	792	1.628	0.050	3.146	7.94
38.10	1140	2.338	0.103	5.424	9.53
50.80	2027	3.740	0.327	12.864	12.70
63.50	3167	5.844	0.798	25.138	15.88
76.20	4561	8.416	1.655	43.442	19.05

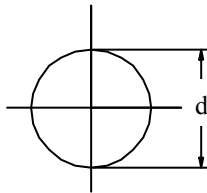


Fig 6.40 Round Tubes

O.D	I.D	wall t	A	W	I	Z	r
mm	mm	mm	mm ²	kg/m	mm ⁴ *10 ⁶	mm ³ *10 ³	mm
12.7	7.95	2.29	77	0.14	0.00121	0.34	3.73
19.05	12.7	3.18	158	0.27	0.00499	0.54	5.66
25.4	19.05	3.18	222	0.40	0.01415	1.10	7.95
25.4	15.88	4.75	309	0.53	0.01707	1.34	7.49
25.4	12.7	6.35	380	0.66	0.01915	1.51	5.49
31.75	26.67	2.54	233	0.40	0.02497	1.57	10.36
31.75	25.4	3.18	285	0.46	0.02955	1.85	10.16
31.75	22.23	4.75	403	0.70	0.03788	2.39	9.68
38.1	31.75	3.18	348	0.63	0.05369	2.82	12.40
38.1	25.4	6.35	634	1.07	0.08283	4.36	11.46
39.7	30.2	4.75	529	0.98	0.08991	4.36	13.06
47.6	39.7	3.96	548	1.01	0.1290	5.41	15.49
50.8	44.45	3.18	475	0.87	0.1353	5.33	16.87
50.8	38.1	6.35	886	1.65	0.2235	8.80	15.88
63.5	50.8	6.35	1140	1.93	0.4712	14.85	20.32
76.2	63.5	6.35	1394	2.34	0.857	22.50	24.79
88.9	76.2	6.35	1645	3.04	1.411	31.63	29.21

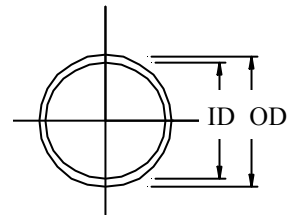


Fig 6.39 (Imperial) Solid Rounds

d	A	w	I	S	r
in.	in ²	lb/ft.	in ⁴	in ³	in.
0.187	0.028	0.022	0.00006	0.00064	0.0467
0.25	0.049	0.044	0.0002	0.0016	0.0625
0.2969	0.069	0.055	0.00038	0.0026	0.074
0.3125	0.077	0.068	0.0005	0.0032	0.078
0.375	0.11	0.098	0.001	0.0053	0.0938
0.4063	0.129	0.104	0.0013	0.0066	0.101
0.4375	0.15	0.133	0.002	0.0091	0.109
0.5	0.196	0.174	0.003	0.012	0.125
0.625	0.307	0.273	0.007	0.0224	0.1563
0.75	0.442	0.391	0.016	0.0425	0.187
0.8125	0.518	0.46	0.021	0.0527	0.203
0.875	0.601	0.534	0.029	0.0664	0.2188
1	0.785	0.697	0.049	0.098	0.25
1.25	1.227	1.094	0.12	0.192	0.3125
1.5	1.767	1.571	0.248	0.331	0.375
2	3.1416	2.513	0.785	0.785	0.5
2.5	4.909	3.927	1.917	1.534	0.625
3	7.069	5.655	3.976	2.651	0.75

Fig 6.40 (Imperial) Round Tubes

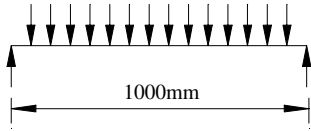
O.D	I.D	wall t	A	Wt.	I	S	r
in.	in.	in.	in ²	lbs./ft.	in ⁴	in ³	in
0.5	0.313	0.09	0.119	0.095	0.0029	0.021	0.147
0.75	0.5	0.125	0.245	0.18	0.012	0.033	0.223
1	0.75	0.125	0.344	0.268	0.034	0.067	0.313
1	0.625	0.187	0.479	0.358	0.041	0.082	0.295
1	0.5	0.25	0.589	0.442	0.046	0.092	0.216
1.25	1.05	0.1	0.361	0.271	0.06	0.096	0.408
1.25	1	0.125	0.442	0.31	0.071	0.113	0.4
1.25	0.875	0.187	0.625	0.469	0.091	0.146	0.381
1.5	1.25	0.125	0.54	0.42	0.129	0.172	0.488
1.5	1	0.25	0.982	0.72	0.199	0.266	0.451
1.563	1.188	0.187	0.82	0.656	0.216	0.266	0.514
1.875	1.563	0.156	0.85	0.68	0.31	0.33	0.61
2	1.75	0.125	0.736	0.582	0.325	0.325	0.664
2	1.5	0.25	1.374	1.11	0.537	0.537	0.625
2.5	2	0.25	1.767	1.3	1.132	0.906	0.8
3	2.5	0.25	2.16	1.575	2.059	1.373	0.976
3.5	3	0.25	2.55	2.04	3.39	1.93	1.15

Section properties of top hat sections

The Tables given in Figs 6.40 to 6.42 list the 2nd moment of area, section modulus, area and position of neutral axis for a variety of "top hat" sections.

Example. A 4 mm thick C.S.M. panel 1 m x 0.5 m supported as shown in the sketch is to be stiffened to limit the deflection to 2mm. What size of top hat section would be suitable?

Simply supported panel subjected to U.D.L. of 1 kN/m²
Total load of 500N. Say E = 6500 N/mm²



$$\text{Now deflection} = \frac{5 W L^3}{384 E I}$$

$$\text{Therefore } 2 \text{ mm} = \frac{5 \times 500 \times 1000^3}{384 \times 6500 \times I}$$

$$\text{Therefore } I \text{ required} = \frac{5 \times 500 \times 1000^3}{2 \times 384 \times 6500}$$

$$= 500,000 \text{ mm}^4$$

This can be achieved with one top hat stiffener 4 mm thick with height 60 mm or with two top hat stiffeners each of I value 250,000 mm⁴ from the tables a suitable section would be 4 mm thick, with height 50 mm. In each case the existing plate forms the base for the section.

If the strength of the FRP is 100 N/mm² what will be the factor of safety on bending strength using the 2 stiffeners of 4mm thickness, 50mm high?

From the tables for the section with base width 60 mm.

$$y = 19.69 \text{ mm}$$

$$I = 260,677 \text{ mm}^4$$

$$\text{Max. stress} = \frac{W L y}{8 I}$$

$$= \frac{500 \times 1000 \times 19.69}{8 \times 2 \times 260677} = 2.36 \text{ N/mm}^2$$

Which gives a factor of safety of 42 times. for this mode of failure (other modes have been ignored). This result is typical of G.R.P. in that the design is very often deflection limited rather than strength limited. An alternative solution would have been to use more than two stiffeners, again the necessary size can be obtained from the tables.

Fig 6.40 Section properties of top hat sections (SMALL RANGE)

Thickness (mm)	2	3	4	2	3	4	2	3	4	2	3	4
Base width (mm)	160	160	160	120	120	120	100	100	100	60	60	60
Height mm	50	50	50	50	50	50	50	50	50	50	50	50
y mm	12.71	13.19	13.67	14.53	15.2	15.51	15.67	16.17	16.66	18.63	19.16	19.69
Area mm ²	596	888	1175	516	768	1015	476	708	935	396	588	775
Z 1000 mm ³	14.1	19.9	25.1	11.4	16.2	20.5	10.1	14.3	18.1	7.4	10.5	13.2
I 1000 mm ⁴	178.8	262.8	343.8	166.0	243.7	318.3	158.1	231.8	302.4	137.4	200.6	260.7
Height mm	40	40	40	40	40	40	40	40	40	40	40	40
y mm	9.66	10.15	10.64	11.11	11.61	12.12	12.3	12.55	13.06	14.5	15.05	15.59
Area mm ²	557	829	1099	477	709	937	437	649	859	357	529	699
Z 1000 mm ³	10.8	15.1	18.8	8.8	12.3	15.3	7.7	10.8	13.5	5.6	7.8	9.8
I 1000 mm ⁴	104.3	153.1	200.1	97.3	142.5	185.9	92.8	135.8	176.8	80.9	117.7	152.6
Height mm	30	30	30	30	30	30	30	30	30	30	30	30
y mm	6.9	7.42	7.93	7.98	8.5	9.03	8.68	9.21	9.74	10.61	11.17	11.73
Area mm ²	518	773	1023	438	653	863	398	593	783	318	473	623
Z 1000 mm ³	7.6	10.4	12.8	6.2	8.5	10.4	5.4	7.5	9.2	3.9	5.4	6.6
I 1000 mm ⁴	52.7	77.3	101.1	49.4	72.3	94.2	47.3	69.0	89.8	41.3	59.9	77.5
Height mm	20	20	20	20	20	20	20	20	20	20	20	20
y mm	4.53	5.07	5.61	5.23	5.78	6.34	5.7	6.26	6.82	7.03	7.63	8.22
Area mm ²	482	718	951	402	598	791	362	538	711	289	418	550
Z 1000 mm ³	4.6	6.0	7.2	3.7	4.9	5.9	3.3	4.4	5.2	2.3	3.1	3.7
I 1000 mm ⁴	20.7	30.5	40.3	19.5	28.6	37.6	18.7	27.3	35.8	16.4	23.7	30.8

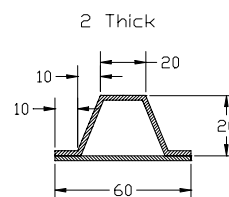
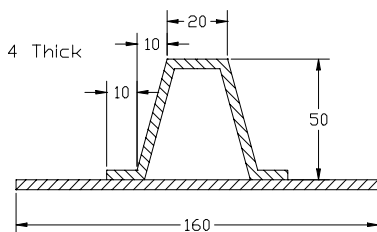


Fig 6.41 Section properties of top hat sections (MEDIUM RANGE)

Thickness (mm)	4	5	6	4	5	6	4	5	6	4	5	6
Base width (mm)	240	240	240	180	180	180	150	150	150	90	90	90
Height mm	60	60	60	60	60	60	60	60	60	60	60	60
y mm	14.98	15.47	15.96	17.17	17.67	18.17	18.56	19.7	19.59	22.3	22.84	23.38
Area mm ²	1664	2070	2473	1424	1770	2113	1304	1620	1933	1064	1320	1573
Z 1000 mm ³	46.3	55.3	63.5	37.7	45.0	51.8	33.2	39.7	45.7	24.0	28.7	33.0
I 1000 mm ⁴	693.9	855.3	1013.0	646.3	795.7	941.1	616.0	757.6	895.2	535.0	655.9	772.4
Height mm	50	50	50	50	50	50	50	50	50	50	50	50
y mm	12.18	12.68	13.19	13.99	14.51	15.03	15.17	15.69	16.22	18.37	18.92	19.48
Area mm ²	1587	1974	2358	1347	1674	1998	1227	1524	1818	987	1224	1458
Z 1000 mm ³	36.9	43.6	49.7	30.0	35.6	40.6	26.4	31.4	35.8	19.0	22.5	25.8
I 1000 mm ⁴	449.2	553.6	655.7	419.6	516.3	610.5	400.5	492.2	581.4	348.4	426.6	501.9
Height mm	40	40	40	40	40	40	40	40	40	40	40	40
y mm	9.62	10.14	10.66	11.06	11.59	12.12	12	12.54	13.08	14.63	15.2	15.78
Area mm ²	1512	1881	2246	1272	1581	1886	1152	1431	1706	912	1131	1346
Z 1000 mm ³	27.7	32.4	36.5	22.6	26.5	30.0	19.9	23.4	26.5	14.2	16.7	18.9
I 1000 mm ⁴	266.2	328.3	389.5	249.4	306.9	363.3	238.3	292.9	346.2	207.7	254.0	298.7

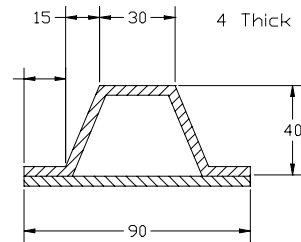
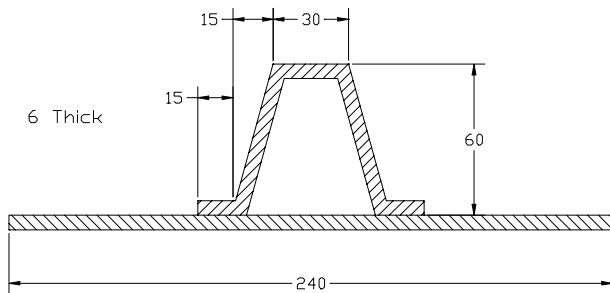
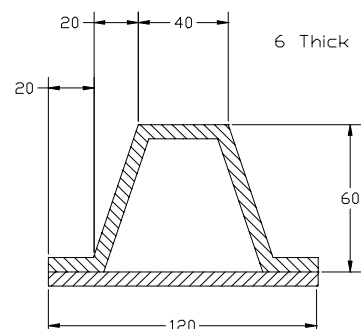
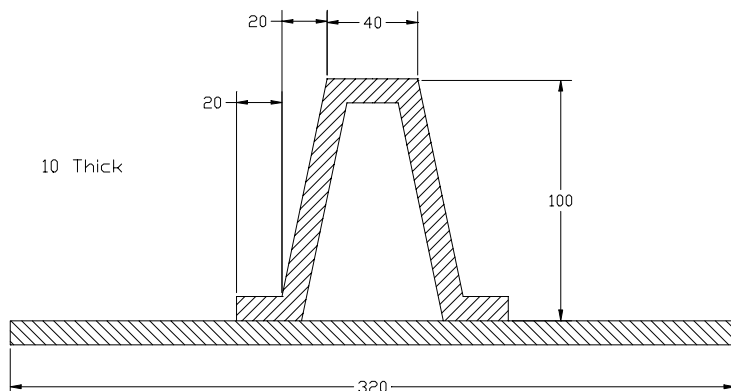


Fig 6.42 Section properties of top hat sections (LARGE RANGE)

Thickness (mm)	6	8	10	6	8	10	6	8	10	6	8	10
Base width (mm)	320	320	320	240	240	240	200	200	200	120	120	120
Height mm	100	100	100	100	100	100	100	100	100	100	100	100
y mm	26.39	27.35	28.31	30.04	31.2	32	32.33	33.33	34.33	38.31	39.37	40.43
Area mm ²	3553	4706	5844	3073	4066	5044	2833	3746	4644	2353	3106	3844
Z 1000 mm ³	159.3	201.1	238.6	129.8	164.2	195.1	114.7	145.2	172.6	83.8	105.9	125.8
I 1000 mm ⁴	4205	5501	6754	3900	5094	6244	3708	4838	5923	3210	4171	5085
Height mm	80	80	80	80	80	80	80	80	80	80	80	80
y mm	20.3	21.29	22.27	23.22	24.23	25.24	25.09	26.12	27.14	30.9	31.18	32.27
Area mm ²	3320	4396	5456	2840	3755	4656	2600	3436	4256	2120	2796	3456
Z 1000 mm ³	120.7	150.4	176.4	98.2	122.7	144.3	86.6	108.3	127.5	62.6	78.3	92.1
I 1000 mm ⁴	2450	3202	3930	2280	2974	3643	2172	2829	3461	1884	2441	2971
Height mm	60	60	60	60	60	60	60	60	60	60	60	60
y mm	14.83	15.85	16.88	17.1	18.05	19.1	18.24	19.49	20.56	22.34	23.47	24.6
Area mm ²	3091	4091	5077	2611	3451	4277	2371	3131	3877	1891	2491	3077
Z 1000 mm ³	83.4	102.0	117.9	68.0	83.5	96.8	59.9	73.7	85.6	42.9	52.8	61.3
I 1000 mm ⁴	1237	1618	1991	1156	1508	1850	1103	1436	1759	959	1240	1508



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7 Economics

Introduction

This chapter is concerned with the economic considerations of composites. The inherent cost per kg of the materials themselves is of course highly pertinent. But the amount of material needed to be used depends on what is the critical design criterion, which property is relevant to that design criterion and how much of that property can be purchased per £.

The processes used to convert composite materials into components each use various materials which are suitable to that particular production method. A change of process requires a re-consideration of the materials used. For example to produce a component by Hand Lay-up would probably use chopped strand mat. But if an alternative option was to use Spray-up this would require the use of chopped roving. Although similar to CSM in that they are both random in nature, the spray-up laminate would have a lower glass content giving a different set of properties. Cost per kg has changed, performance per kg has also changed and therefore cost per performance has changed. Hence it is not possible to design a component in composite materials without taking into account which process is to be used.

Firstly we will consider the weight and the cost per kg of a variety of materials and how they compare in terms of several pertinent properties. Then we will look at the total cost of a fictitious component produced by a selection of processes and how the cost varies with the number of components produced. Finally there is the question of how much reinforcement should be used in the laminate. It can be argued that this is determined by the process itself. To a large extent this is true but most of the processes have some latitude in the fibre content that can be tolerated.

This begs the question - Is there an optimum level to work at? Highest, lowest or somewhere in between?

The Comparative Performance of Materials

All engineering problems are involved with either cost or weight of achieving a level of performance. This is particularly so with composite materials which are generally light but can be intrinsically expensive.

Of course to state that a material is light or expensive is a simplistic statement which has to be qualified. Even to say that a material has low mass doesn't help a great deal unless the materials in which we are interested happen to have the same level of performance (strength, modulus etc.).

To say that a material is light if it has a low density (mass / volume) is meaningless unless we want to simply fill a space. Such applications probably exist but none spring to mind other than the mundane.

Materials are generally purchased by weight and we say that a material is cheap if it has a low price per kg. Again this is only relevant if the property we require happens to be the same level for the materials under comparison. Consequently a comparison of the cost or weight of materials must relate to a particular property. There are a multitude of properties which may be relevant but probably the most commonly used primary design criterion are:

- Bending Strength
- Bending Stiffness
- Tensile Strength
- Tensile Stiffness

Some generic composite materials are compared in terms of either weight or cost. The properties which have been used are shown in Fig 7.1. They are indicative of a range rather than precise values, but nevertheless they allow conclusions to be drawn concerning the relative merits of the material op-

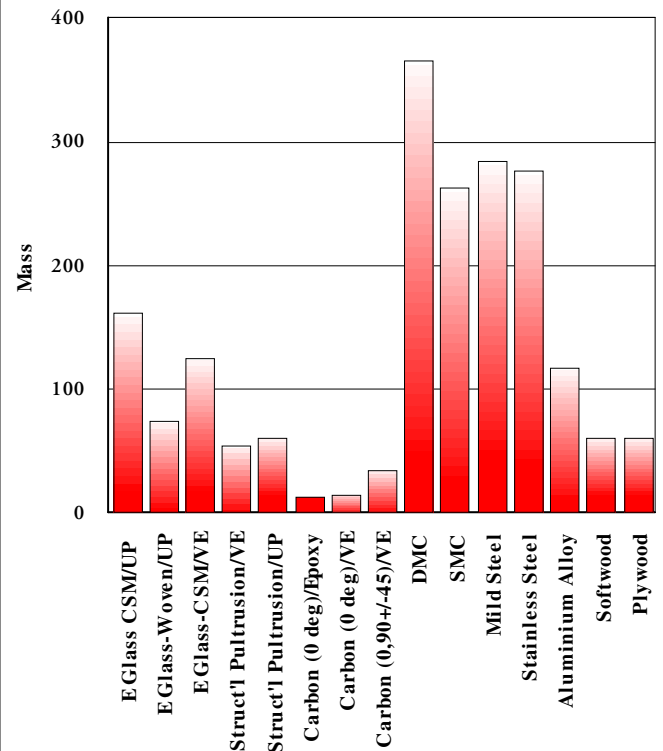
Fig 7.1 Indicative Properties

	Price Index	Density		Tensile Strength		Tensile Modulus	
		g/cm ³	Lb/in ³	MPa	psi	GPa	Msi
E Glass -CSM/UP	1.6	1.61	0.058	100	14500	7	1.02
E Glass-Woven /UP	2.1	1.85	0.067	250	36250	15	2.12
E Glass-CSM/VE	3	1.5	0.054	120	17400	8	1.16
Structural Pultrusion /VE	2.6	1.8	0.065	330	47850	17	2.47
Structural Pultrusion /UP	1.6	1.8	0.065	300	43500	17	2.47
Carbon (0°)/Epoxy	23	1.56	0.056	1200	174000	140	20.3
Carbon (0°)/VE	20	1.53	0.055	1100	159500	140	20.3
Carbon (0°,90°+/-45°)/VE	40	1.55	0.056	450	65250	55	7.98
DMC	1.7	1.9	0.069	52	7540	8	1.16
SMC	2	1.84	0.066	70	10150	12	1.74
Mild Steel Grade 43	0.45	7.8	0.281	275	39900	205	29.5
Stainless Steel 316	2	8	0.289	290	42050	192	27.8
Aluminium Alloy 6063	1.1	2.8	0.101	240	34800	69	10.0
Softwood	0.29	0.48	0.017	80	11600	12	1.74
Plywood	0.32	0.54	0.02	90	13050	14	2.03

Material descriptions

- 1) A typical Hand lay-up construction of E glass chopped strand mat with Polyester resin - (E glass CSM / UP).
- 2) As 1) but using Woven Roving rather than CSM (E glass Woven / UP).
- 3) As 1) but using Vinyl ester rather than Polyester resin (E glass Woven / VE).
- 4) A Pultruded laminate of continuous filament mat and uni-directional roving with filled vinyl ester resin. Typically used for structural items such as 'I' beams and box sections. (Struct'l Pultrusion / VE).
- 5) As 4) but using polyester rather than vinyl ester resin (Struct'l Pultrusion / UP).
- 6) Unidirectional carbon fibre XAS laminate with epoxy resin. (Carbon (0 deg) / epoxy).
- 7) As 6) but using Vinyl ester rather than epoxy resin. (Carbon (0 deg) / VE).
- 8) Quasi isotropic carbon (XAS) laminate with vinyl ester resin. (Carbon (0,90+/-45)/VE).
- 9) Dough (or Bulk) Moulding Compound with polyester resin. Used in hot press compression moulding. (DMC or BMC).
- 10) Sheet moulding compound with polyester resin. (SMC)
- 11) Mild steel grade 43. Standard structural applications.
- 12) Stainless steel grade 316
- 13) Aluminium Alloy 6063. Extrusion grade, architectural.
- 14) Pine suitable for building use (Softwood).
- 15) Marine grade plywood (Plywood)

Fig 7.2 Mass of Material for same Tensile Strength



Mass for same Tensile Strength

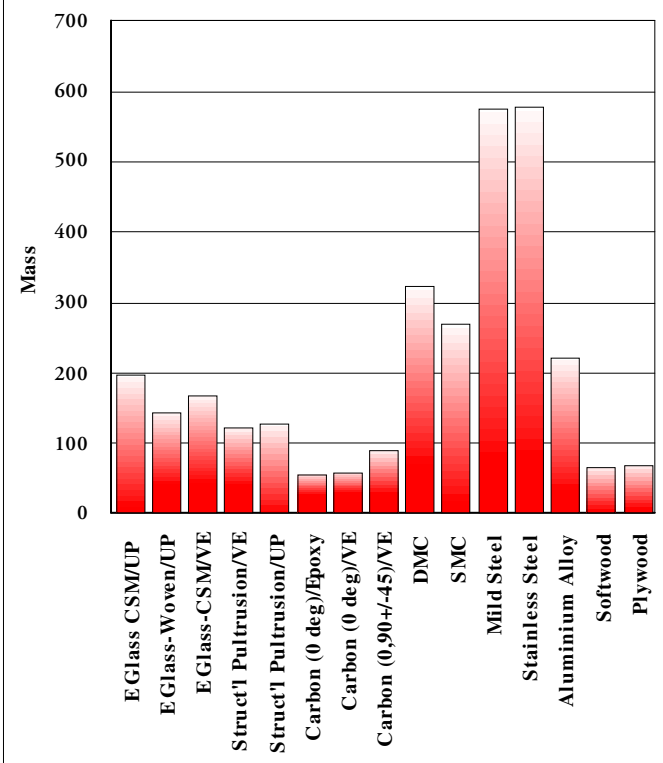
Fig 7.2 compares the mass required for each material to have the same tensile load carrying capacity. SMC, Mild steel and stainless steel are the poorest performers in this respect (assuming of course that the aim is to minimise mass). At the other extreme the carbon fibre variants are an order of magnitude lower in mass. This is one of the design criterion about which the lightweight reputation of composites was formed.

An is example is between pultrusion and mild steel for use in structural applications. I beams, channel sections etc. are available in both materials. It can be seen that the pultruded option is significantly lighter than the mild steel option. This can be highly pertinent when for instance there is a limitation on foundation loading or when an existing structure needs to be enlarged within an existing specification.

Mass for same Tensile Strength

A similar pattern is seen in Fig 7.3 which compares the mass required of each material for the the same flexural load carrying capacity. An example is the design of automotive body panels which can be dominated by flexural strength considerations. The SMC or DMC version would be about 1/2 the mass of the mild steel version. The design could also be dominated by bending stiffness rather than strength depending on the specific details. See Fig 7.5

Fig 7.3 Mass of Material for same Bending Strength



Mass of Material for same Tensile Stiffness

The Young's modulus of composites covers an enormous range, from those which compare with (or exceed) steel to those with similar modulus to thermoplastics (but without their inherent creep problem). The mass of the various materials for the same tensile stiffness is illustrated in Fig 7.4. This criterion is important in for instance very long tension members e.g. Elevator cables) where the mass of the cable is an appreciable factor in the design considerations. This is usually the domain of very high performance steel. But carbon fibre composites in unidirectional format have very considerable potential in this application due to there low mass for the same tensile stiffness and strength.

Mass of Material for same Bending Stiffness

There are many applications where the design is dominated by bending stiffness at minimum mass which Fig 7.5 illustrates. In spite of the significant differences in the modulii of the materials, the peaks and troughs in the graph are less pronounced in this case. This is because the effect is mitigated by the fact that an increase in thickness has a cube effect on bending stiffness. Hence, for instance to double the stiffness it is only necessary to increase thickness by $2^{1/3}$.

It can be seen that all of the composite options perform better in this respect than the steel options cited. The glass fibre composites will have similar mass to aluminium for this design criterion.

This is probably the dominant design criterion in the design of automotive body panels. In which case SMC and DMC are about 2/3 of the mass of steel, but probably a little heavier than aluminium.

A good rule of thumb for the designer is apparent in this case: If the item can be made appropriately from wood then that is the lightest option if the criterion is bending stiffness. For example WWII Mosquito aircraft made from plywood.

Material Costs

Figs 7.6 to 7.9 compare the cost of the various material options for the design criterion:

tensile strength, bending strength, tensile stiffness and bending stiffness.

Some important observations can be made. In general carbon composites are more expensive than the alternative materials to do the same job. However it should be noted that unidirectional carbon composites compete very well against stainless steel when the design criterion is tensile strength and bending strength. Although the glass fibre composites tend to have higher material cost than mild steel and aluminium there are some exceptions. For instance structural pultrusions have lower material cost when designing for tensile or bending strength.

Although material cost is an important part of the total cost there are other costs to be considered which can alter the picture significantly as we shall see in the following sections.

Fig 7.4 Mass of Material for same Tensile Stiffness

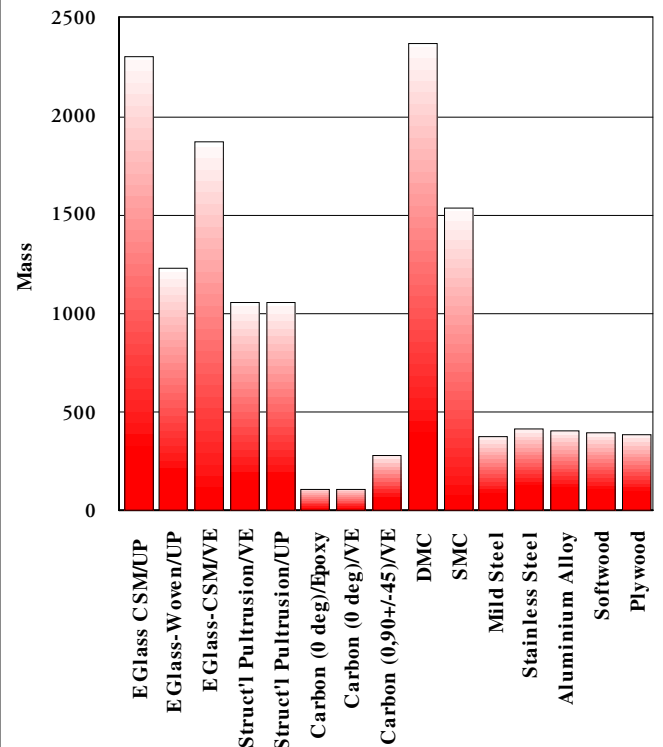


Fig 7.5 Mass of Material for same Bending Stiffness

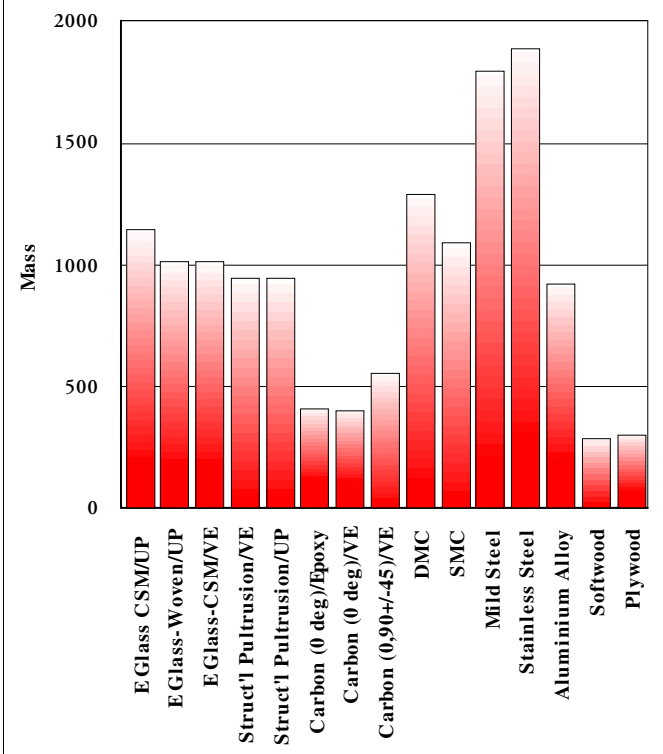


Fig 7.6 Cost of Material for same Tensile Strength

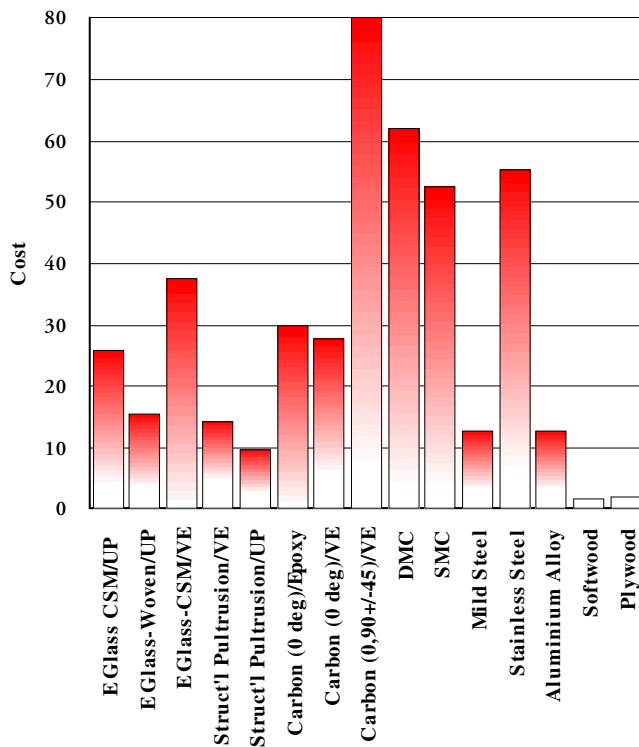


Fig 7.7 Cost of Material for same Bending Strength

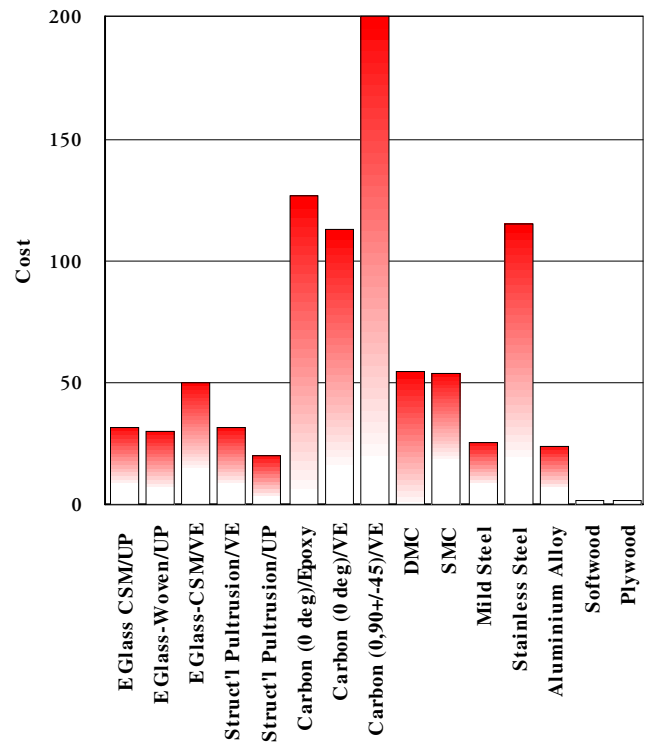


Fig 7.8 Cost of Material for same Tensile Stiffness

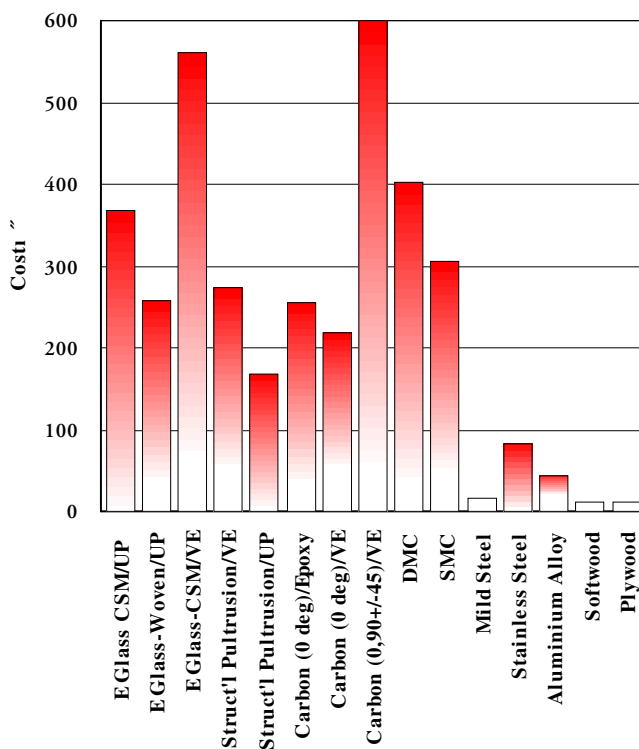
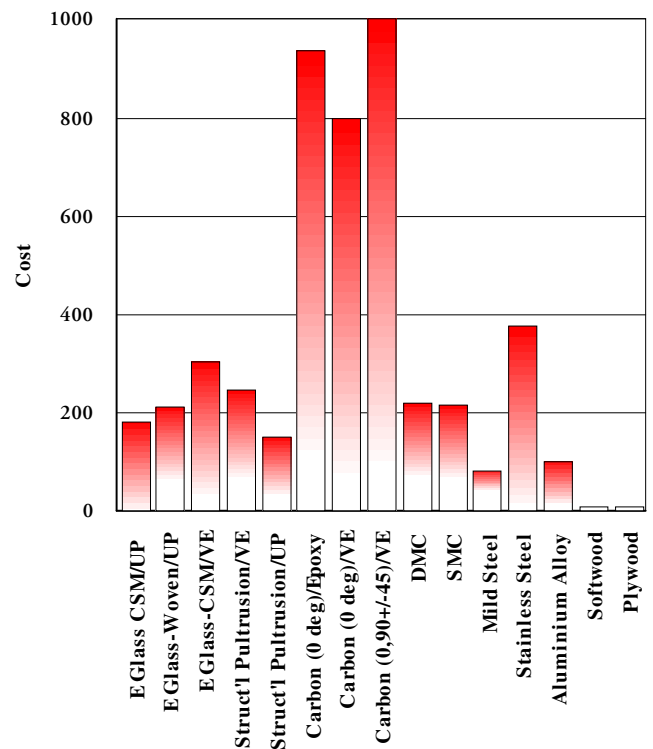


Fig 7.9 Cost of Material for same Bending Stiffness



Effect of Quantity on Cost

INTRODUCTION

The choice of process to use for the manufacture of a composite component is dependant on several factors ; whether the equipment is available or if it must be acquired, its capability to produce the shape, whether it can produce the quantity required etc. Once these questions have been addressed then the dominant question is cost. What is the total cost associated with the production of the component by the candidate processes.

In the perfect world the choice of process would involve a detailed cost exercise for each competing process. As this takes place within the iterations of the design process, every time the design is changed, the process selection should be reassessed economically. In reality the selection of perhaps two candidate processes is generally made on the basis of experience. This is open to error. In order to avoid this problem and to aid in decision making a series of graphs have been drawn up which illustrate the effect, on the component cost, of varying the quantity produced for several processes. The processes which are considered are :

- Hand lay-up,
- Spray-up,
- Compression Moulded Sheet Moulding Compound (SMC),
- Compression Moulded Dough Moulding Compound (DMC),
- Resin Transfer moulding (RTM).

For the purposes of this exercise a fictitious but valid product has been selected which could be produced by any of the five processes using glass fibre and polyester resin. It consists of a simple box shape, with 1m by 1m overall dimensions and a total surface area of 2m². The thickness for the Hand lay-up version is kept constant at 4 mm. Glass contents have been selected which are typical of those encountered in practice.

The effect of all components having the same thickness is considered, but in practice this would not happen. Each process tends to use different types of material and therefore have different properties. Two properties have been considered, flexural stiffness and flexural strength, the relevant thickness required for each and the subsequent material costs have been taken into account. Flexural stiffness and flexural strength have been chosen for this exercise because they tend to dominate the design requirements.

MATERIAL COST

Material cost has been calculated for each of the processes for the three situations:

- 1) In which each component has the same thickness (4 mm),
- 2) In which each component has the same flexural strength (the thickness required in each case is calculated).
- 3) In which each component has the same flexural stiffness (again, the thickness required to achieve this is calculated).

Fig 7.10 shows the results of the material cost calculation. It can be seen that both material cost and the weight of the component can vary considerably depending upon the process used and the design criterion on which the analysis is based. For instance when the design criterion is flexural strength the most expensive material (DMC) is almost twice the cost of the least expensive option (Hand lay-up).

In this exercise no attempt has been made to include the cost of finishing the components. The press moulded components may or may not be painted after moulding. RTM components may or may not have a gel coat. Hand lay-up and Spray-up moulding normally would have a gel coat. The possibilities are too numerous to have been taken into account in this exercise. Therefore for simplicity, both material and production costs of gel coats and paint finishing have been ignored.

It is difficult to assess what raw material price is typical in the market place. Various factors enter which confuse the picture. Not the least being the fact that the price of a raw material is a function of the buying power of the customer. Large quantities purchased demand lower prices. For the purpose of this exercise the aim is to compare costs of the processes at comparable production levels. Consequently at a particular production level the material cost used may not reflect the exact picture, however as each process is subject to the same effect it is reasonable to ignore this fact. A factor which cannot be taken into account is that SMC and DMC may be purchased from a supplier (this has been assumed to be the case in this exercise) or manufactured 'in-house'. This makes a significant reduction in material cost. Possibly as much as 20%. No attempt has been made to take this into account.

Continued on page 7.6

Fig 7.10		Equal Thickness	Equal Stiffness					Equal Flexural Strength				
	Glass Content	Material Cost	Thickness		Material Cost	Total weight		Thickness		Material Cost	Total weight	
	(%)	(£)	(mm)	(in)	(£)	(kg)	Lb	(mm)	(in)	(£)	(kg)	(Lb)
Hand Lay-up	35	18.4	4	0.157	18.4	11.68	25.70	4	0.157	18.4	11.68	25.70
Spray-up	30	16	4.2	0.165	16.87	11.87	26.11	4.34	0.171	17.37	12.23	26.91
SMC	25	28.32	3.24	0.128	22.98	11.49	25.28	4.49	0.177	31.8	15.88	34.94
DMC	18	26.25	3.41	0.134	22.38	13.96	30.71	5.4	0.213	35.4	20.82	45.80
RTM	24	19.26	4.48	0.176	21.55	12.17	26.77	4.62	0.182	22.24	12.56	27.63

MATERIAL COST PLUS PRODUCTION COST

If it is assumed first of all, that the components produced by each of the processes has the same thickness (4mm) then the total cost is simply the sum of the material cost and the production cost. Production costs have been calculated by the use of simple mathematical models, which simulate the process, and the use of known cost constants. The results of these calculations are shown graphically in Figs 7.11 - 7.16 which plot total cost of each unit against total production.

Unit cost if Equal Thickness (equipment available)

Fig 7.11 represents the situation where all equipment is already installed and available for use. In terms of cost of the component it is simply charged for on a 'time utilised' basis i.e. cost per hour of production. It has been assumed in this graph that each component has the same thickness. This is an unreal situation which only happens on rare occasions when mechanical performance is not important, simply that the component has a particular thickness.

In this case it can be seen that for all levels of production, Spray-up is the most economic option. There is however a limit, for each process, to the quantity of components which can be produced in a given time. The graphs are only valid up to the production quantity which can be produced in the time scale of interest.

For example the production quantity per annum for RTM is about 3500 components per annum (allowing for some process efficiency). Hence if 10,000 components are required in one year it is unlikely that the RTM process will be chosen even though at first sight it might appear to be the favoured option under some circumstances.

Similarly it can be seen that the Spray-up process is the cheapest option for all levels of production. This is only true within the sensible range of its capacity. If the spray machine is occupied for 10 minutes per component then the theoretical maximum number of components which can be produced per annum is :

$6 \text{ per hour} \times 40 \text{ hours per week} \times 46 \text{ weeks per annum} = \text{about } 10,000 \text{ components (including a production efficiency factor).}$

In reality a more realistic maximum quantity per annum for this component is probably 4000. Thus if the yearly requirement for this component exceeds 4000, then another process is likely to be chosen. In this case it would probably be Hot press moulded DMC.

If however the 10000 components were required over say 3 years then the Spray process could cope and its use would be justified, allowing consequent cost savings.

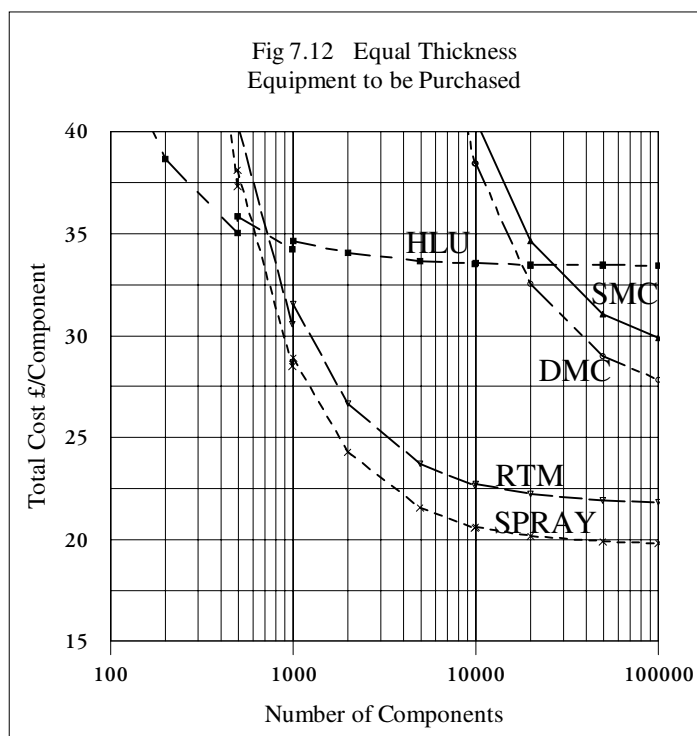
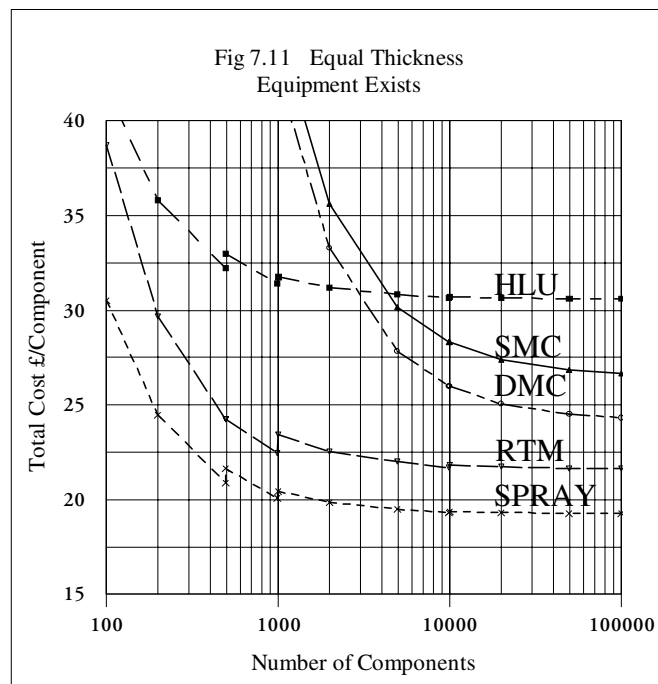
Sensible production quantities for several processes are shown in the process characterisation chart in chapter 3.

Equal Thickness (equipment to be purchased) Fig 7.12

In this case none of the equipment options are currently installed and the exercise is to determine the most cost effective option to install. Hence it is assumed that the cost of the equipment is to be recovered over the length of the production run of the component. This is a very simplistic approach, for instance, it ignores the residual value of the equipment at the end of the run. However for the purpose of this exercise it is sufficiently accurate. It allows trends and inferences to be drawn which lead to the most likely

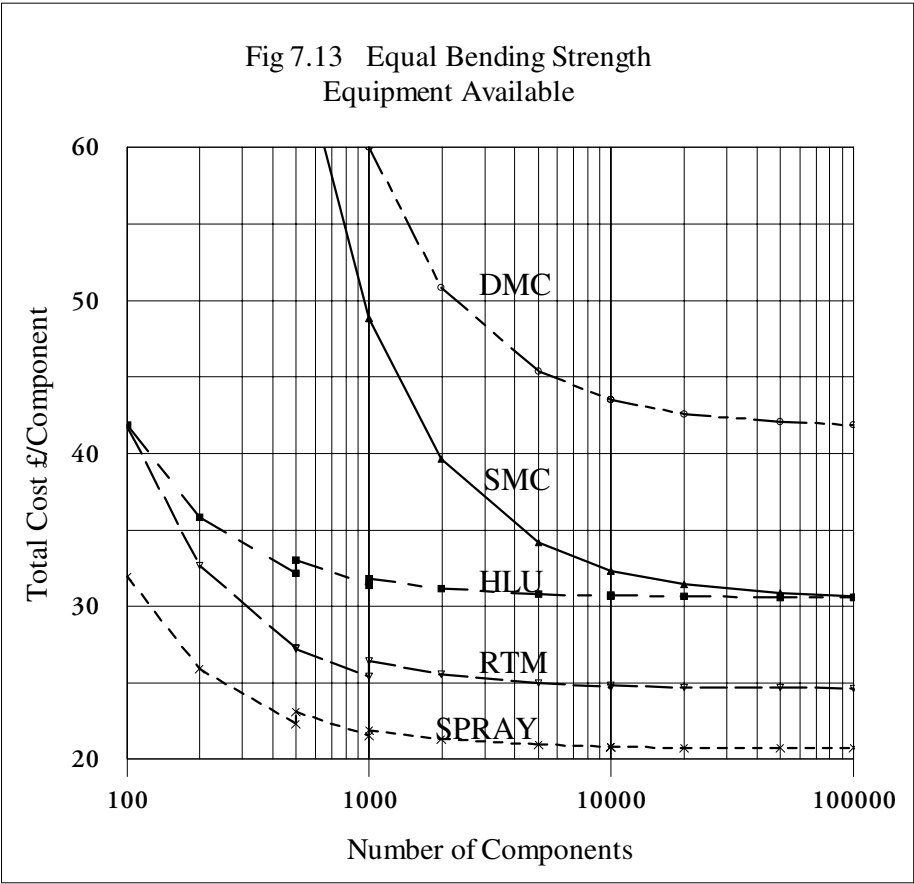
options which would then be subject to a more exhaustive financial scrutiny.

It can be seen from Fig 7.12 (where Equal Thickness is assumed) that HLU is the most economic process up to about 800 components. Beyond this Spray-up takes over with RTM on a very similar curve. If the component requires two smooth surfaces then RTM would be chosen rather than Spray-up even though there is a premium.



Equal bending strength (equipment available)

Fig 7.13 shows this relationship. The Spray-up process is again the most economic for all levels of production. Again with the assumption that the required time scales are compatible.

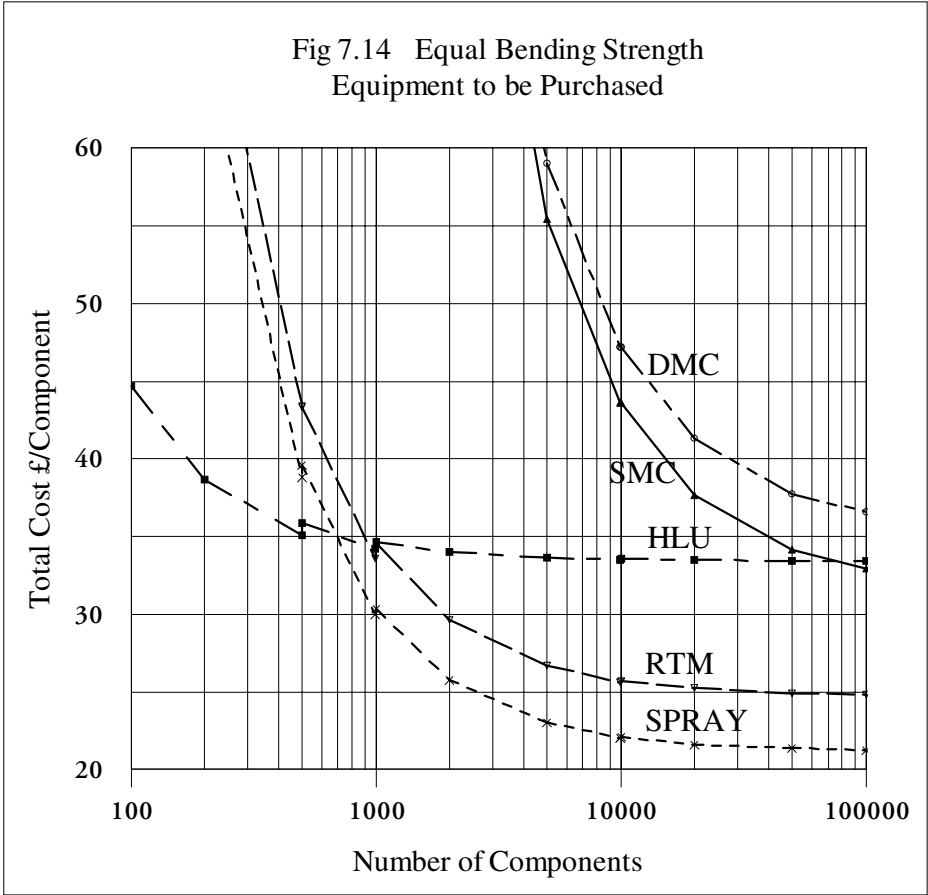


Equal Bending strength. (equipment to be purchased)

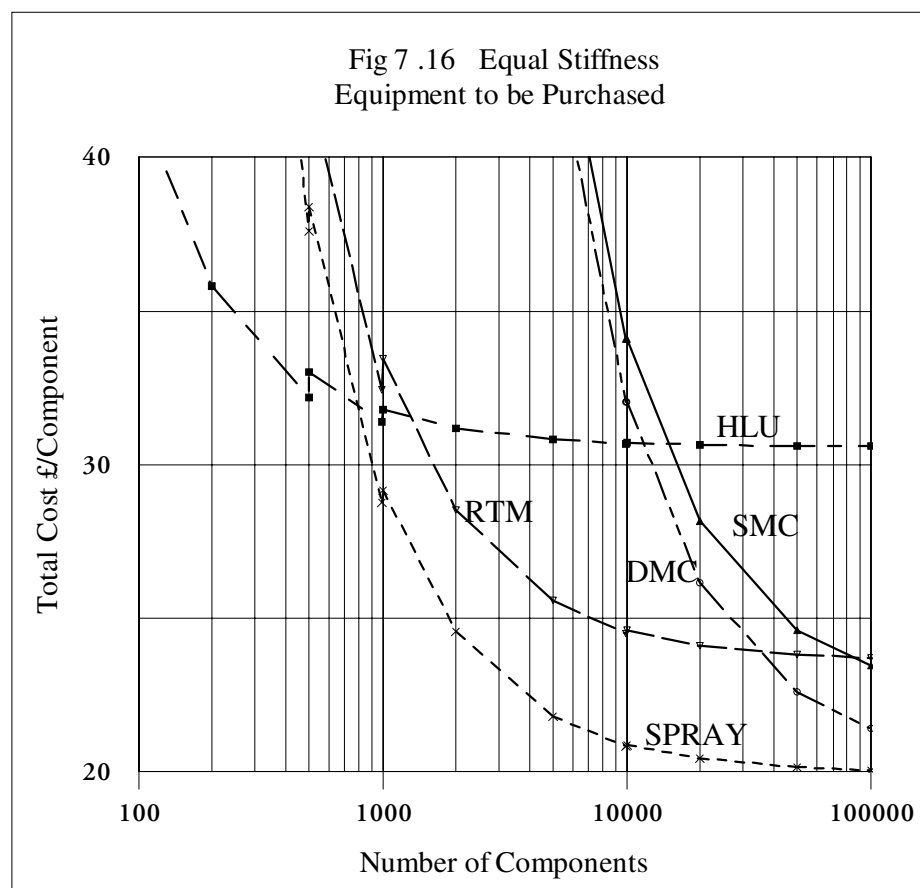
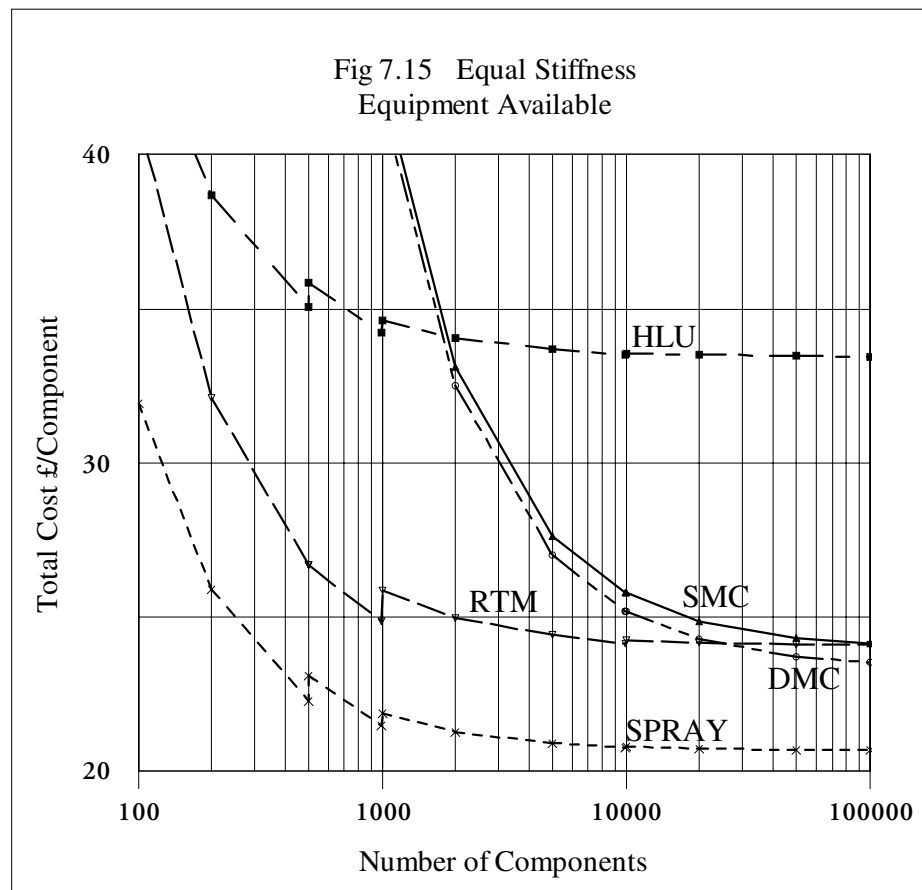
If however the design criterion is bending strength (Fig 7.14) then Hand lay-up is the most economic up to about 1000 components after which Spray and RTM would be chosen depending on whether two smooth surfaces were required. Again it is assumed the time scale allows this. If it doesn't then the choice beyond about 30,000 components is SMC.

An application which has this design criterion is small water tanks. They might, in fact, not look too different in size to the theoretical component selected for this exercise.

At low quantities they are produced by Hand lay-up. At moderate quantities per annum they are produced by Spray-up and at high volume per annum they are produced by Hot Press Moulding of SMC.



In this case the spray-up process is most the most economic option, after which the RTM would be used up to about 20000 components. Hot press moulded DMC then takes over. DMC is marginally more cost effective than SMC due to the relatively low cost of DMC per volume which benefits from the fact that bending stiffness increases by the cube of thickness. Hence increasing thickness has a very beneficial effect on bending stiffness without a significant material cost penalty.



Equal stiffness, equipment to be purchased
(Fig 7.16)

Stiffness as the primary design requirement together with the question of whether or not to purchase equipment is a common situation with glass fibre composites. This figure is therefore very pertinent to the decision making process. It complies with the general perception that moulders hold about where the processes relate to one another. i.e. That hand lay-up is the most cost effective up to about 800 components, after which spray up and RTM moulding become viable at about 800 and 1500 respectively.

It is apparent that Spray-up is a very cost effective option assuming that the quantity per annum is within the capabilities of one machine and only one smooth surface is required.

If not then RTM would be the best choice between 800 and 30000 components. DMC would be preferred to SMC again because of its cost effectiveness in stiffness dominated design criteria.

Fig 7.17 PROPERTIES ASSUMED

	GLASS CONTENT BY MASS	FLEXURAL MODULUS		FLEXURAL STRENGTH	
	%	MPa	Msi	MPa	Ksi
HAND LAY-UP	35	7000	1.02	200	29.0
SPRAY-UP	30	6000	0.87	170	24.7
SMC	25	10500	1.52	150	21.8
DMC	18	10500	1.52	65	9.4
RTM	24	5000	0.73	150	21.8

Fig 7.18 EQUIPMENT COSTS

	TOTAL M/C COST OVER LIFE	M/C LIFE IN TONNES OF COMPOUND	CAPITAL EX- PENDITURE PER kg
	£		
HAND LAY- UP	ZERO		
SPRAY-UP	8000	700	0.0114
SMC	100000		
DMC	AS SMC		
RTM	8000		

Optimum Fibre Content

To optimise a laminate is to find the construction which will give the performance which is most suitable for the intended purpose. It is generally concerned with two considerations:

- to determine the most favourable reinforcement geometry and
 - to determine the most favourable amount of fibre to use, not as an absolute value but as a fraction of the laminate.
- In this exercise we shall be concerned with the latter only.

The percentage of fibre that can be incorporated into a laminate is mainly governed by the moulding method used and the geometry of the reinforcement. For example chopped strand mat moulded by hand lay-up generally has a glass content of about 15% by volume (28% by mass), but if compression moulded then it can be increased to about 25% by volume (40% by mass).

Any attempt to significantly exceed this fibre content would result in crushing of the fibres. On the other hand, in the hand lay-up process, if there is insufficient fibre present then problems such as drainage will occur. Typical fibre contents encountered are given in the table.

It is generally assumed that the more fibre in the laminate, the better. This is often not the case, particularly when the design requirement is flexural performance. There are of course many design criteria which may be optimised but the most important are strength and stiffness. These can be optimised with respect either to weight or to cost but not to both simultaneously, except by chance.

Hence the designer is attempting to maximise one of the following:

Stiffness at minimum cost

Strength at minimum cost

Stiffness at minimum weight

Strength at minimum weight

It is necessary to decide in the first instance which of the above is the most important characteristic. This is more difficult than it would first appear, as human nature generally decrees that more than one are essential. However in spite of our inclination to the contrary only one may be selected. The full process of optimisation is complex and time consuming even if carried out on a regular basis and particularly so when carried out on an ad hoc basis. Hence a series of graphs have been drawn up to aid the process.

A 'rule of mixtures' model of the behaviour of the composite has been used for simplicity. As we are interested in trends rather than absolute values this is acceptable.

The graphs have been drawn on the following basis:

a) Stiffness per cost

- The density of the reinforcement and resin are known.
- For each fibre volume fraction selected, the fibre mass fraction has been calculated from the equation 4.6.
- The cost per kg of the reinforcement and that of the resin are

known, therefore the mass per m² of reinforcement has been calculated from the following equation :

$$m_f = C_k / \{C_f + C_m(1/M_f - 1)\} \quad \text{Equation 7.1}$$

Where m_f = Mass per m² of reinforcement kg/m²
 M_f = Mass fraction of reinforcement fibre
 C_k = Cost £/kg of the laminate (£1)
 C_f = Cost £/kg of the reinforcement
 C_m = Cost £/kg of the resin mix

4) This allows the laminate thickness to be calculated from Equation 4.9:

Laminate thickness (mm) =

$$\text{fibre mass (kg/m}^2\text{)} / (\text{fibre density (g/cm}^3\text{)} \times V_f)$$

5) Young's modulus (E) of the laminate is calculated using the simple rule of mixtures equation with an efficiency factor to allow for the fibre directionality (Eq 5.3).

$$E_k = E_f V_f \beta + E_m (1 - V_f)$$

6) The laminate flexural rigidity has then calculated assuming the following equation:

$$E_k I_k = 1000 (E_k t_k^3) / 12$$

Hence Flexural rigidity has been plotted against fibre volume fraction for constant cost.

b) Strength per cost

The same procedure is used as in a) steps 1) to 4) above.

Step 5) is changed to a model of the strength of the composite as follows:

$$\sigma_k = \sigma_f V_f \beta + \sigma_m (1 - V_f)$$

(See chapter 5)

and Step 5) has been changed to a model of the bending moment at failure of the composite:

$$M_k = (\sigma_k t_k^2) / 6$$

Hence bending moment at failure (which reflects the strength in flexure) is plotted against fibre volume fraction for constant cost.

c) Stiffness per mass

In this case the procedure used in a) is repeated with one change. As we are now specifying the laminate mass to be 1 kg then Equation 4.1₁ is deleted and the following equation used to calculate the fibre mass per m².

$$\text{fibre mass/m}^2 = \text{laminate mass} \times \text{fibre mass fraction}$$

Hence Flexural rigidity has been plotted against fibre volume fraction for constant mass.

d) Strength per mass

In this case procedure b) is used but with the change as in c).

Hence Bending moment at failure (Flexural strength) has been plotted against fibre volume fraction for constant mass.

STRENGTH PER COST Glass fibre / Polyester

Figs 7.19 & 20 have been drawn to show the effect on flexural strength of varying the volume fraction of fibres while keeping material cost constant. Flexural strength is taken to mean the bending moment to cause failure. The approximate ranges over which each reinforcement type can be processed are shown in bold. They compare E glass / polyester laminates of Unidirectional, Bi-directional and Random fibre layups. The Unidirectional construction gives highest flexural strength per cost followed by Bi-directional (woven roving) and then Random construction (chopped strand mat).

The curves for random and woven glass fibre are shown in Fig7.19. Here it can be seen that the woven reinforcement has a negative slope over its operational range. Therefore the optimum fibre content is the lowest which can be achieved.

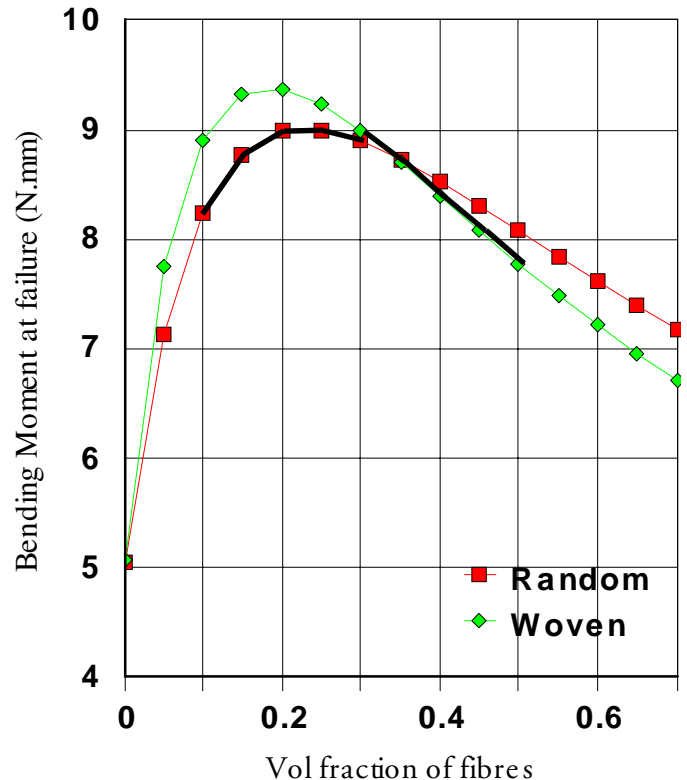
The applicable range of volume fractions for random laminates is 10 - 30 %. It can be seen that there is a maximum at about 22 %. Therefore a departure from this value, either to a higher or a lower volume fraction will give a less cost effective laminate in terms of flexural strength.

Many moulders work at a resin / glass ratio of 2/1 which is equivalent to a volume fraction of about 19%. They are therefore reasonably close to the optimum level if flexural strength is the design criterion.

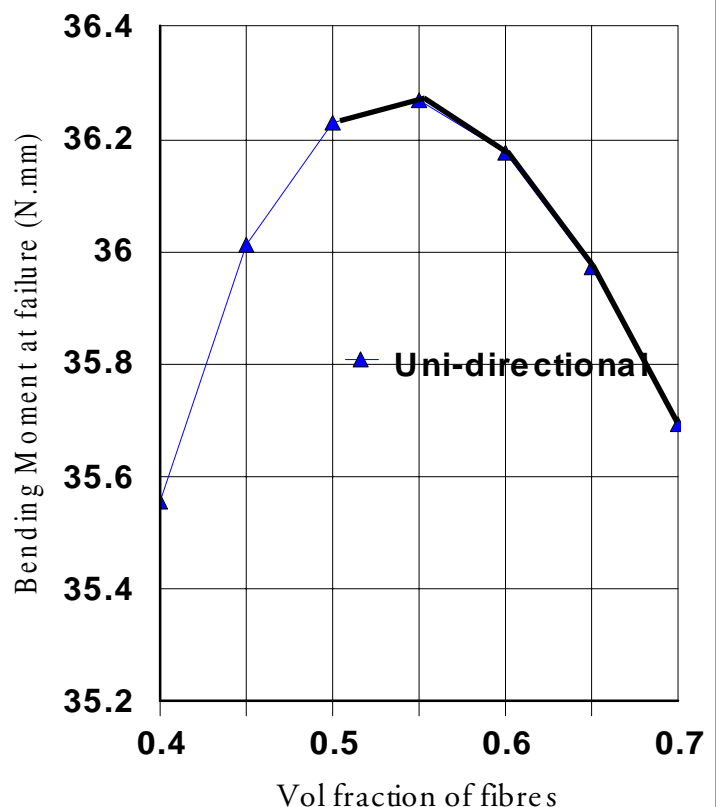
An interesting fact is illustrated in Fig 7.19 if we compare the mean value of each range. At 20% for random we get a strength of 9 units and at 40% for woven we only get about 8.4 units. This goes against the general conception that woven glass laminates are stronger than random laminates. They are stronger in flexure when the basis is 'same thickness' but not when the basis is 'same strength'.

The curve for the Unidirectional laminate has been magnified in Fig 7.20. This shows that there is a maximum value at about 55% volume fraction. If the fibre volume fraction is other than this value then less flexural strength is achieved per £. However note that the effect in this case has greatly magnified to illustrate the point.

**Fig 7.19 Flexural Strength /£
Glass fibre / Polyester**



**Fig 7.20 Flexural Strength /£
Glass fibre / Polyester**



STIFFNESS PER COST Glass fibre / Polyester

Figs 7.21 illustrates the case where we are interested in the amount of flexural rigidity that can be obtained per £. We want to know what is the volume fraction of fibre which will give the highest flexural rigidity if we have only £1 per square metre to spend on materials.

The three curves represent Unidirectional (Roving), Bi-directional (woven roving) and Random (chopped strand mat) constructions.

The range of volume fractions which is applicable is marked in bold. Laminates generally have fibre volume fractions in the following ranges:-

Unidirectional	50 - 70 %.
Bi-directional	30 - 50 % (Woven)
Random	10 - 30 % (Mat)

Hence most of each curve which is drawn is of academic interest only. The applicable ranges being marked in bold.

Each of the three curves have a negative slope which means that in each case the most flexural rigidity will be achieved at the lowest end of the applicable range of fibre content. Hence the laminate is that which achieves its flexural rigidity requirement with lowest glass content.

It should be noted that the random laminate achieves more flexural rigidity per £ than the woven roving laminate. For example the middle of the woven range ($V_f = 40\%$) the flexural rigidity is 80 units, whereas the middle of the random range (20%) gives a flexural rigidity of 130 units. In other words about 70% more flexural rigidity is bought per £ with a random laminate than with a woven laminate. Or for the same flexural rigidity the woven laminate costs 62% more than the random laminate.

FLEXURAL STRENGTH PER MASS Glass fibre / Polyester

In this case the *mass* of the laminate has been kept constant (1 kg/m²) and the flexural *strength* of the laminate has been calculated, for varying levels of fibre content.

Figs 7.22 considers E glass / polyester laminates with Unidirectional, Bi-directional and Random reinforcement types.

Each of the three curves have a positive slope which means that in each case the most flexural strength will be achieved at the highest end of the applicable range of fibre content. Hence the more reinforcement fibre which can be incorporated in the laminate, the better.

Therefore if flexural strength is the design criterion, and we consider average volume fraction values, a woven laminate achieves 20 units compared with 12 units for the random laminate which is 67% better performance for the same weight or 60% of the weight for the same performance.

Fig 7.21 Flexural Rigidity / £
Glass fibre / Polyester

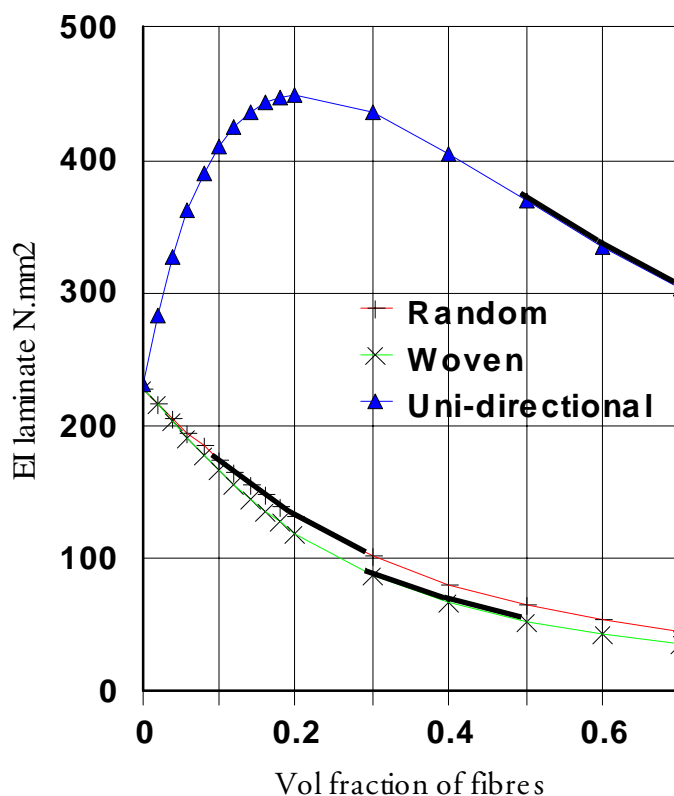
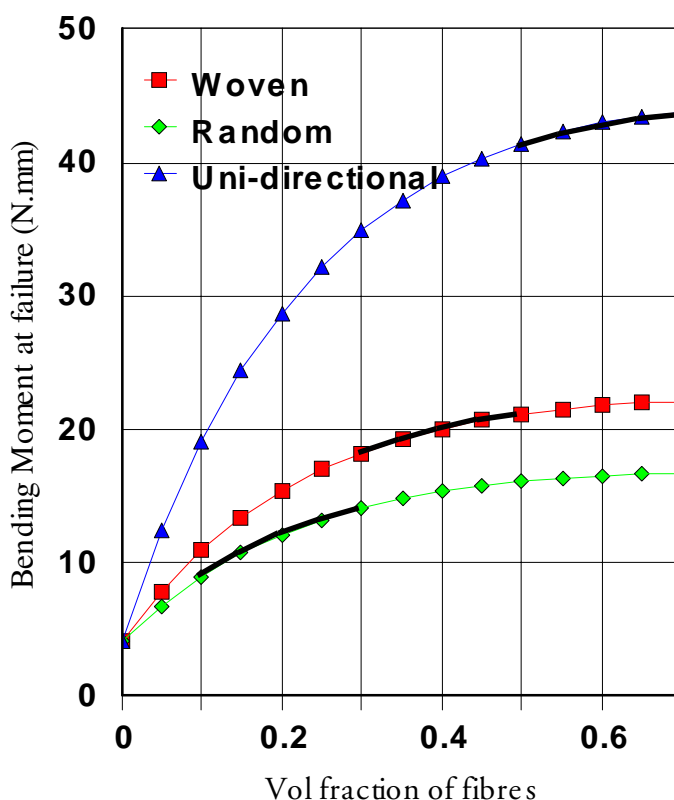


Fig 7.22 Flexural Strength / kg
Glass fibre / Polyester



FLEXURAL RIGIDITY PER MASS Glass fibre / Polyester

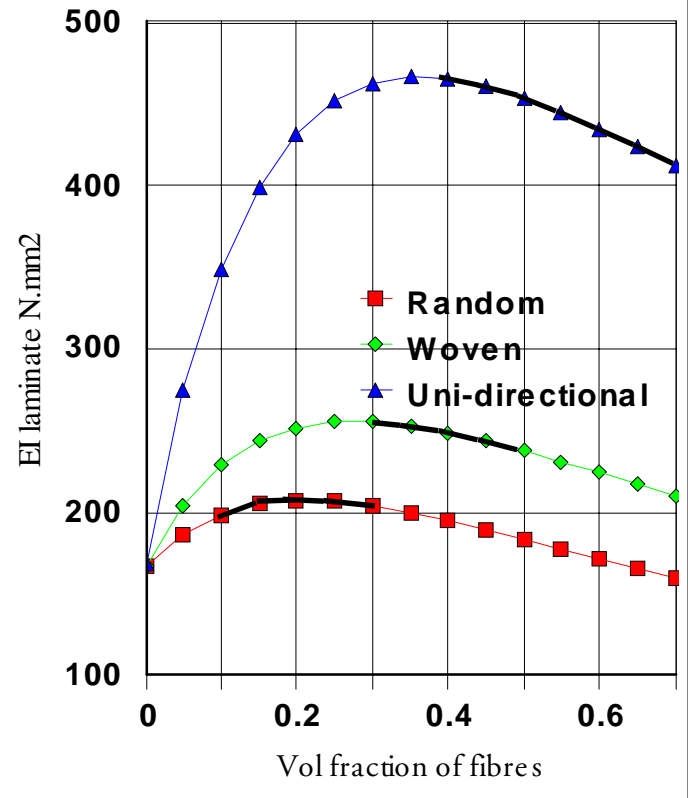
In this case the *mass* of the laminate has been kept constant at 1 kg/m² and the flexural *rigidity* of the laminate calculated for varying levels of fibre content. Fig 7.23 considers E glass / polyester laminates with Unidirectional, Bi-directional and Random reinforcement types. Fig 7.24 shows the random & woven options magnified.

The Unidirectional and Bi-directional laminates have negative slopes and therefore benefit from the lowest feasible fibre content. This is contrary to what might be expected. The initial assumption generally is that to achieve the best flexural rigidity the more glass fibre the better. But if mass of the laminate is the criterion then the amount of fibre should be minimised. In other words the flexural rigidity is best achieved by increasing the thickness of the laminate with resin rather than by the addition of glass fibre.

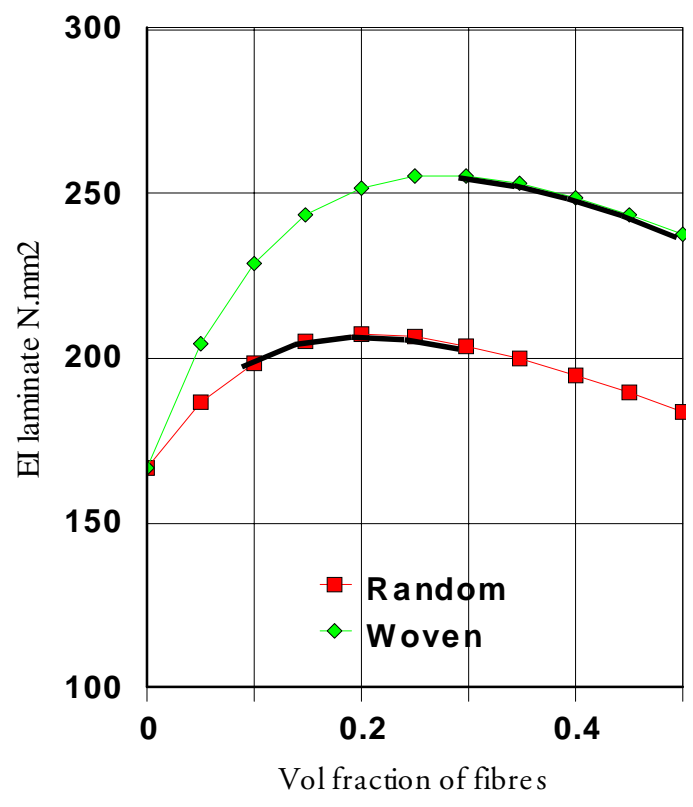
This is the same as the case where cost is the important factor hence both weight and cost can be optimised when the design criterion is flexural rigidity.

The Random laminate has a peak within its operative range at about 20 % hence this is the best fibre content to work at. The benefit for working at the optimum volume fraction represents about a 5% improvement on flexural rigidity at 10% volume fraction.

**Fig 7.23 Flexural Rigidity /kg
Glass fibre / Polyester**



**Fig 7.24 Flexural Rigidity /kg
Glass fibre / Polyester**



Figures 7.25 - 7.28 are concerned with *Carbon Fibre* laminates. The range of typical fibre volume fractions in the case of carbon fibre non-woven laminates is 50 - 70% for (0), (0,90) and (0,90,+/-45) constructions. But if *woven* fabric (0,90) is under consideration then the range of volume fractions would be 30-50%. Fig 7.25 shows flexural *strength per £* for carbon / epoxy in Unidirectional (0), Bi-directional (0,90) and Random (0,90,+/-45) constructions. Each has a slightly negative curve throughout and hence the minimum fibre content is best. Although the curves for (0,90) and (0,90,+/-45) are only slightly negative therefore the benefit is not great.

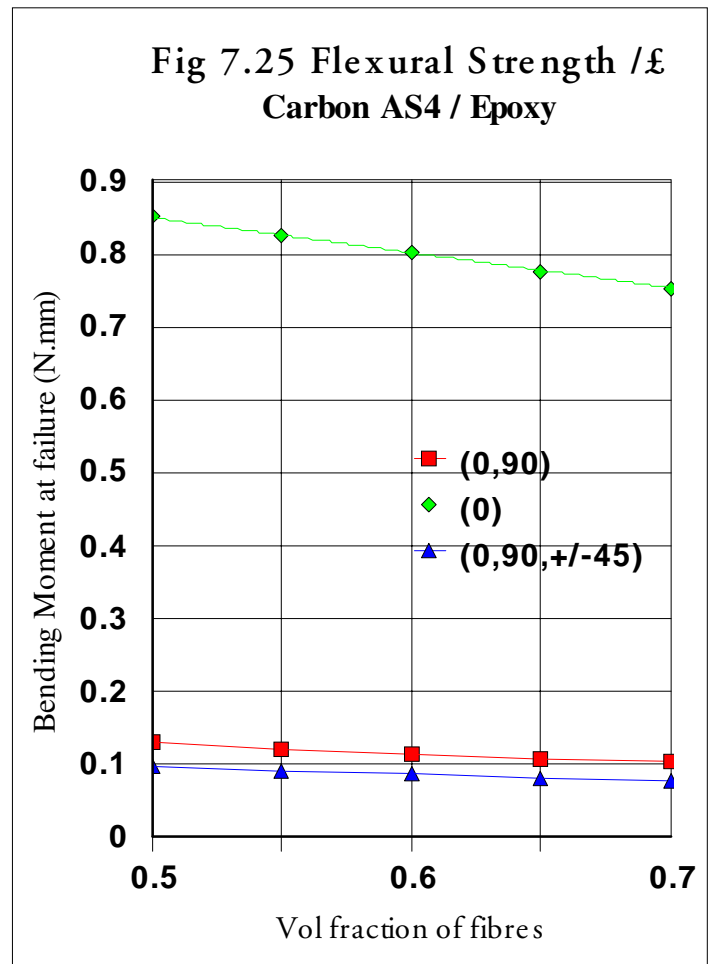


Fig 7.26 shows flexural *rigidity per £* for carbon / epoxy in Uni directional (0), Bi-directional (0,90) and Random (0,90,+/-45) constructions. Each curve is again negative but steeper than the previous case, hence there is more benefit to be gained from the lowest fibre content.

However when we consider strength and stiffness with respect to mass the opposite picture emerges. See Fig 7.27

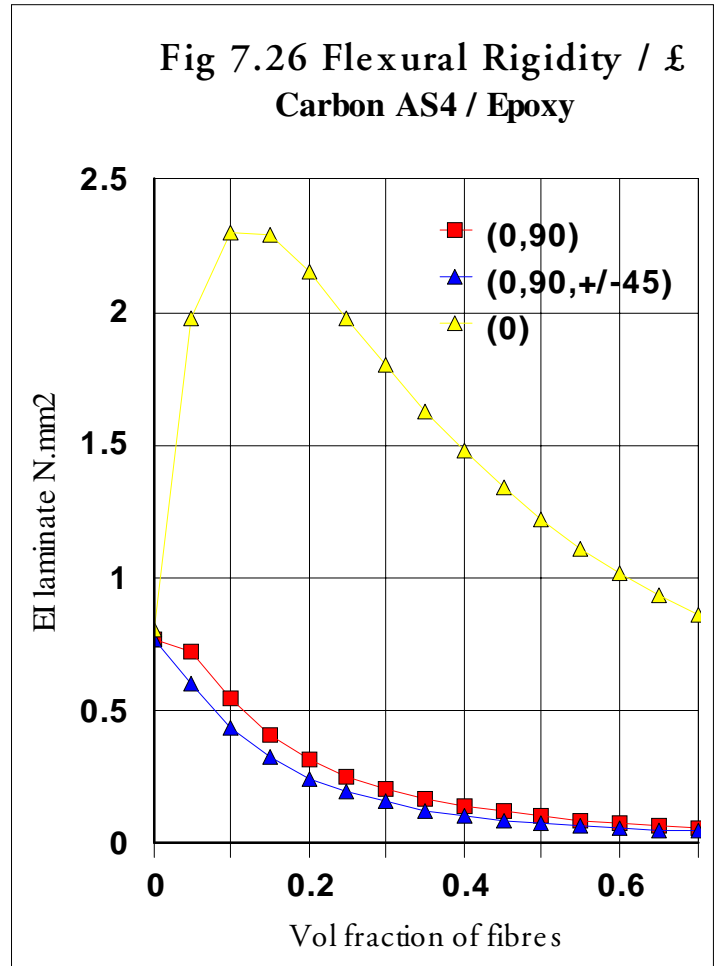


Fig 7.27 shows Flexural Strength / kg, each curve is positive and therefore indicates that the highest fibre content would be most appropriate. This is also the case in Fig 7.28 which covers Flexural Rigidity / kg.

It should be noted that this exercise has not attempted to illustrate all circumstances and has of necessity used a limited range of material prices. Different values will produce significantly different effects. The intention has been to draw attention to the value of this type of analysis so that it may be applied in practical circumstances.

The mathematical models which have been used are of course simplistic but never the less acceptable for the purposes of this exercise, which is more concerned with comparisons and trends rather than absolute values. Even so real values have been used rather than cost ratios to reflect as closely as possible the real world.

Material prices fluctuate overtime and significant departures from the values quoted would of course invalidate the conclusions. The table summarises these the points illustrated in the various graphs.

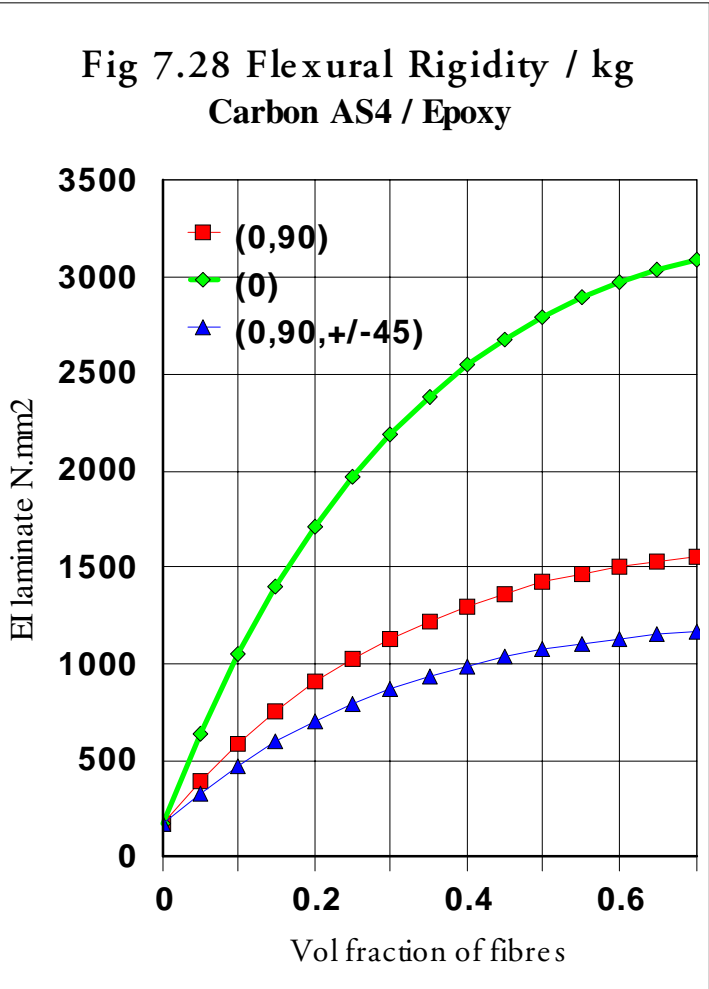
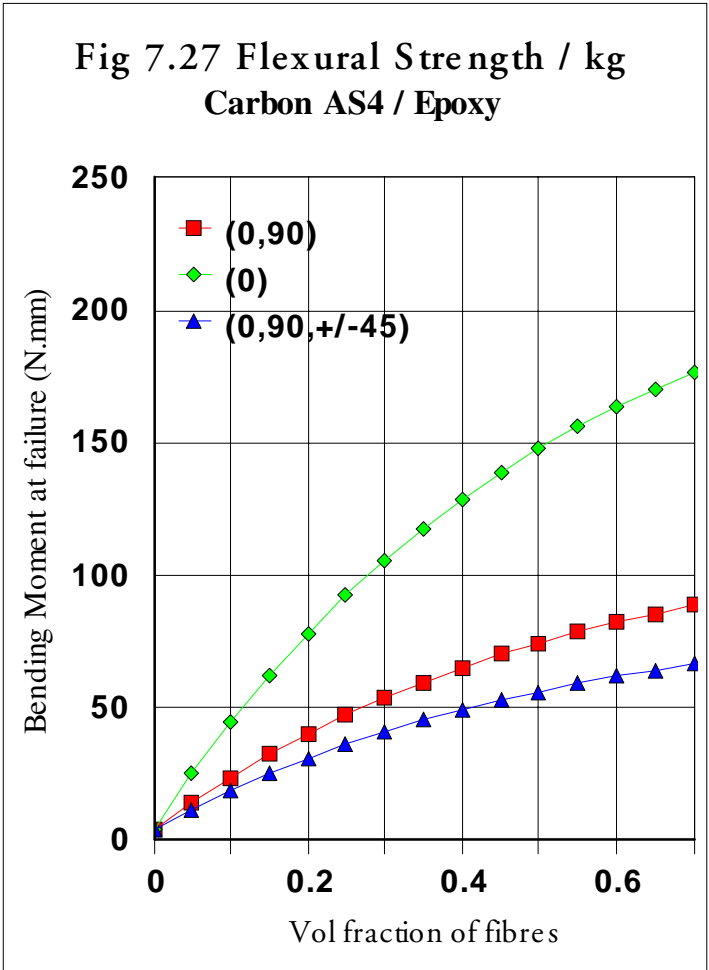


Fig 7.29 Assumed Material Prices			£/kg
Carbon AS4 / Epoxy	(0)		18.00
	(0,90)		36.00
	(0,90,90,+/-45)		36.00
E' Glass fibre / Polyester	Unidirectional		1.15
	Bi-directional		2.00
	Random		1.65

Fig 7.30 Material Properties Assumed

		Carbon AS4	E Glass	Polyester Resin	Epoxy Resin
Young's Modulus	N/mm ²	221000	68900	3445	4000
	Msi	32.05	10	0.50	0.58
Strength	N/mm ²	3930	1725	35	40
	Ksi	570	250	5.1	5.8
Density	g/cc	1.79	2.56	1.2	1.2
	Lb/in ³	0.0646	0.0924	0.0433	0.0433

Fig 7.31 Summary of best options for fibre volume fraction

		Flex. Strength		Flex. Rigidity	
		per Cost	per Mass	per Cost	per Mass
Glass fibre	Unidirectional	55%	Max	Min	Min
	Woven	Min	Max	Min	20 %
	Random	20%	Max	Min	Max
Carbon fibre	0°	Min	Max	Min	Max
	0°,90°	Min	Max	Min	Max
	0°,90°,±45°	Min	Max	Min	Max

8 Reference

- 8.1 Moulders & Fabricators
- 8.2 Distributors of Materials
- 8.3 Suppliers of materials & equipment detailed in the Manual
- 8.4 Imperial / Metric / Imperial Converter
- 8.5 Index

Armfibre Ltd

Drove Rd
 Everton, Sandy
 Bedfordshire SG19 2HX
 Phone 01767 651811
 Fax 01767 651901
 Contact Mr Peter Marsh

Armfibre carry out the design, development and manufacture of cost-effective reinforced plastic products. They have particular expertise in the design and manufacture of large structural components. Dedicated in-house design office using CAD and FEA. Fully equipped pattern and mould making shop. 1000m² moulding shop with Cold Press, RTM and Open-mould laminating. Post cure oven. 600m² finishing and assembly shop with CNC machining facility. Certified to ISO9001.

Bastion Glassfibre Rod & Sections Ltd

12 Harvey Close
 Crowther Ind Est, Washington
 Tyne & Wear NE38 0AB
 Phone 01914166394
 Fax 01914154961
 Contact Mr Jeff Redmayne

Bastion produce very high quality epoxy glass fibre rod by pultrusion. Developed specifically for 400kV circuit breakers where high quality and reliability are of extreme importance there are countless other applications. Dimensions available are: any dia 2mm to 40mm without tooling costs. Diameters up to 10mm can be supplied unground, unvarnished in coils of 200ft max. Max length of ground rod is 4.5m. End fittings in S/S, M.S. or Al. supplied crimped or cemented.

Blondecell Ltd

Cracknore Industrial Park
 Cracknore Rd, Marchwood
 Southampton SO40 4ZD
 Phone +44 (0) 2380 663437
 Fax +44 (0) 2380 868799
 Contact Mr Tony Brewer - M.D.
 Mr Colin Pipkin - Sales & marketing Mgr

Blondecell Ltd has 20 years experience of glassfibre engineering. From a boat building background the company today produce high quality plugs, moulds and mouldings for customers involved in aerospace, water treatment, leisure, shipping and architectural activities. Large mouldings up to 100ft length can be produced under controlled conditions. Hand lay-up. RTM, vacuum bagging and 'Polygran' gelcoat spray processes. Blondecell Ltd is assessed to ISO 9001.

British Mica Co Ltd

123 Barkers Lane,
 Bedford MK41 9RS
 Phone +44 (0) 1234 327977
 Fax +44 (0) 1234 352016
 E-mail info@britishmica.co.uk
 Contact Mr John Allen Man. Dir.

British Mica produce a range of custom designed Arc Barriers by hand lay-up. The material used, Brimico 300, is free from halogens. Smoke and toxic emissions are only a fraction of other more conventional materials used in public vehicles. All recent refurbishments on London Underground's Central, Metropolitan, Jubilee, Picadilly, Hammersmith and City and Northern Lines have been fitted with Brimico 300 arc barriers.

Broadfield Plastics

Sun Mill
 Foxcroft St
 Littleborough OL15 8LB
 Phone 01706 378636
 Fax 01706 377131
 Contact Mr. Jerry Docker

Broadfield Plastics has over 30 years of experience in the GRP industry. A family business offering personal service Their experience allows them to offer competitive prices whilst maintaining the highest quality. Facilities include Hand lay-up, Spray-up and Pattern Making. They have experience in many industries including marine, automotive, building and construction, chemical plant and water treatment.

Broadwater Mouldings Ltd

Horham, Eye
 Suffolk
 IP21 5DQ
 Phone 01379 384145
 Fax 01379 384150
 Contact Mr David Morphew

Broadwater have 70 employees working in a recently commissioned 70,000 sq ft site. They specialise in Hand Lay-up and Spray-up but also have RTM and Cold Press capability. They have experience in supply to demanding markets including Medical, Printing, Electronic industry, Bus and Commercial vehicle body panels and Cab conversions. Quality systems approved to BS EN ISO 9002.

CCT Ltd

5-8 Millbrook Close
 Chandlers Ford Ind Est
 Eastleigh Hampshire SO53 4BZ
 Phone +44 (0)2380 255232
 Fax +44 (0)2380 251297
 Contact Mr John Ward-Business Manager

CCT (Previously Borden) have over 35 years experience in the production of high quality composite tooling and components for the aerospace, automobile and communication industries. In a 25000 sq ft facility they are equipped with a 2m x 6.5m autoclave, clean room, RTM equipment and 3 dimensional measuring tables, curing ovens with vacuum facilities, routers, presses and their own engineering workshop. They employ epoxy, phenolic, polyester and polyurethane resins and are assessed to ISO 9002 together with many aerospace and military approvals.

W L Cunliffe (Southport) Ltd

Gratton Place, East Gillibrands
 Skelmersdale, Lancashire WN8 9UE
 Phone 01695 711800
 Fax 01695 711811
 Contact Mr Brian Spencer
 Email sales@wlcunliffe.com
 Web site www.wlcunliffe.com

W L Cunliffe Ltd offer a service from initial concept through to volume production. Facilities include in-house pattern making, and components are produced in hand lay-up, RTM, cold and hot press. Customers are spread across the truck, bus, medical, printing and sewage industries.
 BS EN ISO 9002 approved.

Cobham Composites Ltd

Davey House, Gelders Hall Lane
 Shepshed, Loughborough
 Leicestershire LE12 9NH
 Phone 01509 504541
 Fax 01509 507563
 Contact Roger Manwaring Sales Mgr
 Email r.manwaring@cobhamcomposites.co.uk

Cobham Composites Ltd was formed in 1973 to design and manufacture composite components for the Aerospace, Rail and Transportation, Defence, Communication and Industrial markets. Production techniques range from Hand Lamination, RTM, Compression Moulding to full Autoclave processing.

A team of design and development engineers, combined with an in house pattern and mould manufacturing facility allows prototype components as well as high volume production. Cobham Composites Ltd has numerous company approvals and is certified to BS EN ISO 9001, stringent QA systems are supplemented by 3 axis CMM and ultrasonic A scan facilities.

Country Leisure (GRP Ltd)

Cholderton, Salisbury
 Wiltshire SP4 0EQ
 Phone 01980 629 555
 Fax 01980 629 501
 Email sales@countryleisure.co.uk
 Website www.countryleisure.co.uk
 Contacts Mr Malcolm Brown - MD
 Mr Karl Fear - Production Director

Country Leisure founded in 1985 enjoys a reputation with its customers for quality hand-lay and spray deposited mouldings. Traditionally, customers lay in the field of Swimming Pool Industry, until 1988 when the company branched out into the Leisure Industry, as manufactures of Water Slide and Theme Park Ride mouldings.

They offer a total capability in the supply of the widest range of Swimming Pool Step Units, associated Wall Panelling including Diving Boards, Sun Loungers and Swimming Pool Slides. Whilst they specialise in the Leisure Industry, they are interested in any form of GRP manufacturing for any other industry sector.

Engineering & Glassfibre Developments

Walverden Park Works
 Nelson, Lancs BB9 0TA
 Phone 01282 618 221
 Fax 01282 698 499
 Email egdltd@compuserve.com
 Web site www.egdgrp.co.uk
 Contact Mr Anthony Davies MD
 Mr Alf Paulauskas— Sales & Project Mgr

Founded in 1964, EGD Ltd is one of the country's leading innovators in supplying high quality GRP solutions. Not being constrained to just one market sector, they can apply their knowledge and experience and utilise it in others. EGD specialise in producing mouldings from polyester, vinyl-ester and phenolic resins using handlay, spray and resin inject processes. Having achieved in 1966 BS ISO 9002 on their first assessment, they are now seeking accreditation to ISO 9000:2000. Quality, reliability, service and support are the foundation to EGD's continuing success.

Ex-Press Plastics Ltd

8 Beccles Road
 Loddon
 Norfolk NL14 6JL
 Phone 01508 528000
 Fax 01508 528764

Express Plastics have over 25 years experience in the GRP industry. Express claim to offer a novel solution for the medium volume market by the uses of low pressure moulding techniques. This allows short lead time together with matched mould accuracy and finish. They have 33 presses with platens up to 5m by 2.5m

Fibrelite Composites Ltd
Snaygill Industrial Estate
Keighley Road, Skipton
North Yorkshire, BD23 2QR
Phone 01 756 799 773
Fax 01 756 799 539

The Fibresec Group established in 1986 employs 60 people in three UK Plants (RTM composites: rigid structural foam: handlay and spray GRP). Fibrelite, a major UK producer by RTM have an annual output in excess of 500 tonnes of composite parts, Fibrelite products are used by almost all major oil companies worldwide. They are also suppliers to both road and rail transport sectors. Platen sizes to 2300 x 2300 are available for RTM together with robotic machining facilities.

Forbes
Denver
Downham Market
Norfolk PE38 0DR
Phone 01 366 388 941
Fax 01 366 385 274

Forbes' core business since the late 1950's, has been the manufacture of high quality, competitively priced tanks, vessels, degassers, scrubbers and other chemical plant in plastics materials as recognized by their accreditation to BS EN ISO 9001. Utilising a broad scope of up to the minute manufacturing techniques, Forbes are able to produce a vast product range from storage tanks up to 200,000 litres through to complex scrubbing systems.

G & A Plastics Ltd
Hagg Works, Hyndburn Road
Accrington Lancs BB5 4AH
Phone 01254 871919
Fax 01254 390967
Contact Mr David Challans

G & A Plastics have a reputation for high quality Thermoplastic & GRP process plant which they have built up over the 25 years that they have been in operation. Their capability includes in-house detail design of vessels and ducting / pipework systems. Their experience includes vertical and horizontal cylindrical vessels, rectangular tanks, scrubbers and stacks ventilation and extraction systems, and specialised plastic fabrications.

Gloucester Composites Ltd
Sudmeadow Rd
Sevenside Ind Est, Hempstead
Gloucester GL2 6HS
Phone 01452 384422
Fax 01452 384123
Contact Mr Don Fenner

Gloucester Composites Ltd is run by Don Fenner and Dave Bolton well known in the industry for many years. Produce Polyester SMC and DMC and compression mould general engineering and water storage products. The company is Water Council approved for these purposes. Facilities include presses ranging from 160 tonnes to 500 tonnes with bed size up to 6ft by 4ft.

Hampton Mouldings Ltd
Piory Ind Est London Rd
Tetbury
Gloucestershire GL8 8HZ
Phone 01 666 502 603
Fax 01 666 504 646

With 35 years experience, the company is recognized by many as the UK's leading thermoset composite moulder. With a full in-house design, pattern making and prototyping facility, the firm is available to handle all aspects of a project from conception to production. Manufacturing facilities include the very latest RTM MIT™ technology, SMC and DMC hot press facilities, plus several CNC machining centres.

Hepworth GRP Products Division
Pollard Moor Works Padiham
Burnley BB12 7JR
Phone 01282 772533
Fax 01282 779950

Hepworth have over 20 years experience in compression moulding polyester SMC and DMC and have in-house compounding pressing capabilities from 100 - 1500 tonnes, platen sizes up to 3m x 2m and extensive assembly and finishing facilities. Product areas include supply to automotive, truck, utility, signage and consumer durable markets.

Haywood Plastics Ltd

Greengrove Mill, Dyehouse Lane
 Rochdale OL16 2 QY
 Phone 01706 753500
 Fax 01706 753501
 email Haywood-Plastics.co.uk
 Contact Bob Butterworth

Haywood Plastics is a major supplier of composite and rotational mouldings to the Automotive, Rail, Traffic Management and Safety Equipment industries. Their facilities include pattern / model making, open and closed tool moulding, spray processes and rotational moulding of thermoplastics, enabling their customers to work with one company from design to production. Their ISO 9002 accreditation assures that their products are to the highest standard achievable

Lionweld Kennedy Ltd

Composites Engineering Div.
 Brignell Rd, Middlesbrough
 Cleveland TS2 1PS
 Phone 01642 245151
 Fax 01642 232978

Established for over 15 years Lionweld Kennedy has maintained its status as one of the largest fabricators of GRP products in the UK and Europe. They supply access products, such as grating, handrailing and ladders, access structures and structural tank covers into the offshore, petrochemical and water and waste processing industries. They have a design capability and a fully equipped workshop for machining products

Motherwell Bridge Composite Structures

PO Box 4 Logans Rd
 Motherwell ML1 3NP
 Phone 01698 242462
 Fax 01698 242478
 Contact Simon Eves M.D.

A wholly owned division of the Motherwell Bridge Group, they specialise in products and structural fabrications made with Pultruded profiles. They have structural design engineers, CAD and extensive fabrication workshops to build standard and custom fabrications. They are also the UK Authorized Distributor for Strongwell, the World's leading pultruder. Structural Profiles, Fibrebolt, Grating, Handrailing & Ladders other construction products are supplied from stock. Product brochures and Structural Design Manual are available.

MB Plastics Ltd

Forward Works Woolston
 Warrington WA1 4BA
 Phone 01925 822811
 Fax 01925 818907
 Contact :- Mr Malcolm Clayton

Founded over 30 years ago, manufacture a comprehensive range of chemical resistant products in glass fibre composite materials, including Tanks, Pressure Vessels, Scrubbing Columns, Ducting and Pipe-work Systems. The company operates a comprehensive installation and After Sales Service throughout the UK. and Overseas for all its products. The Stockport factory also manufactures tanks, pipework, vessels, ductwork and has particular expertise in custom built plastic fabrications and the moulding and fabrication of GRP structures and walkways. The company is BS EN ISO9002 accredited.

Mitras Composites (UK) Ltd

New St, Biddulph Moor
 Staffordshire ST8 7NL
 Phone +44 (0)178 522 433
 Fax +44 (0)1782 522 652
 E-mail sales@mitras-composites.co.uk
 Internet www.mitras-composites.co.uk

Mitras Composites (UK), is part of the Mitras Industries Group, Europe's largest specialist GRP moulder. Situated in Biddulph Moor it serves the electrical and electronic, utility, construction, public transport and chemical markets. Focused on SMC products, they have a modern facility incorporating compression moulding presses from 50 to 1200 tonnes. They also have facilities for Hand Lamination, RTM, Post Mould Machining, Finishing & Assembly and are ISO9002 approved.

Polymer Engineering Ltd

Gateway
 Crewe
 Cheshire CW1 1YY
 Phone 01270 583723
 Fax 01270580846
 Contact :- Mr Nick Clarke

Polymer Engineering Ltd, established in 1982, set about an extensive R&D programme into RTM moulding in which they now specialise. They have a workforce of over 60 and carry out design and prototyping in-house. Thus they can supply high quality designs and finished components to industries as demanding as Automotive, Rail and Engineering. Major clients include Foden Trucks, ABB, Volvo, Rolls Royce, Aston Martin, Ford, ERF Trucks and Seddon Atkinson.

Readings Composites Ltd

Lysons Ave, Ash Vale

Aldershot

Hampshire GU12 5QF

Phone 01252 549 777

Fax 01252 549 729

Contact Mr J K Beaumont

Founded in 1958, Readings Composites Produces high quality, high specification composite mouldings using Hand lay-up, Cold Press and Resin Injection techniques. They specialise in offering a fast prototype through to production service with the minimum of formal drawings. The production area of 25000 Sq ft includes their own Pattern Making facilities. Quality system approved to ISO9002.

Redman Fisher Engineering Ltd

Birmingham New Rd

West Midlands DY4 9AA

Phone (44) (0) 1902 880 880

Fax (44) (0) 1902 880 446

E-mail flooring@redmanfisher.co.uk

Contact John Freeman - General Manager

Developed by Redman Fisher FlowGRiP* is a revolutionary flooring plank featuring the unique Tongue and Groove interlocking system. FlowGRiP* reduces cost while increasing safety. With their total solutions approach Redman Fisher not only supply: Flooring, Handrailing, Stair Treads, Structures, Cable Management System, they also offer full design and installation service.

Vosper Thornycroft (UK) Ltd

Woolston

Southampton SO19 9RR

Phone 01703 445144

Fax 01703 685913

Contact:- Composites Engineering Mgr

Vosper Thornycroft's expertise is in the design and fabrication of large glass fibre reinforced structures. These range from 60m Boats to passive fire protection on Oil and Gas platforms. They use total project engineering to ensure the most efficient design, manufacturing methods and materials are used.

8.2 Distributors of Materials to the Composites Industry

Freeman Distribution Ltd

PO Box 8
5 Civic Way, Ellesmere Port
South Wirral, L65 0HB
Phone 0151 356 3111
Fax 0151 355 3772
Contact: Paul Brittles

Freeman Distribution as part of the DSM Group of companies enjoys a position in the forefront of the UK distributors. Operating from six strategically positioned depots, Freeman offer DSM's resin products (including gel coat, fire retardant and corrosion resistant grades), Organic Peroxide curing agents from Peroxid Chemie, glass reinforcements from Owens Corning, Epoxide resins from Shell and Epoxide curing agents from Air Products.

GRP Material Supplies Ltd

Head Office :
Tel (01705) 677940 Fax (01705) 699582
Depots:
Portsmouth Tel (01705) 697444 Fax (01705) 654769
Avonmouth Tel (01179) 821341 Fax (01179) 235394
Rochdale Tel (01706) 630151 Fax (01706) 860411
Kettering Tel (01536) 525146 Fax (01536) 410950

GRP Material Supplies Ltd - Distributor of reinforced plastic raw materials, encompassing a complete range of Glass Fibre Re-inforcements, Core materials including Foam & Coremat, Catalysts & Ancillary Equipment, Polyesters & Gel Coat Products from CVT, Neste, Jotun & BIP

Hawk International Distributors Ltd

Waterside
Brightlingsea
Essex CO7 0AS
Tel (44) 01206 304010
Fax (44) 01206 304226
Contact: Stephen Olle

Hawk distributes vinylester, isophthalic and ISO NPG resins for open and closed moulds including SMC, BMC and RTM, from Alpha/Owens Corning - a world leader in DCPD base polyester technology. Other products include Durabuild polyester and vinylester coatings for plug and pattern surfacing, mould repair, mould resurfacing (including tooling gelcoats), and T R release agents.

K & C. MOULDINGS (ENGLAND) LTD

Spa House
Shelfanger
Diss, Norfolk
IP22 2DF
Tel (44) 01379 642660
Fax (44) 01379 650304
Contact Mr George Edens

K. & C. Mouldings Limited was established in 1958 to manufacture glassfibre mouldings and to design and manufacture machinery to improve production of GRP mouldings. They distribute raw material also including Reichhold resins and Owens Corning glassfibres, but tend to specialise in the supply of machinery and ancillaries ranging from spraying machines through diamond trimming tools to brushes and rollers.

8.3 Suppliers of Materials or Equipment detailed in the Manual

Advanced Composite Group Ltd

Composites House, Sinclair Close
Heanor Gate Ind Est
Heanor, Derbyshire DE75 7SP
Phone 01773 763441 Fax 01773 530245
e-mail: info@acg.co.uk,
Web site: www.advanced-composites.com,
Contact Sales Manager

UK customers contact:

Akzo Nobel Chemicals Ltd

1-5 Queens Road
Hersham, Walton on Thames
Surrey KT12 5NL England
tel. 01932 247891 Fax. 01932 231204

For customer outside the UK contact:

Akzo Nobel Chemicals bv

Stationsplein 4 3818 LE Amersfoort, Netherlands
tel +31 334676581 Fax +31 334676151
Hans Jurgen Sager, Marketing Manager

Cray Valley Structural Resins

Laporte Rd
Stallingborough
North East Lincolnshire DN37 8DR
Tel 01469 572464 Fax 01469 572988

Creative Pultrusions Inc

6 The Drive
Rushden
Northants NN10 9JT
Phone 01933 56652 Fax 01933 411976
Contact Mr Ron Brown

Chemical Release Company Ltd

12 Cheltenham Mount
Harrogate
North Yorkshire HG1 1DL
Phone 01423 569715 Fax 01423 563384
Contact Keith Godber
Email crc@releaseagents.co.uk
Web site www.releaseagents.co.uk

Dow Plastics

Lakeside House
Stockley Park Uxbridge
Middlesex UB11 1BE
Phone 0181 848 8688 Fax 0181 848 5422

Fibrebat Ltd

Mavor Avenue, Nerston West
East Kilbride
Glasgow G74 4QY
Phone 013552 38351 Fax 013552 30386

Fibreforce Composites Ltd

Fairoak Lane, Whitehouse, Runcorn,
Cheshire, England, WA7 3DU.
Tel.: +44 1928 701515/714413
Sales Direct: +44 1928 719016 Fax: +44 1928 713572
Email: sales@fibreforce.co.uk

Fibreforce Composites Ltd

Brunel Road, Clacton On Sea,
Essex, England, CO15 4LU.
Tel.: +44 1255 220569 Fax: +44 1255 431002
Email: sales@fibreforceclacton.co.uk

Flemings Industrial Fabrics

Belford Mills, Lawson St
Kilmarnock, Ayrshire
Scotland KA1 3HZ
Phone 44 (0) 1563 525203 Fax 44 (0) 1563 522022
E-mail: flemings@scott-fyfe.com

Lantor bv

P.O. Box 45
3900 AA VEENENDAAL
The Netherlands
Tel.: 31 (0) 318 537111 Fax: 31 (0) 318 537299
Email lantorbv@lantor.nl

LLewellyn Ryland Ltd

Haden St
Birmingham B12 9DB
Phone 44 (0) 121440 2284 Fax 44 (0) 121440 0281
Email sales@llewellyn-ryland.co.uk

Pultrex Ltd

Century House, North Station Road
Colchester
Essex CO1 1PD England
Tel No: 44 (0)1206 369555 Fax 44 (0)1206 576554
Email: sales@pultrex.com

Saint-Gobain BTI

Unit 4/5 Walworth Ind Est
Andover Hants SP10 4DY
Phone 44 (0)1264 333 400 Fax 44 (0)1264 359610
Contact Mr Malcolm Lee
www.cotech.com

Technical Fibre Products Ltd

Burnside Mills
Kendal
Cumbria LA9 6PZ. UK
Phone 44 (0)1539 818264 Fax 01539 733850
www.techfibres.com

8.4 Imperial / Metric / Imperial Converter

The following Figures 8.1 to 8.7 allow conversion between metric and imperial units.

Examples

1) To convert 27 ft² to m²

From Fig 8.2

$$27 \text{ ft}^2 = 0.0929 \times 27 = 2.51 \text{ m}^2$$

2) To convert 300 g/m² to oz/ft² :

From Fig 8.5

$$300 \text{ g/m}^2 = 3.277 / 1000 \times 300 = 0.98 \text{ oz/ft}^2$$

Fig 8.1 Length

Imperial to Metric

Input			Output	
1	inch	=	25.4	mm
			2.54	cm
			0.0254	m
			0.000025	km
1	foot	=	304.8	mm
			30.48	cm
			0.3048	m
			0.0003048	km
1	yard	=	914.4	mm
			91.44	cm
			0.9144	m
			0.0009144	km
1	mile	=	1587398.4	mm
			158739.84	cm
			1587.3984	m
			1.5873984	km

Metric to Imperial

Input			Output	
1	mm	=	0.039370	inches
		=	0.003281	feet
		=	0.001094	yards
		=	0.00000062	miles
1	cm	=	0.393701	inches
		=	0.032808	feet
		=	0.010936	yards
		=	0.0000062	miles
1	m	=	39.3701	inches
		=	3.28084	feet
		=	1.09361	yards
		=	0.000621	miles
1	km	=	39370.08	inches
		=	3280.84	feet
		=	1093.61	yards
		=	0.621371	miles

Fig 8.2 Area

Imperial to Metric

Input			Output	
1	inch ²	=	645.16	mm ²
			6.4516	cm ²
			0.00064516	m ²
			6.4516E-10	km ²
1	foot ²	=	92903.04	mm ²
			929.0304	cm ²
			0.09290304	m ²
			9.2903E-08	km ²
1	yard ²	=	836127.36	mm ²
			8361.2736	cm ²
			0.83612736	m ²
			8.3613E-07	km ²
1	mile ²	=	2.590E+12	mm ²
			2.590E+10	cm ²
			2589988	m ²
			2.58999	km ²

Metric to Imperial

Input			Output	
1	mm ²	=	0.0015500	inches ²
		=	1.0764E-05	feet ²
		=	1.1960E-06	yards ²
		=	4.6332E-12	miles ²
1	cm ²	=	0.155000	inches ²
		=	0.001076	feet ²
		=	0.0001196	yards ²
		=	3.8610E-11	miles ²
1	m ²	=	1550.003	inches ²
		=	10.76391	feet ²
		=	1.19599	yards ²
		=	3.861E-07	miles ²
1	km ²	=	1550003100	inches ²
		=	10763910	feet ²
		=	1195990	yards ²
		=	0.386102	miles ²

Fig 8.3 Volume & Capacity**Imperial to Metric**

Input		Output	
1	inch ³	= 16387.06	mm ³
		= 16.3871	cm ³
		= 1.6387E-05	m ³
		= 0.016387	litre
1	foot ³	= 28316847	mm ³
		= 28317	cm ³
		= 0.028317	m ³
		= 28.3168	litre
1	yard ³	= 764554858	mm ³
		= 764554.86	cm ³
		= 0.764555	m ³
		= 764.555	litre
1	gal	= 4.54600	litre
		= 4546.00	cm ³
1	USgal	= 3.78541	litre
		= 3785.41	cm ³

Metric to Imperial

Input		Output	
1	mm ³	= 0.00006102	inches ³
		= 3.5315E-08	feet ³
		= 1.3080E-09	yards ³
1	cm ³	= 0.06102374	inches ³
		= 0.00003531	feet ³
		= 1.3080E-06	yards ³
1	m ³	= 61023.74	inches ³
		= 35.31467	feet ³
		= 1.30795	yards ³
1	litre	= 61.0230	inches ³
		= 0.035314	feet ³
		= 0.001308	yards ³
		= 0.219980	gal
		= 0.264200	USgal

Fig 8.4 Mass & Force**Imperial to Metric**

Input		Output	
1	oz	= 28.34952	g
		= 0.0283495	kg
		= 2.8350E-05	tonne
1	lb	= 453.5924	g
		= 0.4535924	kg
		= 0.0004536	tonne
1	ton	= 1016047	g
		= 1016.05	kg
		= 1.01605	tonne

Metric to Imperial

Input		Output	
1	g	= 0.035274	oz
		= 0.002205	lb
		= 9.8421E-07	ton
1	kg	= 35.273962	oz
		= 2.204623	lb
		= 0.000984	ton
1	tonne	= 35273.96	oz
		= 2204.62	lb
		= 0.984207	ton

Fig 8.5 Pressure, Stress & Mass per unit area

Msi = 1000 Ksi = 1000000 Psi
Psi = lb/in²

1 bar = 0.1 MPa = 0.1 N/mm²
N/mm² = MPa = MN/m²

Imperial to Metric

Input			Output	
1	lb/in ²	=	0.070307	kg/cm ²
		=	703.0696	kg/m ²
		=	703070	g/m ²
	lbf/in ²	=	0.006895	N/mm ²
		=	0.068947	bar
1	lb/ft ²	=	4.8824E-04	kg/cm ²
		=	4.882430	kg/m ²
		=	4882.43	g/m ²
	lbf/ft ²	=	0.000479	bar
1	oz/ft ²	=	3.0515E-05	kg/cm ²
		=	0.305152	kg/m ²
		=	305.1519	g/m ²
1	oz/yd ²	=	3.3906E-06	kg/cm ²
		=	0.033906	kg/m ²
		=	33.90576	g/m ²

Metric to Imperial

Input			Output	
1	kg/cm ²	=	14.2233	lb/in ²
		=	2048.16	lb/ft ²
		=	32771	oz/ft ²
		=	294935	oz/yd ²
1	g/m ²	=	1.4223E-06	lb/in ²
		=	0.0002048	lb/ft ²
		=	0.003277	oz/ft ²
		=	0.029494	oz/yd ²
1	kg/m ²	=	1.4223E-03	lb/in ²
		=	0.204816	lb/ft ²
		=	3.277058	oz/ft ²
		=	29.49352	oz/yd ²
1	N/mm ²	=	145.0380	lbf/in ²
		=	20885.47	lbf/ft ²
1	bar	=	14.5038	lbf/in ²
		=	2088.547	lbf/ft ²

Fig 8.6 Density & Specific gravity

Imperial to Metric

Input			Output	
1	lb/in ³	=	27.6799	g/cm ³
		=	27679.90	kg/m ³
		=	27.6799	kg/litre
1	lb/ft ³	=	0.016018	g/cm ³
		=	16.0185	kg/m ³
		=	0.016018	kg/litre
1	lb/gal	=	0.099776	g/cm ³
		=	99.7763	kg/m ³
		=	0.099776	kg/litre

Metric to Imperial

Input			Output	
1	g/cm ³	=	0.036127	lb/in ³
		=	62.4280	lb/ft ³
		=	10.0224	lb/gal
1	kg/m ³	=	3.6127E-05	lb/in ³
		=	0.062428	lb/ft ³
		=	0.010022	lb/gal
1	kg/litre	=	0.036127	lb/in ³
		=	62.4280	lb/ft ³
		=	10.0224	lb/gal

Fig 8.7 I value per unit width, Unit load per mass of fibre

Imperial to Metric

Input			Output	
1	in ⁴ /ft width	=	1365589	mm ⁴ /m width
1	lb/in per oz/ft ² of reinforcement	=	0.573900	N/mm per kg/m ² of reinforcement

Metric to Imperial

Input			Output	
1	mm ⁴ /m width	=	7.32285E-07	in ⁴ /ft width
1	N/mm per kg/m ² of reinforcement	=	1.742463	lb/in per oz/ft ² of reinforcement

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About James Quinn Associates Ltd:

Created in 1991, the practice offers a consultancy service specialising in all aspects of composite materials and their use. This covers the design and production engineering of polymer composites from GRP's to Advanced Composites and includes specification, inspection and litigatory work.

AREAS OF ACTIVITY

Design and Analysis

This represents a broad spectrum of capabilities comprising the design of Components, Structural Elements and Structures for:-

Chemical and Water treatment plant Marine and Off-shore;
Aerospace and Defence;

Civil and Structural applications etc

The individual requirements may be as diverse as the design of structural elements such as beams and columns to the design of cylindrical and rectangular tanks to BS4994. The practice has experience in the design of a large variety of components and structures which include:-

Multi-sphere tank system for underground storage;

Hyperbolic paraboloid roof structure for a market hall;

Range of flagpoles;

Pultruded process plant walkways, handrails and there associated structural support platforms, Marine Radome structures
Design and testing of Pultruded cable tray system and support framework for the Channel Tunnel.

Pultruded monococque walkway flooring

Pultruded industrial roofing system

Where appropriate, Laminate Analysis is used for the design of components.

Production Engineering

The production Engineering capability covers Pultrusion, Compression moulding, Autoclave, Vacuum and the Intermediate processes, RTM etc and includes: Process selection, Economics, Process optimisation, Material optimisation, Trouble shooting etc.

Product Design & Development

It is generally more economic to employ the services of an outside resource to design and develop a new product rather than to maintain an in-house capability which would be under utilised. Hence product design and development on behalf of a client is a field of increasing activity. We have experience in the development of a variety of products ranging from industrial to consumer white goods.

Pultrusion Technology Service

Specialist experience in all areas of pultrusion technology.

Ranging from initial product design ie construction and shape optimisation, through to tooling design.

J A Quinn C.Eng, M.I.Mfg.E.

Served a Technician Apprenticeship and as a draughtsman at Plessey Co Liverpool. He joined Fibreglass Ltd in 1965 as Design Draughtsman and held various roles concerned with the design and production of composite materials concluding with the position of Applications Manager. He joined Bridon Composites in 1983 as Design and Development Manager and became Technical Manager in 1987. After the acquisition by Shell and company name change to Fibreforce Composites he became Technical Director.

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He was a member of the Board of Halcrow Polymerics Ltd, a subsidiary of Sir William Halcrow & Ptns - Consulting Engineers.

Chartered Engineer and a member of the Institution of Manufacturing Engineers.

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Publications

'Design Data - Fibreglass Composites' Fibreglass Ltd

'Design Manual - Engineered Composite Profiles'

Design Methodology for Rectangular Tanks in GRP
(Internal Document Fibreglass Ltd)

Chapter 3: 'Properties of Thermoset Polymer Composites' of
'Design with Advanced Composite Materials' Edited by Leslie Phillips OBE

Papers Presented Include

'Cost and Weight Optimisation Decisions for GRP' ICCM III
Paris, 1980

'Composites Selection Methods for Designers' FRC 84, Liverpool

'The Application of Acoustic Emission Techniques to the Characterisation of Pultrusion'. Liverpool Conference 1988

'Compliance of Composite Reinforcement Materials used in Pultrusion' FRC90.

'The Potential for Polymer Composites in Offshore Applications' ISOPE San Francisco, 1992.

'The Application of Pultruded Composites in Structural Engineering Applications' 18th BPF Congress., Manchester 1992.

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