Annex C
(normative)

FRP laminates properties and calculations

C.1 Methods for the determination of mechanical properties

C.1.1 General

Mechanical properties for use in determining scantling requirements from 8.1, 8.4, 9.1, 9.2 and Annex H shall be determined by one of three methods that depend on the mechanical property evaluation level (EL) used by the builder and defined in Table C.1.

Table C.1 — Evaluation level of mechanical property determination method

Evaluation level	Definition	Method
EL-a	Mechanical properties and fibre content by mass are determined by measurement using recognised test standards for samples that are representative of the product as manufactured.	Use measured data corrected as per C.1.1.
EL-b	Fibre content by mass is determined by measurement. Spot checks are carried out using recognised test standards for samples that are representative of the product as manufactured to ensure the product meets or exceeds the values from Tables C.4 to C.7.	Default data (Tables C.4 to C.7)
EL-c	No explicit measurements are made on fibre content and mechanical properties. Fibre content is taken from Table C.2 or other nominal values.	Default data (Tables C.4 to C.7) with multiplying factor of 0,8.

C.1.2 Evaluation level method “EL-a”

Mechanical properties and fibre mass content shall be determined experimentally and shall consist of those properties explicitly required by the scantling equations of Clauses 10 and 11 and Annex H.

The test sample shall be representative of the product as manufactured. In general, the specimen shall be manufactured under the same typical workshop conditions using the same material, fibre contents and sequence, methods of lay-up, thermal treatment and time sequence.

Tests to determine mechanical properties shall be conducted in accordance with the applicable or appropriate International Standard, e.g.

— the tensile strength and modulus shall be determined in accordance with ISO 527-1 and ISO 527-2;

— the flexural strength and modulus shall be determined in accordance with ISO 178.

Where an International Standard does not exist, a national standard may be used instead. The number of samples to be tested shall be as laid down in international or national standards but shall not be less than five samples for any given property.

When determining the flexural strength, the gel coat side of the specimen shall be stressed in tension.

The mechanical properties used in the calculations shall be corrected as follows:

— for strength, 90 % of the mean ultimate strength or the mean value minus two standard deviations, whichever is the lesser;

— for elastic modulus, the mean value.

The fibre content by mass in the laminate ψ may be determined for a specimen by ignition or ingestion of the resin or by direct measurement of the laminate, in kilograms per square metre, from the known fibre mass (see Example C.3.1).

The measured fibre content and actual fibre mass of the test samples shall be used to determine the nominal sample thickness using thickness equations. These values shall be used for converting measured failure loads and deflection into ultimate strength and modulus. Where the measured thickness deviates by > 15 % from the nominal thickness, a note to this effect shall be included in the test report.

Thickness equations

Equations for E glass

$$\frac{t}{w} = \frac{1}{3{,}072}\left(\frac{2{,}56}{\psi} - 1{,}36\right) \tag{C.1}$$

$$\psi = \frac{2{,}56}{3{,}072\frac{t}{w} + 1{,}36} \tag{C.2}$$

Tabulated values of Equation (C.1) are given in Table C.3.

Equations for high-strength carbon

$$\frac{t}{w} = \frac{1}{2{,}16}\left(\frac{1{,}8}{\psi} - 0{,}6\right) \tag{C.3}$$

$$\psi = \frac{1{,}8}{2{,}16\frac{t}{w} + 0{,}6} \tag{C.4}$$

Equations for aramid

$$\frac{t}{w} = \frac{1}{1{,}74}\left(\frac{1{,}45}{\psi} - 0{,}25\right) \tag{C.5}$$

$$\psi = \frac{1{,}45}{1{,}74\frac{t}{w} + 0{,}25} \tag{C.6}$$

where

t is the thickness, in millimetres;

w is the mass of fibre, in kilograms per square metre;

ψ is the mass content of fibre in the laminate (dry mass of fibre divided by the mass of the fibre plus resin).

Equations (C.1), (C.3) and (C.5) shall be used to find the required fibre mass that corresponds to a required thickness (as given in Clauses 10 and 11 and Annex H) at a specified fibre content by mass value. They can also be used to calculate thickness on a ply-by-ply basis or for the total laminate where ψ is the total mass of fibre divided by the total mass of the fibre plus resin. See example C.3.2.

Equations (C.2), (C.4) and (C.6) may be used to find the average mass content of a laminate for which the fibre mass and thickness are known (see H.2.1.8).

C.1.3 Evaluation level method “EL-b”

Two conditions shall be satisfied:

a) the fibre content by mass shall be established at least by direct measurement (see Example C.3.1) and with “occasional” spot checks by resin ignition or ingestion methods;

b) mechanical tests need not be carried out systematically, provided “occasional” spot-check tests on representative samples using recognised test standards and corrected as given in C.1.2 demonstrate that the builder can normally meet or exceed the values obtained from Tables C.4 to C.7.

Under these conditions, the mechanical properties may be taken from Tables C.4 to C.7 at the appropriate fibre content by mass.

The definition of “occasional” shall be such as to satisfy the builder that he is able to meet or exceed the values given in Tables C.4 to C.7 since it is his responsibility to demonstrate this. See C.1.5.

By way of guidance, as a minimum, “occasional” should include strength and modulus tests by three- or four-point bending methods for single-skin samples and sandwich beam bending tests by variable span methods.

Spot checks should always be carried out where the laminate schedule for a product is not broadly similar to a schedule for which use of data in Tables C.4 to C.7 has been validated by previous spot checks.

However, EL-b differs from EL-a in that a full set of mechanical data tests is not anticipated. It therefore follows that a builder may wish to test some critical items under EL-a while using Tables C.4 to C.7 for other non-tested properties.

C.1.4 Evaluation level method “EL-c”

The fibre content is taken from Table C.2 or from other data sources without explicit measurement of the fibre content by mass from representative samples taken from the product. Occasional spot-check tests on representative samples using recognised test standards and corrected as given in C.1.2 are rarely or never conducted. The ratio between thickness in millimetres and glass weight in kilograms per square metre is tabulated in Table C.3 for the values of ψ given in Table C.2.

Under these conditions, the mechanical properties may be taken from Tables C.4 to C.7 at the appropriate fibre content by mass, but all values so obtained shall be multiplied by a factor of 0,8.

Table C.2 — Nominal fibre content by mass

Type of ply reinforcement	Glass fibre laminate — Glass content by mass ψ		
	Open mould		Vacuum bag
	Simple surface [b]	Complex surface [b]	
Chopped strand mat (CSM) sprayed up	0,30	0,25	(0,36)
Chopped strand mat hand lay up	0,30	0,25	(0,36)
Woven roving (WR)	0,48	0,36	0,58
Roving mat combination [a]	0,46-0,18 R	0,35-0,11 R	0,56-0,22 R
Multidirectional fabric	0,50	0,38	0,60
Unidirectional fabric	0,55	0,41	0,66
Non-glass fibres (suitable for equivalent glass content by mass > 0,4, i.e. not CSM)			
For carbon fibre The fibre content by mass ψ which gives the same fibre content by volume as the values above for glass may be estimated using $\psi_{carbon} = 0{,}99\ \psi_{glass}$ from the table $-$ 0,08 (see example C.3.3). Alternatively, one can take the value of Φ corresponding to ψ_{glass} in Table C.4 b) and use the same value in Table C.5.			
For aramid fibre The fibre content by mass which gives the same fibre content by volume as the values above for glass may be estimated using ψ aramid = 0,95 ψ glass from the table $-$ 0,11.			

[a] R = total mass of mat (kg/m^2)/total mass of glass in laminate (mat and woven roving) (kg/m^2).

[b] A "simple" surface is a surface where resin impregnation and wetting-out is easy (e.g. large and accessible surfaces like hull and deck, cockpit bottom). A "complex" surface is a surface where resin impregnation and wetting-out is not easy (e.g. deep coamings, deep stiffeners or tray mouldings, etc.). The differentiation is up to the builder.

Table C.3 — Tabulated values of t/w in function of glass content by mass ψ

ψ	0,25	0,30	0,36	0,38	0,41	0,50	0,55	0,58	0,60	0,66
t/w [a]	2,89	2,34	1,87	1,75	1,59	1,22	1,07	0,99	0,95	0,82

[a] Ratio between thickness in millimetres and mass of dry glass in kilograms per square metre.

C.1.5 Builders' responsibilities

Builders proceeding under any of the above evaluation level methods should recognise that responsibility for ensuring that the mechanical properties of any product meet or exceed those values used to determine the scantlings, howsoever these values were obtained (test or Tables C.4 to C.7), rests with the builder. Use of values from Tables C.4 to C.7 does not in itself make any statement about the actual built quality of the product.

In most instances, it will be in the builders' interest to adopt level "a" or combination of levels "a" and "b". Use of level "c" carries a considerable penalty since neither the actual fibre content by mass, nor the quality of fabrication can be quantified with any certainty.

C.2 Default mechanical properties

C.2.1 Status of default equations

The equations and values listed in Tables C.4 to C.7 are not intended to represent absolute minimums. The values are intended to be lower-bound estimates that are achievable by builders who use high-end industry standard quality material control and fabrication procedures.

The values will not be consistently achievable by builders who do not use best practice. Where there is any doubt as to the suitability of Tables C.4 to C.7, the onus is on the builder to satisfy himself that the values so obtained are achievable in practice.

The Tables are not suitable for hybrid plies, i.e. different fibres contained within a single ply. However, they may be used for a same fibre ply in a multi-fibre stack and analysed using the methods outlined in Annex H.

Tables C.4 to C.7 are mostly relevant for hand laminates or vacuum bag laminates (maybe with epoxy for carbon fibre). Oven cured pre-preg laminates, possibly in an autoclave, will show much higher strength values, but are closer to aerospace construction, and not fully within the scope of this part of ISO 12215.

C.2.2 Default values for glass-based composites

The values derived from Table C.4 a) correspond to E glass in polyester only.

Table C.4 a) — E glass fibre mechanical properties

Property	Values N/mm^2	
Hand-laminated chopped strand mat (CSM), combined mat/woven roving, woven roving (WR) and crossplied (CP) – 0/90 reinforcement [a]		
Ultimate tensile strength, σ_{ut}	$800\ \psi^2 - 80\ \psi + 37$	
Ultimate compressive strength, σ_{uc}	$150\ \psi + 72$	
Ultimate flexural strength, σ_{uf}	$502\ \psi^2 + 107$	
Ultimate in-plane shear strength, τ_u	$80\ \psi + 38$	
In-plane modulus, E	$38\ 000\ \psi - 5\ 000$	
In-plane shear modulus G	$1\ 700\ \psi + 2\ 240$	
Interlaminar (out of plane) shear strength $\tau_{u\ inter}$	$22{,}5 - 17{,}5\ \psi$	
Sprayed chopped strand mat		
Ultimate tensile strength, σ_{ut}	$150\ \psi + 25$	
Ultimate flexural strength, σ_{uf}	$300\ \psi^2 + 107$	
Other properties for sprayed CSM shall be obtained from the CSM equations above.		
Uni-directional (UD) reinforcement		
Property	**Parallel to the fibres**	**Perpendicular to the fibres**
Ultimate tensile strength, σ_{ut}	$880\ \psi^2 + 140\ \psi + 140$	42
Ultimate compressive strength, σ_{uc}	$250\ \psi + 190$	105
In-plane modulus, E	$46\ 600\ \psi^2 + 7\ 200\ \psi + 7\ 250$	$48\ 600\ \psi^2 - 39\ 000\ \psi + 12\ 500$
In-plane shear modulus, G	$14\ 380\ \psi^2 - 10\ 560\ \psi + 3\ 840$	
In-plane shear strength, τ_u	50	
Major Poisson's ratio, ν_{12}	0,3	
[a] For combined mat and woven roving, ψ may be the overall value. See Example C.3.2.		

The value for interlaminar (out of plane) shear strength of 22,5 to 17,5 ψ for CSM and WR can be used for sprayed mat and UD.

C.2.3 Comments on calculated Tables C.4 b) and C.5 b)

Tables C.4 b) and C.5 b) are displayed to help in the application of Tables C.4 a) and C.5 a). They are:

— in the upper part, calculated values of Tables C.4 a) and C.5 a), respectively for glass and carbon laminate;

— in the lower part, calculated values of Table C.7 for double bias (diagonal ± 45°) and balanced multiaxial (0/90/+45/–45) made from glass or high-strength carbon.

Double bias exhibit low values for σ and high values for τ compared with 0/90°. It is suggested that the use of pure double bias should be restricted to elements that are predominantly loaded in shear (web of high stiffeners, web of multihull crossbeams).

Table C.4 b) — GRP calculated values of Table C.4. a) and Table C.7

ψ Mass content	ϕ Volume content	Mixed mat/roving/multiaxial						Sprayed mat		UD (unidirectional)			
		σ_{ut}	σ_{uc}	σ_{uf}	τ_u	E	G	σ_{ut}	σ_{uc}	$\sigma_{ut}//$	$\sigma_{uc}//$	τ_u	E
		N/mm^2											
0,250	0,135	67	110	138	58	4 500	2 665	63	126				
0,275	0,151	76	113	145	60	5 450	2 708	66	130				
0,300	0,167	85	117	152	62	6 400	2 750	70	134				
0,325	0,184	96	121	160	64	7 350	2 793	74	139				
0,350	0,202	107	125	168	66	8 300	2 835	78	144	297	278	50	15 479
0,375	0,220	120	128	178	68	9 250	2 878			316	284	50	16 503
0,400	0,238	133	132	187	70	10 200	2 920			337	290	50	17 586
0,425	0,257	148	136	198	72	11 150	2 963			358	296	50	18 727
0,450	0,277	163	140	209	74	12 100	3 005			381	303	50	19 927
0,480	0,302	183	144	223	76	13 240	3 056			405	309	50	21 184
0,500	0,319	197	147	233	78	14 000	3 090			430	315	50	22 500
0,525	0,341	216	151	245	80	14 950	3 133			456	321	50	23 874
0,550	0,364	235	155	259	82	15 900	3 175			483	328	50	25 307
0,575	0,388	256	158	273	84	16 850	3 218			511	334	50	26 797
0,600	0,413	277	162	288	86	17 800	3 260			541	340	50	28 346

ψ Mass content	ϕ Volume content	Double bias [a] +/– 45°				Balanced quadraxial 0/45/90/–45			
		σ_{ut}	σ_{uc}	τ_u	E	σ_{ut}	σ_{uc}	τ_u	E
		N/mm^2							
0,500	0,319	95	95	140	6 300	148	147	86	10 500
0,525	0,341	95	95	144	6 728	162	151	88	11 210
0,550	0,364	95	95	148	7 155	176	155	90	11 920
0,575	0,388	95	95	151	7 583	192	158	92	12 640
0,600	0,413	95	95	155	8 010	208	162	95	13 350

[a] The data for double bias and quadraxial are only informative due to absence of extensive test data.

C.2.4 Carbon-based composites

The values derived from Tables C.5 a) and C.5 b) correspond to high-strength carbon only. High or intermediate modulus carbon is not considered. The associated resin system is assumed to be fully compatible with the fibres and provide excellent bonding and load-distribution qualities.

Carbon fibres are normally expected to be employed in the skins of sandwich panels, for which the in-plane properties (i.e. in-plane modulus, ultimate tensile and compressive strengths) are appropriate.

On occasions where an all-carbon single-skin FRP panel is to be analysed, only an approximate estimate of flexural properties may be obtained using Tables C.5 a) and C.5 b) (see C.3.4). Mechanical test of a representative laminate is strongly recommended.

Table C.5 a) — High-strength carbon fibre mechanical properties

Property	**Values** N/mm^2	
Hand-laminated, woven roving (WR) and crossplied (CP) — 0/90 reinforcement high-strength carbon fibre in compatible resin [a]		
Ultimate tensile strength, σ_{ut} (0 or 90 direction)	$990\ \psi - 90$	
Ultimate compressive strength, σ_{uc} (0 or 90 direction)	$610\ \psi - 55$	
In-plane modulus, E (0 or 90 direction)	$100\,000\ \psi - 9\,000$	
Ultimate in-plane shear strength, τ_u	$40\ \psi + 31$	
In-plane shear modulus G	5 100	
Poisson's ratio	0,05	
Unidirectional (UD) reinforcement		
Property	**Parallel to the fibres**	**Perpendicular to the fibres**
Ultimate tensile strength, σ_{ut}	$2\,000\ \psi - 200$	$50\ \psi^2 - 20\ \psi + 20$
Ultimate compressive strength, σ_{uc}	$1\,100\ \psi - 110$	$150\ \psi^2 - 60\ \psi + 60$
In-plane modulus, E	$202\,000\ \psi - 21\,000$	$10\,700\ \psi^2 - 4\,200\ \psi + 4\,400$
In-plane shear modulus, G	$22\,000\ \psi^2 - 17\,300\ \psi + 5\,700$	
Ultimate in-plane shear strength, τ_u	$310\ \psi^2 - 240\ \psi + 80$	
Major Poisson's ratio, ν_{12}	0,32	
Ultimate flexural strength, $\sigma_{uf} = 2{,}5\ \sigma_{ut} / (1 + \sigma_{ut}/\sigma_{uc})$. See example C.3.4		

[a] The mechanical properties are intended to be lower-bound values but not absolute minima. They are indicative of reasonable quality fabrication and primarily intended for preliminary design purposes. Testing in accordance with C.1 is strongly recommended.

Table C.5 b) — Carbon composite calculated values of Table C.5 a) and Table C.7

ψ Mass	ϕ Volume	Mixed roving and crossplies					UD carbon (high strength)							
		σ_{ut}	σ_{uc}	τ_u	E	G	$\sigma_{ut}//$	$\sigma_{uc}//$	$E//$	σ_{ut} perp	σ_{uc} perp	E perp	G	τ_u
Content		N/mm^2												
0,400	0,308	306	189	47	31 000	5 100	600	330	59 800	20	60	4 432	2 300	34
0,425	0,330	331	204	48	33 500	5 100	650	358	64 850	21	62	4 548	2 321	34
0,450	0,353	356	220	49	36 000	5 100	700	385	69 900	21	63	4 677	2 370	35
0,475	0,376	380	235	50	38 500	5 100	750	413	74 950	22	65	4 819	2 446	36
0,500	0,400	405	250	51	41 000	5 100	800	440	80 000	23	68	4 975	2 550	38
ψ Mass	ϕ Volume	Double bias [a] $\pm$ 45°					Balanced quadraxial 0/45/90/–45							
		σ_{ut}	σ_{uc}	τ_u	E		σ_{ut}	σ_{uc}	τ_u	E				
Content		N/mm^2												
0,400	0,308	61	57	188	7 750		184	113	118	21 700				
0,425	0,330	66	61	192	8 370		199	123	120	23 400				
0,450	0,353	71	66	196	9 000		214	132	123	25 200				
0,475	0,376	76	70	200	9 620		228	141	125	26 900				
0,500	0,400	81	75	204	10 250		243	150	128	28 700				

[a] The data for double bias and quadraxial are only informative due to absence of extensive test data.

C.2.5 Aramid-based composites

The values derived from Table C.6 correspond to aramid fibres of the type usually used in marine hull structures. The associated resin system is assumed to be fully compatible with the fibres and provide excellent bonding and load-distribution qualities.

Aramid fibres are normally expected to be used in the skins of sandwich panels, for which the in-plane properties (i.e. in-plane modulus, ultimate tensile and compressive strengths) are appropriate.

On occasions where an all-aramid single-skin FRP panel is to be analysed, only an approximate estimate of flexural properties may be obtained using Table C.6. See C.3.4.

Table C.6 — Aramid fibre mechanical properties

Property	**Values** N/mm^2	
Hand-laminated, woven roving (WR) and crossplied (CP) — 0/90 reinforcement aramid fibre in compatible resin [a]		
Ultimate tensile strength, σ_{ut} (0 or 90° direction)	$720\ \psi - 10$	
Ultimate compressive strength, σ_{uc} (0 or 90° direction)	$250\ \psi$	
Ultimate in-plane shear strength, τ_u	45	
In-plane modulus, E_t (0 or 90° direction)	$50\,000\ \psi + 750$	
In-plane shear modulus G	3 400	
Poisson's ratio	0,05	
Unidirectional (UD) reinforcement		
Property	Parallel to the fibres	Perpendicular to the fibres
In-plane modulus, E	$103\,000\ \psi - 1\,400$	$1\,550\ \psi + 2\,600$
Ultimate tensile strength, σ_{ut}	$1\,400\ \psi - 20$	$12\ \psi + 20$
Ultimate compressive strength, σ_{uc}	$340\ \psi$	$30\ \psi + 50$
In-plane shear modulus, G	$6\,900\ \psi^2 - 2\,250\ \psi + 1\,800$	
Ultimate in-plane shear strength, τ_u	$100\ \psi^2 - 32\ \psi + 25$	
Major Poisson's ratio, ν_{12}	0,4	
Ultimate flexural strength, $\sigma_{uf} = 2{,}5\ \sigma_{ut}/(1 + \sigma_{ut}/\sigma_{uc})$.		
[a] The mechanical properties are intended to be lower-bound values but not absolute minima. They are indicative of reasonable quality fabrication.		

C.2.6 Values for double bias or quadraxial laminates

The angles for plies 0°, +45°, 90°, –45°, etc. for multidirectional plies or laminates are the respective angles of the fibre plies from the b direction of a rectangular $l \times b$ panel (see Figure H.1).

The use of quadraxial laminates (UD balanced 0/45/90/–45) is becoming more common, particularly in sandwich laminates. The properties are usually in between those of roving and double bias.

Testing of double bias laminates is highly recommended, but in the absence of tested values, the following method can be applied for glass or carbon laminates with $0{,}5 < \psi < 0{,}6$ for GRP and $0{,}4 < \psi < 0{,}5$ for carbon laminates. Values for aramid laminates are currently not available.

Tables C.4 a) and C.5 b) incorporate the values of Table C.7.

Table C.7 — Mechanical properties of double bias or quadraxial E glass or HS carbon laminates

Mechanical property	E glass [a]	HS carbon [a]
Range of applicable ψ values	$0,5 < \psi < 0,6$	$0,4 < \psi < 0,5$
Double bias (± 45°) **laminates compared to woven roving and 0/90 reinforcements**		
Ultimate tensile strength, σ_{ut} (0 or 90°)	95 N/mm^2	0,20 σ_{ut} of woven roving or biaxial
Ultimate compressive strength, σ_{uc} (0 or 90°)	95 N/mm^2	0,30 σ_{uc} of woven roving or biaxial
Ultimate in-plane shear strength, τ_u	1,8 τ_u of woven roving or biaxial	4 τ_u of woven roving or biaxial
In-plane modulus, E_t (0 or 90° direction)	0,45 E_t of woven roving or biaxial	0,25 E_t of woven roving or biaxial
Quadraxial (0/45/90/–45) **laminates compared to woven roving and 0/90 reinforcements**		
Ultimate tensile strength, σ_{ut} (0 or 90°)	0,75 σ_{ut} of woven roving or biaxial	0,6 σ_{ut} of woven roving or biaxial
Ultimate compressive strength, σ_{uc} (0 or 90°)	1,0 σ_{uc} of woven roving or biaxial	0,6 σ_{uc} of woven roving or biaxial
Ultimate in-plane shear strength, τ_u	1,1 τ_u of woven roving or biaxial	2,5 τ_u of woven roving or biaxial
In-plane modulus, E_t (0 or 90° direction)	0,75 E_t of woven roving or biaxial	0,7 E_t of woven roving or biaxial

[a] When there is a ratio of mechanical properties, it applies for the same material (E glass or carbon HS) at the same ψ value.

C.3 Examples

C.3.1 Fibre mass by direct measurement

Procedure:

1) measure the length and width of five representative samples for which the actual fibre mass, in kilograms per square metre, is known;

2) weigh each sample with a balance that reads to an accuracy > 1 % of the sample mass;

3) divide the mass obtained at step 2, in kilograms, by the product of length and width, in metres;

4) divide the known actual fibre mass by the mass obtained at step 3.

Worked example:

Sample dimensions: 100 mm × 100 mm; mass of sample = 0,131 kg;

Mass of sample per square metre: 0,131/(0,1 × 0,1) = 13,1 kg/m^2;

Laminate schedule: 300 CSM + 4 × (450 CSM + 850 WR). Total glass = 5,5 kg/m^2;

Overall fibre content by mass: 5,5/13,1 = 0,42.

Repeat for four other samples.

C.3.2 Overall fibre content by mass by calculation

A boatbuilder builds a craft in an open mould with the following laminate for the hull bottom:

gel coat + 2 mat 225 + 3 (rov-mat 500/300) + rov 500.

The total amount of glass is 2 × 0,225 + 3 × 0,8 + 0,5 = 3,35kg/m^2.

From Table C.2: For mat $\psi_1 = 0{,}30$ (simple surface) and $w_1 = 0{,}450$ kg/m^2.

For rov-mat $R = 0{,}9/2{,}4 = 0{,}375$, therefore (simple surface), $\psi_2 = (0{,}46 - 0{,}18 \times 0{,}375) = 0{,}39$ and $w_2 = 2{,}4$ kg/m^2.

For woven roving, $\psi_3 = 0{,}48$ (simple surface) and $w_3 = 0{,}5$ kg/m^2.

The overall glass content is:

$$\psi = \frac{w_1 + w_2 + w_3}{\dfrac{w_1}{\psi_1} + \dfrac{w_2}{\psi_2} + \dfrac{w_3}{\psi_3}} = \frac{0{,}450 + 2{,}4 + 0{,}5}{\dfrac{0{,}450}{0{,}30} + \dfrac{2{,}4}{0{,}39} + \dfrac{0{,}5}{0{,}48}} = \frac{3{,}35}{8{,}7} = 0{,}39$$

From Equation (C.1), the thickness is: $t = \dfrac{w}{3{,}072}\left(\dfrac{2{,}56}{\psi} - 1{,}36\right) = \dfrac{3{,}35}{3{,}072}\left(\dfrac{2{,}56}{0{,}39} - 1{,}36\right) = 5{,}68$ mm

C.3.3 Fibre content by mass for non-glass fibre from Table C.2

Take a vacuum-bagged unidirectional. The fibre content by mass is 0,66 for glass.

For carbon, the figure giving the same fibre volume fraction would be:

ψ carbon $= 0{,}99$ ψ glass from Table C.2 $- 0{,}08 = 0{,}99 \times 0{,}66 - 0{,}08 = 0{,}57$.

C.3.4 Flexural properties of non-glass laminates

Calculate in-plane properties for the appropriate fibre content by mass.

Woven roving from Table C.2 ψ glass $= 0{,}58$.

ψ carbon $= 0{,}99$ ψ glass from Table C.2 $- 0{,}08 = 0{,}99 \times 0{,}58 - 0{,}08 = 0{,}49$.

$E = (100\,000\ \psi - 9\,000) = 40\,000$ N/mm^2 [see also Table C.5 a) for the following data].

$\sigma_{ut} = (990\ \psi - 90) = 395$ N/mm^2; $\sigma_{uc} = (610\ \psi - 55) = 244$ N/mm^2.

Estimate of flexural properties:

Ultimate flexural strength, $\sigma_{uf} = 2{,}5\ \sigma_{ut}/(1 + \sigma_{ut}/\sigma_{uc}) = 2{,}5 \times 395/(1 + 395/244) = 377$ N/mm^2.

NOTE Mechanical test of a representative laminate is strongly recommended.

C.3.5 Flexural strength of mixed spray-up CSM and WR

The flexural strength of sprayed CSM is lower than that of hand-laid CSM, typically by 12 %.

For normal hand-laid CSM/WR, the σ_{uf} formula is the same so it is only necessary to calculate the overall glass fraction.

For all sprayed CSM, the formula in Table C.4 a) shall be used, i.e. $\sigma_{uf} = 300\ \psi^2 + 107$.

For a combination of spray-up CSM and WR, in the absence of test data (the preferred method), the following approximate formula may be used:

$$\sigma_{uf} = (502 - 202\ R_{spray})\ \psi^2 + 107$$

where R_{spray} = mass of sprayed CSM glass/mass of glass.

EXAMPLE For 50 % sprayed CSM, $R_{spray} = 0{,}5$ and $\sigma_{uf} = 401\ \psi^2 + 107$.