

Specification for

Design and construction of vessels and tanks in reinforced plastics

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- Associated Offices Technical Committee
- British Chemical Engineering Contractors' Association
- British Plastics Federation
- Chemical Industries Association
- Department of Trade and Industry (National Physical Laboratory)
- Engineering Equipment and Materials Users' Association
- Health and Safety Executive
- Institution of Mechanical Engineers
- Process Plant Association

The following bodies were also represented in the drafting of the standard, through subcommittees and panels:

- Electricity Supply Industry in England and Wales
- Plastics and Rubber Institute

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Foreword

This British Standard has been prepared under the direction of the Pressure Vessel Standards Committee and is a revision of BS 4994:1973, which is now withdrawn together with its explanatory supplement PD 6480. Its purpose is to establish a general standard for the design, fabrication and use of vessels and tanks in reinforced plastics for industrial service.

This revision has been made to take account of experience with reinforced plastics vessels and tanks and opportunity has been taken to extend the scope to include filament winding and rectangular tanks and to categorize vessels in relation to duty.

In the 1973 edition of this standard the minimum value for the overall design factor was 6. In this edition that value has been increased to 8. The change is made because experience has shown that the overall strain limitation does not permit lower values than 8.

The manufacture of vessels and tanks in reinforced plastics is a wide field, involving a large number of materials, both plastics and reinforcing systems, and widely different methods of manufacture. It is not practicable to cover all aspects in a single standard and this standard covers part of the field, namely, the use of polyester, epoxy and furane resins in wet lay-up systems.

Information on the engineering properties of reinforced plastics is somewhat limited and this applies particularly to the changes in such properties over long periods. In the absence of comprehensive long-term properties, therefore, the material properties used for design are based on short-term tests. Material property data should be presented in the form recommended in BS 4618.

Metallic vessels, being made from materials which are normally isotropic, are conveniently designed by calculating permissible stresses, based on measured tensile and ductility properties. In contrast, laminar constructions are usually anisotropic and the design method in this standard, being based on unit loadings, is particularly suited to the design of composites of reinforced plastics.

The calculation of an appropriate laminate construction is based on the allowable unit loading and unit modulus for the type of composite proposed. In addition, the allowable strain in the laminate is limited to ensure that breakdown of the resin-reinforcement bond does not occur in any part of the structure.

NOTE 1 Debonding occurs at a strain of approximately 0.3 % for the resin-glass fibre composites at present in general use. (See references [1] to [8].)

Design factors are included to cover such variables as:

- a) deterioration of the composite properties over a long period;
- b) the effect of temperature on the properties of the composite;
- c) repeated or alternating loading.

As a result of adopting what was effectively a minimum design factor of 8 and taking into account the other design factors, environmental stress cracking of the laminates in aqueous environments has not been a cause of failure in vessels and tanks produced in accordance with this standard. This mode of failure has been a common source of trouble in other laminates. Furthermore, test work has shown that the allowable strains are below the level at which environmental stress cracking is likely to occur.

It has been assumed in the drafting of this British Standard that the execution of its provisions is entrusted to appropriately qualified and experienced people.

NOTE 2 The numbers in square brackets used throughout the text of this standard relate to the bibliographic references in Appendix K.

A British Standard does not purport to include all the necessary provisions of a contract. Users of British Standards are responsible for their correct application.

Compliance with a British Standard does not of itself confer immunity from legal obligations.

Summary of pages

This document comprises a front cover, an inside front cover, pages i to viii, pages 1 to 188, an inside back cover and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

Section 1. General

1 Scope

This British Standard 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 lining of thermoplastics are included.

It is implicit that vessels and tanks covered by this standard are made only by manufacturers who are competent and suitably equipped to comply with all the requirements of this standard. Compliance with these requirements may be proven by documentation of past experience, or prototype testing, to the satisfaction of the purchaser or Inspecting Authority, as appropriate (see clause 38).

In addition to the definitive requirements, this standard also requires the items detailed in clause 4 to be documented. For compliance with this standard, both the definitive requirements and the documented items have to be satisfied.

This standard covers vessels and tanks subject to temperatures between -30°C and 110°C .

NOTE 1 There is experience with vessels and tanks at temperatures above 110°C but these require special consideration.

NOTE 2 The following vessels and tanks also require special consideration:

- a) jacketed vessels and tanks;
- b) vessels and tanks for the transport of liquids and gases;
- c) buried tanks.

NOTE 3 The titles of the publications referred to in this standard are listed on the inside back cover.

2 Definitions

For the purposes of this British Standard the definitions of *plastics*, *resin*, *thermoset*, *thermoplastics* and *reinforced plastics* given in BS 1755-1 apply, together with the following definitions and those listed in Table 1.

NOTE Where the words purchaser, manufacturer and Inspecting Authority occur in the text, they are intended also to include representatives of the purchaser, manufacturer and Inspecting Authority.

2.1

cure

the chemical reaction resulting in the final polymerized product

NOTE It may be effected at ambient temperature or by the use of heat. In certain resin systems the cure has to be effected in two stages; the first stage may, and the second stage does, involve the application of heat. This second stage is known as the "post-cure".

2.2

gel coat

a thin layer of resin on the surface of a laminate, that may or may not be reinforced with a fabric, tissue or scrim

2.3

laminate

a resin sheet or moulding reinforced with a form of glass fibre or other suitable material

2.4

laying-up

a process of applying or producing laminates in position on a former prior to cure

2.5

manufacturer

the organization, that designs and fabricates the vessel or tank in accordance with the purchaser's requirements

NOTE The design and fabrication functions may be carried out by separate organizations.

2.6

purchaser

the organization or individual that buys the finished vessel or tank for its own use or as an agent for the owner

2.7

inspecting authority

the body or association that checks that the design, materials and construction comply with this standard

2.8

vessel

a closed container subject to applied pressure or vacuum, with or without hydrostatic head

NOTE The term vessel includes branches up to the first flanged connection.

2.9

tank

a container for the storage of fluids subject only to its own hydrostatic head and freely vented to atmosphere

NOTE The term tank includes branches up to the first flanged connection.

3 Nomenclature

Several terms relating to the strength and load-carrying capacity of individual layers of the composite laminate are used in this standard. Some have similar but quite distinct meanings and because of both their similarity and their application, particular care is required in their use.

The terms concerned are listed in Table 1, with their definitions, symbols and units.

4 Information and requirements to be agreed and to be documented

4.1 Information to be supplied by the purchaser

The following information shall be supplied by the purchaser and shall be fully documented. Both the definitive requirements specified throughout the standard and the documented items shall be satisfied before a claim of compliance with this standard can be made and verified.

- a) Process conditions.
 - 1) Materials to be handled (names, concentrations and relative densities) including likely impurities or contaminants.
 - 2) Design pressure (or vacuum) including test requirements and design temperature.
 - 3) Operating pressure (or vacuum) and temperature.
 - 4) Mode of operation, e.g. process cycling conditions.
 - 5) Any abrasion or erosion problems which may be encountered.
- b) Site conditions.
 - 1) Nature of ambient atmosphere including any extremes of temperature.
 - 2) Superimposed loads, e.g. wind, snow and associated pipework.
 - 3) Loads imposed by personnel during erection and operation.
 - 4) In the case of buried vessels and tanks, soil conditions and expected loading, e.g. traffic.
 - 5) Seismic loading.
- c) Special conditions.
 - 1) Boiling but.
 - 2) Vibration due to adjacent plant.
 - 3) Agitation details.
 - 4) Danger of mechanical impact and damage.
 - 5) Loads imposed during transport.
 - 6) Finish, e.g. if fire-resisting (see clause 8).
- e) Details of any special or additional tests or inspection required and where these are to be carried out (see clause 33 and 39.1).
- f) Exemption to apply a pigmented coating to the vessel before final inspection (see clause 33).
- g) Facilities for testing (see Table 4 and 39.1).
- h) Name of Inspecting Authority, if applicable.
- i) Requirements for packaging, despatch and installation.

Table 1 — Nomenclature, symbols and units

Term	Definition	Derivation	Symbol	Unit
Ultimate tensile unit strength (UTUS)	The strength of a reinforcement type, expressed as force per unit width, per unit mass of reinforcement	Obtained from the fracture load of a laminate of known construction, in a tensile test	u	N/mm per kg/m ² glass
Load-limited allowable unit loading	The load permitted to be applied to a reinforcement type per unit width, per unit mass of reinforcement, not taking strain into account	Determined by dividing the ultimate tensile unit strength by the design factor, K	u_L	N/mm per kg/m ² glass
Strain-limited allowable unit loading	The load permitted to be applied to a reinforcement type per unit width, per unit mass of reinforcement, taking only strain into account	Determined by multiplying the unit modulus, X , by the allowable strain for the particular laminate layer	u_S	N/mm per kg/m ² glass
Design unit loading (layer design unit loading)	The load permitted to be applied to a reinforcement type per unit width per unit mass of reinforcement, for the vessel or tank under consideration	Whichever is the smaller of u_S or u_L at the design strain, ϵ_d	u_z	N/mm per kg/m ² glass
Unit modulus	The ratio of the load per unit width to the corresponding direct strain, in a loaded tensile test specimen per unit mass of a single glass reinforcement type	Obtained from the measured load and strain in a tensile test	X	N/mm per kg/m ² glass
Overall unit modulus	The calculated ratio of the load per unit width to the corresponding direct strain in full laminate of single or multiple glass reinforcement type	Obtained from a summation of the products of unit modulus and mass of each glass reinforcement type in a laminate [see equation (12)]	X_{LAM} (may be identified by further subscript)	N/mm
Design strength (laminate design unit loading)	The load carrying capacity of a laminate, expressed as force per unit width	Obtained by summing the load carrying capacities of all the layers in the laminate (u , m , n terms). The subscripts indicate a main (U_{LAM}) or an overlay (U_{OVL}) laminate	U_{LAM} U_{OVL}	N/mm width
Unit load	The force per unit width carried by a laminate resulting from pressure or other loads applied to the vessel or tank	Obtained from the appropriate design calculations for the portion of vessel or tank under consideration (see section 3)	Q	N/mm width

4.2 Requirements to be agreed and documented

The following items to be agreed between the purchaser, or the Inspecting Authority, where appropriate, and the manufacturer shall be fully documented. Both the definitive requirements specified throughout the standard and the documented items shall be satisfied before a claim of compliance with this standard can be made and verified.

- Resin system to be used [see 6.1 a)].
- Use of reinforcing materials other than those complying with BS 3396, BS 3496, BS 3691 or BS 3749, as appropriate (see 6.2).
- Mechanical properties of materials (see 6.4.1).
- Type of chemical barrier to be used (see 7.1 and 27.3).
- Where a thermoset lining is used on tanks and vessels which are constructed in accordance with categories I and II, whether it is permissible to reduce the backing layer (see 7.3).
- Design details (see clause 11).
 - Essential dimensions, including tolerances (see also 30.2.7), preferably on a drawing.
 - Design calculations with references.
 - Nominal thickness, including tolerance, of corrosion-resistant lining (thermoplastics or gel coat) which does not contribute to strength.
 - Form(s) of reinforcement including type, number and arrangement of individual layers.
 - Form(s) of local stiffening, where used.
 - Details of welds in thermoplastics linings.

- 7) Bolting and flange materials and details (see also Figure 24).
- 8) Gasket materials and details.
- 9) Details of external finish, including steelwork (see also 28.6).
- 10) Requirements for access and inspection openings (see also 20.5).
- g) Where the design incorporates reinforcement with directional properties, the orientation of the fibres (see clause 11).
- h) Lining and laminate system to be employed (see 13.4).
- i) Supports (see 22.1).
- j) Any modification to the approved design (see clause 25).
- k) Where site fabrication is employed, the special procedures to be adopted (see clause 26).
- l) Repair of laminate defects and method of repair (see 27.2).
- m) Whether hot plate welding is to be used (see 27.3).
- n) For cylindrical shells, the tolerance on the circumference where this is not 5 mm for shells up to and including 600 mm outside diameter or 0.25 % of the calculated circumference for larger shells (see 30.2.2).
- o) Arrangements for access to manufacturer's premises (see 31.4).
- p) The provision of special test laminates and the extent of mechanical testing to be carried out either on cut-outs or prepared laminates (see 37.1).
- q) If the prototype tests are not to be witnessed by the purchaser, and the Inspecting Authority, where applicable, (see 38.1).
- r) The nature of prototype tests, the hydraulic test pressure if it is higher than the design pressure and the limits of cyclic variations to determine fatigue strength (see 38.3).

5 Categories of vessels and tanks

5.1 General

The design, documentation and inspection and test requirements for vessels and tanks, shall be related to one of three categories that shall be determined from all the factors given in Table 2 when considered in combination.

5.2 Design documentation

The design documentation shall be as given in Table 3.

5.3 Quality control (tests and records)

The quality control shall be as given in Table 4.

Table 2 — Minimum categories of vessel or tank

	Category I	Category II	Category III
Contents^a			
Toxic	X		
Highly corrosive	X		
Corrosive			X
Flammable	X		
Others			X
Chemical compatibility of liner with process fluid			
Known long-term compatibility based on service experience			X
Compatibility based on related performance data		X	
Only specimen data (dip coupons) available	X		
Design temperature, <i>T</i>			
<i>T</i> < 60 ° C and <i>T</i> ≤ (HDT ^a – 40 °C)			X
<i>T</i> ≥ 60 ° C and T ≤ (HDT – 40 °C)		X	
<i>T</i> > (HDT – 40 °C) and <i>T</i> ≤ (HDT – 20 °C)	X		
Design pressure and/or vacuum			
Static head only			X
< ± 5 mbar ^b (above static head)		X	
≥ ± 5 mbar (above static head)	X		
Size of vessel or tank (capacity)			
< 10 m ³			X
50 m ³ ≤ capacity ≤ 10 m ³		X	
> 50 m ³	X		
Geometry and supports			
Flat bottom full support			X
Any other, e.g. legs, skirts, saddles, rings and frames		X	
Other criteria			
If item is critical to safety	X		
^a Description of contents classification			
Toxic.	The contents could present a significant risk to health of persons exposed.		
Highly corrosive.	The contents could severely burn, blind, disfigure or maim an individual.		
Corrosive.	The contents could cause damage to the skin or eye.		
Flammable.	The contents have a flash point equal to or less than 55 °C.		
Others.	The contents are not considered to burn, blind or injure individuals.		
^a Heat distortion temperature of resin (see 6.4.2).			
^b 1 mbar = 100 N/m ² = 100 Pa.			

Table 3 — Design documentation and drawing requirements

	Category I	Category II	Category III
Design calculations			
a) Independent approval required	X		
b) Calculations to cover			
1) Hydrostatic loadings	X	X	X
2) Applied pressure	X	X	
3) Applied vacuum	X	X	
4) Wind loads	X	X	
5) Lifting arrangements	X	X	X
6) Supporting	X	X	
7) Seismic loading (if applicable)	X	X	
Drawing requirements			
Vessel/tank general arrangement	X	X	X
Full fabrication drawings showing method of manufacture	X	X	
Installation procedure	X	X	X

Table 4 — Quality control: tests and records

	Category I	Category II	Category III
Material records			
Record of resin type and quantity	X		
Record of glass type and quantity	X		
Record of personnel on the fabrication	X	X	
Record of layers and type of glass	X	X	X
Record of cure system	X	X	X
Record of post cure (when used)	X	X	
Quality control tests			
Spark test on thermoplastics liners	X	X	X
Adequate documented information on the mechanical properties of the particular resin/glass laminate to be provided. If this is not available for categories II or III, production test samples to be tested as required for category I.	X	X	X
A production test coupon to be laminated with the vessel or obtained from nozzle cut-outs. The coupons to be tested, as follows.			
Ultimate tensile unit strength	X		
Unit modulus	X		
Lap shear strength	X		
Visual examination of nozzle cut-outs	X	X	X
Ash test on nozzle cut-outs	X		
Thickness measurement ^a	X	X	
Acetone test (polyester resin)	X	X	X
Barcol hardness measurement	X	X	X
Residual styrene (polyester resin) ^b	X	X	
Also, in the case of thermoplastics lined glass reinforced plastics (GRP) tanks and vessels, the following to be demonstrated.			
Weld strength	X	X	
Bond strength	X	X	
Quality control records			
Hardness test (Barcol)	X	X	X
Thickness measurement	X	X	X
Nameplate details	X	X	X
Documentation requirements			
Pressure/vac./hydrostatic head	X	X	
Ultimate tensile unit strength	X	X	
Unit modulus	X	X	
Lap shear strength	X	X	
Weld strength	X	X	
Bond strength	X	X	
Ash test on cut-out	X		
Independent inspection	X		
^a To verify minimum design thickness. Particular attention is to be paid to points of discontinuity, e.g. nozzles and end attachments.			
^b See 37.2.			

Section 2. Materials and design loadings

6 Materials

6.1 Thermosetting resin systems

The resin system(s) to be used shall be agreed between the purchaser and the manufacturer [see 4.2 a)].

The resin selected shall be of a suitable commercial grade which complies with the technical requirements of the application and for polyester resins the minimum requirements of BS 3532.

NOTE 1 The specified classes of resins used for the preparation of laminates are polyester resins, epoxy resins and furane resins. There are many resin systems in each class and the properties of these systems vary, especially with respect to chemical resistance and heat distortion temperature. See also Appendix A.

The recommendations of the resin suppliers for the use of hardeners, catalysts and accelerators shall be followed.

NOTE 2 The amount of these materials used is critical as it can affect both the rate of the reaction and extent of the cure.

Pigments shall not be used except in the external finish [see clause 33 j)].

NOTE 3 Limited use of thixotropic agents can be made provided that they do not interfere with visual inspection and chemical resistance of the laminate.

Data, procedures and figures in this standard refer to laminates containing no filler materials. Where special-purpose additives are used, special consideration shall be given to design and manufacture as there may be an effect on the laminate properties.

6.2 Reinforcing materials

The reinforcing material shall be a suitable grade of glass fibre having a glass finish compatible with the resin used and shall either comply with BS 3396, BS 3496, BS 3691 or BS 3749, as appropriate, or be the subject of agreement between the purchaser and the manufacturer [see 4.2 b)].

6.3 Thermoplastics lining material

A number of thermoplastics, for example, polyvinyl chloride (PVC), polypropylene (PP), polyvinylidene fluoride (PVDF), ethylene chlorotrifluoroethylene (ECTFE), chlorinated PVC (CPVC) and fluorinated ethylene propylene copolymer (FEP) are available as lining materials and the thermoplastics selected shall comply with 7.1.

The thickness of PVC shall not be less than 2.5 mm. In the case of other thermoplastics, the minimum thickness shall be 2.00 mm except in the case of pipes and branches of 100 mm diameter or less, when the minimum thickness shall be 1.5 mm.

NOTE Experience has shown that the use of PVC liners in excess of 4.5 mm thickness can lead to problems in service when the operating temperature is above 40 °C.

6.4 Mechanical properties

6.4.1 The mechanical properties of the laminate layers shall be agreed between the purchaser and the manufacturer [see 4.2 c)] and shall be not less than the values given in Table 5, when tested in accordance with Appendix B. The values given in Table 5 apply to laminates incorporating only E glass reinforcement complying with BS 3396, BS 3496, BS 3691 or BS 3749 and having a glass content by mass within the range 28 % to 45 % for chopped strand mat (CSM), 45 % to 55 % for woven roving (WR) cloth and 65 % to 75 % for filament windings and values for laminates including other types of reinforcement or other glass contents shall be on the basis of test results.

Where WR cloth with a directional bias is used, the figure for ultimate tensile unit strength shall be 500 P , where P is the proportion of glass fibres running in the direction concerned. The unit modulus in the warp and weft direction will be different to that given in Table 5 and shall be established by test. Where the bias is greater than 5 to 1, the strength in the weft direction shall be ignored.

6.4.2 The heat distortion temperature of the fully cured resin system used for the reinforced laminate shall be not less than 20 °C higher than the design temperature of the vessel when determined as described in BS 2782:Method 121A (see also B.4).

6.5 Chemical properties

As the chemical resistance of lining materials varies with the source and type of polymer, the suitability of the material, including adequate corrosion and erosion resistance, shall be established by tests; a suitable reference document is BS 4618-4.1. It is important in any such tests that the test liquors are fully representative of the process, particularly with respect to the presence of trace organics, and, where possible, the test specimens shall be subjected to a level of strain not less than the design strain.

Table 5 — Minimum properties of reinforced laminate layers

Type of reinforcement	Ultimate tensile unit strength (UTUS)	Unit modulus	Lap shear strength
	N/mm width per kg/m ² glass	N/mm width per kg/m ² glass	N/mm ²
CSM (resins other than furane)	200	14 000	7.0
CSM (furane)	140	14 000	5.0
WR cloth plain weave (warp and weft directions) (resins other than furane)	250	16 000	6.0
WR cloth plain weave (warp and weft directions) (furane)	160	16 000	4.0
Unidirectional filament (fibre direction)	500	28 000	6.0

6.6 Water quality

When selecting materials, account shall be taken of the effects of materials on water quality (see Appendix C).

7 Construction of chemical barrier

7.1 The type of chemical barrier to be used shall be agreed between the purchaser and the manufacturer [see 4.2 d)].

7.2 Where a thermoplastics lining is used, the minimum bond strength of the reinforcement to the lining shall be 7 N/mm² in direct shear and 5 N/mm width in peel when tested in accordance with **B.10** and **B.11**.

NOTE This bond strength may be achieved by the inclusion of a minimum of 0.45 kg/m² chopped glass strand or CSM immediately behind the thermoplastics lining.

7.3 Where a thermoset lining is used, in order to achieve the optimum properties the construction of the laminate in contact with the corrodent shall consist of the following.

- Surface layer.* A resin-rich surface layer reinforced with C glass surfacing mat, synthetic fibres or other suitable material, with a thickness between 0.25 mm and 0.50 mm.
- Backing layer.* A backing layer normally containing a minimum of 1.2 kg/m² chopped glass strand or CSM with a soluble binder with between 25 % and 33 % glass content, by mass.

For tanks and vessels which are constructed in accordance with categories II and III it is permissible to reduce the backing layer to 0.6 kg/m² chopped glass strand or CSM if agreed between the purchaser and the manufacturer [see 4.2 e)].

8 Flammability

Where a vessel or tank is intended to contain flammable fluids the external surface layers shall be modified so as to have a surface spread of flame characteristic which at least complies with the class 1 requirements of BS 476-7.

In other cases the finish shall be as specified by the purchaser [see 4.1 c) 6)].

9 Allowable and design unit loadings

9.1 Symbols

For the purposes of clause 9 the following symbols apply.

F_ϕ	circumferential factor
F_x	longitudinal factor
k_1	factor relating to method of manufacture
k_2	factor relating to long-term behaviour
k_3	factor relating to temperature
k_4	factor relating to cyclic loading
k_5	factor relating to curing procedure
K	overall design factor determined from equation (1)
u_z	design unit loading (in N/mm per kg/m ² glass) for layer of type z
u_L	load-limited allowable unit loading, i.e. ultimate tensile unit strength (in N/mm per kg/m ² glass) divided by K
u_S	strain-limited allowable unit loading, i.e. unit modulus (in N/mm per kg/m ² glass) multiplied by allowable strain
X_ϕ	unit modulus in circumferential direction (in N/mm per kg/m ² glass)
X_x	unit modulus in longitudinal direction (in N/mm per kg/m ² glass)
X_z	unit modulus of layer of type z (in N/mm per kg/m ² glass)
ϵ_L	strain under unit loading u_L
ϵ	maximum allowable strain
ϵ_d	least strain, determined from allowable loadings and resin properties
ϵ_R	extension to failure (fracture strain) of unreinforced resin determined in accordance with Appendix B
θ	angle to the longitudinal axis of filament winding

9.2 Design calculations

9.2.1 When designing in reinforced plastics, it is desirable to work in terms of unit load, i.e. force per unit width, rather than stresses, i.e. force per unit area, and therefore the following calculations shall be adopted.

The maximum allowable unit load for each type of layer shall be determined from the material properties given in Table 5 as follows (see Appendix D for worked examples and abbreviated method).

Where the design calculations (see section 3) require the use of allowable compressive unit loadings, these shall be determined in accordance with **9.2.2** to **9.2.6**, substituting the ultimate compressive unit strength for the ultimate tensile unit strength in equation (2).

Ultimate compressive unit load shall be determined, when required, for each laminate layer concerned, in accordance with **B.8**.

9.2.2 The design factor K shall be determined from equation (1):

$$K = 3 \times k_1 \times k_2 \times k_3 \times k_4 \times k_5 \quad (1)$$

where the factor 3 represents a constant which allows for the reduction of material strength caused by long-term loading (required even for loading in air), and k_1 to k_5 represent factors determined by the method of manufacture and operating conditions. No vessel or tank shall have a design factor K of less than 8.

NOTE For a rarely occurring, short-term emergency condition (less than 10 times in the life of the vessel, each duration less than 30 min) a design factor less than the calculated design factor, but not less than 8, may be used.

The chemical liner, see clause 7, shall be ignored in strength calculations.

Values for factors k shall be determined as follows.

a) *Factor relating to method of manufacture, k_1 .* This factor shall be the value taken from Table 6 appropriate to the method of manufacture to be adopted.

When rovings are chopped for spray application, the length of individual strands shall be not less than 32 mm.

Table 6 — Factor relating to method of manufacture

Method of manufacture	Factor k_1
Handwork	1.5
Machine-controlled filament winding	1.5
Machine-controlled spray application	1.5
Hand-held spray application	3.0

b) *Factor for chemical environment (and associated strength loss), k_2 .* This factor shall be 1.2 for vessels having a thermoplastics lining unless lack of experience or suitable test data suggests that a higher value is required. The factor for vessels without a thermoplastics lining shall be selected within the range 1.2 to 2.0.

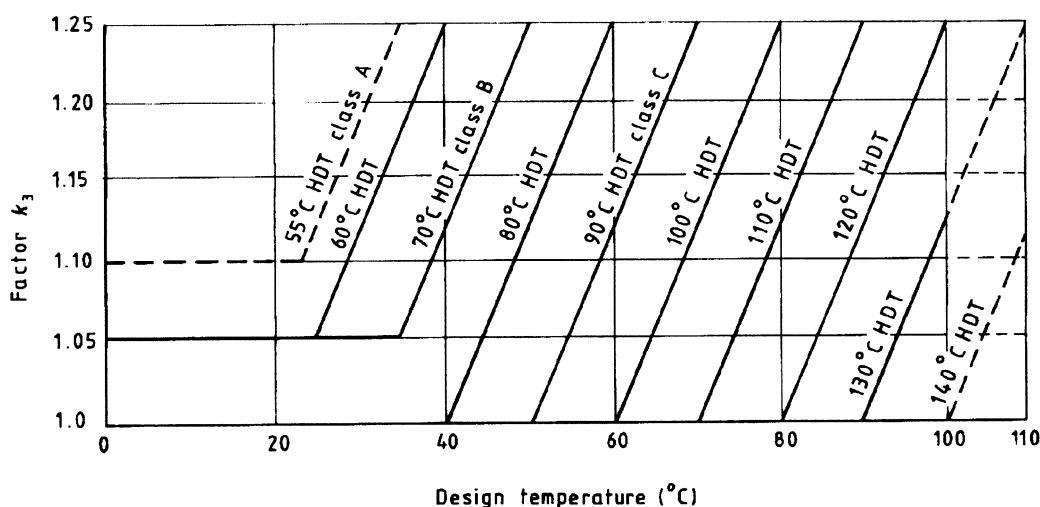
NOTE A guide to establishing the value of k_2 is given in Appendix E.

c) *Factor relating to temperature, k_3 .* This factor shall be within the range 1 to 1.25, dependent upon the heat distortion temperature and be determined from Figure 1.

d) *Factor relating to cyclic loading, k_4 .* This factor shall be determined from Figure 2, having regard to the expected operating conditions of the vessel.

e) *Factor relating to the curing procedure, k_5 .* Where the vessel is subjected to a complete curing procedure, including a full post-cure at elevated temperature appropriate to the resin system, at the manufacturer's works the factor k_5 shall be taken as 1.1. Copies of the temperature chart shall be supplied to the Inspecting Authority (information to be obtained from the resin supplier). Vessels not subjected to full post-cure shall have the factor k_5 taken as 1.3 when they are designed for operating temperatures up to and including 45 °C and 1.5 when they are designed for operating temperatures over 45 °C.

NOTE The post-curing temperature should be chosen to ensure that the laminate will comply with the mechanical, temperature and chemical performance required by the design. High-performance resin systems generally require a post-cure temperature of at least 80 °C to develop their optimum properties and, wherever possible, the tank or vessel should be post-cured at the design temperature.



NOTE Experience in the range above 100 °C is limited and it is therefore recommended there is a full discussion between the manufacturer and the purchaser if a vessel is required to operate in this range.

Figure 1 — Factor relating to temperature, k_3

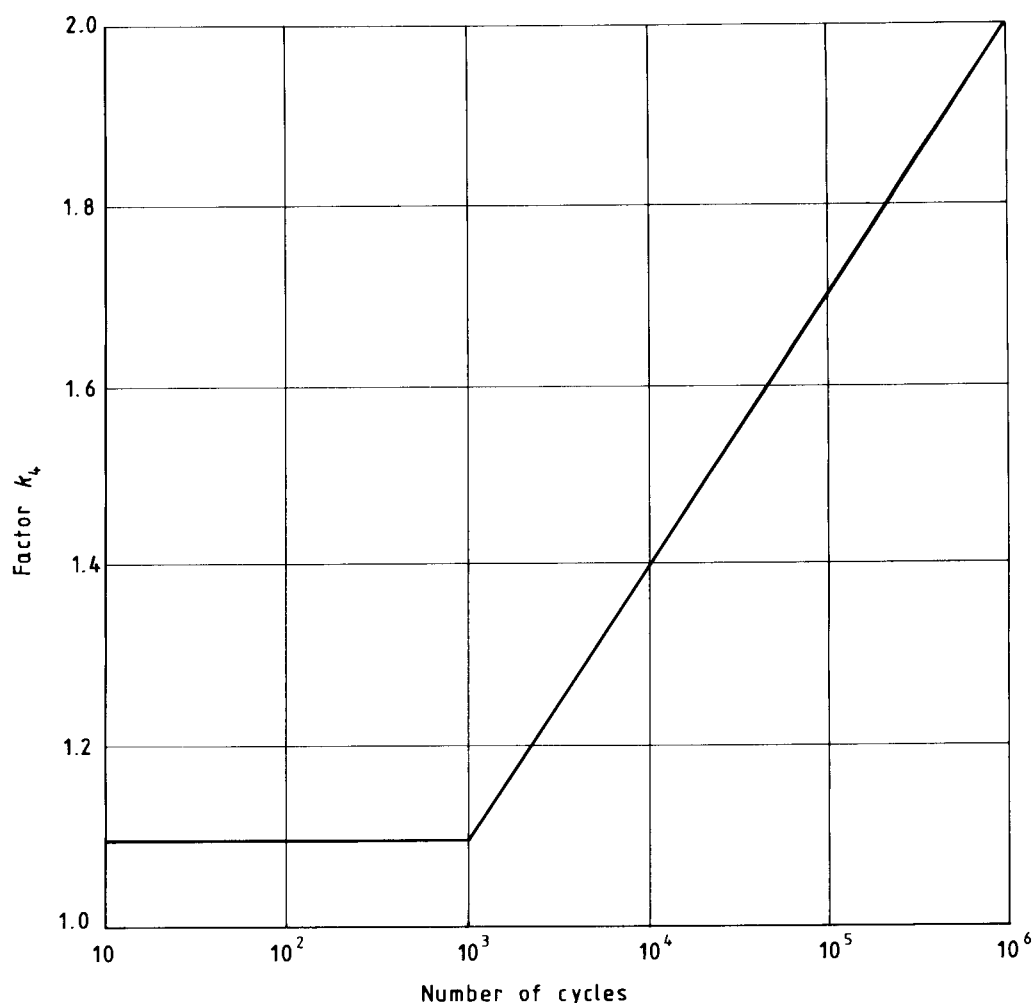


Figure 2 — Factor relating to cyclic loading, k_4

9.2.3 The load-limited allowable unit loading, u_L , shall be determined from equation (2):

$$u_L = \frac{u}{K} \quad (2)$$

where u is UTUS from Table 5.

9.2.4 The maximum allowable strain, ϵ , shall be determined.

- The maximum allowable strain shall not exceed 0.1 ϵ_R or 0.2 %, whichever is the smaller.
- For chemically resistant resin surface layers, the extension to failure of the unreinforced resin shall be determined in accordance with **B.5**. The maximum allowable strain for the whole of the laminate shall be that value determined from the smallest extension to failure of the resins to be incorporated.

NOTE For thermoplastics linings a maximum allowable strain of 0.2 % will be satisfactory, so that these linings will not introduce a more severe strain limitation into the vessel design.

9.2.5 The strain-limited allowable unit loading, u_S , shall be determined from equation (3):

$$u_S = X_z \epsilon \quad (3)$$

9.2.6 The design unit loading, u_z , for each type of layer shall be determined.

- If u_S is smaller than u_L for all layers, the appropriate value of u_S shall be taken as the design unit loading, u_z for each layer.

NOTE A laminate design is strain-limited when u_S is smaller than u_L for all the layers.

b) If, for some or all of the layers, u_L is smaller than u_S , the strain for each layer concerned shall be determined from equation (4):

$$\epsilon_L = \frac{u_L}{X_z} \quad (4)$$

Considering all the layers making up the laminate, the allowable strain for that laminate, ϵ_d , shall be the smallest of the values of ϵ_L so determined. The design unit loading for each layer, u_z , shall then be determined from equation (5):

$$u_z = X_z \epsilon_d \quad (5)$$

The design unit loadings for each type of layer, u_z , determined from a) or b), as appropriate, shall then be substituted as required in the design equations in section 3.

9.2.7 The procedure in **9.2.6** does not apply when continuous rovings are filament wound at an angle of θ (in degrees) to the vessel or tank axis and in this case values of circumferential and longitudinal unit modulus X_ϕ and X_x for individual layers shall be obtained by reference to Figure 3. Values of circumferential and longitudinal design unit load shall be determined from equations 5(a) or (b) and by application of the factors given in Table 7, as appropriate.

In circumferential direction:

$$u_z = X_\phi \epsilon_d F_\phi \quad [5(a)]$$

In longitudinal direction:

$$u_z = X_x \epsilon_d F_x \quad [5(b)]$$

Where a laminate construction using filament winding is subjected to a simultaneous application of loading in the circumferential and longitudinal directions then, depending upon the combination of direction and type, i.e. tensile or compressive, of loading, the maximum allowable loads are not necessarily as great as the individual unit loads derived from the calculations of this section and, therefore, the acceptability of the combined loadings shall be determined by means of a biaxial design envelope, details of which are given in the worked examples of **D.4**.

Table 7 — Factors to be applied to the design unit loading of continuous rovings for different winding angles

Filament winding angle to axis θ	Circumferential factor F_ϕ	Longitudinal factor F_x
degrees		
$0 < \theta \leq 15$	0	1
$15 < \theta \leq 75$	0.5	0.5
$75 < \theta \leq 90$	1	0

NOTE Higher values may be used for these factors if a rigorous anisotropic elastic analysis is carried out. This analysis allows for the contribution from each layer in the laminate and for the interaction between normal and shear strains (see references [9], [10] and [11]).

It shall be ensured that the strain transverse to the fibre direction is less than 0.1 %. In the absence of a rigorous anisotropic analysis, the axial strain shall be limited to 0.1 % for a winding angle greater than 75°.

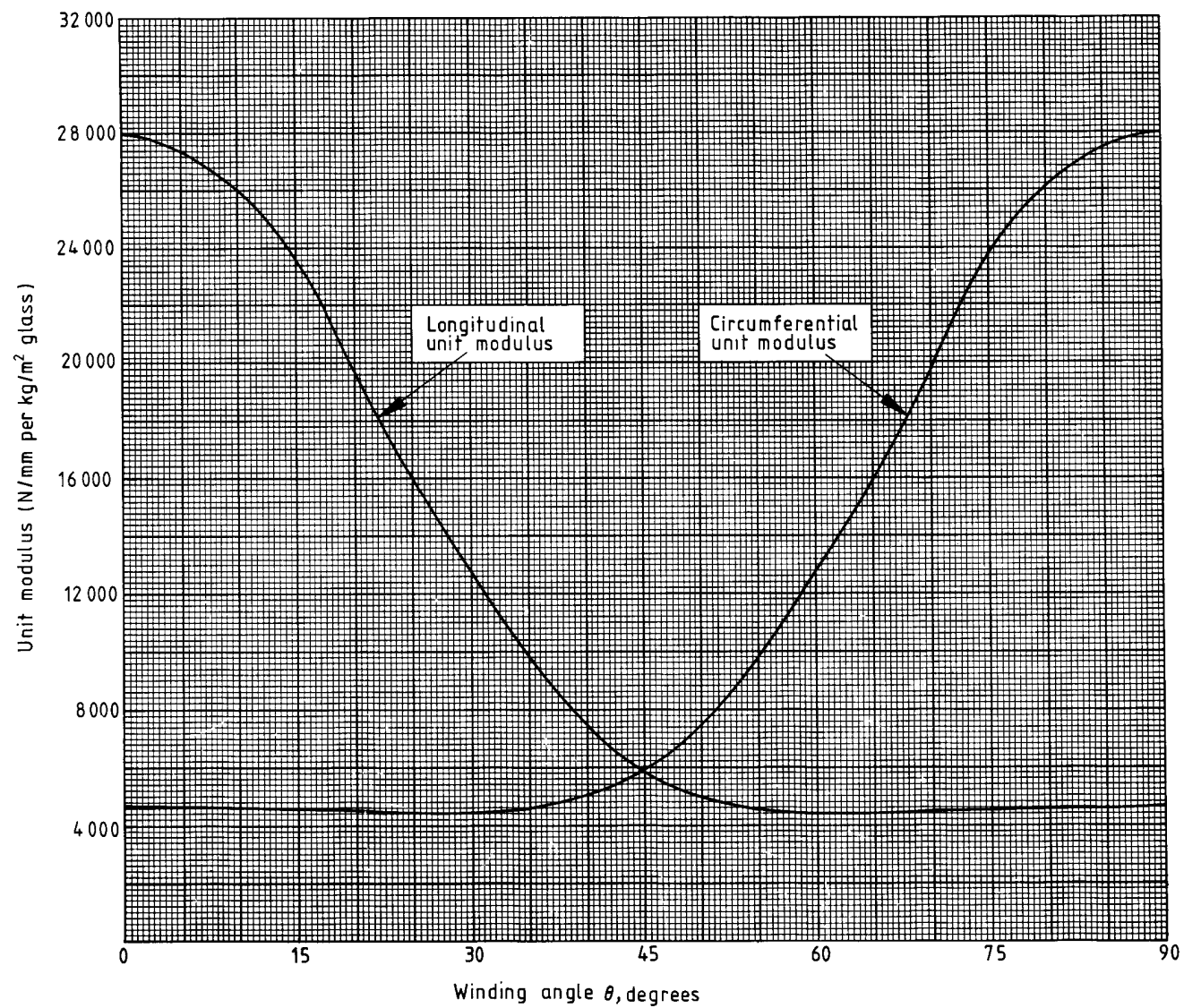


Figure 3 — Unit modulus/winding angle

Section 3. Design

10 General

The vessel or tank shall be designed for the most severe combination of conditions which may include:

- a) internal or external pressure;
- b) static head of contents (working and test conditions);
- c) weight of vessel or tank and contents;
- d) design temperature;
- e) superimposed and wind loads;
- f) bending moments due to eccentric loads;
- g) localized loads acting at the supports, lugs and other attachments;
- h) shock loads;
- i) loads due to heating or cooling and thermal gradients;
- j) loads applied during transport or erection;
- k) loads imposed by personnel during erection and operation;
- l) fatigue.

11 Design basis

The vessel or tank shall be designed in accordance with this section. The actual design details shall be agreed between the purchaser and the manufacturer, and the Inspecting Authority, where applicable, [see 4.2 f)].

NOTE 1 The design calculations in this standard take advantage of the ease with which the laminate details can be varied to suit the loads imposed by operating and test conditions in the different regions.

Where the design incorporates reinforcement with directional properties (e.g. WR), the orientation of the fibres shall be agreed between the purchaser and the manufacturer [see 4.2 g)] and shall be specified on drawings and calculations in order to ensure that the structural properties required by the design are obtained.

NOTE 2 The objective of the calculations specified in this section is, therefore, to determine acceptable laminate constructions for each part and detail, e.g. shell, ends, manholes, branches and supports.

12 Design details

12.1 Design temperature

The design temperature shall be the maximum temperature it is possible for the vessel or tank to attain under operating conditions (including boil-out, where applicable).

NOTE Where necessary, provision should be made in the design to permit expansion or contraction, to avoid severe thermal loads. Thermal loads arising from temperature gradients may also require evaluation.

12.2 Design pressure

The design pressure, i.e. the pressure to be used in calculations to establish the required strength of the component parts of a vessel or tank, shall be not less than:

- a) the pressure which will exist in such parts of the vessel or tank when the pressure-relieving device(s) start(s) to relieve or the set pressure of the pressure-relieving device(s), whichever is the higher;
- b) the maximum pressure or head which can be achieved in service where this is not limited by relieving device(s).

Notwithstanding this, the strength of the laminates so calculated shall be increased where necessary to ensure that during hydraulic pressure or static head tests the laminate is at no point strained beyond the limiting values specified in clause 39, i.e. 0.26 %, or $1.3 \epsilon_d$, whichever is the smaller, where ϵ_d is the least strain, determined from allowable loadings and resin properties.

The value of the design pressure(s) to be used in calculation shall include the static head of content or test medium, as applicable, taking due account of relative density.

Vessels subject to external pressure shall be designed for the maximum differential pressure to which the vessel may be subjected in service.

NOTE 1 It is recommended that vessels subjected to vacuum be designed for a full negative pressure of 1 bar unless a vacuum break valve or similar device is provided, in which case a lower design pressure may be agreed between the purchaser and the manufacturer.

The total discharge capacity of the pressure-relieving device(s) shall be such that during discharge the pressure within the vessel or tank does not exceed the design pressure by more than 10 %.

NOTE 2 Where bursting discs are used, it is essential that their manufacturer be consulted before the design pressure is decided as the bursting pressure of the disc is dependent upon disc material and operating temperature. See also BS 2915.

13 Laminate design and thickness

13.1 Symbols

For the purposes of clause 13 the following symbols apply.

- m_z mass of reinforcement per unit area (in kg/m² glass) in one layer of type z
- n_z number of layers of type z in construction under consideration (for filament winding a layer shall consist of two helixes wound at $\pm \theta^\circ$)
- Q maximum applied unit load (in N/mm), i.e. maximum force per unit width, to be carried by the laminate
- u_z design unit loading (in N/mm per kg/m² glass) for layer of type z

13.2 Design calculation

For each region of the vessel or tank, a proposed laminate construction shall be determined by taking into account the design unit loading for each constituent laminate layer (as calculated in accordance with section 2). These loadings shall be related to the unit loads to be carried by the region concerned. Clauses 14 to 23, inclusive, specify calculations for unit loads, determined from the vessel geometry and the greatest of these unit loads shall be used in equation (6).

The suitability of the proposed laminate construction shall then in every case be checked by using equation (6):

$$u_1 m_1 n_1 + u_2 m_2 n_2 + \dots + u_z m_z n_z \geq Q \quad (6)$$

NOTE 1 It may happen that the value of more than one n_z is undetermined. The check should then be by a trial and error method and more than one acceptable solution may be found in these circumstances.

Alternatively, all but one (or two interdependent) values of n_z may be fixed and the remaining value determined.

If the sum of the terms is less than Q , one or more of the values of n shall be increased or a different laminate construction proposed and the calculations repeated until the required condition is satisfied. If the sum of the terms exceeds Q by a large margin, the laminate is overdesigned for the region concerned.

NOTE 2 Worked examples of this design method are given in Appendix D and examples of construction are shown in Figure 4.

NOTE 3 Additional consideration is necessary if the vessel or tank is filament wound and subjected to biaxial loading. It is important to note that the response of a filament-wound vessel or tank to combinations of load applied simultaneously is different from the response of those loads applied independently.

To assess the behaviour of a filament-wound vessel or tank to combined loads either:

- a complete anisotropic stress/strain analysis shall be carried out, the response of the material to those combined loads examined, and the shear or normal strain present within each layer shall be less than that calculated in 9.2.6; or
- a biaxial failure envelope shall be constructed as shown in the worked example given in Appendix D (see reference [16]).

NOTE 4 Where WR are to be used in the construction of vessels for use in vacuum service they should have a 1 to 1 warp to weft ratio.

13.3 Thickness

Where values of thickness are required in the equations in this section, the thickness of the laminate in the region under consideration shall be taken as the sum of the thicknesses of the individual layers making up that laminate.

The thickness of each layer, for design purposes, shall be determined from the glass content for that layer by using the graph (see Figure 5). Glass content shall be specified on the vessel drawings (see B.2 for test method).

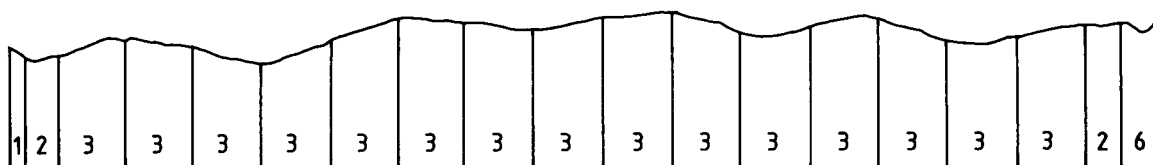
In no case shall the laminate thickness (excluding any lining) be less than 3 mm for tanks subject only to hydrostatic head of liquid contents, and 5 mm for vessels subject to internal pressure or vacuum.

Abrupt changes in laminate thickness shall be avoided. The blending taper between regions of differing thickness shall not be steeper than 1 in 6 (see Figure 6 and Figure 7).

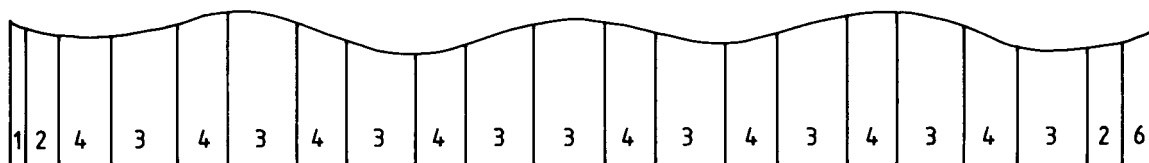
13.4 Choice of construction

The lining and laminate system to be employed shall be specified in full on the drawing and agreed between the purchaser and the manufacturer before manufacture commences [see 4.2 h)].

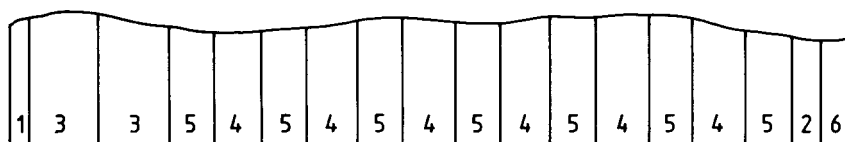
NOTE The outermost layers of the vessel or tank should normally be CSM (300 g/m² minimum), and a tissue with a resin-rich surface.



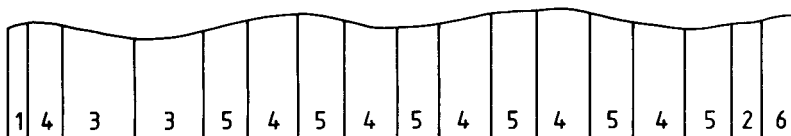
(a) Effective thickness 24 mm



(b) Effective thickness 24 mm



(c) Effective thickness 16.7 mm



(d) Effective thickness 15.8 mm

Key

1 Chemical barrier (see clause 7 and 9.2.2)

2 Chopped strand mat 0.3 kg/m²

3 Chopped strand mat 0.6 kg/m²

4 Chopped strand mat 0.45 kg/m²

5 Woven roving cloth 0.8 kg/m²

6 Resin-rich surface layer with binding tissue

NOTE Constructions (a), (b) and (d) all have a similar load carrying capacity (see Appendix D).

Figure 4 — Four typical examples of laminate construction (without thermoplastics lining)

14 Cylindrical and spherical shells

NOTE The equations in this clause are derived from thin shell theory and do not apply to vessels having a total laminate thickness greater than 10 % of the shell internal diameter.

14.1 Symbols

For the purposes of clause 14 the following symbols apply.

d	relative density of resin
D_i	inside diameter of shell (in mm)
D_o	outside diameter of shell (in mm)
D_s	diameter of neutral axis of stiffening ring (in mm)
E_{LAM}	Young's modulus (in N/mm ²) ^a of laminate under consideration
F	factor of safety against collapse by buckling [see equations (13), (15), (16) and (19)]
h_i	internal height of end (in mm)
I_{s2}	second moment of area of stiffening ring (in mm ⁴)
L	effective shell length (in mm) (see Figure 8)
L_s	length of shell which may be regarded as contributing to the second moment of area of a stiffening ring (in mm)
M	bending moment (in N mm) due to weight of vessel or tank and contents at point under consideration and wind or other applied loadings
m_g	percentage glass content by mass
m_z	mass of reinforcement per unit area (in kg/m ² glass) in one layer of type z
n_z	number of layers of type z in construction under consideration
p	total effective pressure (in N/mm ²), i.e. design pressure (negative if vacuum) plus hydrostatic head at point under consideration
Q_x	maximum longitudinal unit load (in N/mm) at point under consideration
Q_ϕ	maximum circumferential unit load (in N/mm) at point under consideration
Q_p	maximum permissible compressive unit load (in N/mm) [see equation (13)]
R_o	outside radius of spherical shell (in mm)
t	laminate thickness of shell (in mm) calculated from laminate details
t_m	laminate thickness of shell (in mm) derived from buckling criteria [see equations (15), (16) and (19)]
T	taper length (in mm)
W	weight of contents and/or vessel depending on support detail (in N)
X_{LAM}	overall unit modulus (in N/mm) of laminate under consideration [see equation (12)]
X_z	unit modulus (in N/mm per kg/m ² glass) of layer of type z

^a 1 N/mm² = 1 MN/m² = 1 MPa.

14.2 Cylindrical and spherical shells subject to internal pressure

The maximum circumferential unit load, Q_ϕ , shall be determined from equations (7) or (8).

For cylindrical shells:

$$Q_\phi = \frac{pD_i}{2} \quad (7)$$

For spherical shells:

$$Q_\phi = \frac{pD_i}{4} \quad (8)$$

14.3 Cylindrical shells subject to combined loads

14.3.1 Vertical vessels and tanks. The maximum longitudinal unit load, Q_x , resulting from the combined effects of:

- a) total effective pressure;
- b) bending moment due to wind loads (calculated in accordance with CP 3:Chapter V-2) or other causes;
- c) total weight of vessel or tank, fittings, attachments and contents;

shall be determined from equations (9) and (10).

NOTE 1 Negative values of Q_x denote compressive loads.

NOTE 2 Pressure, p , excludes static head. Negative values of p denote external pressure.

For points above the plane of support:

$$Q_x = \frac{pD_i}{4} \pm \frac{4M}{\pi D_i^2} - \frac{W}{\pi D_i} \quad (9)$$

where

W is the weight of those parts of the vessel or tank and fittings, attachments and fluid content supported above the point considered.

For points below plane of support:

$$Q_x = \frac{pD_i}{4} \pm \frac{4M}{\pi D_i^2} + \frac{W}{\pi D_i} \quad (10)$$

where

W is the weight of those parts of the vessel or tank and fittings, attachments and fluid content supported below the point considered.

NOTE 3 In equation (10), W normally includes the total fluid content by weight.

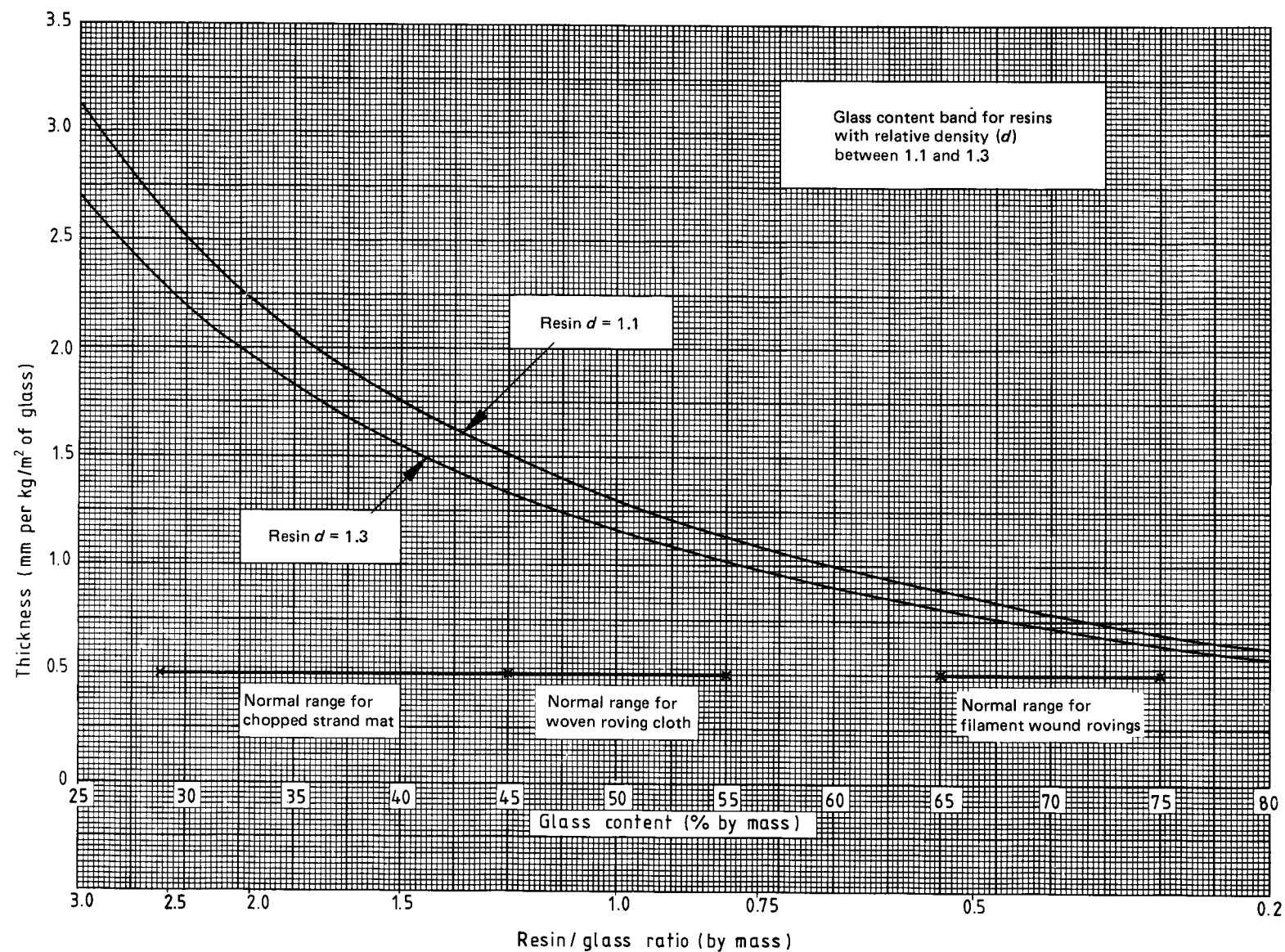


Figure 5 — Relationship between thickness and glass content

Values are calculated from the equation:

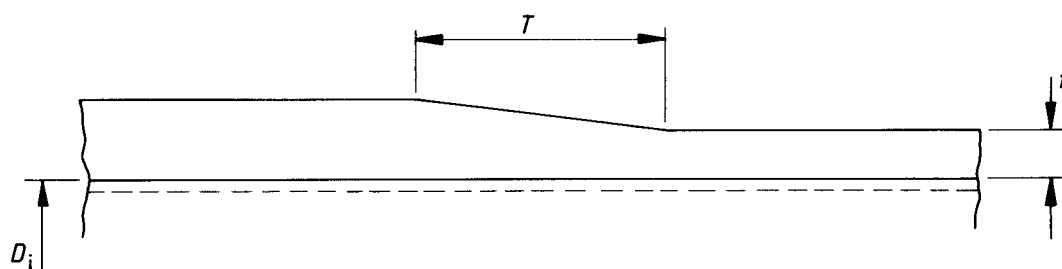
$$\frac{\text{Thickness (mm)}}{\text{Glass mass}} = \frac{1}{2.56} + \frac{100 - m_g}{m_g d}$$

where

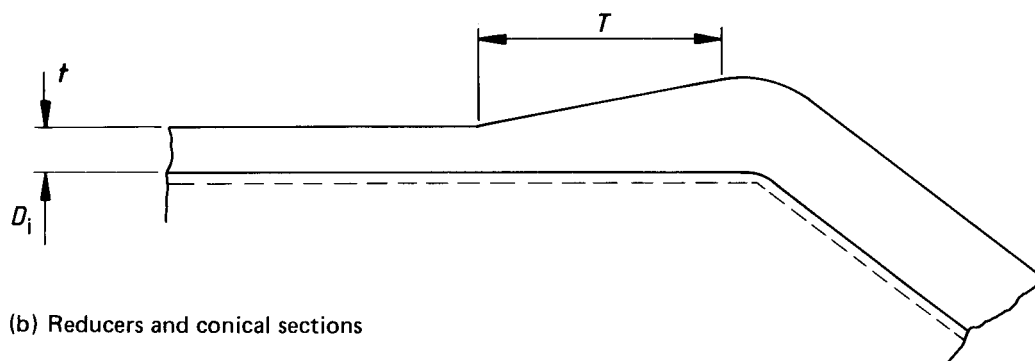
m_g is the percentage glass content by mass;
 d is the relative density of resin.

Glass content %	25	30	35	40	45	50	55	60	65	70	75	80
Thickness (Resin $d = 1.1$) mm per kg/m ² of glass	3.12	2.51	2.08	1.75	1.50	1.30	1.13	1.00	0.88	0.78	0.69	0.62
Thickness (Resin $d = 1.3$) mm per kg/m ² of glass	2.70	2.19	1.82	1.54	1.33	1.16	1.02	0.90	0.80	0.72	0.65	0.58

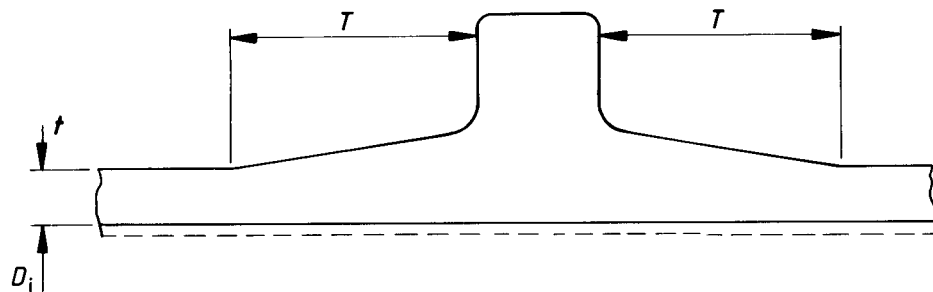
Figure 5 — Relationship between thickness and glass content (*concluded*)



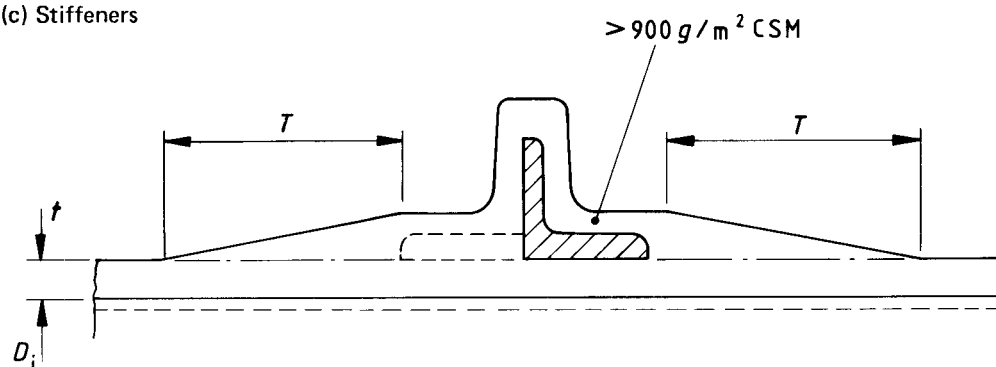
(a) Cylindrical shell



(b) Reducers and conical sections



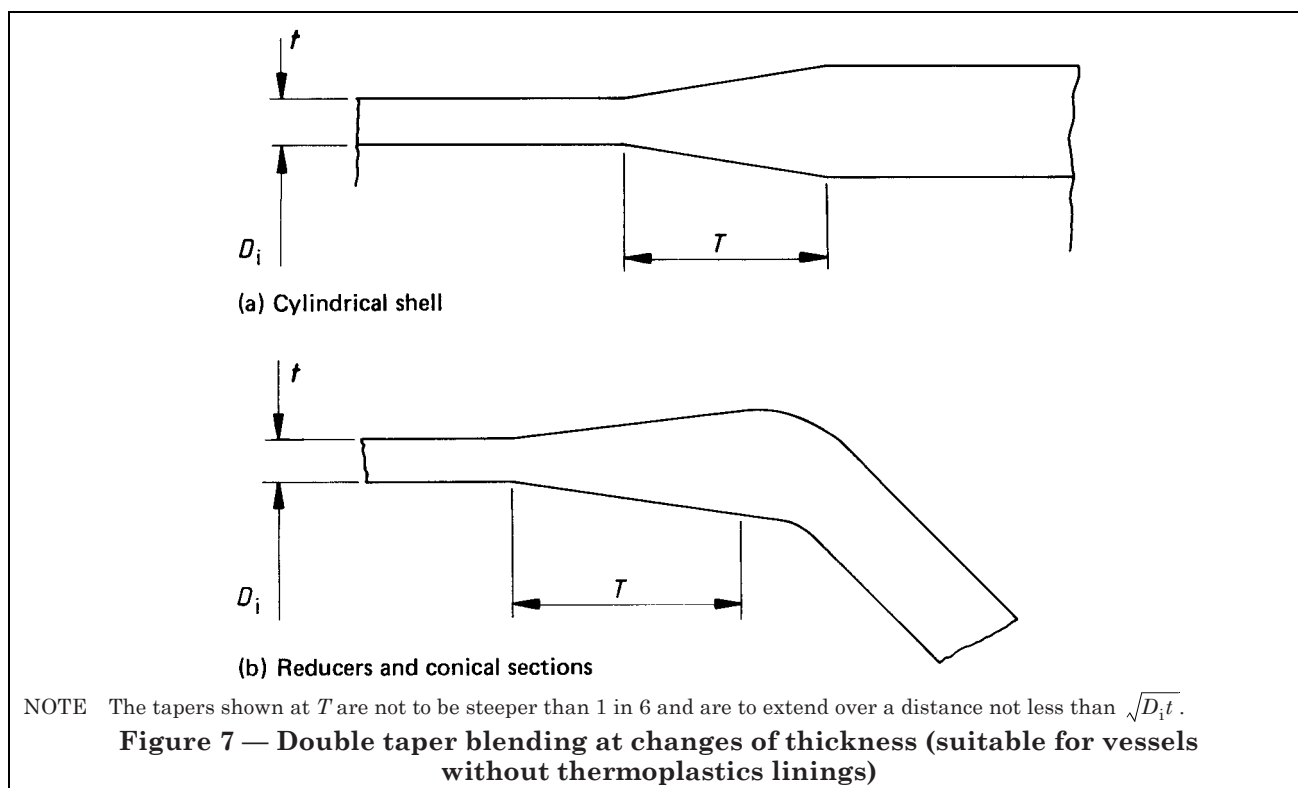
(c) Stiffeners



(d) Stiffeners (incorporating steel angle or tee ring)

NOTE The tapers shown at T are not to be steeper than 1 in 6 and are to extend over a distance not less than $\sqrt{D_i t}$.

Figure 6 — Single taper blending at changes of thickness (suitable for vessels with or without thermoplastics linings)



14.3.2 Horizontal vessels and tanks. The maximum longitudinal unit load resulting from the combined effects of:

- total effective pressure;
- bending moment due to the weight of vessel or tank and contents, as determined by the support configuration;

shall be determined from equation (11).

$$Q_x = \frac{\rho D_i}{4} \pm \frac{4M}{\pi D_i^2} \quad (11)$$

The maximum tensile and compressive values of longitudinal unit loads for the full range of possible loading conditions shall be determined.

14.3.3 Permissible compressive load. Where there is a compressive axial load, check calculation shall be made to ensure that the region of the shell subject to the greatest compressive load is adequate to resist collapse by buckling. To make this check the overall unit modulus, X_{LAM} , for the laminate construction decided upon shall be determined from equation (12):

$$X_{LAM} = X_1 m_1 n_1 + X_2 m_2 n_2 + \dots X_z m_z n_z \quad (12)$$

The permissible maximum compressive unit load shall then be determined from equation (13):

$$Q_p = \frac{0.6tX_{LAM}}{FD_o} \quad (13)$$

F shall be taken as 4.

The maximum compressive unit load shall in no case exceed the value of Q_p so obtained.

NOTE The laminate construction may need to be modified, and the necessary calculations repeated until the condition is satisfied.

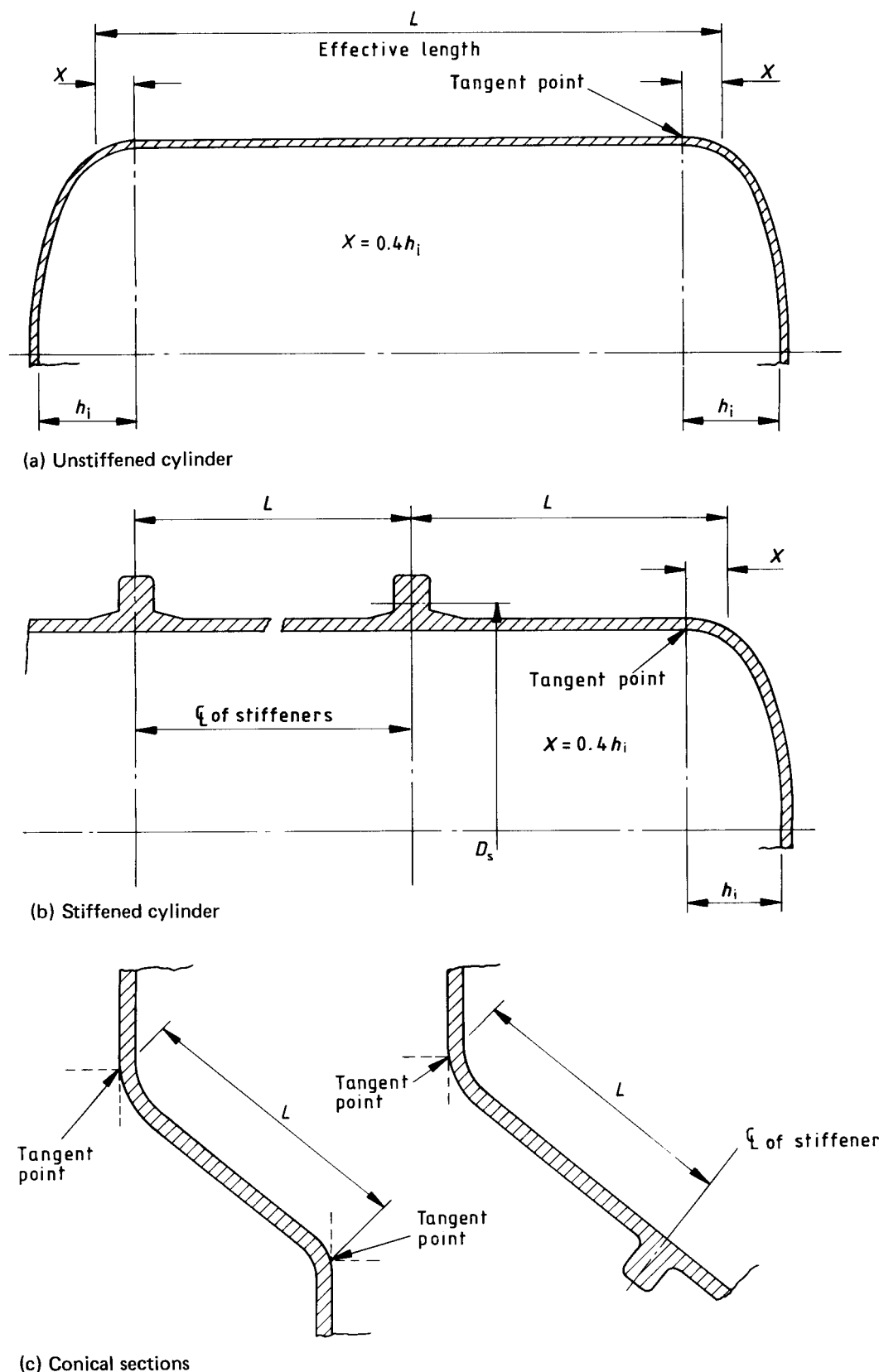


Figure 8 — Effective length between stiffeners under external pressure

Special consideration shall be given to the laminates where circumferential and longitudinal moduli are different, e.g. filament-wound tanks or vessels. In such circumstances a rigorous anisotropic analysis shall be carried out to assess the permissible maximum compressive unit load. In the absence of such an analysis the lower of the two moduli shall be used in equation (13).

See also 9.2.7 and D.4 for cases of simultaneous application of circumferential and longitudinal loads to laminates incorporating filament winding, where a check shall be made using a biaxial design envelope.

14.4 Cylindrical and spherical shells subject to external pressure

14.4.1 Cylindrical shells. The circumferential unit load, Q_ϕ , shall be determined from equation (7). The maximum direct longitudinal unit load, Q_x , shall be determined from equations (9), (10) and (11), as appropriate. The greater of these values shall be substituted in equation (6). Using as a basis a laminate construction which complies with this requirement, the total thickness of the laminate, t , shall be determined in accordance with 13.3. The composite modulus of the laminate shall also be determined from equation (14):

$$E_{\text{LAM}} = \frac{X_{\text{LAM}}}{t} \quad (14)$$

The minimum permissible laminate thickness, t_m , to prevent buckling shall be determined from equations (15) or (16), as appropriate.

$$\text{If } \frac{L}{D_o} \geq 1.35 \left(\frac{E_{\text{LAM}}}{\rho F} \right)^{0.17}$$

Then

$$t_m = D_o \left(\frac{\rho F}{2 E_{\text{LAM}}} \right)^{0.33} \quad (15)$$

$$\text{And if } \frac{L}{D_o} < 1.35 \left(\frac{E_{\text{LAM}}}{\rho F} \right)^{0.17}$$

Then

$$t_m = D_o \left(\frac{0.4 \rho F}{E_{\text{LAM}}} \times \frac{L}{D_o} \right)^{0.40} \quad (16)$$

F shall be taken as 4.

It shall be ensured that t is not less than t_m .

NOTE t_m/D_o increases as L/D_o increases up to a limiting value. Beyond this value, t_m/D_o is independent of L/D_o .

If the proposed design does not comply with this requirement, the design shall be changed either by redesigning the laminate or by providing additional stiffening rings. The calculations shall then be repeated until an acceptable construction is indicated.

14.4.2 Cylindrical shells with stiffening rings. Where the calculations in 14.4.1 indicate an unacceptable laminate thickness it may be preferable to redesign to include stiffening rings and the first step shall be to obtain a new effective shell length, L , from:

- direct subdivision of the effective length of the unstiffened shell;
- requirements for the support of internal fittings, such as trays, etc.; or
- considerations of the design of the supports, in the case of horizontal vessels or tanks.

For a proposed stiffening ring profile and composition it is then necessary to determine the diameter, D_s , of its neutral axis.

It shall then be ensured that the second moment of area I_{s2} of the stiffening ring section is greater than or equal to:

$$0.18 D_o L D_s^2 \frac{\rho}{E_{\text{LAM}}} \quad (17)$$

The appropriate E_{LAM} shall be determined from equation (14).

Where a steel stiffening ring fully bonded to the shell [see Figure 6(d)] is used, the modulus for steel shall replace E_{LAM} . In this case the steel section only shall be considered as the stiffener.

The permissible length of shell, L_s , which may be regarded as effectively contributing to the second moment of area of the stiffening ring section shall be:

$$L_s = 0.75 \sqrt{t D_o} \quad (18)$$

but in no case shall L_s be taken greater than L .

Stiffening rings shall extend completely round the circumference of the shell and any joints shall be so designed as to develop the full stiffness of the ring. There shall be no spaces between shell and ring.

The design shall be checked for stresses in the GRP caused by restraint to thermal expansion/contraction by stiffening rings where the design temperature is above 60 °C or below 0 °C.

14.4.3 Spherical shells. The unit circumferential load, Q_ϕ , shall be calculated from equation (8) and this value then substituted in equation (6). Using as a basis a laminate construction which complies with this requirement, the total thickness of the laminate, t , shall be determined in accordance with 13.3.

The appropriate E_{LAM} shall be determined from equation (14).

The minimum permissible laminate thickness, t_m , to prevent buckling shall be determined from equation (19):

$$t_m = 1.7 R_o \sqrt{\frac{\rho F}{E_{\text{LAM}}}} \quad (19)$$

F shall be taken as 4.

It shall be ensured that t is not less than t_m .

If the proposed design does not comply with this requirement, the laminate shall be redesigned and the calculations repeated until an acceptable laminate, construction is indicated.

15 Shells subjected to wind loading

15.1 Symbols

For the purposes of clause 15 the following symbols apply.

D_o	outside diameter of shell (in mm)
F	factor of safety against collapse by buckling
h	actual height of course or part of course under consideration (in mm)
h_e	equivalent height (in mm) at thickness $t_{\min}$ of the shell course or part of course of thickness t_h and height h under consideration
h_1	actual height (in mm) from stiffener to top of course in which it is positioned
h_{1e}	equivalent height (in mm) at thickness $t_{\min}$ from stiffener to top of equivalent height course in which it is positioned
H (H_1, H_2 , etc.)	equivalent height(s) (in mm) from proposed position(s) of stiffener(s) to top equivalent height tank
H_A	actual height (in mm) from proposed position(s) of stiffener(s) to top of tank
H_e	total equivalent height (in mm) at thickness $t_{\min}$ of all shell courses of thickness(es) $t_{h1}, t_{h2} \dots t_{hx}$ and height(s) $h_1, h_2, \dots, h_x$
H_p	maximum equivalent height (in mm) at thickness $t_{\min}$ over which secondary stiffeners are not required
L	effective shell length (in mm) at thickness $t_{\min}$ between stiffeners or other points of support
p	total external pressure (in N/mm ²), i.e. wind pressure plus any internal vacuum
t_h	thickness of course under consideration (in mm)
$t_{\min}$	thickness of top course (in mm)
$X_{\text{LAM } h}$	overall unit modulus (in N/mm) of course under consideration
$X_{\text{LAM min}}$	overall unit modulus (in N/mm) of top course

15.2 Design calculations

As many vessels and tanks designed and constructed in accordance with this standard are situated in the open, consideration shall be given to wind loading which subjects the vessels and tanks not only to an overturning moment (requirements for which are specified in Appendix F) but to the local collapsing effect of the wind pressure to which, because of the relatively low elastic modulus of GRP, they are particularly susceptible.

The laminate thickness(es) of such vessels and tanks shall be checked for suitability for this pressure in accordance with the requirements for external pressure contained in this section and where there is also an internal vacuum condition, the pressure, p , used in the calculations shall be the sum of the wind pressure and the vacuum.

The wind pressure shall be determined in accordance with CP 3:Chapter V-2.

Tanks designed for static head of liquid content only are frequently designed with shell courses of varying laminate construction and thickness and in such cases an equivalent height of courses shall be established to determine the value of L , to be used in equations (15), (16) and (17) in conjunction with X_{LAM} and thickness values for the top, weakest, course as follows.

$$L = \Sigma h_e \text{ between adjacent stiffeners or supports} \quad (20)$$

where for each course or part thereof of height h and thickness t_h :

$$h_e = h \left(\frac{X_{\text{LAM min}}}{X_{\text{LAM } h}} \right) \left(\frac{t_{\text{min}}}{t_h} \right)^{1.5} \quad (21)$$

The vertical positioning of secondary rings shall be calculated by first determining the height of a complete tank shell of equivalent stability, at the same diameter, and of the same thickness as the top course of the shell. An analysis of this equivalent tank shell in association with the required wind and vacuum design criteria shall be used to determine the number of secondary rings required.

In many cases these rings will be located on the top course, or on a course of similar thickness, but if the location is not on such a course the actual positioning shall be determined by converting back the equivalent shell course heights to their actual values.

A secondary ring shall not be located within 150 mm of a main circumferential tank seam or change of section.

In line with BS 2654, the equivalent height of the tank shall be the summation of all individual courses, i.e.:

$$H_e = \Sigma h_e \text{ between tank base and equivalent tank top} \quad (22)$$

Values of h_e are determined from equation (21).

Secondary wind stiffeners shall be necessary when the ratio of $H_e/H_p > 1$.

where

$$H_p = \frac{X_{\text{LAM min}} t_{\text{min}}^{1.5}}{0.4 F p D_o^{1.5}}$$

F shall be taken as 4.

To obtain the number of secondary stiffeners, the integer of the ratio H_e/H_p shall be used, i.e. if $H_e/H_p = 2.5$ then two wind stiffeners are required spaced, for example, at $H_1 = H_e/3$ and $H_2 = 2H_e/3$ from the top.

To find the actual position of the stiffeners the following method of calculation shall be used.

- A table of relevant details including tank course height(s) h and the corresponding equivalent height(s) h_e shall be constructed (see D.7).
- The course(s) in which the stiffener(s) will be positioned shall be located by inspection of the table.
- The position(s) of stiffener(s) with the course(s) shall be determined as follows:

$$h_{le} = H - \Sigma h_e \text{ between top of stiffened course under consideration and equivalent tank top}$$

The true distance of the stiffener from the stiffened course top, h_l , shall be derived from equation (21):

$$h_l = h_{le} \left(\frac{X_{\text{LAM } h}}{X_{\text{LAM min}}} \right) \left(\frac{t_h}{t_{\text{min}}} \right)^{1.5}$$

The true distance, H_A , of the stiffener from the actual tank top shall be determined from equation (23):

$$H_A = h_1 + \Sigma h \quad \text{between top of stiffened course under consideration and actual tank top} \quad (23)$$

NOTE A worked example is provided in Appendix D.

In the case of open-top or fixed-roof tanks, adequate primary stiffening at the upper edge of the top course either by external stiffener or inherent stiffness in the shell/roof junction shall be provided. The second moment of area of such stiffening, and of secondary stiffeners shall comply with 14.4.

16 Rectangular tanks

16.1 Small unstiffened rectangular tanks

Small unstiffened rectangular tanks, without supporting ribs or frames shall be considered as a number of individual panels joined at the corners. Each such panel shall be designed in accordance with clause 17 using type 2 edge coding constants appropriate to its proportions, edge conditions and type of loading.

16.2 Stiffened rectangular tanks

It is permissible for the arrangement of stiffening ribs to be bidirectional but for economy the ribs are usually arranged in the vertical or horizontal axes; however arranged, the stiffening ribs may be fabricated into a framework. Such constructions shall be considered as a number of individual, rectangular panels, and designed in accordance with clause 17. For calculation purposes the load to be carried by each rib shall be the load carried by the half of each adjacent panel, due account being taken of any snow or wind loads.

16.3 Design of stiffening ribs

16.3.1 General. Stiffening ribs shall be of steel or reinforced plastics construction. In either case the proportions of these integral ribs shall be calculated using conventional bending theory.

The design shall be checked for stresses in the GRP caused by restraint to thermal expansion/contraction by stiffening ribs where the design temperature is above 60 °C or below 0 °C.

16.3.2 Steel stiffening ribs. All assemblies of ribs shall be designed to ensure adequate strength at all welded junctions, and at butt welded connections the edges to be welded shall be so prepared to ensure full penetration welds developing the full strength of the sections.

The calculated stress in the steel section shall not exceed $0.25 \times$ tensile strength. The calculated stress in fillet welds shall not exceed $0.1 \times$ tensile strength of the steel section. The load-carrying area of a fillet weld shall be the product of its length and throat thickness, where the throat shall be taken as not more than $0.7 \times$ weld leg length.

The calculated stress in butt welds shall not exceed $0.16 \times$ tensile strength.

16.3.3 GRP stiffening ribs. The ribs shall be fabricated using only CSM as the reinforcing material. The overlay laminate shall be extended either side of the rib for a sufficient distance to carry all shear loads and shall not be less than 75 mm.

It is permissible to regard the panel to which the rib is overlayed as contributing to the strength of the rib for a distance not exceeding $16 \times$ panel thickness on either side of the rib provided there is such a clear distance available. No part of the panel shall be regarded as contributing to more than one rib. The material over which the rib is formed shall not be regarded as contributing to the strength of the rib.

17 Flat panels

17.1 General

Flat panels designed in accordance with this standard shall be manufactured using only chopped strand or CSM as the reinforcing material.

The equations in this clause are based on a consideration of both the maximum allowable unit skin loading, tensile or compressive, and an over-riding limiting deflection of t , where t is the thickness of the panel and t shall always be equal to or greater than $t_{\min}$, where $t_{\min}$ is the required minimum thickness of the panel.

NOTE 1 It is considered that the membrane component of loading arising when the maximum deflection equals the panel thickness does not significantly affect the validity of the bending analysis from which the equations were derived.

NOTE 2 Whilst it is recognized that edge conditions can be of great significance when calculating in this manner, it is considered that in many cases the effect of change in such conditions is only marginal and for the purposes of this clause the edge conditions have been directed into type 1 and type 2. These are illustrated in Figure 9 and Figure 10.

The edge conditions for a particular panel shall be either type 1 or type 2 or a combination of both depending on conditions.

17.2 Symbols

For the purposes of clause 17 the following symbols apply.

a	panel dimension, longest span (length) (in mm) (see Figure 9 and Figure 10)
b	panel dimension, shortest span (breadth) (in mm) (see Figure 9 and Figure 10)
c	depth of core (in mm)
d	depth of sandwich (in mm) between neutral axes of faces
D_p	panel dimension, circular panels (diameter) (in mm) (see Figure 9 and Figure 10)
E_{LAM}	Young's modulus (in N/mm ²) of laminate under consideration
F	factor of safety
m_{CSM}	total mass of CSM reinforcement (in kg/m ²)
M_d	design moment = total moment induced in the panel by the worst combination of distributed loads plus moment due to any local load (in N mm)
M_l	moment due to local load (in N mm)
M_p	moment due to distributed load (in N mm)
p	pressure (particular definitions are given throughout the text) (in N/mm ²)
Q_s	maximum unit load (in N/mm) in skin of laminate
r_l	radius of local load (in mm)
r_p	panel radius (in mm) or in the case of an isosceles triangular plate, the length of one of the equal sides
S	maximum shear force per unit width (in N/mm) acting on panel
t	solid panel thickness (in mm)
t_g	laminate thickness (in mm per kg/m ² glass) determined from Figure 5
$t_{\min}$	required minimum thickness of panel (in mm)
t_s	skin thickness (in mm)
t_t	total thickness (in mm) of sandwich to outside of the structural layers
u_{CSM}	design unit loading for CSM layers (in N/mm per kg/m ² glass)
W_l	applied local load (in N)
α	constant appropriate to combination of edge conditions and type of loading
β	constant appropriate to combination of edge conditions and type of loading
τ_c	maximum shear stress (in N/mm ²) in core and in skin to core interface

17.3 Panel shapes and loads

The design of flat panels shall be undertaken in accordance with 17.4 to 17.10, which cover panels of circular, rectangular, triangular and segmented shape subjected to uniformly distributed loads and uniformly varying loads, as in the case of a static head of liquid, and circular and rectangular panels for concentrated loads applied to the centre of the panels.

NOTE 1 This provides for panels subject to access loadings as given in BS 6399-1 and gives a worst case for fixed direct loads.

For loads remote from the panel centre, designs shall be based upon reference [11] for rectangular panels and references [11] and [12] for circular panels.

NOTE 2 The effects of external moments on flat panels cannot readily be assessed and such loadings should be avoided whenever possible.

17.4 Design method for all panel shapes

The design moment, M_d , shall be the total moment induced in the panel by the worst combination of distributed loads that could occur, e.g. pressure, vacuum, static head, wind and snow loads, plus the moment due to any local load, for example:

$$M_d = M_{\text{vacuum}} + M_{\text{snow}} + M_{\text{wind}} + M_{\text{local load}}$$

A check calculation shall be made to ensure that the thickness of the resulting laminate is such that the deflection of the panel does not exceed the panel thickness.

17.5 Rectangular panels

17.5.1 General. One of the following four arrangements of edge conditions shall be adopted. The considered and appropriate constants shall be as given in Table 8.

Case A. Type 1 edge conditions on all four sides. For example, a bolted cover with a joint extending beyond the bolt holes or one of an assembly of panels with balanced fixing at stiffeners or corners.

Case B. Type 1 edge conditions on both short edges and one long edge with type 2 edge conditions on the other long edge. For example, one of an assembly of panels forming the side of an open topped tank with one long edge carried by the tank top flange or support frame.

Case C. As an alternative to case B, panels with type 1 edge conditions on two long edges and one short edge and type 2 on the other short edge.

Case D. Type 2 edge conditions on all four sides, e.g. a loose cover plate.

17.5.2 Rectangular panels under distributed load. The moment, M_p , due to a uniformly distributed load on a rectangular panel shall be determined from equation (24):

$$M_p = \beta_1 p b^2 \quad (24)$$

where

β_1 is obtained from Table 8;

p is the uniform internal or external pressure, a uniform load such as snow or wind or such a combination of these as will give rise to the greatest differential pressure across the panel with due regard being taken to the sign or direction of application of each form of load.

The moment, M_p , due to a static head of liquid decreasing from maximum pressure at the base of the panel to zero at the top shall be determined from equation (25):

$$M_p = 0.67 \beta_1 p b^2 \quad (25)$$

where

β_1 is obtained from Table 8;

p is the pressure at the base of the panel, i.e. the maximum pressure on the panel.

The moment, M_p , due to a static head of liquid decreasing from a maximum pressure at the base of the panel but which is not zero at the top shall be determined from equation (24) using the maximum value of pressure for the panel concerned.

17.5.3 Rectangular panels under central local loads. Cases A and D only shall be considered when panels are subjected to local loads.

NOTE Panels of case B may be considered as case D and panels of case C may be considered as case A for local loads only.

The moment, M_l , due to local load on a rectangular panel shall be determined from the greater value given by equations (26) and (27) for case A and equation (26) only for case D:

$$M_l = \frac{W_l}{4\pi} \left(1.3 \ln \frac{2b}{\pi r_1} + \beta_2 \right) \quad (26)$$

$$M_l = \beta_3 W_l \quad (27)$$

where

β_2 and β_3 are obtained from Table 9.

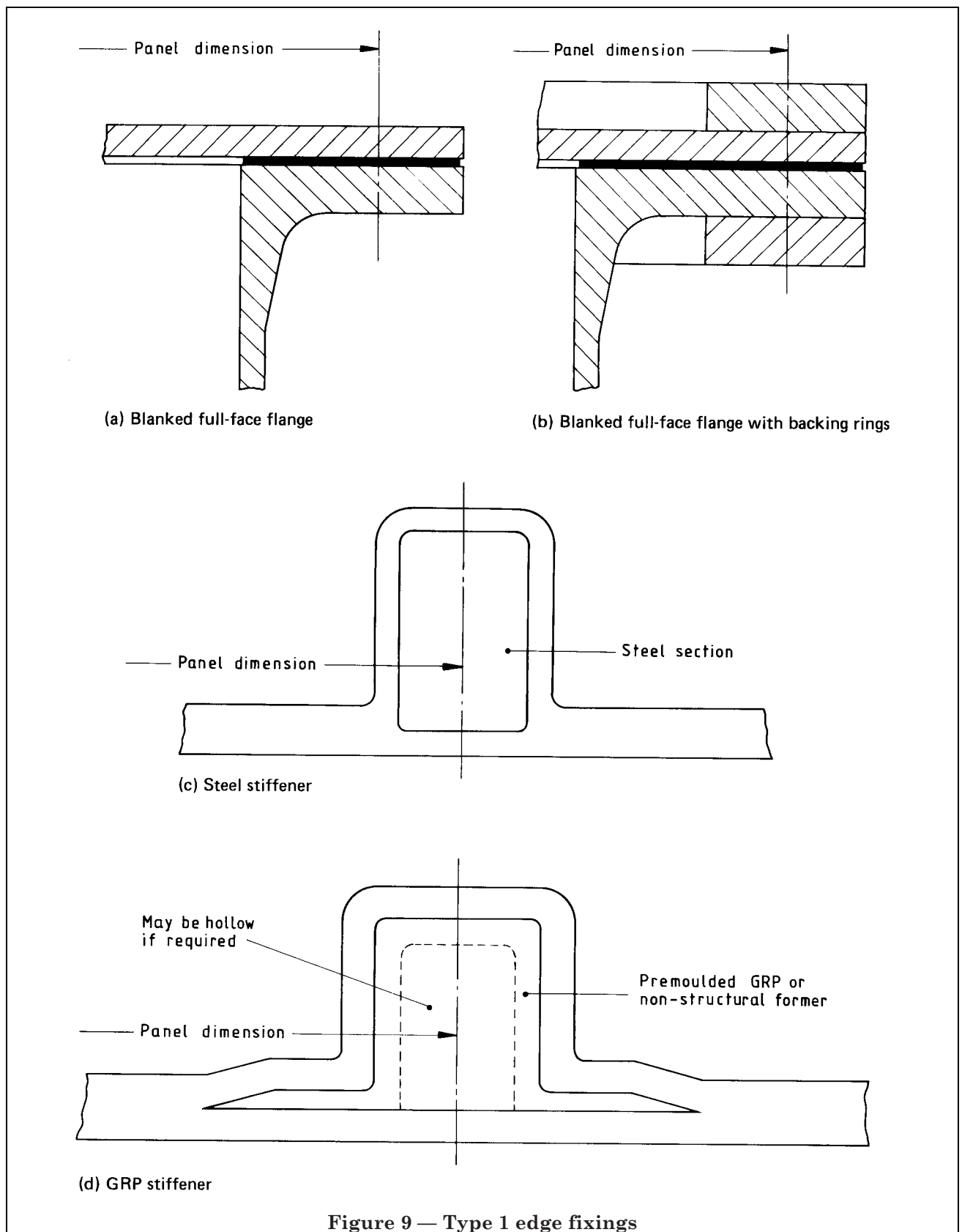
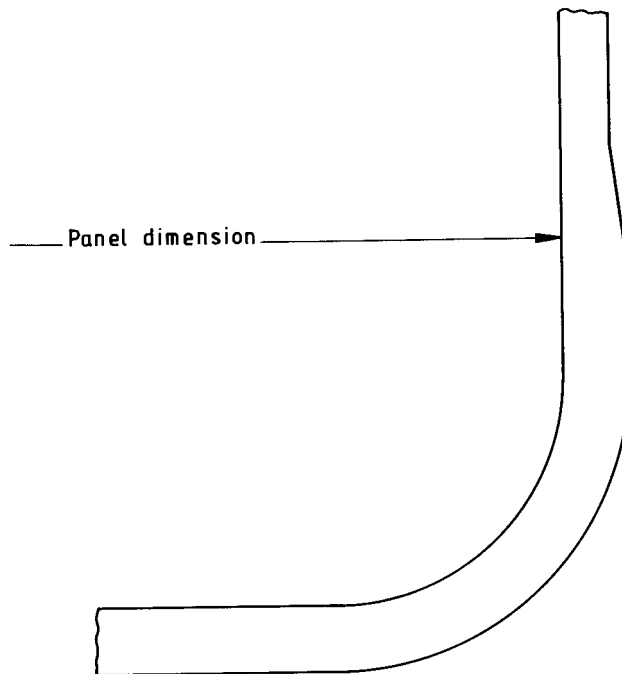


Figure 9 — Type 1 edge fixings



(e) Typical panel/panel connection

Figure 9 — Type 1 edge fixings (concluded)

17.5.4 Mass of reinforcement. The total mass of CSM reinforcement, m_{CSM} (in kg/m²), shall be determined from equation (28):

$$m_{\text{CSM}} = \left(\frac{6M_d}{u_{\text{CSM}} \times t_g} \right)^{0.5} \quad (28)$$

where

M_d is the total moment as defined in 17.4.

A check of the laminate thickness shall be made to ensure that the deflection of the panel does not exceed the panel thickness. The required minimum thickness of the panel shall be determined from equation (29):

$$t_{\min} = \left(\frac{\alpha_1 p b^4}{E_{\text{LAM}}} + \frac{\alpha_2 W_1 b^2}{E_{\text{LAM}}} \right)^{0.25} \quad (29)$$

where

α_1 is obtained from Table 8;

α_2 is obtained from Table 9;

p is the design unit pressure (worst combination of pressure, vacuum, snow, wind loading, etc.).

17.6 Circular panels

17.6.1 Circular panels under uniformly distributed load. The moment, M_p , due to uniformly distributed load shall be determined from equation (30):

$$M_p = \beta_1 D^2 p \quad (30)$$

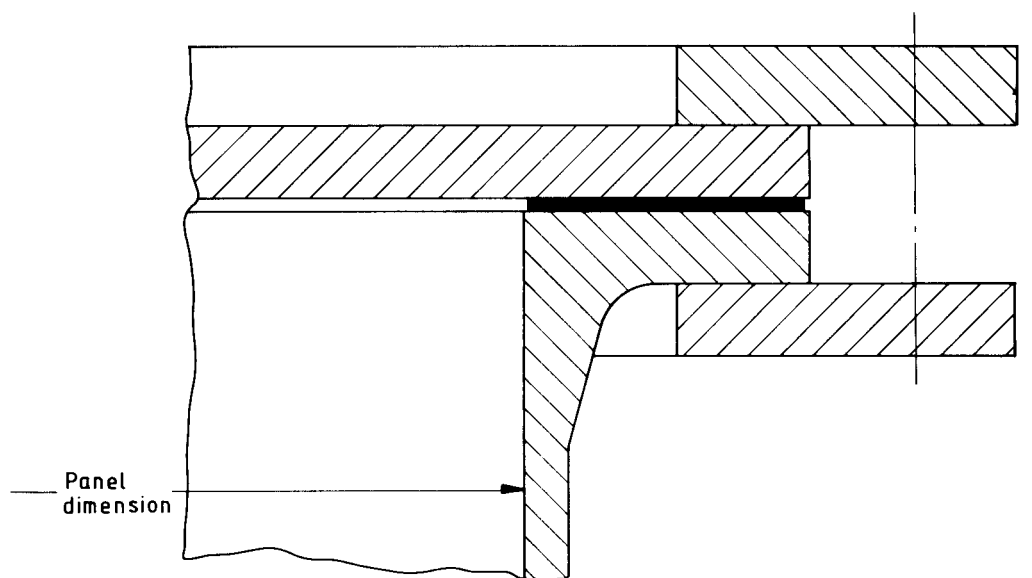
where

β_1 is a constant equal to:

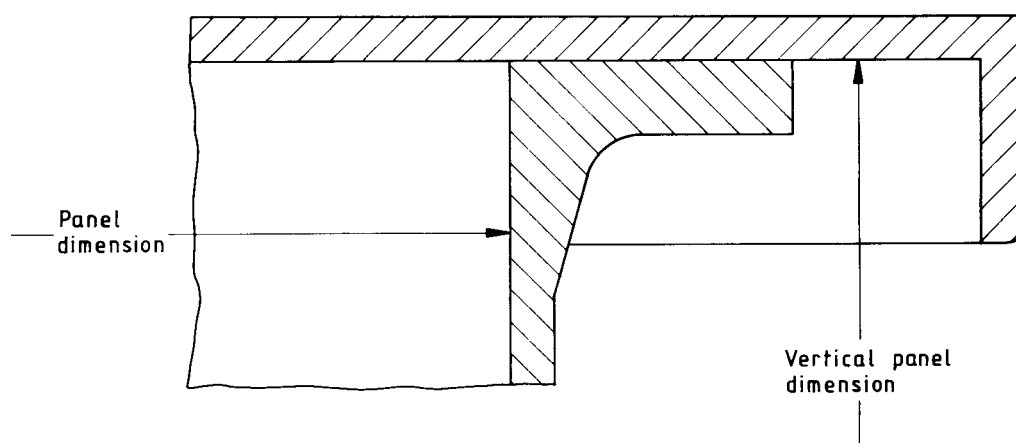
0.03 125 for type 1 edge conditions;

0.0516 for type 2 edge conditions;

p is the design unit pressure (worst combination of pressure, vacuum, snow, wind loading, etc.).



(a) Blanked stub flange with backing rings



(b) Loose cover

Figure 10 — Type 2 edge fixings

Table 8 — Deflection and bending moment constants for flat plates

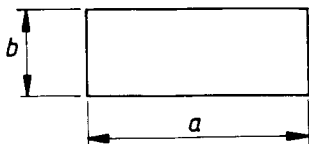
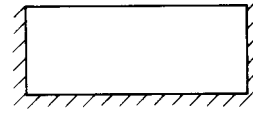
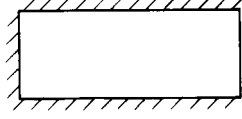
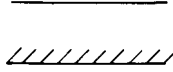
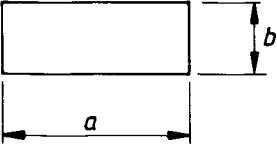
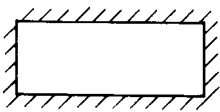
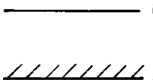
Boundary condition	Constant	Length/breadth ratio a/b										Case
		1.0	1.25	1.5	1.75	2.0	2.5	3.0	4.0	5.0	> 5.0	
	β_1	0.048	0.067	0.081	0.093	0.102	0.113	0.119	0.125	0.125	0.125	D
	α_1	0.044	0.060	0.084	0.099	0.111	0.126	0.134	0.140	0.142	0.142	D
	β_1	0.051	0.067	0.075	0.080	0.083	0.083	0.083	0.083	0.083	0.083	A
	α_1	0.014	0.020	0.024	0.026	0.028	0.0281	0.0282	0.0284	0.0284	0.0284	A
	β_1	0.060	0.077	0.094	0.107	0.114	0.121	0.124	0.124	0.124	0.124	B
	α_1	0.017	0.028	0.037	0.044	0.049	0.055	0.057	0.058	0.058	0.058	B
	β_1	0.060	0.073	0.079	0.082	0.083	0.083	0.083	0.083	0.083	0.083	C
	α_1	0.017	0.022	0.025	0.027	0.028	0.0284	0.0284	0.0284	0.0284	0.0284	C
	Type 2 fixing, simply supported Type 1 fixing, built-in edge											

Table 9 — Deflection and bending moment constants for central local loads on rectangular flat plates

Boundary condition	Constant	Length/breadth ratio a/b										Case
		1.0	1.25	1.5	1.75	2.0	2.5	3.0	4.0	5.0	> 5.0	
	α_2	0.1267	0.1518	0.1671	0.1763	0.1805	0.1821	0.1831	0.1842	0.1849	0.1851	D
	β_2	0.435	0.691	0.838	0.917	0.958	0.976	0.986	0.997	1.000	1.000	D
	α_2	0.0611	0.0720	0.0768	0.0785	0.0788	0.0790	0.0791	0.0791	0.0791	0.0791	A
	β_2	-0.238	-0.052	0.036	0.067	0.067	0.067	0.067	0.067	0.067	0.067	A
	β_3	0.1257	0.1530	0.1632	0.1665	0.1674	0.1677	0.1679	0.1680	0.1680	0.1680	A
	Type 2 fixing, simply supported Type 1 fixing, built-in edge											

17.6.2 Circular panels under central local load.

The moment M_l due to local load shall be determined from the greater of equations (31) and (32) for type 1 edge condition and equation (33) only for type 2 edge condition.

Type 1:

$$M_l = 0.325 \frac{W_l}{\pi} \ln \frac{D_p}{2r_l} \quad (31)$$

or

$$M_l = \frac{W_l}{4\pi} \quad (32)$$

Type 2:

$$M_l = \frac{W_l}{4\pi} \left(1.3 \ln \frac{D_p}{2r_l} + 1 \right) \quad (33)$$

17.6.3 Mass of reinforcement. The required mass of CSM reinforcement, m_{CSM} (in kg/m²), shall be determined from equation (34):

$$m_{\text{CSM}} = \left(\frac{6M_d}{u_{\text{CSM}} \times t_g} \right)^{0.5} \quad (34)$$

A check of the laminate thickness shall be made to ensure that the deflection of the panel does not exceed its thickness.

The minimum laminate thickness shall be determined from equation (35):

$$t_{\min} = \left(\frac{\alpha_1 p D_p^4}{E_{\text{LAM}}} + \frac{\alpha_2 W_l D_p^2}{E_{\text{LAM}}} \right)^{0.25} \quad (35)$$

where

α_1 is a constant equal to:

0.01066 for type 1 edge condition;

0.04347 for type 2 edge condition;

α_2 is a constant equal to:

0.05431 for type 1 edge condition;

0.13787 for type 2 edge condition;

p is the design unit pressure (worst combination of pressure, vacuum, snow, wind loading, etc.).

Table 10 — α and β constants for sector and triangular plates

Angle	π	$\pi/2$	$\pi/3$	$\pi/4$
Type 1. Fixing on sector edges				
α	0.0368	0.0144	0.0062	0.0031
β	0.0756	0.0488	0.034	0.025
Type 2. Fixing on all sides				
α	0.0886	0.0246	0.01	0.0054
β	0.0868	0.0381	0.0255	0.0183

17.7 Plates in the form of a sector of a circle and triangular plates

Plates in the form of a sector of a circle and triangular plates shall be designed using the values of (α and β) obtained from Table 10.

The moment on the panel, M_p , shall be determined from equation (36):

$$M_p = \beta p r_p^2 \quad (36)$$

where

β is obtained from Table 10;

p is the design uniform pressure (worst combination of pressure, vacuum, snow, wind loading, etc.).

The required mass of CSM reinforcement, m_{CSM} , is then determined from equation (37):

$$m_{\text{CSM}} = \left(\frac{6M_p}{u_{\text{CSM}} \times t_g} \right)^{0.5} \quad (37)$$

A check of the panel deflection shall be made using equation (38) to ensure the deflection does not exceed the panel thickness:

$$t_{\text{min}} = r_p \left(\frac{\alpha p}{E_{\text{LAM}}} \right)^{0.25} \quad (38)$$

where

α is obtained from Table 10.

17.8 Sandwich construction panels

17.8.1 General. A sandwich construction panel shall consist of two reinforced plastics skins separated by and bonded to a core of low load-carrying capability in order to improve the strength and stiffness of the flat panel with economy of reinforcement material.

In these calculations the core material is not considered to contribute any strength to the panel. However, its ultimate shear strength in any direction shall not be less than 0.2 N/mm² as determined in accordance with B.13.

17.8.2 Design conditions. Where flat sandwich panels are used as an alternative to solid panels, the following conditions shall be satisfied.

- The thickness of each skin shall in no case be less than the thickness specified in 13.3.
- The ultimate shear strength of the core shall not be less than 0.2 N/mm².
- The design temperature shall not exceed 60 °C.
- The flexural rigidity of the core shall be ignored and the skins shall be composed of CSM unless more detailed analysis of the panel is undertaken.

NOTE Consideration should be given to the ability of the core material to withstand local compressive loads at the intersections of panels and stiffening ribs.

17.8.3 Design calculations. In order to obtain an initial construction, the thickness required for a solid panel shall be determined (necessary to limit the deflection to the panel thickness) in accordance with 17.4. The overall thickness, t_t , of the sandwich panel shall then be obtained by assuming a core thickness and using equation (39):

$$t_t = (t^3 + c^3)^{0.33} \quad (39)$$

The skin thickness, t_s , shall then be determined from equation (40):

$$t_s = \frac{(t_t - c)}{2} \quad (40)$$

In no case shall t_s be less than that specified in 17.8.2 a).

The skin unit loading shall be checked to ensure that the design unit loading is not exceeded using equation (41):

$$Q_s = \frac{M_d t_t}{d^2} \quad (41)$$

This value of unit load shall be substituted in equation (6).

In addition the core shear stress shall be determined from equation (42):

$$\tau_c = \frac{S}{d} \quad (42)$$

where the maximum shear force S is determined for the loading present. τ_c shall not exceed:

$$\frac{\text{Ultimate shear strength of the core}}{F}$$

or

$$\frac{\text{Ultimate shear strength between the core and the skin}}{F}$$

F shall be taken as not less than 4.

NOTE See worked example in Appendix D.

17.9 Panels at design temperature above ambient

For panels with design temperature above ambient, the following design cases shall be considered:

- a) ambient temperature, design loading;
- b) design temperature, design loading;
- c) design temperature, no loading.

NOTE Further information on calculating thermally induced moments and deflections is given in reference [12].

18 Ends

18.1 Symbols

For the purposes of clause 18 the following symbols apply.

- A_b actual total cross-sectional area (in mm²) of bolts at root of thread or section of least diameter under stress
- A_m total required cross-sectional area of bolts (in mm²), taken as greater of A_{m1} and A_{m2}
- A_{m1} total cross-sectional area of bolts (in mm²) at root of thread or section of least diameter under stress, required for operating conditions, = W_{m1}/S_b
- A_{m2} total cross-sectional area of bolts (in mm²) at root of thread or section of least diameter under stress, required for gasket seating, = W_{m2}/S_a
- b effective gasket width, = $2.52 \sqrt{N/2}$ (in mm)
- B inside diameter of flange (in mm) [see Figure 14(a)]
- D_m gasket mean diameter (in mm) [see Figure 13(a)]
- D outside diameter of gasket contact face (in mm)
- D_b pitch circle diameter of cover bolts (in mm) [see Figure 13(b) and Figure 14(b)]
- D_i inside diameter of shell (in mm)
- D_k inside diameter at large base of cone (in mm)
- D_o outside diameter of shell (in mm)
- f allowable design stress for material used for steel backing plate:
- $\frac{\text{Room temperature tensile strength}}{4}$
- or
- $\frac{\text{Room temperature yield or proof stress}}{1.6}$
- whichever is lower (in N/mm²)
- G diameter at location of gasket load reaction, = $D - 2b$ (in mm)

- h_g radial distance from gasket load reaction to the bolt circle, = $\frac{D_b - G}{2}$ (in mm)
- h_i inside head height (in mm), i.e. distance from tangent point between knuckle and parallel skirt (see Figure 11).
For a torispherical head:
- $$h_i = R_i - \left\{ \left(R_i - \frac{D_i}{2} \right) \left(R_i + \frac{D_i}{2} - 2r_i \right) \right\}^{0.5}$$
- H total hydrostatic end force, = $0.785 B^2 p$ (in N)
- H_p compression load on gasket to ensure tight joint, = $2b \times 3.14 G m p$ (in N)
- K_{c1} shape factor for use with cone/cylinder intersections with knuckle radius, obtained from Table 12 to determine longitudinal unit loading [see equation (48)]
- K_{c2} shape factor for use with cone/cylinder intersections without a knuckle, where permitted in accordance with 18.4.1, obtained from Table 13 to determine longitudinal unit loading [see equation (49)]
- K_e shape factor, for use with semi-ellipsoidal ends under external pressure, taken from Figure 15
- K_s shape factor for use with domed ends, obtained from Table 11
- L effective shell length (in mm)
- L_c distance (in mm) from cone/cylinder intersection for which both cone and cylinder are to be increased to thickness t_c , $\left(= \sqrt{\frac{D_i t_c}{\cos \phi}} \right)$
- m gasket factor = 1 for soft rubber without fabric or asbestos reinforcement
- m_{CSM} total mass of glass per unit area (in kg/m²) in complete laminate required for ring supported flat covers
- N width of gasket in contact with flange face (in mm)
- p total effective pressure (in N/mm²), i.e. design pressure including hydrostatic head at point under consideration
- Q maximum unit load (in N/mm), i.e. maximum force per unit width, to be carried by the laminate
- Q_{x1} longitudinal unit load (in N/mm) for cone/cylinder intersections with knuckle [see equation (48)]
- Q_{x2} longitudinal unit load (in N/mm) for cone/cylinder intersections without knuckle, where permitted in accordance with 18.4.1 [see equation (49)]
- r_i inside knuckle radius of dished end or of transition between conical end and cylinder (in mm)
- R radius of corner (in mm) (see Figure 16)
- R_i inside radius of spherical portion of dished end (in mm)
- R_o outside radius of spherical shell (in mm)
- S_a bolt nominal design stress at atmospheric temperature (see Table 15)
- S_b bolt nominal design stress at design temperature (see Table 15)
- t laminate thickness of end (in mm) calculated from laminate details
- t_c design thickness of cone/cylinder intersection (in mm). It extends along the cone and cylinder for a distance not less than L_c (see 18.4.3)
- t_g thickness per unit mass of glass determined from Figure 5 after glass content has been fixed (in mm per kg/m² glass)
- t_B thickness of steel backing plate (in mm)
- u_{CSM} design unit loading (in N/mm per kg/m² glass) for CSM layers (from 9.2)

- W flange design bolt load (in N), based on actual size bolts used to provide the greater of W_{m1} and W_{m2} and ends $\frac{(A_m + A_b) S_a}{2}$
- W_{m1} minimum required bolt load for operating conditions (in N), $= H + H_p$
- W_{m2} minimum required bolt load for gasket seating (in N), $= 3.14 \times b G y$
- y is the gasket or joint contact surface unit seating stress $= 2.32 \text{ N/mm}^2$ for soft rubber without fabric or asbestos reinforcement
- ϕ angle of slope of conical section to vessel axis (see Figure 12)

18.2 Limitations of shape

Ends shall be one of the following shapes:

- hemispherical [see Figure 11(a)];
- semi-ellipsoidal: the ratio of inside head height, h_i , to inside diameter, D_i , shall be not less than 0.2 [see Figure 11(b)];
- torispherical: the inside radius of dishing, R_i , shall be not greater than the inside diameter, D_i , and the inside knuckle radius, r_i , shall be not less than one-tenth of the inside diameter, D_i , [see Figure 11(c)];
- conical [see Figure 12(a) and Figure 12(b)];
- flat: fully supported or ribbed;
- bolted flat covers (see Figure 13 and Figure 14).

NOTE The type of end in which the convex surface of the end forms part of the inner surface of the vessel or tank is not covered by this standard.

18.3 Domed ends

18.3.1 General. Domed ends shall include shapes listed as 18.2 a), b), and c).

18.3.2 Domed ends subject to internal pressure. The unit load to be substituted in equation (6) shall be determined from equation (43):

$$Q = 0.5p D_i K_s \quad (43)$$

Since the value of K_s to be used is dependent on the thickness of the domed end, and this thickness cannot be accurately determined until the laminate has been designed, a value for the t/D_i ratio shall be assumed in order to select an appropriate value K_s .

The value of K_s so determined shall be substituted in equation (43) to determine the notional unit load, Q , and this value of Q used in equation (6) for the determination of a suitable laminate.

The thickness of the laminate so calculated shall then be determined, in accordance with 13.3, and the value of t/D_i given by this thickness shall be compared with the ratio assumed. If the difference is significant, the calculations shall be repeated using a new value of K_s appropriate to the likely thickness of the final laminate.

NOTE As an alternative to repeating the calculation, it may be found preferable to redesign the end with larger head height, h_i , and knuckle radius, r_i , thus reducing the value of K_s to be used in the design calculations.

18.3.3 Hemispherical and torispherical ends subject to external pressure. The unit load to be substituted in equation (6) shall be determined from equation (44):

$$Q = 0.66p D_i K_s \quad (44)$$

Additionally, the minimum permissible laminate thickness, t_m , to prevent buckling shall be determined from equation (19).

It shall be ensured that t is not less than t_m .

If, in the proposed design, this condition is not fulfilled the laminate shall be redesigned and the calculations repeated until an acceptable laminate construction is indicated.