

Traceability and Qualification in Design with Composite Materials

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ABSTRACT

The availability of design codes, test method standards and specifications standards is crucial for the growth of the market for composite material products and thereby the growth of the designers, fabricators and users of these materials, which are predominately SME. This report concentrates on the necessary infrastructure of material standards and specifications in support of the qualification and traceability of formal approval and design procedures or codes for composite materials products. These infrastructure “tools” will be increasingly important with the arrival of further “safety orientated” European Union Directives and other regulatory requirements.

The development of an infrastructure to support the use of composite components has been a major target of the work at NPL for the last few years. Initially, the work concentrated on harmonisation and rationalisation of the multitude of similar materials test methods. Excellent progress was made in the drafting and balloting of several short-term test methods that have been published over the last few years as BS EN ISO standards, achieving a high level of harmonisation with ASTM test methods. These test methods now form the basis of an ISO database standard aimed at satisfying the technical data-sheet level.

The next requirement is to integrate these new test methods into product design standards and specifications. This has been started with the European specification standard for pultruded profiles developed by NPL in liaison with the European Pultrusion Industry. At the level of full product design codes, contributions are being made by several organisations including international standards bodies (eg CEN, ISO) and other regulatory bodies. This report reviews the infrastructure now existing and assesses its integration into the composite materials product specifications and design codes, together with identifying the reverse demands of design codes on the supporting infrastructure.

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Approved on behalf of Managing Director, NPL, by Dr C Lea,
Head of NPL Materials Centre.

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INTRODUCTION

The availability of an infrastructure based on design codes, test method standards and material specifications is crucial for the growth of the market for composite material products. This infrastructure is particularly important for the growth of the many SME companies (small to medium enterprises) encompassing designers, processors, fabricators and users of these materials that cannot afford the cost of individual qualifications for each project. This report concentrates on the development and integration of the infrastructure in support of formal design procedures for composite materials products, particularly to meet regulatory requirements. Before using specific data or information from report, the latest copy of the referenced documents should be obtained as in many cases the documents were under development during this review and changes may have occurred subsequently.

For example, one of the earliest design standards for a composite product was British Standard, BS 4994¹ covering manufacture of GRP (glass-reinforced plastic) Pressure Vessels. Having been revised once as a British Standard, it is now being reincarnated as an European standard, prEN 13121, with input from other European countries. However, this standard is still under development with substantial technical comments during balloting, so that final publication is not expected until September 2003. Compliance with this EN standard will be the easiest and most cost effective way to demonstrate compliance with the EU Directive on Pressure Equipment when designing a GRP pressure vessel. This area of component and product specification and design is the main concern in CEN (Comité Européen de Normalisation) due to the use of these standards in support of the EU Directives, and effectively counter-balances the preference in CEN for test methods to be principally prepared in ISO (International Standards Organisation).

The research programmes at the National Physical Laboratory (NPL) on composite materials have been directed at developing this infrastructure in support of UK industry [1]. The work has been extremely instrumental in the progress achieved in establishing an infrastructure of test methods and simplified design procedures [2, 3]. Standards drafted at NPL and successfully balloted are now in place as triple numbered (BS EN ISO) documents covering several in-plane coupon test methods. Further work has enabled the submission of NPL test method drafts to BSI on through-thickness properties and by the UK to ISO covering structural test elements (OHC, OHT, pin-bearing).

The work at NPL has been extended through working, as a CEN convenor, with the European pultruders and associated interests (e.g. resin and glass-fibre manufacturers) with the publication of the first specification standard for a finished composite product (i.e. pultruded profiles). This standard is particularly important as it covers an off-the-shelf composite, when most have to be formed and cured, and introduces designer and users to the advantages of composites, which can then be translated to more complex forms, lay-ups and processes including custom profiles.

The final stage in the development of the infrastructure concerns product design codes, when the underpinning material infrastructure shows its worth and effectiveness by allowing extensive cross-references to other standards rather than needing to produce specific test method annexes. This enables the demonstration of traceability in support of Directives etc., to be more straightforward.

¹ Full references to standards, directives etc. are given in the appendice

Some areas where product standards/design codes are being developed are:-

- GRP pressure vessels and piping
- GRP boats
- Filament wound gas cylinders
- Aircraft and very light aircraft
- Construction

In Sections 2-4 the background of product traceability, standardisation bodies and materials test method and specification standards are reviewed. In Section 5, composite product standards and codes are reviewed for their essential features. Section 6 reviews twenty aspects (e.g. material test methods and the related property data) across the codes for commonality and differences. Concluding comments are given in Section 7. Appendices cover a general bibliography and standards for composite materials.

2. PRODUCT TRACEABILITY

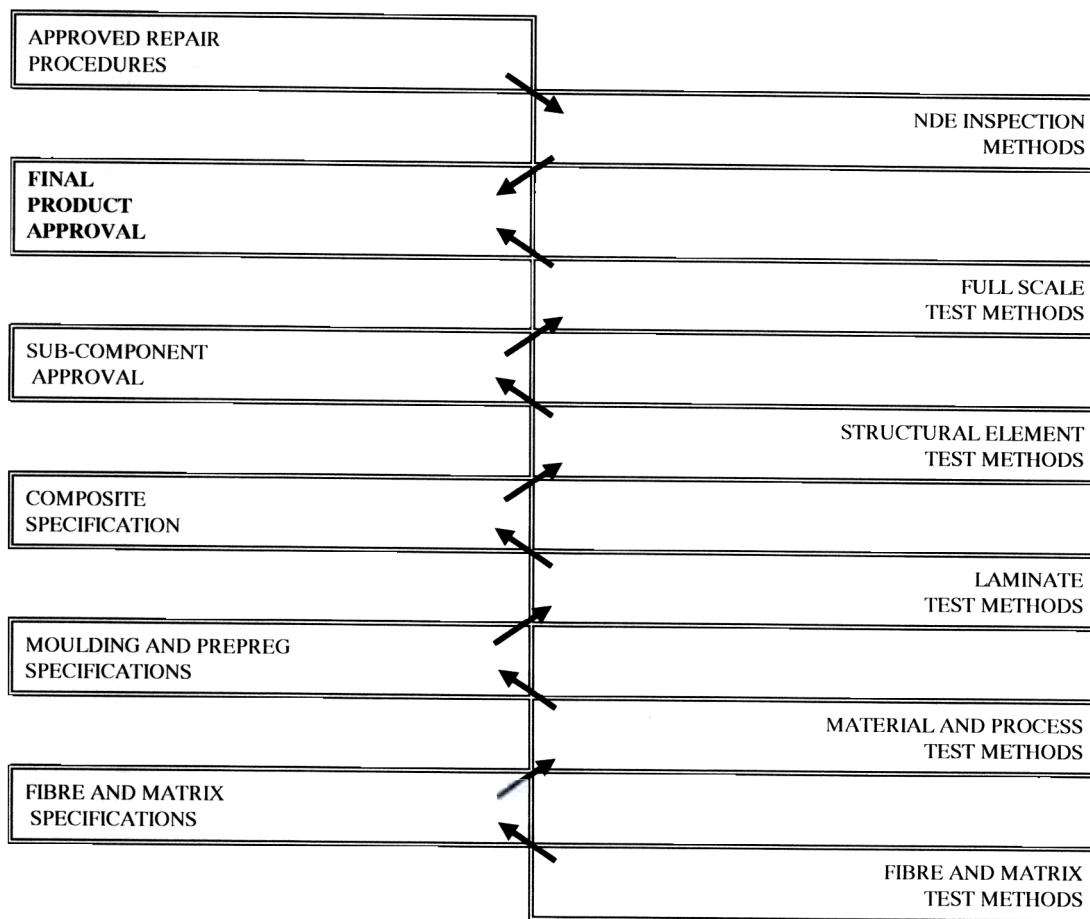


Figure 1: Chain of validation for composites products

As the harmonisation of practices within the EU and the need to demonstrate compliance with safety orientated EU directives develops, there is a need for a supporting infrastructure at all levels (i.e. from constituents to final application, including in-service maintenance and repair), so that the pyramid of substantiation often quoted for aircraft certification will become

increasingly familiar in other application areas. A “validation chain” can also be used to show, see figure 1, the alternating dependence of specification and test methods standards at each level. In this report a cross-section of documents representing different approaches and different applications are reviewed.

3. STANDARDISATION BODIES

Many different bodies are involved in standardisation activities. These include the international and national standards organisations (eg ANSI, AFNOR, BSI, DIN, JIS), regulatory bodies such as the CAA and FAA, trade groupings and societies (eg ASTM). ISO has the largest country membership with 167 countries. The CEN standards covering Europe, including countries outside the European Union, has a higher “legal” profile and is encouraging increased attention to precision statements. It is important that the repeatability and reproducibility of the test method are known for both free trade and liability uses of the standard. The Vienna agreement between ISO and CEN ensures that work is not duplicated and allows a fast approval by CEN of existing ISO standards (UAP ballot - Unique Approval Procedure - YES/NO without comment).

Standards approved by CEN must be published by national committees and national standards of the same scope withdrawn. In the UK they will be dual numbered BS EN or triple numbered BS EN ISO, if accepted as an ISO standard as well and similarly numbered, NF EN ISO and DIN EN ISO in France and Germany, respectively. Sometimes, the test will also be numbered within the main BSI Plastic series of test methods, BS 2782.

Other bodies are developing standards in different application areas such as AECMA for EN Aerospace – often with input from Airbus Industries Test Methods (AITM) and ASTM principally in the USA. ASTM has had a specialised group, D-30, for many years and made strong input into international standardisation. ASTM is developing with ISO a similar “Vienna” relationship as exists for CEN so that ASTM standards can be fast-tracked into ISO standards. JIS also makes significant inputs particularly on carbon-fibre test methods.

Table 1: International and National Standards Organisations

ISO	International Standards Organisations
CEN	Comité Européen de Normalisation
AFNOR	Association Française de Normalisation
ANSI	American National Standards Institute
DIN	Deutsches Institut für Normung
AECMA	Aerospace Series of CEN standards prepared by European Aerospace Trade Federation
ASTM	American Society for Testing and Materials
BSI	British Standards Institution
JIS	Japanese Industrial Standards

ISO documents are progressed through CD (committee draft – 3 months), DIS (Draft International Standard – 5 months) and FDIS (Formal DIS – 2 months) ballots within the ISO process, with a target development time of 44 months. The CD is the main stage for technical comment. Well written NPL drafted test methods, complete with precision data (repeatability and reproducibility) from experimental round-robin exercises, enable rapid progress to be made including missing the FDIS ballot through 100% approval at the DIS ballot. Within CEN, the prEN ballot is the main public enquiry stage.

4. MATERIALS APPROVAL INFRASTRUCTURE

In this Section, the materials test methods and specification standards infrastructure produced principally by international standardisation bodies is reviewed. The adoption of this infrastructure in product standardisation is reviewed in later sections of the report, principally from the material supply, certification and validation viewpoints.

4.1 MATERIAL SPECIFICATION AND TEST METHODS

The supply of the constituent materials is covered by a fairly complete sets of ISO standards for fibres and resins covering both testing and specification requirements, which will be adopted and extended for the EN General series. In addition, the European Aerospace (AECMA) series has adopted all the ISO carbon fibre test methods: a useful step towards harmonisation. However, AECMA is developing its version of the ISO standard on carbon fibre designation.

ISO is currently developing harmonised test methods (eg twist, linear density) for all the textile size fibres in preference to the historical development of first glass-fibre, then carbon-fibre and the anticipated aramid-fibres methods. Material non-specific test methods will aid both the generation of comparable data and the introduction of new materials if a suitable test method is available immediately without any gestation period.

There is a full set of test methods and specifications for the resin matrices mainly due to their use as unreinforced plastics. These standards are principally in the ISO series and are included in the >150 standards that are being adopted as CEN standards by the UAP ballot.

4.2 COUPON LEVEL DATA

At the next higher level of laminates testing, it is necessary to undertake coupon tests cut from the product or from a test panel. An existing standard ISO 1268 has been revised to cover the manufacture of test plates for all process routes for long-fibre composites (see Table 2), supported by existing ISO standards (i.e. ISO 293-295) for short fibre composites.

Table 2: Parts of (EN) ISO 1268 for test plate manufacture

No.	Title
1	General principles
2	Contact and spray-up moulding
3	Wet compression moulding
4	Moulding of preimpregnates
5	Filament moulding
6	Pultrusion moulding
7	Resin transfer moulding
8	Moulding of SMC/BMC
9	Moulding of GMT/STC
10	Injection moulding of BMC/DMC

Part 4 on pre-pregs, drafted by NPL, references a designation code for ply orientations that can be generally applied and is the only part that includes precision data. The data is based on the

results of a NPL round-robin that showed participants could prepare panels to a consistent and high standard [2]. An important issue not yet covered satisfactorily is the machining of composites and specimen preparation. Some minimal instructions are included in the test methods described in Section 4.3 as a common annex. Some further information is given in the ASTM standard (D 5687) for test panel manufacture. It is hoped that the recent NPL Measurement Good Practice Guide No. 38 [5] on “*Machining of Composites and Specimen Preparation*” can provide the basis of a future standard equivalent to ISO 2818 - “*Machining of Plastics*”. The traceability of the inspection of the test panel by ultrasonic C-scanning inspection techniques will be greatly improved through EN standards based on the procedures developed in a prior NPL/Quinetiq research programme [6].

4.3 LAMINATE TEST METHODS

Laminate test methods have been established for all composites. The work conducted by NPL over the last few years led to the publication of six standards in the period 1997 to 1999. These six standards, shown in Table 3, provide the basic coupon tests used for design (in-plane tension, shear and compression) and QA (ILSS, flexure). These tests have been heavily harmonised with ASTM and one (i.e BS EN ISO 14129) is based on the equivalent ASTM test. The drafting took account of existing ISO, national standards, the EN Aerospace series and CRAG recommendations [7]. Where the new standard is based on an existing ISO standard, they will replace that standard, together with national standards of the same scope.

Table 3: Harmonised BS EN ISO Test Methods

Property	International Standard	ASTM/CRAG Methods
Tension- “Isotropic” (nominally)	BS EN ISO 527-4	D 3930/CRAG 300
Tension- Unidirectional (anisotropic)	BS EN ISO 527-5	D 3930/CRAG 300
Flexure	BS EN ISO 14125	D 695/ CRAG 200
Compression	BS EN ISO 14126	D 3410/CRAG 400
Shear - $\pm 45^\circ$ Tension	BS EN ISO 14129	D 3815/CRAG 101
Shear - interlaminar by short beam flexure	BS EN ISO 14130	D 2344/CRAG 100

Other coupon test methods recently published are:

- fatigue (ISO 13003),
- in-plane shear modulus by plate twist (ISO 15310) and
- Mode I delamination fracture toughness (ISO 15024).

It is noted that other test method covering, for instance, the thermal and chemical response of the composite material and/or the structure are required. These are dealt with as they arise for individual products, but it should be noted that more generic methods are being developed in current NPL projects. For example, NPL is the project lead on ISO 6721-11 on measurement of T_g (glass transition) using dynamic mechanical analysis (DMA) methods. Work on a Mode II fracture toughness test is expected shortly, following a VAMAS (Versailles Project on Advanced Materials and Standards) TWA5 round-robin programme aimed at identifying the preferred method for standardisation. VAMAS is a G7/G8 project for pre-normalisation activities to attain early harmonisation of test methods, databases, etc., and TWA 5 covers Polymer Composites activities.

4.4 MATERIAL DATABASE STANDARDS

These laminate test methods are highlighted in the new database standard aimed initially at a minimal set of properties for technical data sheets. The standard ISO 10350-2, drafted at NPL, has been prepared as a composite materials version of the plastics database standard that has been extremely successful in encouraging the use of ISO test methods to achieve comparable data. If there are options in the reference test methods, then a particular version will be identified by the database standard. However, the “default” method will be increasingly identified in the test methods itself as to support the Single Market needs in trade or liability matters there is a need to reduce unnecessary confusion and complexity in underpinning standards. This database standard may provide a starting point for an extended database covering design data.

NPL has started a new project to develop a standard qualification plan (SQP) that is aimed at considerably reducing the cost of qualifying new materials by allowing standard data to be provided by the supplier suitable for materials selection and preliminary design. It is widely recognised that major costs are involved in bringing a new material to the market. For example, it cost one supplier 15 times the cost of a single qualification for undertaking it ten times to (slightly?) different user specifications. Both supplier and the ten users incurred the additional costs. The SQP will also minimise product design costs through the immediate availability of the data, rather than awaiting the completion of multiple bilateral qualification programmes between a supplier and each of its customers independently.

4.5 STRUCTURAL ELEMENT TEST METHODS

At the next level of validation there is concern to understand and measure the effect of stress concentrations. The pin-bearing test is one of three methods using common a geometry being balloted as ISO NWI (New Work Items) following a BSI submission based on NPL prepared drafts and NPL organised round-robin (RR) experiments for precision data. The other two methods are open/filled hole compression (OHC) and open-hole tension (OHT). In every case, a 6 mm diameter hole in a 36 mm wide coupon is used, or an English unit equivalent based on 0.25” diameter hole and a 1.5” wide coupon (i.e. a 1:6 ratio). Although the pin-bearing test is used for aerospace material, there is a need for this information for all types of composites, such as GRP roofing sheets. In fact, the first mandatory use of the pin-bearing test will be in the specification standard for pultruded profiles (i.e. prEN 13706) in recognition of the frequent use of bolting for assembly structures from these profiles (c.f. alternative of bonding).

4.6 SUB-COMPONENT SPECIFICATION

At the sub-component level specification, standards are being developed in CEN for pultruded profiles, prEN 13706 with NPL project leadership and convenorship. These products are one of the few cases where composites are available in a final cured form for immediate use, normally as bolted or bonded assemblies

The technical specification in Part 3 of the standard required to show compliance uses property data obtained from the standard laminate test methods (BS EN ISO's) discussed in Section 4.2. In addition, the materials modulus forming the designation code (eg E 23) is obtained from a long beam test on a full section of the pultrusion (see Annex D of EN13706). An alternative test

requiring repeat tests at different loading spans in flexure and torsion has also been drafted to give the full section flexure, shear and torsion properties (see Annex G of EN13706). In addition, recommended tests are given for all other material properties including further mechanical properties (eg impact), electrical, thermal, environmental and fire properties. These methods are normally in the ISO or EN series. The best compilation of these methods is in EN 13706 or ISO 10350-2.

Other specification standards relate to moulding compounds, such as SMC (sheet moulding compound) and GMT (glass mat thermoplastic) that require compaction, flow and, for thermosets cure, before being finally formed.

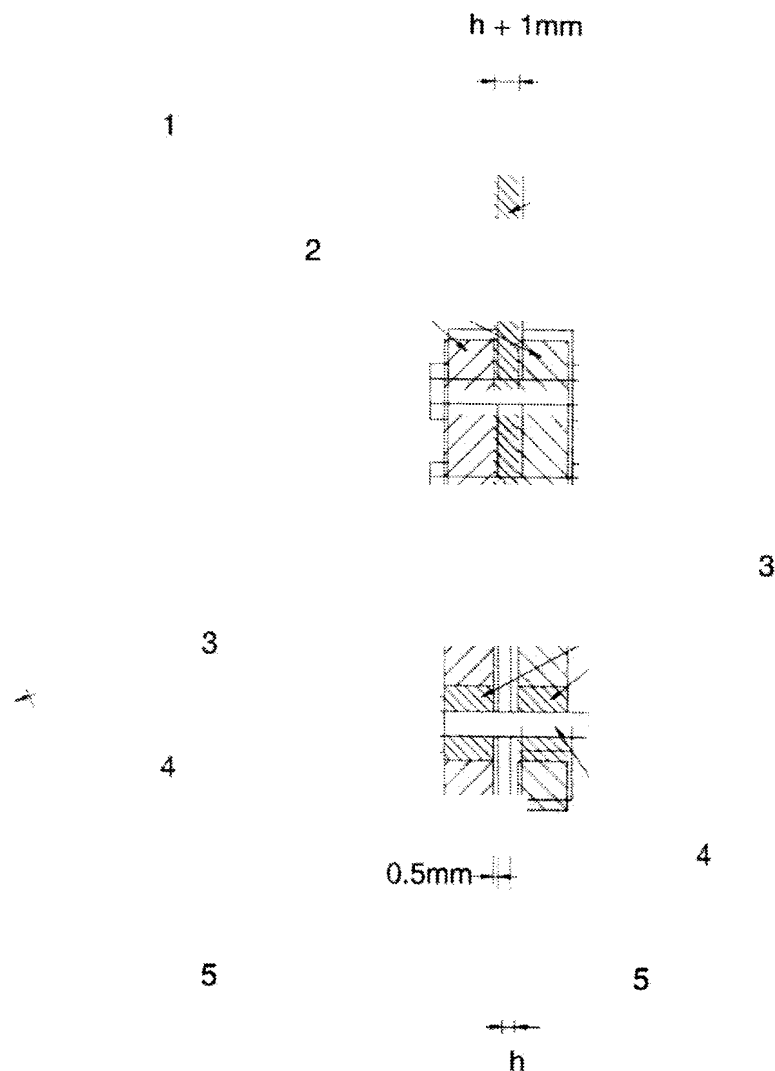


Figure 2 Pin Bearing Specimen and Test Rig (*nb plain pin, no torque applied*)

5. PRODUCT APPROVAL - CODES AND STANDARDS

Several bodies are involved in developing product specification and approvals. Within Europe the main source will be from CEN in support of European Directives. There are several committees working on product standardisation, which may be for a composites product only (e.g. GRP pressure vessels - CEN/TC 210, piping – ISO TC 138/ CEN TC 155) with equivalent standards covering use of other materials in the same application, or an area where a single standard covers all competing materials (e.g. access engineering (i.e. ladders, walkways and handrails) - CEN/TC 114). In addition, a standard for off-shore GRP piping has been prepared under ISO/TC67 based on the guidance document [8] developed by the UK Offshore Operators Association. Harmonisation, or complimentary action, of CEN and ISO work in the general area of GRP piping is obviously desirable. In some specialised areas, such as civil aircraft and marine, then other bodies have the regulatory responsibility such as the Civil Aircraft Authority (CAA) and Lloyd's Register (LR), respectively.

Product standards, as for access engineering, open to all materials that can meet the technical requirements (e.g. maximum acceptable deflections under prescribed loads) are preferred. These performance base standards are preferred to the more prescriptive standards that either prevent completely the use of composites or inhibit the design freedom necessary for the most cost effective solution. It is important in these cases, that the standards do not include any requirement that prevents unnecessarily a composite material based design solution.

Progress is being made with several documents being balloted. However, as the developments in the test methods and the product standards are often concurrent there are often delays in implementing the new test methods in the product standards unless there is good liaison between the responsible committees. Equally, it is of interest in encouraging the of greater use composite materials by engineers that there is consistency in the design approach used (eg the choice of performance or prescriptive based approaches). In this Section the following standards and codes are reviewed:

- GRP pressure vessels –prEN 13121*
- GRP piping offshore – ISO/DIS 14692*
- GRP Water piping – BS 7159/6464
- GRP Water tanks – BS EN 13280*
- Lloyd's Register:- Special service Craft*
- DNV - High Speed and Light Craft*
- Commercial Aircraft Certification
- Military Handbook 17
- UK Defence standard 0933
- Access Engineering – prEN14122
- FRP Lighting Columns – prEN 40-7
- GRP Rockbolts – BS 7861
- Inspection Chambers – BS 7158
- EUROCOMP Design Guide*
- Wrapped Gas Cylinders – prEN 12445/prEN12447/ISO 11119 (3 parts)

A more comprehensive list of composite product standards is given in Appendix B.

In the following Section, several product standards and approval requirements (asterisked) are examined for implementation of the materials standards infrastructure and the treatment of several inter-related material/design issues.

5. GRP PRESSURE VESSELS - prEN 13121

(a) Background and scope

The British Standard for GRP pressure vessels, BS 4994, was a leading document in 1973 as one of the first “design” standards for a reinforced plastics/composites product. BS 4994 was basically a prescriptive document that set down minimum requirements representative of current practice at that time. The document was revised in 1987 when several parts were extended, but the basic structure and approach remained unaltered. CEN Technical Committee (TC) 210 has been responsible for developing an European standard for these products, prEN 13121, with input from, amongst others, the existing UK (i.e. BS 4994) and German documents. The work on the new EN standard has become quite protracted, with completion not expected now until September 2003. Part of the delay has been due to the delayed availability of the relevant EC Pressure Equipment Directive (97/23/EC).

The standard is divided into 4 parts:

- Part 1 – Raw materials - acceptance and usage conditions,
- Part 2 – Chemical resistance,
- Part 3 – Design, calculation and workmanship,
- Part 4 – Delivery, installation and maintenance.

Part 1 has comprehensive references to ISO test methods and specifications for the constituent materials. Part 2 recognises the major need to quantify the chemical resistance in view of the planned use of many of these pressure vessels. Chemical resistance can be obtained either through a welded lining thermoplastic sheets or resin rich glass-fibre/resins.

The design of GRP pressure vessels is comprehensively dealt with in Part 3, covering 240 pages. The main development from BS 4994 is the inclusion of a design procedure based on test results and performance requirements, rather than the prescriptive requirements in the BS standard. It is proposed to increase the critical maximum applied strain from 0.2% to 0.25%, and to implement for the first time the use of a strain limit of 0.4% for short-term upset conditions. Finally, Part 4 covers handling, installation and repair issues in more detail than most other documents.

Two related standards cover underground storage of petroleum (prEN 976 Parts 1-4) and filament wound pressure vessels (prEN 13923). The latter, in particular, uses extensive cross-references to prEN 13121. All these documents are under the control of CEN TC 210.

The detailed aspects of the 4 parts are considered in Section 6, where this standard is used as the reference document, for comparison with other documentation. This reference has been adopted partly as the prior document, BS 4994, was a leading standard and well-known in the UK, but, unfortunately, there is uncertainty over the content due to its protracted ten years development.

(b) Design approach and verification

The EN version, builds on the purely prescriptive approach of BS 4994, by proposing an alternative performance based approach. This can only be used if sufficient knowledge and competence is demonstrated. Several aspects are similar for the three design approaches as given in Table 4.

Table 4: Summary of design methods and design factors proposed in prEN 13121

	Permissible Design Approach		
	Advanced Design	Basic Design	
		either	or
Derivation of mechanical properties (test)	User defined material properties may be used based on rigorous testing (15 samples minimum).	Minimum specified properties as defined in the standard supported by limited testing (5 samples).	
Historical test data	Historical data not acceptable without support from a limited production test programme.	Historical data acceptable if similar laminate design has been produced within 12 months of the last test.	Historical data acceptable if similar laminate design has been produced within 18 months of the last test.
Design factor related to method of manufacture	A ₁ = 1.0 (vessel cut-out) A ₁ = 1.1 (sample laminate) (For mechanical properties) A ₁ = 1.1 when using historical test data and verifying tests.	A ₁ = 1.2 (vessel cut-out) A ₁ = 1.3 (sample laminate) A ₁ = 1.5 (if no additional testing is carried out and historical test data is used to support the design properties).	A ₁ = 2.0
Minimum design factor	K (Minimum) = 4 K (Minimum) = 5 if A ₅ is not determined by a suitable test programme	K (Minimum) = 6	K (Minimum) = 8

In addition, there have been modifications to the “K” partial factors, see Table 5, used in the original prescriptive approach. The K factor used is the multiple of these design factors (A₁ to A_x) and the overall factor of safety (S), which is taken as 2,

$$K = S \times A_1 \times A_2 \times A_3 \times A_4 \times A_5,$$

subject to the minimum values given in Table 4.

Guidance is given on derivation of actual values within these ranges. The value of A₃ is given by the following equation,

$$A_3 = 1 + 0.4 (T_s - 20/\text{HDT} - 4)$$

where T_s is the design temperature and HDT is the heat deflection temperature (now referred to as the Deflection Temperature Under Load - DTUL), both in degrees C. This equation highlights the importance of correctly measuring the HDT temperature, which is likely to increase if conducted on the composite using the newly published version of ISO 75-3 [9].

The A₅ factor is related to the mass of reinforcement, the fibre format and the resin type. Both A₄ and A₅ are obtained from calibration curves, as shown later.

Table 5 Design part factors proposed in prEN 13121

Design Factors	Min.	Max.
Effect of manufacturing and quality control level, A_1	1.00	2.00
Effect of vessel contents and environment, A_2	1.10	1.80
Effect of design temperature and resin HDT, A_3	1.00	1.40
Effect of cyclic loading, A_4	1.20	2.00
Effect of long term behaviour, A_5	1.25	2.00

In Part 3, minimum laminate properties are given, which are used to form the **basic design method**, whereas if extended mechanical test data are established, **the advanced design method** can be used. The CEN document, in common with BS 4994, uses a unit strength per mass of glass-fibre (N/mm per kg/m² glass-fibre) approach rather than a stress (N/mm²). This is based on the assumption that the load carrying capacity is controlled by the weight of reinforcement present, and that the amount of resin, while above the minimum for undertaking the fibre protection, stress transfer etc. roles, will vary the calculated maximum stress (i.e. load per unit area) but will not influence the load carrying capacity. This approach mirrors the production process that specifies the amount of fibre, whether as dry chopped strand mat or fabric layers.

The other major design input is the allowable design strain, which is equal for each type of resin to 10% of the resin tensile elongation to failure, and for each type of reinforcing material it is determined by the following equation:

$$e_{az} = u_z / (K X_2) \quad (3)$$

where u_z is the Ultimate Tensile Unit Strength (UTUS) and X_2 is the Unit Modulus from the given minimum value or from test data. An allowable design unit loading (u_z) for each type z of reinforcing material is equal to $e_d \times X_z$. These design strains are limited by the maximum value allowed, which is proposed to be of 0.25% (cf 0.2% in BS 4994), with an allowance for overloads due to short term emergencies (i.e. lasting less than 30 mins.) of 0.4% if using resins with elongation to failure greater than 2%.

The design process is based on the evaluation of both internal loads (e.g. pressure, static head, bending moments) and external factors (eg seismic loads, snow and wind loads). The load analysis is checked against the allowable strain levels. Detailed design guidance is given on:-

- conical, dished, flat, ellipsoidal and domed ends,
- knuckle radii, lugs, fixing points, saddle supports,
- seam joints, buckling failures,
- integral branch pipes and bolted flanges,
- panel (square, circular) design, including with stiffeners,

The panel analysis is similar to the procedures available in the NPL CoDA PC Windows software for preliminary design. Panel deflection is limited to 1.5 times the panel thickness. Verification tests on prototype design includes:

- measurement of local strains when vessel pressurised,
- determination of fatigue strength,
- determination of maximum failure load (check on safety factor) and failure mode.

GRP PIPING

Offshore – ISO/DIS 14692

(a) Background and scope

A working group under ISO 67 was formed initially on GRP piping for off-shore use has seen the opportunity to increase the coverage, eventually, to on-shore, chemical and marine uses. The standard, ISO/DIS 14692, which will reach the last formal ballot in 2002 draws heavily from the document [6] produced by UKOOA, the UK Off-shore Oil Operators Association. This document was well accepted and had been the basis of company documents, in particular for Shell where the scope was first extended to cover on-shore and chemical uses. The working group as well as having worldwide representations, enabled contact with the ASTM committee dealing with GRP marine piping. The standard is likely to have a long term significance for the future acceptance of GRP piping.

The standard has been prepared in 4 parts, totalling 240 pages, that show some agreement with the structure of prEN 13121. The parts are:

- Part 1: Applications and materials – mainly covers scope, terminology and material limits,
- Part 2: Qualification and manufacture – mainly covers test and qualification requirements,
- Part 3: System design – covers design procedures,
- Part 4: Fabrication, installation and operation – covers aspects relevant to meeting specified use of pipework system.

Pipes with wall thicknesses up to $0.1 \times$ pipe diameter are within the scope of the standard, with a minimum wall thickness of 3 mm for pipe internal diameters less than 100 mm and greater than $0.75 \times$ pipe internal diameter for larger sizes.

(b) Design approach and verification

Several aspects are similar to the approaches used in prEN 13121, with variations related to the product type and application. For example, jet fires are referenced as related to off-shore use; erosion, cavitation and water hammer related to fluid flow through the pipework; and aspects such as jointing options, acceptable free span lengths and system stresses related to the pipework system. For example, acceptable unsupported spans vary from $80 \times$ diameter for 25 mm diameter pipes to $10 \times$ diameter for 600 mm diameter pipes (equivalent to lesser of 0.5% of span or 12.5 mm deflection).

As for pressure vessels, part factors (or partial/safety) are used to allow for temperature (A_1), chemical resistance (A_2) and cyclic service (A_3) to give the factored qualified pressure (p_{qt}), where the qualified pressure (p_q) is based on a 20 year life. It should be noted that although amongst others, the determination of chemical resistance via Part 2 of prEN 13121 is referenced, a formal system is not established for determining A_2 .

Finally, the manufacturer's pressure rating (p_{NPR}) is given by:

$$(p_{NPR}) = f_2 \times f_3 \times p_q \quad (4)$$

where f_2 load factor based on system loading characteristics and f_3 allows for the limited axial load capacity of these pipes (eg effect of bending stresses/expansion differentials etc.).

5.2.2 Water piping – BS 7159

The GRP piping standard, BS 7159, is a document of similar age and coverage to BS 4994 but, places increased emphasis on filament winding as a more frequently used process route. Being used for the same application areas as the pressure vessels, similar approaches are taken to the design piping. This standard, and others such as BS 5480 will be replaced by international standards generated through ISO TC 138 and CEN TC 155. Relevant standards include:

BS EN 1115 Plastics piping systems for underground drainage and sewage under pressure. Glass-reinforced thermosetting plastics (GRP) pipes based on unsaturated polyester resins (UP).

BS EN 1636 (6 parts) Plastics piping systems for non-pressure drainage and sewage under pressure. Glass-reinforced thermosetting plastics (GRP) pipes based on unsaturated polyester resins (UP).

prEN 1796 (6 parts) Plastics piping systems for water supply with or without pressure. Glass-reinforced thermosetting plastics (GRP) pipes based on unsaturated polyester resins (UP) (see also ISO/DIS 10639).

The ability to develop these product standards relies on available test methods as listed below for pipes and pipe sections (c.f. coupon tests in Section 4). These tests are listed in Table 6:

Table 6: Test methods for “Plastics piping systems – glass reinforced thermosetting plastics (GRP) pipes and fittings”

ISO 7511 – test methods to prove the leaktightness of the wall under short-term internal pressure (see also BS EN 1229).
ISO 7684 – determination of the creep factor under dry conditions (see also BS EN 761).
ISO 7685 – determination of initial specific ring stiffness (see also BS EN 1228)
ISO/DIS 8483 – test methods to prove the design of bolted flange joints (see also BS EN 1450).
ISO/DIS 8513 – determination of initial longitudinal tensile properties (see also BS EN 1393).
ISO 8521 – determination of the apparent initial circumferential tensile strength (see also BS EN 1394).
ISO/DIS 8533 – test methods to prove the design of cemented or wrapped joints.
ISO/DIS 8639 – test methods for leaktightness and resistance to damage of flexible and reduced-articulation joints (see also BS EN 1119).
ISO 10466 – test method to prove the resistance to initial ring deflection (see also BS EN 1226).
ISO 10928 – methods for regression analysis and their use (see also BS EN 750).
ISO 10952 – determination of the resistance to chemical attack from the inside of a section in a deflected condition (see also BS EN 1120).
ISO/DIS 10468 – determination of the long-term specific creep stiffness under wet conditions and calculation of the wet creep factor (see also BS EN 1225).
ISO/DIS 10471 – determination of the long-term ultimate bending strain and the long-term ultimate relative ring deflection under wet conditions.
ISO/DIS 14828 – determination of the long-term specific ring relaxation stiffness under wet conditioned and calculation of the wet relaxation factor.
BS EN 1638 - test method for the effect of cyclic internal pressure.
BS EN 1862 – determination of the relative flexural creep following exposure to a chemical environment.

There is obviously a need to ensure that the work in CEN and ISO on GRP piping, including offshore piping, is well coordinated and, at least, aware of the work content in each case to avoid duplication and unnecessarily different procedures. These standards are covered in Section 6.

5.3 GRP WATER TANKS – BS EN 13280 (similar to BS 7491)

(a) Background and scope

CEN standard, EN 13280 published in 2000 covers one-piece (500 litre to 100,000 litre) and sectional tanks (500 litre and larger) support the EU Directive 80/778/EEC. The standard has been developed by a separate working group within TC 210, which is also responsible for prEN13121. A major input into the standard came from BS 7491-3 through the convenor, from a UK SME. Specific aspects due to the application are the measurement opacity to ISO 3474 and meeting the Drinking Water Directive 80/778/EEC as tanks are used for potable water applications.

(b) Design approach and verification

The design approach is controlled by final product tests.. Both leakage test and a pressure test are required. The pressure test is undertaken on an individual panel supported at its periphery and loaded by a pressure load through a water bag. Load is applied at 5 kN/m² per min. to a maximum load equal to 6 x service load. The service load is equal to the tank being filled to within 250 mm of the top edge. No rupture should be observed. Other product tests include:

- deformation of strengthening ribs or flanges (Annex B/BS EN 13280 - less than 10 mm or 1% of the length),
- impact of cover (Annex F/BS EN 13280 – drop weight test with no rupture),
- rigidity of cover (Annex J/BS EN 13280 – 2.5kg over 200 mm by 200 mm for 7 days, report depression of cover),

Conditions are given for when re-“type testing” is required (change in production or raw materials, greater than 10% change (increase or decrease) in wall thickness, length dimensions or height change greater than 300 mm), or if there is a change in depth of use for the panel.

5.4 MARINE AND OFFSHORE.

5.4.1 Lloyd’s Register (LR) - Rules and Regulations for Classification of Special Service Craft

(a) Background and scope

Due to the long history of GRP for marine applications, the background regulations and requirements are well established. The proposed design must be approved by a LR Surveyor, who can accept alternatives and modifications when the technical arguments are sufficiently persuasive. The surveyor also will monitor build, and require demonstrated test data etc., in a manner similar to local building inspector.

Several parts cover composites as follows:

- Volume 2 Part 2 Section 14 – Plastics Materials
- Volume 2 Part 8
- Volume 6 Part 8 Hull Construction in Composite
- Version 1 Design Details
- Version 1 Calculations Procedures for Composite Construction

In addition, the other parts have general applicability across all construction materials. Updates are published in Notices, which should be checked carefully. Software is available from Lloyd's Register (LR) that covers many of the requirements and calculations. A separate section deals with plain or reinforced plastic pipes.

The control of composite materials through specified test methods and property level requirements is covered in Volume 2/Part 2/Section 14. Testing is carried out in the initial approval stages for both products and individual production sites. Testing can also be required during production and re-testing is required if two successive specimens fail the test in question. Where there are no natural cut-outs for testing it may be necessary to manufacture a test plate at the same time.

Tests are prescribed for the unreinforced thermoset resin covering tensile (EN ISO 3268), compressive (EN ISO 604), flexural (EN ISO 178), deflection temperature under load (EN ISO 75) and water absorption (EN ISO 62). (n.b. ISO 527 Part 1 and 2 now replace EN ISO 3268 for tension). Tests for density, gel time, viscosity and appearance are required for all types of thermosets with additional chemical (eg volatiles, epoxide content) properties depending on the system. (eg polyesters/vinylesters, epoxides and phenolics). EN ISO test methods are similarly quoted for determining the properties of the reinforced laminate. Properties required at room temperature include tension, compression, flexural, interlaminar shear, fibre content and water absorption. In addition, for one direction only, the tensile modulus and the flexural strength are determined after immersion at 35°C for 28 days. Minimum requirements are given for the gel-coat resin, the (structural) laminating resin and laminates (30% by weight CSM).

(b) Design approach and verification

In Volume 6 of the regulations, both material properties and design issues are covered. Material properties used for scantling (rib) design, the lesser of either the 90% value of the mean first ply failure stress, or the mean value minus two standard deviations based on a set of five specimens (i.e. standard ISO conditions). In the absence of suitable test data, equations based on glass-fibre content for different formats are given. These are similar to the equations used in CoDA software [3].

Also covered are recommendations for bolting, including with adhesive bonding that allows larger pitch distances between bolts. The diameter of a fastening should be greater than the thickness of the thinner component being joined, with a minimum of 6 mm. Bolt holes should be carefully drilled with a tolerance of $\pm 2\%$ of the bolt diameter. Finally, in this volume detailed calculations are given for sizing panels and stiffeners for both solid and sandwich panels. The specifications are fairly prescriptive but as for other aspects, alternatives can be offered, providing sufficient evidence or justification is given, to the LR Surveyor.

There are recommendations on overlap distances and thickening requirement where stiffeners or bulkheads are attached to the main hull. These guidelines are taken further in the section of Design Detail, which gives examples of improved detailing. The software available from Lloyd's allows any design of stiffener and ply placement to be defined. Usefully, the software can undertake "back-calculations" to determine, for example, the span spacing for stiffeners to meet a particular deflection criteria.

5.4.2 Det Norske Veritas (DNV) on High Speed and Light Craft

(a) Background and scope

Det Norske Veritas (Norway) has extensive experience of GRP applications in the marine and off-shore industries that has been summarised in their rules in Part 3 Section 4 entitled "Hull Structural Design, Fibre Composites and Sandwich Constructions". The materials used in construction must pass DNV Type Approval Programmes that cover:

- adhesives
- polyester resin, vinylester resin, gelcoat and topcoat
- glass-fibre reinforcements
- sandwich core materials
- aramid fibres
- sandwich adhesives.

Other parts of the Part 3/Section4 document cover:

- structural principles
- sandwich panels
- manufacturing
- stiffened single skin construction
- web frames and girder systems.

There are several other requirements that reflect the application:

hulls shall use Grade 1 polyester for single-skin of outer sandwich skins,
outer reinforcement to be at least 450g/m^2 of CSM containing as little water soluble bonding components as possible, alternatively 300g/m^2 plus surface veil,
inside of tanks to be composed of at least 600g/m^2 CSM with Grade 1 polyester, also for other hull areas continuously exposed to water (eg bilges),
areas exposed to water shall have an efficient surface coating (eg. topcoat, gelcoat or epoxy based paint),
minimum materials testing should include tensile tests of skin laminates of hull panel (ISO 3268), shear testing of core with skin attached (ISO 1922/ASTM C 273) and tensile testing of flange laminates,
verification that the bond strength is greater than the core shear strength by 4-point sandwich test (ASTM C 393),
additional testing needed if fatigue or environmental effects are not known for material combinations or lay-ups,

(b) Design approach and verification

The calculation of stresses and deflections is allowed either by “using the full stiffness and strength properties of the laminate in all directions” or by a simplified method. The simplified methods may be employed if:

- the principle directions of the laminate reinforcement is parallel to the panel edges
- the difference in elastic modulus in the two principal direction is less than 20%.
- for sandwich laminates, the skins are thin.

Direct calculations use the laminate analysis based on the Tsai-Wu composite strength criteria, as adopted in CoDA [3], and must consider all the loads on the panel. The value of r , the failure strength ratio, is given for both first ply failure (1.5) and last ply failure (3.3). These values increase to 2.25 and 4.5 respectively for structures under long-term static loads.

The design requirements for single skin construction are as follows:

- skins must contain at least 40% continuous fibre,
- formula and standard values given for minimum thickness (3.5 to 9 depending on component) based on load uniformly distributed,
- the thickness must also meet criteria associated with bending and in-plane loads, based on two factors given in by a calibration curves as a function of aspect ratio,
- limit set on maximum combined bending and membrane stresses are $0.3 \times$ ultimate tensile strength, except reduced to 0.2 for long term loads, and deflections are limited to 0.9 - 1.0 times thickness but reduced again to $0.5 \times$ thickness for long term loads which limits the amount of membrane stresses present.

These analyses are similar in concept to those used in the plate and beam modules of CoDA.

Where stiffeners are used minimum values are given for the section modulus depending on the type of loading and degree of end constraint. The values are also dependent on a stress of $0.25 \times$ ultimate tensile stress that is reduced to 0.15 times for structures exposed to long term loads.

5.5 COMMERCIAL AIRCRAFT CERTIFICATION

(a) Background and scope

Several countries support Joint Accreditation Regulations (JARs) with additional advice for composites often based on FAA drafted Advisory Circulars that are circulated as ACJs. So that within the CAA rules on certification of airworthiness of aeroplanes, such as JAR 25 for large aircraft, the document ACJ 25.063 “Composite Aircraft Structure (Acceptable Means of Compliance) sets forth “acceptable means but not the only means” of showing compliance with the provisions of JAR 25 for certification of composite aircraft structures. The main point made is that all the factors that must be considered will depend on the individual case.

The material design database shall include the effect of environmental degradation on the static strength, fatigue and stiffness properties established by test (e.g. accelerated environmental tests) or applicable service data. The effects of moisture and temperature cycling should be evaluated.

The material system design values or allowables should be established on the laminate level by test or by test of the laminae in conjunction with a test-validated analytical method. This last approach is similar to that used in validation of the CoDA laminate module [4].

Design values may be established, which include the effects of appropriate design features (holes, joints), such as in recent NPL structural test methods and design procedures developments. It is suggested that impact damage is covered by limiting the design strain level.

(b) Design approach and verification

The “proof of structure” for static loads is based principally on testing components but allows use of prior experience and data to reduce the testing programme. Some particular aspects are:

If the critical loads are associated with repeated loading or environmental conditioning, the structure should either be tested after prior appropriate conditioning, or by the relationship under the applied conditions determined through coupon/element/sub-component test data, which are used either in the initial analysis or are applied to the static test load.

For the important effect of where the material and processing variability of the composite structure is higher than the current metallic structure, the difference should be considered in the static strength substantiation by,

- deriving proper allowables or design values for use in the analysis, and the analysis of the results of supporting tests, or
- accounting for I in the state test when static proof of structure is accomplished by component test.

Although data on composite variability is frequently requested, similar data are not always available for metals. This is not surprising for ductile materials but more surprising for high strength alloys.

For impact damage, it should be shown that below the threshold of damage detection (related to the non-destructive testing (NDT) method used) it will not reduce the strength below the ultimate load capability. It can be shown by analysis supported by test evidence; or by tests at the coupon, element or sub-component level.

The similar demonstration for fatigue and damage tolerance is as expected a large commitment, particular if no prior data or application exists. A warning is included that when selecting damage tolerance or safe life approach, that attention should be given to geometry, inspectability, good design practice and the type of damage/degradation under consideration.

Other aspects high lighted are:

- flutter
- impact (crash) dynamics
- flammability
- lighting protection
- protection of structure
- quality control
- production specifications
- inspection and maintenance
- substantiation of repair.

In support of two aspects are, an Advisory Circular (AC 145-6) available from the FAA on “Repair Stations for Composite and Bonded Aircraft Structure”, which include a discussion of

NDT techniques, and a further AC (21-26) on quality control for the manufacture of composite structures. The latter document includes control of the curing and secondary bonding processes.

Most of the documented numbers refer to the flight performance or flight loads, with virtually no direct material requirements, for materials data, test method or minimum property levels. The design approach relies on satisfying the CAA requirements through direct “negotiation”, so that the approach and validation used on each issue is demonstrated. Consequently, this document is not analysed further in Section 6.

5.6 DEFENCE DOCUMENTATION

5.6.1 Military Handbook 17 (USA)

(a) Background and scope

The Military Handbook (Mil. Hbk) series from the USA Department of Defence are well known and cover in Volume 17 reinforced plastics/composite materials of the high performance type, such as unidirectional, multidirectional aligned continuous and fabric reinforcements. The three volumes cover:

- Volume 1 - Guidelines for characterisation of structural materials
- Volume 2 - Materials Database
- Volume 3 - Material usage, design and analysis.

Volume 1 contains extensive information on material test methods at the fibre, matrix, preimpregnate and laminate levels and are based principally on ASTM test methods, which as noted earlier, are increasingly being harmonised with EN ISO standards. SACMA tests are also referenced but these are no longer maintained. They may be introduced now to ASTM via the Composites Fabricators Association. The test methods include ASTM versions of the structural element test methods drafted by NPL and compression-after-impact for damage tolerance. Test methods cover mechanical, electrical, thermal/physical and chemical properties. A large section covers the statistical methods that should be applied, including the generation of “A” and “B” basis design values (i.e. statistically derived design values). Guidance is given on screening techniques, effect of temperature, moisture etc.

Volume 2 contains a comprehensive database on laminates. The laminates were tested mainly more than ten years ago, but the data are valuable as specific grades are mentioned together with cure schedules used. The data mainly relates to mechanical properties. Properties are given at ambient and non-ambient temperatures, and after environmental conditioning.

(b) Design approach and verification

Volume 3 provides a complete dissertation on design aspects including effect of variability, production quality control, design and analysis (e.g. predicting composite material properties), structural reliability and supportability. The style is more of a text book with extensive useful information rather than a design guide or code as it is not product specific. Consequently, this document is not analysed further in Section 6

5.6.2 UK Defence Standard 0933

The equivalent, although narrower in scope, UK document Defence Standard 0933 is nominally under revision, but progress has stopped due to a lack of funds within the UK Ministry of Defence. The database in the current version is based on old style aerospace materials introduced typically 20 years ago. Due to the high cost of producing composite test data it is normally difficult to obtain qualification data funded either by customer and supplier liaisons, or in government funded projects until a considerable time later. This highlights the commercial value of comprehensive databases. In the discussions on the revision, it was made clear that data on current materials could be made available immediately by one material supplier with consequent benefit to the industry and potential end users. The harmonisation of the test methods [1] will support the open provision of data as it will benefit the supplier to provide the data freely to current and new users. The new research programme (ie MMS – (Measurement of Material Systems) supported by DTI at NPL is developing a standard qualification plan (SQP), which will also aid the availability of data. Many defence product specifications have recently been identified to be discontinued (e.g. DDT 5595). BSI is consulting industry on which of these drafts should be rewritten as BS standards as still required for specification purposes. This standard is not considered in Section 6 as product requirements are absent.

5.7 CONSTRUCTION

5.7.1 Access Engineering – EN 14122 (4 Parts).

(a) Background and scope

CEN TC 114 is producing a standard, prEN 14122 (4 parts) for access engineering (stairways, stepladders and guardrails) under a mandate related to the Safety of Machinery Directive (see EN 292 Safety of Machinery). There are detailed specifications for loads and dimensions of these systems. The standard allows any type of material to be used that meets the stated technical requirements. The materials used must be selected “to withstand the foreseeable conditions of use” and to meet the safety objectives of the standard, including resisting corrosion due to the surrounding atmosphere (climate, chemical agents and corrosive gases).

(b) Design approach and verification

Product design is controlled by product mechanical test requirements. For example, the deflection of a handrail at the stanchion and at the midpoint of a handrail span L (in metres) due to an applied horizontal load of $300N \times L$ must be less than 30 mm. There should be no permanent deflection after a 1 minute loading period. Similar tests exist for ladder stiles and rungs. Other aspects cover avoidance of galvanic action, thermal stresses, slippage and bad design features (sharp edges, water accumulation).

This type of performance standard is helpful to composites as allowing a free choice of suitable materials. The pultruded profiles for which a specification standard, prEN 13706, will shortly be published in Europe are successfully used in these applications, particularly in aggressive environments. This standard will not be considered in detail in Section 6.

FRP Lighting Columns – prEN 40-7

(a) Background and scope

This draft standard, prEN40-7, is part of a series dealing with different construction materials under CEN TC 50 (eg Part 4 concrete, Part 5 steel, Part 6 aluminium). These specifications relate to Parts 1 to 3 dealing with definitions, general requirements and dimensions, and design and verification. The scope covers columns up to 20 m tall for post-top lanterns and 18 m tall for side entry lanterns. As well as meeting the horizontal wind loads (EN40-3), it must also meet the performance in impact under the Essential Requirements No. 4 Safety in Use.

(b) Design approach and verification

Buckling equations are given as the application is based on thin walled circular or hexagonal section tubes. These calculations rely on values for the flexural modulus in the longitudinal and transverse direction of the column, the in-plane shear modulus and two principal Poisson's ratios. It is suggested that the later three values can be obtained from "industry standard laminate analysis" of the type initially popularised by Stephen Tsai in the USA. This gives rise to two concerns, one is the lack of a definite reference and the second is the applicability of these analyses, which are normally related only to fully aligned systems. The analysis use in the NPL CoDA product would be more appropriate as it deals with non-homogenous systems (i.e. more than one reinforcement type).

There are similar concerns over using EN ISO 14129 test methods for shear strength as it only applies to 0°/90° cross-ply or square balanced fabrics tested at $\pm 45^\circ$. The design equations appear similar to those developed by NPL for the Ministry of Transport several years ago for this application. For the prediction of the torsional buckling strength an additional factor to allow for the effect of cut-outs, for access doors, must be justified by adequate (undefined) testing. An Annex Z is included indicating the clause dealing with essential requirements of the EU Construction Products Directives (89/106). This covers horizontal (wind) loading, impact performance and durability, together with the use of these lighting columns in circulation areas. CE marking for product conformity is also covered in this annex.

The verification is according to the design procedures given in Parts 2 and 3 of the standard with modification due to the anisotropy of the composite properties, given by equations in Part 7. There is some concern that the correct properties are used. For example the torsional strength is related to the interlaminar shear strength, with no test method quoted, rather than the in-plane shear strength for which a test methods is given. This standard will not be covered in Section 6.

GRP Rockbolts – BS 7861

(a) Background and scope

This standard contains requirement and test methods for both steel and GRP rockbolts used as strata reinforcement in coal mines. It covers dimensional, material and performance requirements, but not installation. GRP rockbolts must have a minimum diameter of 21.5 mm, a minimum length of 1.2 m and a non-metallic thread of 150 mm. Nuts can be steel or GRP, with 36 mm across flats. Whereas, steel rockbolts have a specific alloy composition description,

there is not even a clause for the GRP specification, or for the supply of raw material constituents.

(b) Design approach and verification

There are performance requirements covering anti-static (electrical resistance less than 10^9 ohms), fire resistance (persistence of small flame less than 10s) and mechanical properties (tensile failure load > 300 kN, shear failure load > 120 kN and bond strength between resin and rockbolt of 245 kN for a bond length of 450 mm). Specific product test are given in each case. This standard is not covered in Section 6.

Inspection Chambers – BS 7158

(a) Background and scope

This BS standard covers both plastic and GRP products and is likely to be submitted as a CEN standard, with the ultimate aim of allowing GRP manhole covers to be specified in BS EN 124. This later standard relates mainly to cast iron and steel, although other materials are allowed if they meet the specification, which in being specific relates more to the metal items rather than performance requirements. The material requirements references BS standards, that have ISO equivalents, for the E glass-fibre for the main structure, with C glass-fibre or thermoplastic veils to give increased durability. Aggregate particles, if used in the design, should be in between 0.05 mm and 0.5 mm (e.g. graded silica sands). Fillers for controlling flow should be below 0.05 mm size. Quality control requires that interiors surfaces should be smooth and continuous, and that parts are free from protruding fibres, voids, pits, bubbles, cracks, blisters or foreign matter that would prevent the performance requirements being achieved (see also prEN 13706).

(b) Design approach and verification

All the testing requirements (e.g. vertical and shear loads, pressure loads, etc.) relate to final products tests and the different grades of products. For the vertical loading, displacements should be less than 6% and be free from cracking. Interestingly, there is a prescribed elevated temperature cycling, 2500 cycles, test for cracking or leakage that includes passage of water at 85°C but no requirement is given for the resin DTUL except via the reference to BS 3532 for specifying unsaturated polyester resins. This standard is not considered in Section 6.

EUROCOMP Design Guide

(a) Background and scope

The EUROCOMP consortia working under the Eureka programme produced this major document, consisting of 750 pages. The EUROCOMP manual was developed in line with the Euro Codes for construction, which are now becoming prominent in Europe. The code specifically deals with glass-fibre reinforced systems and originated through interest in the structural use of pultruded profiles, although the principles should be more widely applicable. The encouragement of the wider use of composites in the civil engineering industry was the aim of the EUROCOMP Eureka project. The partners and author would hope to see a future standard based on the design manual, but it has not been progressed to date.

The EUROCOMP manual is in three parts, with the “code” itself in Part 1, with the handbook in Part 2 providing additional support and explanations, followed by Part 3 containing some research reports. The clauses of the code are divided into “Principles” stating necessary requirements and “Applications” that meet the requirements but other approaches can be used if shown to match the requirements. Part 2 covers much of the ground described in the introduction regarding “Design” textbooks.

(b) Design approach and verification

The main design rules are based on the Eurocodes for construction, with numerical values taken from Eurocode 1 for the applied “actions” such as the applied loads, including self-weight, imposed loads and accidental loads (impact from vehicles). These aspects are not reviewed in detail as being common requirements, except where the special nature of composites has some influence.

The structure is designed to reach a serviceability limit state (e.g. excessive deflection, buckling/wrinkling, local damage, environmental damage) before an ultimate limit state is reached resulting in catastrophic collapse of the structure or danger to persons in the vicinity. The design situations identified are:

- normal or persistent conditions of use,
- transient situations (e.g. construction or repair),
- accidental situations.

Actions are described as direct when a load is applied to the structure, or indirect if, for example, due to temperature effects or settlement. The actions may also be permanent (G) due to self-weight etc., variable (Q) due to wind loads, etc.; or accidental (A) from blasts or vehicle impact. The Eurocode gives characteristic values (F_k) for these actions. The design factor, F_d , equals F_k times the γ_f , the product of all the partial safety factors for the actions considered.

Material properties are normally defined by characteristic values X_k corresponding to a suitable statistical treatment of the data obtained using recognised standard test methods. Where insufficient tests have been carried out, the mean value (X_k) can be used in combination with a larger partial safety factor, γ_m . That is in the general case, the design characteristic value, X_d , equals X_k/γ_m . In the absence of test results the laminae stiffness can be calculated by Halpin-Tsai method using different interaction factors depending on the property under consideration. Some typical stiffness data are given by a weight fraction equation similar to that used in the process plant standards for CSM and WR materials. These equations have some surprisingly precise constant included. For strength values the Hart-Smith failure criterion based on factored experimental strengths is recommended. If experimental values are not available, then the Tsai-Wu analysis based on calculated and safety factored ply strength properties can be used.

The partial safety factor for the material, is the product of the three values given in Table 7

Table 7: Partial safety factors for materials from EUROCOMP Design Guide

Partial Safety Coefficient	Description	Range Of Values	
		Max.	Min
$\gamma_{m,1}$	Derivation of material properties from test values	2.25	1.0
$\gamma_{m,2}$	Material and production process	2.7	1.1
$\gamma_{m,3}$	Environmental effects and duration of loading	3.0	1.0

The actual value of each component partial safety factor is given in Tables 8-10. The more directly measured the properties, the more controlled the post-cure and the more automatic the fabrication; the lower the factors that can be used. Lower values can be used if justified by adequate control procedures.

Table 8: Values for $\gamma_{m,1}$ from EUROCOMP Design Guide

Derivation Of Properties (Related to Degree of Uncertainty)	$\gamma_{m,1}$
Properties of constituent materials (fibre and matrix) are derived from test specimen data	2.25
Properties of individual laminae are derived from theory	2.25
Properties of the laminate, panel or pultrusion are derived from theory	2.25
Properties of individual plies are derived from test specimen data	1.5
Properties of individual plies are derived from theory	1.5
Properties of the laminate, panel or pultrusion are derived from test specimen data	1.15

Table 9: Values for $\gamma_{m,2}$ from EUROCOMP Design Guide

Method of Manufacture	Fully post-cured at works	
	Yes	No
Hand-held spray application	2.2	3.2
Machine-controlled spray application	1.4	2.0
Hand lay-up	1.4	2.0
Resin transfer moulding	1.2	1.7
Pre-preg lay-up	1.1	1.7
Machine-controlled filament winding	1.1	1.7
Pultrusion	1.1	1.7

It is also noted that the HDT has a direct influence, as in previous cases, on the factor to be used. It is interesting to note the equivalence of pre-preg, filament winding and pultrusion as manufacturing processes. Pultruded profiles were the main subject of the EUROCOMP code.

Table 10: Values for $\gamma_{m,3}$ from EUROCOMP Design Guide

Operating Design Temperature (°C)	Heat Distortion Temperature (°C)	Short-Term Loading	Long Term Loading
25 – 50	55 - 80	1.2	3.0
	80 - 90	1.1	2.8
	> 90	1.0	2.5
0 – 25	55 - 70	1.1	2.7
	70 - 80	1.0	2.6
	> 80	1.0	2.5

Characteristic data (mean - 1.64 standard deviations) are given for several typical materials of specified lay-up and volume fraction. Creep effects are dealt with using a procedure more common for unreinforced thermoplastics, by substituting a reduced modulus that is appropriate to the loading period. Default normalised curves are given in the absence of suitable experimental data for several fibre formats. It is proposed that accelerated testing should use time-temperature superimposition.

Finally, partial safety factors are given for fatigue depending on the level and frequency of inspection and whether a “fail-safe” or a “non-fail-safe” component. Values vary from 1.5 to 3. Data are also given for the maximum fatigue strain level acceptable to avoid transverse micro-cracking as a function of fatigue cycles and normal strain range (see Table 11).

Table 11: Allowable strains to avoid micro-cracking under cyclic loads

Normal Strain Range, %	Maximum Strain, ± %	Number of Cycles
0.30	0.20	10^3
0.23	0.15	10^4
0.17	0.13	10^5
0.10	0.07	10^6
0.03	0.02	10^7

Interestingly, in the absence of data equations are given that propose to predict the strength as a proportion of the characteristic strengths. As noted in [10] there is a significant difference between the strength normally measured in ~ 60 second duration test and properties obtained at the rate equivalent to the fatigue test loading rate. As GRP materials are rate dependent, it is the “fatigue rate” properties that are needed to obtain a linear stress-Log number of cycles curve

5.8 FRP GAS CYLINDERS - prEN 12245/prEN 12447 and ISO/DIS 1119

(a) Background and scope

Filament wound gas cylinders are a potential composites growth area for both back-pack breathing apparatus and for LPG storage in automobiles. These composite material gas (not LPG) cylinders have developed from fibre over-wrapped metal cylinders to fully composite material versions. CEN TC 23 and ISO TC58 are the responsible technical committees in this case. This area has seen the use of all the three major fibre types (i.e. carbon, glass and aramid) used. The EN and ISO standards are equivalent documents. Cylinders for LPG use are covered by prEN 12257 and ISO/DIS 11439 in the CEN and ISO series, respectively. ISO/DIS 11119 has three parts covering hoop wrapped cylinders (Part 1), fully wrapped composite cylinders with load sharing liners (Part 2) and fully wrapped with non-metallic/non-load sharing metallic liners (Part 3). There have been proposed to replace the ISO standard with the equivalent CEN standard. Consequently, this review will concentrate on prEN 12245 as being typical of the approach and requirements in this application area.

In prEN 12245 the composite properties are measured according to ring specimens, as appropriate for a filament wound structure using ASTM test methods. ISO tensile and DTUL tests are proposed for additional testing. A unique requirement is for the auto-ignition

temperature in oxygen, for oxidising gases only. The remaining material testing relates to the liner material, which may be metallic or plastic.

(b) Design approach and verification

Design is controlled by final product testing, initially of prototype production batches. Several test methods are given for the complete end-product covering:-

- liner pressure test,
- hydraulic proof test,
- cylinder burst test,
- cyclic pressure test,
- immersion in salt water (for underwater applications),
- elevated temperature (70°C) burst test,
- drop test,
- flawed cylinder test,
- extreme temperature pressure test (both vacuum and pressure cycling versions),
- fire resistance test,
- high velocity impact (bullet) test,
- permeability test,
- torque test (of screw threads),
- cylinder stability,
- neck strength.

Conditions are given for changes in design and materials that require re-approval of the cylinder.

6. PRODUCT STANDARDS ANALYSIS

In the remainder of this report, several of the product standards are reviewed to compare the approaches being used for different material aspects and to determine whether any common approaches are evolving. As BS 4994 standard is well known in the UK; the new European version (prEN 13121) is used as the reference, with brief comments regarding the other documents highlighted included as contrast or confirmation. The draft nature of several of these documents should be remembered.

Aspects considered are:

- Constituent materials
- Laminate test methods
- Materials properties - default
- Materials properties - measured
- Temperature capability
- Water absorption
- Chemical resistance
- Impact resistance
- Creep behaviour
- Fatigue and damage behaviour
- Flammability
- Static electricity
- Production control
- Cure assessment
- Non-destructive testing
- Tolerances
- Defects
- Approval of laminators
- Handling, storage and packaging
- Repair and maintenance

6. CONSTITUENT MATERIALS

6.1.1 Pressure Vessels -prEN 13121

Part 1 of prEN 13121 for GRP Pressure Vessels has comprehensive information on resins, including polyesters, vinylesters, epoxies, furane and phenolics. A full set of ISO standards are given for checking uncured resin properties as appropriate (e.g. density, colour, acid number, gel-time, flash point, refractive index, non-volatile matter, etc.) depending on the resin type.

ISO standards are quoted for the cured resin properties as given in Table 12. Also shown in this Table are the ranges of properties (given as minimums for different grades and types of polyester and vinyl-esters, tested unfilled and unreinforced in the classification Table 2 of prEN13121) that must be met in conjunction with chemical resistance requirements under Part 2 of the standard. It is interesting to note that three measures of “cure” are specified, HDT, T_g by torsional pendulum and Barcol hardness.

Table 12: Resin properties from prEN 13121 and prEN 40-7

GRP Vessels and Tanks, prEN 13121			Lighting Columns prEN 40-7	DNV Minimum Properties	
Property	Test Methods	Property Range		Grade 1	Grade 2
Barcol hardness	EN 59		43	35	35
Density	ISO 1183				
Tensile strength	ISO 527	50-75 MPa	79 MPa	60 MPa	50 MPa
Elongation at break	ISO 527	1.5-4 %	3.5 %	2.5 %	1.5 %
Modulus of elasticity in tension	ISO 527		3.4GPa	3 GPa	3 GPa
Flexural strength	ISO 178	75-130 MPa		120MPa	90 MPa
Modulus of elasticity in flexure	ISO 178			2.8 GPa	2.8 GPa
Heat distortion temperature	ISO 75-2	60-120 °C	78 °C	70 °C	62 °C
Glass transition temperature, T _g	ISO 537	85-150 °C			
Water absorption	ISO 62			80 mg	80 mg
NB T _g optional, also listed in classification is the styrene content, which varies from 45 to 55%					

Although, there is a tendency for highest and lowest values to go together across the properties, for an individual resin type, it is least consistent for failure strain. Data given in a classification Table in the standard shows that the T_g values are consistently 20 to 30 °C greater than the HDT values. These relationships have been studied further in NPL/Industry Studio project [9]. Barcol Hardness is included in the standard, but no acceptance criteria are given. It remains an extensively used technique that has been proposed for replacement, but no suitable alternative method is available. Part 1 also describes curing agents, initiators, accelerators, promoters and inhibitors, without test methods.

Table 13: Fibre format specifications and weight ranges proposed in prEN 13121

Product	Specification	Weight Range (g/m ²)
Surface non-wovens	EN 29092	20 - 50
Chopped strand mat (25-50 mm length)	ISO 2559	225 - 600
Continuous strand mats	ISO 2559	225 - 600
Woven fabrics/woven roving fabrics	ISO 2113	240 - 1200
Rovings for winding or chopping	ISO 2797	

For the fibres and fibre formats there is again reference to well-established standards with both test methods and specification standards quoted. The types of fibres available are simply identified (e.g. E-glass is an “*alumina-borosilicate glass, with less than 1% alkali content*”- see DNV comments later). For most products there are stated weight limits, as shown in Table 13. ISO test methods are given for product characteristics such as mass per unit area, tensile strength, moisture, loss on ignition, etc.

Other issues covered include thixotropic agents (up to 5% well mixed), conductive fillers (to assist spark testing of welded thermoplastic liners), fire retardants (added to specified layers), paraffin wax to meet requirements for surface cure in Part 3), aggregates and fillers (non-allowed), ultra-violet absorbers (usually < 0.5% in outer layers), pigments and surface active agents. The other material area covered is for several types of thermoplastics as chemically resistant liners, such as, polypropylene.

6.1.2 Other documents

(a) GRP piping offshore – ISO/DIS 14692: E glass-fibres are referenced as the preferred reinforcement, partly due to a lack of experience of other fibre reinforcements. Carbon-fibres are suggested for particular purposes, such as avoiding static electricity problems. However, there are no references to the available ISO specification standards. A range of resins is allowed, with no reference to available standards. The only material requirement is that Tg should be 30°C greater than the working temperature. For the standard temperature given of 65°C (n.b. nearest ISO reference temperature is 70°C (see ISO 3205)) this results in a Tg requirement of > 95°C. Maximum initial temperatures are given for the allowed resins (e.g. epoxy - 110°C, polyester - 70°C, vinyl ester - 100°C and phenolic - 150°C), although these temperatures would be modified by the aggressiveness of the liquid carried, its concentration and the specific curing agent. The minimum recommended is -35°C, although lower temperatures may be considered.

(b) Water tanks - BS EN 13280: References the EN ISO 2078 for glass-fibre but uses a more specific definition due to the need for good corrosion resistance. ISO standard, ISO 472, is referenced for the polyesters resins. For the alternative to CSM construction, the specification standard ISO 8605 for sheet moulding compounds (SMC) is referenced, although the new EN standards with tolerance levels would now be preferred.

(c) DNV High Speed and Light Craft: Requires that constituents must pass their Type A Approval Programme covering:

- adhesives
- polyester resin, vinylester resin, gelcoat and topcoat
- glass-fibre reinforcements
- sandwich core materials
- aramid fibres
- sandwich adhesives

These documents use a mixture of mainly ISO and ASTM test methods with minimum acceptance requirements, which are related to either the “manufacturer’s specified value (msv), verified to be within $\pm 10\%$ of Type Test results or “manufacturer’s specified minimum value (msmv), verified to be below (mean - 2 x standard deviation) of Type Test results.

In the case of polyester and vinylester resin, two grades are available (Grade 1 – normal and Grade 2 - good water resistance), with additional requirements for particular application (e.g. gelcoats – interlaminar fracture toughness, lifeboats applications - combustibility). Minimum Barcol hardness (EN 59) values of 35 are required for both grades. Other requirements are given in Table 11. Uncured resin properties controlled include:

monomer content (ISO 3521)
viscosity (ISO 2555/2884)
mineral content (DIN 16945)
gel time (ISO 2535).

The DNV approval for glass-fibre reinforcements refers to one *grade* with the possibility to include variants. A *Grade* defines the orientation, number of layers, type of weaves/construction etc., with variants being the same grade but with different weights. Approval is limited to one manufacturer and one site; and lasts for four years if no changes are made in production etc.. The glass-fibres approval includes requirements for moisture content (ISO 3344 – 0.2%), loss on ignition (ISO 187) and weight per unit area (ISO 1889 – rovings, ISO 3374 – mat, ISO 4605 – fabrics all within 10% of mmv (n.b. ISO is merging ISO 3374 and 4605 in current revision)). Chemical composition given for E glass-fibres (see Table 14), is only now being discussed for ISO standardisation by major producers.

Table 14: DNV and prEN 40-7 specifications for E glass-fibres

Constituents	DNV Range	prEN 40 - 7
SiO ₂	52-56 %	54 %
CaO	16-25 %	(+ MgO) 22 %
Al ₂ O ₃	12-16 %	15 %
B ₂ O ₃	6-12 %	6.5 %
Na ₂ O + K ₂ O	0-1 %	
MgO	0-6 %	included above

As part of the testing approval for glass-fibre reinforcements flexure (n.b. mould side in compression) and tensile tests are required on laminated material using the harmonised EN ISO standards prepared by NPL. For CSM, the laminate should have a fibre weight fraction of 30 ± 4 %, and for weaves and fabrics within ± 4 % of the manufacturer's specifications using a marine grade polyester and ambient cure conditions. Specimens are taken in perpendicular directions for mat/fabric/weaves. Minimum specimen properties are given in Table 15.

Table 15: Minimum laminate properties according to ISO test methods

Property	Tension (ISO 527)	Flexure (ISO 14125)
Strength (MPa)	80	130
Modulus (GPa)	7	6

Aramids are similarly tested using glass-fibre roving standards, which supports the development in ISO of material non-specific methods where technically acceptable (i.e all clause can be applied). Interesting, only the approval of aramid fibres requires fatigue data ($> 10^5$ cycles at 0.45 maximum strength (compression or tension) under fully reversed loads. Other mechanical property requirements include interlaminar shear strength (ILSS - msmv > 25 MPa) (n.b. ISO 4585 should be replaced by ISO 14130), impact tests for hull construction to check for penetration at 3.45 J/mm thickness impact energy, tensile and compressive properties. Sampling required in most cases is 10 repeats from at least two batches (ILSS) or 5 repeats from 2 batches (tension/compression).

(d) Lloyd's Register: All international and national standards are generally acceptable, with some variations allowed on an individually approved basis. Updating of referenced standards needs to be undertaken to agree with those given in Table 2. Most of the required data is given through normal application of the standard, but the strain levels of 0.25% to 0.5% for calculating

modulus is not in agreement with the long established ISO values of 0.05% and 0.25% for all plastics, including reinforced systems. There is no explanation of the difference. Thermosetting resins are tested unreinforced as cast sheet using the same cure schedule. Properties required are common physical properties (e.g. SG, viscosity, gel time, appearance), but vary for more chemical aspects depending on resin type (e.g. epoxy, polyester). Similar, but appropriate, evaluation is required for thermoplastics used for laminating. Reinforcements are evaluated using approved resins with samples at least 4 mm thick containing at least 3 layers of reinforcement. For glass-fibre based systems there are nominal weight fraction requirements, which are volume fraction requirements for other fibre types.

(e) FRP Lighting Columns – prEN 40-7: General definitions used only for E glass-fibres with no reference to ISO material specifications, except a typical composition that compares fairly well with the DNV composition as shown in Table 14. Typical properties are also given with tensile modulus of 72 GPa and a tensile strength of 1500 MPa. Alternative fibres are allowed as long as mechanical and durability properties are equivalent or greater than the E-glass-fibres. Data are also given for the effect of pH on the corrosion resistance of E, R and AR glass, but no source is given. Finally, the cured properties of a fully-cured isophthalic resin are given (again without reference) as compared above, in Table 15. Alternatives are similarly allowed. Fillers should not reduce the properties and pigmentation should be used throughout. Certificates of performance are required for components based on the manufacturer's data.

(f) EUROCOMP Design Guide: Where existing, specifications standards given for glass-fibre products. For resins, typical physical and mechanical properties are quoted for different classes of resins with referenced test methods (e.g. ISO). Subsidiary materials such as gel coats, veils and additives are also described.

(g) Wrapped Gas Cylinders - EN 12245: For the fibres, ASTM tensile strand and NOL ring tests referenced, but no product or resin specifications standards given..

Summary

The conclusion is that these materials are complex containing many constituents, but supported by a fairly comprehensive set of ISO test methods and specifications. Appropriate material tests and specifications are available as demonstrated by the better constructed documents, such as prEN 13121. It would benefit other standards to adopt a similar approach.

The publication of a definitive composition for E glass-fibres would be beneficial and protect the industry from unsatisfactory materials, as long term performance and corrosion resistance is needed in many applications, but perhaps without the need for specialist glass composition (e.g. ECR glass). This particularly applies to many of these applications (e.g. gas cylinders, pressure vessels) standards because of the serious consequences of failure.

6.2 LAMINATE TEST METHODS

Pressure Vessels -prEN 13121

Normally, ISO, EN ISO or EN standards are quoted in Part 3 of prEN13121, including several of the 1978 published EN standards in the EN 59-63 series. Three of these latter standards for loss

on ignition, flexural tests, and standard temperature and humidity should be replaced by new EN ISO standards (i.e. EN 60 to EN ISO 1172, EN 62 to ISO 291 and EN 62 to BS EN ISO 14, 125. This leaves only the well-known Barcol hardness measured according to EN 59 is included, although elsewhere in the standard other techniques for cure assessment are quoted. Only Barcol hardness provides a low-cost shop-floor method.

Elsewhere the standard is up-to-date as the tensile test BS EN ISO 527-4 has replaced EN 61. The other test method to note is that for the resistivity of conductive plastics due to the problems experienced with static electricity.

Other documents

(a) GRP piping offshore – ISO/DIS 14692: No flat coupon standards referenced, as not directly related to a filament wound products.

(b) Water tank standard - EN 13280: Does not directly reference coupon standards, but references the SMC specification standard, ISO 8605 (with related test methods, but not specific property level requirements).

(c) DNV High Speed and Light Craft: Good use of both ISO and ASTM standards. ISO standards references are up-to-date.

(d) Lloyd's Register: International standards referenced, but some need updating as noted previously.

(e) FRP Lighting Columns – prEN 40-7: References EN ISO 527 – 4 and – 5, without distinguishing their use (i.e. Part 5 for fully or predominately unidirectional, 1 mm thick only) and flexure test, EN ISO 14125. Shear test, EN ISO 14129, also quoted, but possibly not the appropriate test depending on material lay-up.

(f) EUROCOMP Design Guide: ISO laminate test methods are quoted for use in the Hart-Smith version of the failure criterion (or manufacture's data used), but these are now out-of-date and should be replaced by the EN ISO harmonised laminates tests.

(g) Wrapped Gas Cylinders - EN 12245: Laminate test methods referenced are ISO 527 for tensile properties and ASTM D2344 for interlaminar shear strength, which should be replaced by ISO 14130. ISO 75-3 is used for Deflection Temperature under Load as a measure of service temperature.

Summary

Increasingly, these documents quote ISO standards, with up-to-date references being incorporated. However, some documents need revising at their next revision. It is noted that the area of filament wound test methods relies on ASTM methods that were proposed at one stage to be withdrawn. It may be that ISO or CEN should consider producing standards in this area. A recommended list of test methods is given in Annex B.

6.3 MATERIALS PROPERTIES - DEFAULT

6.3.1 Pressure Vessels -prEN 13121

Default data are given in prEN 13121, see Table 16, to aid the basic design method, which must be validated as noted in the next section. The document, in common with BS 4994, uses a unit strength (N/mm per kg/m² glass) approach rather than a stress (N/mm²). This approach considers that the strength is related to the weight of glass-fibre present and that the resin does not make a significant contribution. Therefore, the actual thickness is not important, although in bending applications thickness (i.e. thickness to the third power) is more important than material modulus (single power).

Table 16: Minimum default properties for different fibre format/resin combinations (as proposed in prEN 13121)

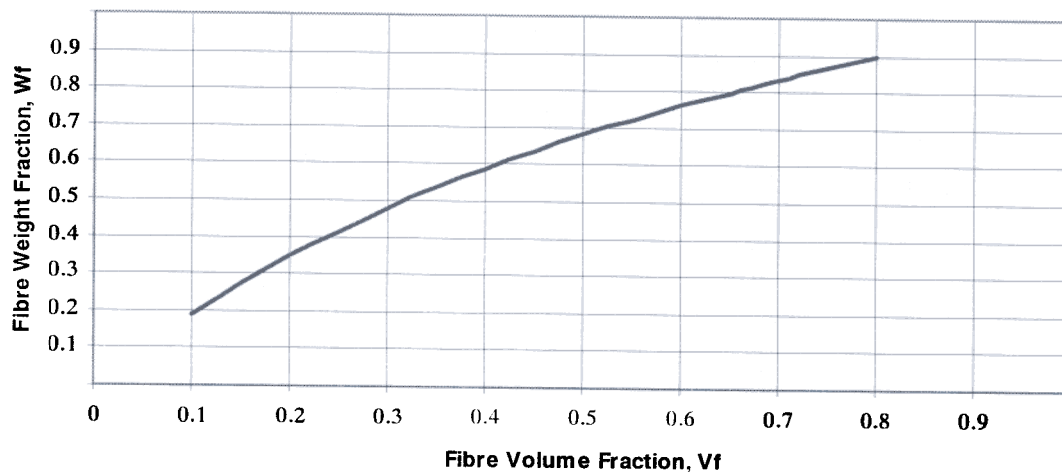
Minimum tensile properties based on layer properties (N/mm per kg/m ²)			Minimum allowable lap shear strength	
	UTUS	Unit modulus		N/mm ²
CSM -	200	140,000	CSM -	7
CSM(furane) -	140	140,000	CSM(furane) -	5
CSM(phenolic) -	140	140,000	CSM(phenolic) -	5
FW tangential	500	28,000	WR Cloth	6
FW meridonal	60	4,000	WR Cloth (furane and phenolic)	4
FW Furane and phenolic tangential	280	28,000	FW	6
meridonal	40	4,000	FW (furane and phenolic)	4
FW values for fibre angles between 88° and 90°. For woven roving (WR) values are calculated using factors depending on mass of glass in that direction see table below.				
Glass-fibre range for above properties		Mass %	Note for a thermoplastic liner the minimum shear strength (by double notch test) is 7N/mm ² .	
Chopped strand mat (CSM) laminates		25 to 45		
Woven roving (WR) laminates		45 to 55		
Filament wound (FR) laminates		60 to 75		

Simple equations are given in Table 17 for predicting the properties of woven roving (WR) reinforced laminates. Some care is needed in using these, and similar, equations as they can be based on either the weight or volume fraction of reinforcement. The relationship between these “fractions” is shown in Figure 3 (N.B. Densities for E glass-fibres = 2560 kg/m³ and for resin = 1200 kg/m³).

Table17: Minimum Tensile properties of woven-roving as proposed in prEN 13121.

Reinforcement	Direction	Criteria	UTUS, U_z	Unit modulus, X_z
			N/mm per kg/m ² glass	
WR	Warp	$x \geq 1/6$	$500 \times f_l$	$4000 + (24000 \times f_l)$
		$x < 1/6$	60	4000
	Weft	$x \geq 1/6$	$500 \times (1-f_l)$	$4000 + (24000 \times (1-f_l))$
		$x < 1/6$	60	4000
WR (furane) WR (phenolic)	Warp	$x \geq 1/6$	$320 \times f_l$	$4000 + (24000 \times f_l)$
		$x < 1/6$	40	4000
	Weft	$x \geq 1/6$	$500 \times (1-f_l)$	$4000 + (24000 \times (1-f_l))$
		$x < 1/6$	40	4000

where f_l is the mass of glass-fibre per unit width in the weft direction to the total mass of glass-fibre (warp and weft) per unit width.

**Figure 3 Comparison of volume and weight fractions for a glass-fibre/resin system.**

6.3.2 Other documents

(a) GRP piping offshore – ISO/DIS 14692: Although no material properties are given, there is the requirement for the range of fibre volume fractions used. The requirements are presented in two tables that give similar information if the quoted mean coincides with the mid-point of the quoted ranges. The ranges are:

- filament wound pipe 70% – 82% (or $\pm 6\%$ of quoted mean by supplier)
- filament wound fittings 65% – 75% (or $\pm 6\%$ of quoted mean by supplier)
- hand lay-up fittings 50% – 65% (or $\pm 7.5\%$ of quoted mean by supplier)

(b) Water tanks - BS EN 13280: No values given.

(c) DNV High Speed and Light Craft: No default values to be used in design, other than minimum required in constituent material approval (see Section 6.1.2).

(d) Lloyd's Register: Equations, similar to those in prEN 13121, are given for CSM and, surprisingly perhaps in the same table, for woven rovings and 0°/90° cross-ply. Separate equations are given for the tensile properties of unidirectional material, again based on weight content of reinforcement. Minimum properties are given for the cast resin and for reinforced laminates, but where incomplete actual values are to be obtained from material manufacturer's and agreed with LR prior to use. These properties are for use in predictive equations and analyses. The values given by equations are slightly lower than this for tensile strength and modulus, but no comparisons are possible for the other formats listed (e.g. bi-directional and unidirectional). Interestingly, common equations are given for all formats for several properties (flexural strength and modulus, compressive strength and modulus and interlaminar shear with the results only dependent on the different fibre contents associated with each format. This is in contrast to the CoDA software that has format specific equations, except for fabrics where no analyses has been found robust enough for reliable strength predictions (n.b. for fabric modulus predictions it is possible to treat as a cross-ply material at the appropriate volume fraction).

(e) FRP Lighting Columns – prEN 40-7: No values given or referenced.

(f) EUROCOMP Design Guide: This document gives “characteristic data” for several laminates based on test specimens with specified manufacturing and operating temperatures. Characteristic data is defined as:- “Mean - 1.64 standard deviations”. This is close to the prEN 13121 approach, but in this case the 1.64 or “k” factor value varies with the number of tests (N) conducted (i.e. $k = 1.60 + (0.4/N)$), which yields higher “characteristic data” for larger test sets. The EUROCOMP guide includes data sheets for laminated and pultruded composites. These are a useful source of data but the user should always check the properties are relevant to their chosen system and process route. The EUROCOMP document also gives simplified equations for different fibre formats, as a function of fibre weight fraction for both upper and lower bound prediction, that are rather similar to those given in the pressure vessel standards.

(g) Wrapped Gas Cylinders - EN 12245: No data given. It is noted that that fatigue data are required for each liner/overwrap combination and that a damage criteria is needed for the filament-wound structure (see Section 6.10)

6.3.3 Summary

In some documents, equations are given for calculating laminate strengths for cases where a combination of fibre formats exist. For example, as included in BS 7159 for “design and construction of glass reinforced plastics (GRP) piping systems for individual plants or sites”, which is similar to the EN1312/BS 4994 document, as can be expected as both are needed to build a complete processing plant. The laminate unit modulus calculation given below demonstrates the prediction of laminate unit modulus based on the weight of glass in each layer:

$$X_{LAM} = n_1 W_1 X_1 + n_2 W_2 X_2 + \dots n_x W_x X_x \quad (5)$$

where

X_{LAM} is laminate unit modulus (N/mm)

n_x is the number of layers of type x,

W_x is the mass of glass reinforcement per unit area (in kg/m²) in one layer of type x,

X_x is the unit modulus of glass reinforcement type x per unit area (in N/mm width (per kg/m²))

The calculated laminate unit modulus is then divided by the laminate thickness (excluding corrosion layers) to give the laminate modulus, E_{LAM} .

The predicted and quoted values in several of the procedures are given in Table 18. The agreements are reasonable in most cases.

Table 18: Comparison of predicted and quoted values.

Property	Predicted values	Quoted values
CSM – 34% w_f - Tensile strength		
EN 13121 (from unit properties. $t = 2\text{mm}$)	100	-
Lloyds ($200 w_f + 25$)	93	90 ($wf = 0.3$)
EUROCOMP ($290 w_f + 10$)	108.6	97
CSM – 34% - Tensile modulus		
EN 13121 (from unit properties. $t = 2\text{mm}$)	7	-
Lloyds ($15 w_f + 2$)	7.1	6.9 ($wf = 0.3$)
EUROCOMP	-	6.8
CSM – 34% w_f - Compressive strength		
EN 13121 (from unit properties. $t = 2\text{mm}$)	-	-
Lloyds ($150 w_f + 72$)	123	125 ($wf = 0.3$)
EUROCOMP ($275 w_f + 60$)	154	97
CSM – 34% w_f - Compressive modulus		
EN 13121 (from unit properties. $t = 2\text{mm}$)	-	-
Lloyds ($40 w_f - 6$)	7.6	6.4 ($wf = 0.3$)
EUROCOMP	-	6.8
WR – 55% w_f - Tensile strength		
EN 13121 from unit properties with $t = 1.07\text{ mm}$	234	-
Lloyds ($400 w_f - 10$)	210	-
EUROCOMP ($(784 w_f - 212)/(893 w_f - 192)$)	219/299	228
WR – 55% w_f - Tensile modulus		
EN 13121 from unit properties with $t = 1.07\text{ mm}$	15	-
Lloyds ($30 w_f - 0.5$)	16	-
EUROCOMP	-	15.2
WR – 55% w_f - Compressive strength		
EN 13121 from unit properties with $t = 1.07\text{ mm}$	-	-
Lloyds ($150 w_f + 72$)	155	-
EUROCOMP ($(182 w_f + 66)/(190 w_f + 109)$)	166/214	129
WR – 55% w_f - Compressive modulus		
EN 13121 from unit properties with $t = 1.07\text{ mm}$	-	-
Lloyds ($40 w_f - 6$)	16	-
EUROCOMP	-	10.9

A good overview of the range of data obtained in actual production is given in [11] prepared by NPL with the assistance of BPF members, with other data sources in [12,13].

6.4 MATERIALS PROPERTIES – TO BE MEASURED

6.4.1 Pressure Vessels -prEN 13121

In prEN 13121, the basic design method for the minimum specified properties must be validated by testing five specimens in each case, but the user has to select either the mean of these five results or the mean of the three remaining results once the maximum and minimum values are discarded. These values must be higher than the minimums specified value.

The properties to be assessed are:-

1. Glass content
2. Unit modulus
3. Ultimate tensile unit strength
4. Lap shear strength
5. Flexural strength and modulus
6. Barcol hardness
7. Short term creep
8. Liner/GRP shear strength
9. Peel strength liner to GRP.
10. UTS of lining material
11. UTS of lining welds tests

If using the advanced design method, at least 15 specimens (i.e. $N \geq 15$) must be tested and the mean and standard deviation (SD) determined. The characteristic advanced design value is equal to:

$$\text{Mean} - k (\text{SD}) \quad \text{where } k = 1.6 + (0.4/N) \quad (6)$$

When historic data is available, a further five specimens shall be tested and the mean determined. As for the minimum properties case, the mean value should be greater than the advanced design characteristic values.

6.4.2 Other documents

(a) GRP piping offshore – ISO/DIS 14692: No requirement outside final product tests.

(b) Water tanks - BS EN 13280: None required to be measured except moisture absorption.

(c) DNV High Speed and Light Craft: Recommended to use the Tsai-Wu failure criteria by measuring the tension and compression strength in the two principle in-plane directions, and the in-plane shear strength.

(d) Lloyd's Register: Tests for laminates need to be updated, including tensile properties (ISO 3168 replaced by BS EN ISO 527-4), flexural properties (ISO 178 by BS EN ISO 14125), compressive properties (ISO 604 by ISO 14126), interlaminar shear (ISO 4585 by BS EN ISO 14130). Values used for design should be the lesser of either 90% of mean first-ply/resin cracking strain or mean minus two standard deviations based on five standard tests. It is noted

that an independent laboratory and calibrated test equipment, accurate to 1%, should be used for testing. In absence of measured data, calculated values can be used.

Recommendations are given for the fibre weight content for both glass-fibres and other unspecified fibres. These vary from 30%, by weight, for chopped strand mat (CSM) to 60% for unidirectional reinforcement. For other fibres, the weight percentages are about 2/3^{ths} of the glass-fibre values. Test plates should contain a minimum of three layers of reinforcement and be at least 4 mm thick, however, it is very difficult to test 4 thick unidirectional specimens because of load transfer problems (NB 1 mm thick in ISO 527-5). Fibre orientations are also specified for the test specimens as follows:

unidirectional	0°,
CSM/sprayed mat	any
woven cloths, including combination products	0° and 90°
± 45°, Triaxail, quadriaxial rovings	0°, 45°, 90° and -45°

(e) FRP Lighting Columns – prEN 40-7: No recommendations given.

(f) EUROCOMP Design Guide: In general it is required to obtain the tensile and compressive strength and modulus in the longitudinal and transverse directions, and the in-plane shear strength and modulus properties. Poisson's ratio values are also required.

(g) Wrapped Gas Cylinders - EN 12245: For the no-liner case, there are additional requirements on the composite material concerning chemical resistance, reaction to oxidising gases and permeability in addition to the mechanical properties. To avoid leakage the elongation of the resin and the shell are important, so that no detectable leakage is obtained below 1.6 x the test pressure. Auto ignition temperature is important when the cylinders are intended to contain gases, which are more oxidising than air.

Summary

Wide variation in approach from final product testing to fairly comprehensive material database requirements. It is noted that the CAA requirement (see Section 5.5) is for replicate sets of 6 specimens, whereas ISO and ASTM standards use sets of 5 specimens. This anomaly should be corrected. For B design values, 30 specimens are normally required (i.e. ten specimens from 3 different batches – Mil. Hbk 17), whereas prEN 13121 proposes at least 15 specimens for determining the characteristic strengths. An agreed approach could aid future database generations. Surprising, there is little mention of shear moduli and Poisson's ratio, which are most different in their relationships to other elastic properties compared isotropic materials. Poisson's ratio values can vary widely (i.e. 0.02 to 0.3).

6.5 TEMPERATURE CAPABILITY

Pressure Vessels -prEN 13121

The minimum heat deflection temperature (HDT, or DTUL) shall be at least 20°C more than design temperature. If HDT is less than 125°C, the minimum unit modulus specified in the standard (see below) is reduced by the factor 1/A₃ when applied to a buckling or bending design

situation For tanks or vessels built on-site the maximum operating temperature is limited to 80 °C.

Other documents

(a) GRP piping offshore – ISO/DIS 14692: A minimum requirement for T_g to be 30°C greater than the service temperature (i.e. 95°C for the standard qualification temperature of 65°C). Temperature performance is controlled by partial factor A_1 , which for temperature alone can be taken to vary linearly from 1 at 65°C to zero at the T_g temperature. The potential problem is the different test procedures allowed, which are known to give different results [9].

(b) Water tanks - BS EN 13280: Requires DUTL (HDT) should not be less than 70°C, which is 40°C above the maximum allowed service temperature (nb drinking water storage is normally less than 20°C). The test is made on the composite material (cf resin in some other standards) according to ISO 75, for which the relevant Part 3 has just been revised. This is likely to be easier to obtain, than the required level as the new version gives higher values. It is noted that often the criteria relates to Part 2 of the standard using the unreinforced resin.

(c) DNV High Speed and Light Craft: The service temperature forms with chemical resistance part of the class structure that controls the design strain. Normal operation is “40 °C below T_g ” and high is between “20°C and 40° C below T_g ”. Use is not allowed when T_g is “less than 20°C” above the service temperature. Part 3 of ISO 75 is specified for testing.

(d) Lloyd’s Register: Unreinforced resin tested according to ISO 75 Part 2 to obtain the DTUL with a minimum requirement of 55°C. For curing intended at room temperature, it is acceptable to follow 24 hours cure at 18°C to 21°C by a 16 hr post-cure at 40°C.

(e) FRP Lighting Columns – prEN 40-7: No requirement but typical resin DTUL shown as 78°C.

(f) EUROCOMP Design Guide: It is suggested that a material with a T_g equal to the service temperature + 20° C can be used for normal operations but this appears rather high for longterm loaded applications, particularly when compared with the requirement in other standards.

(g) Wrapped Gas Cylinders - EN 12245 HDT (DTUL) determined by ISO 75-3 on composite.

Summary

This is one of the most important areas as the choice of an unsuitable material can result in down-rating of the mechanical properties due to falling below fairly approximate temperature requirements, even by a few degrees. Whereas for the Lloyds Register, the resin is tested according to ISO 75 Part 2 to obtain the DTUL, for several other standards use ISO 75 Part 3, which is considered to be unreliable in its current form (i.e. loaded at 0.1 x flexural strength). Part 3 has been reviewed recently at ISO as it has been reported that DTUL values have been obtained for the composite using Part 3 that are lower than obtained by Part 2 for the plain resin. A new procedure proposed by NPL (i.e. loaded at 0.1% of flexural modulus) has been accepted by ISO for use in the revision of ISO 75-3, which will lead to higher results. It is also noted that

T_g values from DMA (dynamic mechanical analysis – ISO/CD 6721-11) tend to be higher than those determined from DSC (differential scanning Calorimetry – ISO 11357). DMA results are high due to incorrect specimen temperature measurements, related to the position and calibration of the temperature sensor. NPL is developing a new calibration procedures, as ISO/CD 6721-12 based on prior research [9] that includes development of a reference calibration samples and round-robins (RRs).

In general T_g should be 20°C - 40°C above the service temperature, with a preference for long term applications to the larger value. In no case should T_g be less than 20°C above the service temperature. Care needs to be taken as there can be differences of this magnitude between the measurements of T_g by DSC or by DMA, and the DTUL value [3].

WATER ABSORPTION

Pressure Vessels - prEN 13121

Water is included as a category 2 media, with a maximum service temperature of 80 °C, but no maximum absorption value given.

Other Documents

- (a) GRP piping offshore – ISO/DIS 14692: Not covered.
- (b) Water tanks - BS EN 13280: Should not exceed 0.5% by mass when tested according to an annex similar to ISO 62 (i.e. 50 mm x 50 mm x 1 mm sample immersed for 24 hrs. at 23°C). The outside face and cut edges are coated with additional resin of similar composition as that used for the inside surface of the tank
- (c) DNV High Speed and Light Craft: Requirements within resin approval that water absorption should not exceed 80 mg and 100 mg, for Grade 1 and 2 respectively, when a 50 mm x 50 mm x 4 mm sample is exposed for 28 days at 23°C according to ISO 62.
- (d) Lloyd's Register: Water absorption, according to ISO 62, limits the maximum uptake to 70 mg, for all laminates, with a property retention requirement greater than 75% of the default mechanical properties. For both resins and laminates the pre-drying, at 50°C, before measuring the moisture uptake is omitted for low-cure temperature systems in order to avoid additional cure not representative of the normal use.
- (e) FRP Lighting Columns – prEN 40-7: Not covered, except by the requirement to seal cut edges to prevent ingress of water or other containment.
- (f) EUROCOMP Design Guide: No requirement in Design Code Part but a warning included in Handbook Part that stiffness and strength values can be strongly effected (e.g. flexural strength reduced by 50% by 1.5% moisture absorption).
- (g) Wrapped Gas Cylinders - EN 12245: Not covered in initial design but a test requirement in order to achieve a claimed 20 year life, the system must survive 1000 hrs at the test pressures at

70°C and RH < 50%. For greater than 20 year life, with surprising no upper limit stated, the test is extended to 2000 hrs. Cylinders for underwater diving use must pass a mandatory salt-water test, which is optional for other uses. The test is conducted in a salt solution (35 mg of NaCl per litre water) under the operating pressure at 15°C for 45 days, followed by a further 45 days without pressure. One of the two cylinders is then pressure tested to burst and the other is pressure cycled at the hydraulic test pressure (P_h).

6.6.3 Summary

ISO 62 is well accepted for basic uptake measurements and should be used as the default test method. It should be used even if there are reasons for using non-standard specimens, and the use of a non-standard specimen noted in the test report.

6.7 CHEMICAL RESISTANCE

Pressure Vessels -prEN 13121

An important aspect for composites in many applications, is that these materials are frequently used for their good corrosion resistance (e.g. boats, process equipment, sewage applications). Part 2 of prEN 13121 is solely devoted to the determination of chemical resistance as befits a standard on chemical process vessels and was the subject of extensive UK comment at the last ballot. Table 1 of the standard gives the required thickness for different protective layers, which may be a single protective layer (SPL), a chemically resistant layer (CRL) or one of several thermoplastic linings (TPL).

In accordance with the main philosophy, the design factor A_2 is determined using one of several methods depending on circumstances. Five methods are given for determining the factor:

- i. through media lists
- ii. resin manufacturer's data
- iii. thermoplastic liner manufacturer's data
- iv. service experience
- v. testing in laboratory/in-situ

It is permissible to use the lowest value, if more than one method is used.

1. The aggressive environments are divided into Cat 1, 2 and 3 media. There are comprehensive instructions depending on service temperatures, type of lining etc.
2. For materials with DTUL 20°C greater than the service temperature, cured according to the manufacturer's instructions, partial factors vary between 1.1 and 1.4, and 1.1 and 1.8, for post cured and non-post cured material, respectively, based on the manufacturer's recommendations.
3. Similar approach for thermoplastic liners when used.
4. For service experience greater than 3 years, the same factor may be used, whereas if it has been inspected after this period and found to be satisfactory a reduction not exceeding 0.1 can be made in the design factor. The same factor can be applied for service experience between 6 months and 3 years if internal inspection is satisfactory.
5. Experimental testing is undertaken using the single-sided exposure arrangement shown in Figure 4, where one test plate is in the vapour phase and one in the fluid phase. Assessment is based a standardised ~ 3 mm laminate of fixed weight content made by a prescribed method.

The tests are undertaken at the design service temperature for a range of exposure times, such as 1, 4, 8, 16 weeks. It is recommended that four exposure units are employed.

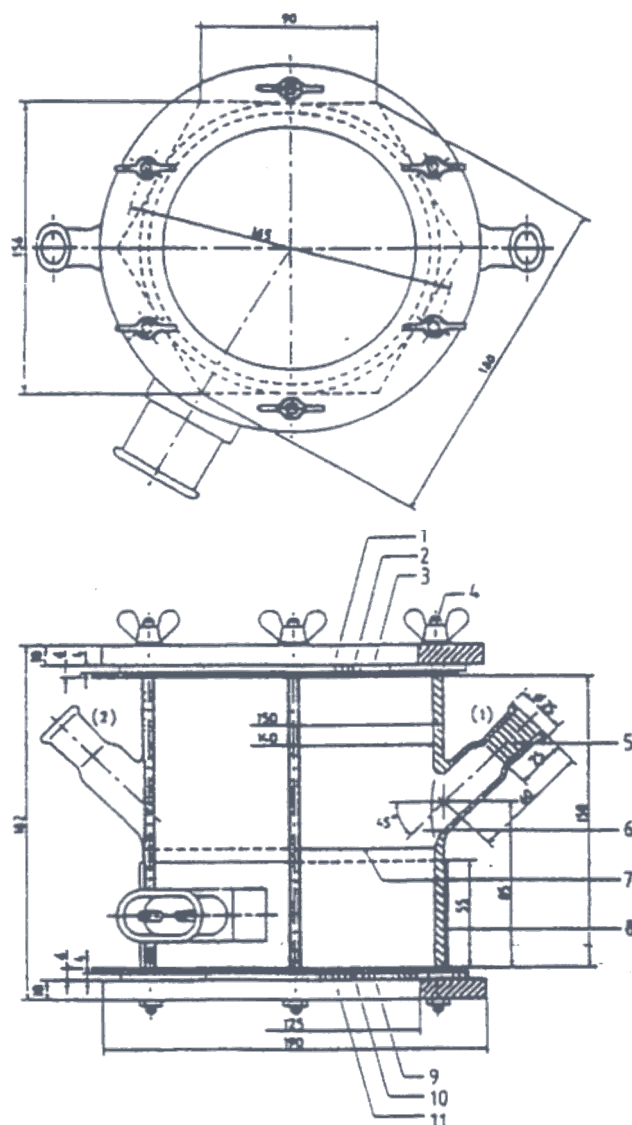


Figure 4 Chemical resistance test (*n.b. flat plate specimens are numbered 2 and 10*)

Degradation is assessed on a combination of appearance changes (uses 10 assessment parameters e.g. gloss), dimensional stability (3 off) and flexural strength/modulus using BS EN ISO 14125. For each property a scoring system is used including a weighting system that increases in order of the above text, with mechanical tests the most important to the final score. The flexural properties are plotted as a function of the exposure time and extrapolated to the 50% retention point. If this point is obtained before 10 years, then the material should be rejected for this application (e.g. temperature, concentration etc.). Otherwise, the score varies from zero to 10 based on the percentage loss after 10 years, from 0% to 50%, respectively. Depending on the total score for all aspects, as a percentage of the maximum that could be obtained for the parameters assessed, the partial factor A_2 is obtained from a chart within the range 1.1 to 1.4. The weighting factors are different for single-sided and full immersion. The

test can be also be conducted by full immersion of 100 mm x 125 mm plates of the laminate or by testing in-situ within a tank.

Other documents

(a) GRP piping offshore – ISO/DIS 14692: Guidance is given in Annex D of Part 2. This highlights both the increased permeability with increased temperature and the increased viscoelastic response of the material (e.g. higher creep rate). There is a need to calculate the partial factors A_1 (temperature) and A_2 (chemical resistance), which except for water often cannot be separated. When the values are in doubt, a 1,000 hr survival test (see comments under creep properties) is proposed using an over-pressure of 15%.

(b) Water tanks - BS EN 13280: No chemical requirement other than water, as noted previously.

(c) DNV High Speed and Light Craft: Not covered.

(d) Lloyd's Register: Not covered

(e) FRP Lighting Columns – prEN 40-7: Although noted in the main text that there are no specific corrosion requirements other than sealing cut edges, recommendations are given in Annex D to extend the service life. This includes use of a polyurethane or other UV resistant coatings in certain parts of EU where there is high UV radiation. It is also recommended to coat the lower 100 mm of the column together with any part below the surface to prevent/delay ingress of certain (unspecified) ground chemicals.

(f) EUROCOMP Design Guide: The degradation process and effects of chemical attack highlighted but no test method(s) proposed. Summary information included is that dilute mineral acids are not aggressive to most resins but concentrated nitric or sulphuric acid can result in oxidation. Alkalis can cause softening of the matrices. Handbook mentions using a liner or chemically-resistant glass-fibres for improved performance under the general heading of stress corrosion.

(g) Wrapped Gas Cylinders - EN 12245: When the composite forms the liner as well, ISO 175 should be used to check chemical resistance against medium contained, or used in production or during use and maintenance (e.g. cleaning fluids).

Summary

The procedures proposed in prEN 13121, if agreed, could provide a suitable framework for chemical resistance assessment for other standards. Several test methods use versions of product tests, either as plates or pipe sections. ISO 175 is the normal material level standard referenced. The most important factor is the requirement that the specimen/product should be under stress when exposed to the atmosphere.

IMPACT RESISTANCE

Pressure Vessels -prEN 13121

No material or design requirements are given regarding impact resistance although these tanks are likely to be submitted to unplanned minor and major impacts both during installation (see Section 6.17) and in-service.

6.8.2 Other documents

(a) GRP piping offshore – ISO/DIS 14692: Impact resistance is an optional property. It is conducted by impacting from a 1 metre drop-height (same as ISO 6603 requirement) using a 0.5 kg weight with a 12 mm radius spherical indenter onto a 1 metre length of empty pipe supported by a flat, firm surface, followed by surviving a 1000 h pressure test. It would have been preferable to use the ISO 6603 10 diameter indenter (n.b. also a 5 mm radius indenter available).

(b) Water tanks - BS EN 13280: For rectangular sectional tanks, there is a specific drop test of a 1 kg, with a 50 mm diameter indenter, from a height of 2 m onto a horizontally panel bolted along all sides to a support frame. Panels are then inspected for cracking. Three repeats are undertaken on both sides, if un-cracked on the first side. A similar test is conducted for covers, while supported on the appropriately sized tank, with a 25 mm diameter 2 kg mass. Tests are conducted centrally and near corners/edges with a no-puncture pass criteria.

(c) DNV High Speed and Light Craft: Requirement to design sandwich construction for bows with impact resistance. No material impact resistance requirement.

(d) Lloyd's Register: No material level test required but testing of scantling designs may be required. If thickness less than Lloyd's minimum thickness rules provide are proposed, demonstration by test will be required to prove no lower impact resistance is obtained.

(e) FRP Lighting Columns – prEN 40-7: No materials test but a product test is defined whereby a type test to impact protection category 1K08 as specified in EN 50102 (covers protection by enclosure of electrical equipment against external mechanical loads). Five impacts are undertaken around the circumference at the mid-door height position. Failure is defined as a dent no greater than 3 mm. One of the additional benefits of the final product is the system failure under impact by a vehicle (see BS EN 12767) that has lead to the trade name Safecomp for one product.

(f) EUROCOMP Design Guide: Design for impact recognises the different scenarios existing covering the type of threat, the effect on ultimate limit or serviceability limit states, needed to be considered in conjunction with dead and imposed loads and effect of prior service. Under testing the limited value of Charpy and Izod test data is correctly identified, together with the preferred use of plate impact test (e.g. ISO 6603-2).

(g) Wrapped Gas Cylinders - EN 12245: Extensive coverage of this point with both a drop test and a high velocity impact test. Drop test is conducted on two 50% full cylinders from 1.2 metres onto a 600 mm x 600 mm x 25 mm thick cotton fabric reinforced phenolic resin plate (stated Brinell hardness) supported by a 1000 mm x 1000 mm x 100 mm concrete block. The

tests are conducted twice each for five orientations of the cylinder, followed by a burst test (1 cylinder) and a cyclic pressure test (1 cycle). The high velocity tests uses a 7.63 mm calibre shot at 850 m/s, with a specified impact point, with satisfactory pass if no evidence of fragmentation.

Summary

At the material level, ISO 6603-2 for instrumented plate impact test is increasingly recognised and its basic test conditions (e.g. drop height) can be applied to product tests. Product level testing is also permissible.

6.9 CREEP BEHAVIOUR

Pressure Vessels -prEN 13121

Creep performance is covered by the partial design factor A_5 in prEN13121-3. The value can be obtained by experimental testing or can be taken from the default plot, which gives values related to the type and amount of reinforcement. Different values are given along and across the axis for filament wound components between stated angles. The recommended test is undertaken in flexure over a minimum of 1,000hrs. at 15%-25% of the bending strength in the appropriate direction. As with all flexure testing, the result for a complex lay-up (e.g. matt plus fabric) is not necessarily usable for other lay-ups. The creep data is used to plot log strain v. log time from 6 mins to 1,000 hrs, and linearly extrapolated to 200,000 hrs. The creep factor, $f_{c, 2 \times 10^5 \text{ h}}$, is obtained from the ratio of deflections (or strains) at 200,000 hrs and at 6 mins (i.e. 10^{-1} h).

A short term creep test is also available in production control for verifying, but not replacing the previously determined partial design factor. The test is undertaken in flexure according to the ISO creep test (ISO 6602). The creep rate, $f_{c, 24 \text{ h}}$, defines a representative part of the creep curve between 1 h and 24 h. Laminate type tests require 5 repeats, with 3 repeats for production control.

The value, $f_{c, 24 \text{ h}}$, is equal to $100 (d_{24} - d_1)/d_1$, the percentage change in deflection from 1hr to 24hrs as a function of the 1hr deflection. The creep design factor is then obtained from this creep rate using the chart shown in Table 19.

Table 19 Relationship of creep rate and creep design factor – short term test – prEN 13121

A_5	1.00	1.25	1.30	1.40	1.50	1.60	1.70	1.80	1.90	2.00	2.20	2.40
$f_{c, 24 \text{ h}, \%}$	0.00	4.50	5.30	6.85	8.30	9.70	11.00	12.30	13.50	14.65	16.80	18.80

Other documents

(a) GRP piping offshore – ISO/DIS 14692: No material level requirement, but extensive product (i.e. pressurised pipe) testing requirements that form the design/qualification requirements of the standard. Constant pressure test initially on the plain pipe, then a reduced testing requirement of 1,000 hours for all features (e.g. bolted or bonded joints, tees). The full testing programme determines the qualification pressure for a twenty year life.

(b) Water tanks – EN 12380: A 7 day (168h) creep test with the “depression” (i.e. deflection) under the load being reported. For circular tanks, the maximum circumferentially extension, at 1/3rd height from base, allowed is 0.2%, and for rectangular tanks the movement of strengthening ribs, flanges or walls is limited to the lesser than 10 mm or 1% of the length.

(c) DNV High Speed and Light Craft: Not covered.

(d) Lloyd’s Register: Not covered.

(e) FRP Lighting Columns – prEN 40-7: No direct creep requirement, but for verification by testing there is a requirement that after removal of the test load (as per Part 2) the permanent deflection must be less than 10% of the test deflection.

(f) EUROCOMP Design Guide: Recommended to use a reduced creep modulus, as used for thermoplastic design, based on measured data. In the absence of experimental data, some typical data curves are given for 10,000 hour tests extrapolated to 20,000 hours. Reduced moduli at 20,000 hours are 95% unidirectional material in fibre direction, between 45% and 60% for CSM and woven reinforcement and 33% for unidirectional loaded in shear. These data highlight the increased creep rate for matrix dominated properties. The use of time-temperature superposition is also discussed, with recommendation that data are collected below 50% of ultimate strength and below (T_g - 20)°C in order to reduce the possibility of a change in the creep mechanism. Typical creep rupture curves are also given, which show that for lives greater than 10 hours, different fibre formats have similar degradation rates up to 20,000hrs, well short of actual service lives (i.e > 20 years or > 175,400 hours).

(g) Wrapped Gas Cylinders - EN 12245 No creep requirement.

Summary

In cases where creep performance is considered relevant, experimental testing is undertaken with extrapolation ideally limited to 1 decade of time, although a larger extrapolation is used in prEN 13121. To limit the cost and time needed for these test programmes, ISO/DIS 14692 introduces reduced testing by allowing survival testing for 1,000 hours for features based on a master creep rupture curve for plain pipes.

FATIGUE AND DAMAGE BEHAVIOUR

6.10.1 Pressure Vessels -prEN 13121

In prEN 13121, fatigue loading requirements are dealt with through the design factor A₄, which can be obtained from experimental tests, but has a minimal value of 1.25. In the absence of test data, a standard chart is used that has a maximum design factor, A₄, of 2 for a life of 10⁶ cycles.

6.10.2 Other documents

(a) GRP piping offshore – ISO/DIS 14692: Cyclic qualification is an optional property. It is conducted for two specimens at a preferred frequency of 25 cycles per minute, between 10% or

less and 90% or more of the qualified pressure for the pipe in question. Failure within 7,000 cycles is unacceptable. Water can be used as the test fluid and only two repeats are needed.

(b) Water tank – EN 13280: Not covered

(c) DNV High Speed and Light Craft General test requirement if sufficient data does not already exist.

(d) Lloyd's Register: Not covered

(e) FRP Lighting Columns – prEN 40-7: It is stated that due to the low working strain involved, compared to the ultimate strain value, it is not normally necessary to consider fatigue aspects.

(f) EUROCOMP Design Guide: The general approach and description is similar to that reviewed for creep and impact behaviour (e.g. range of situations/failure criteria), except in this case partial safety factors are given which depend both on maintenance/inspection levels and whether a fail-safe component. For example, for a fail-safe component the factor increases from 1.5 to 2.5 as inspection reduces from periodic/detailed to not periodic. The equivalent range for non fail-safe components is 2.0 to 3.0. Guidance is also given in the absence of test data on allowable strains for avoidance of debonding. These range from a reasonable $\pm 0.2\%$ at 10^3 cycles to a low $\pm 0.02\%$ at 10^7 cycles.

(g) Wrapped Gas Cylinders - EN 12245: Required to undertake an “environmental cycle” test after conditioning at $\geq 60^\circ\text{C}$ and 95% RH for 45 hrs. Fatigue test consists of 5,000 cycles between atmospheric and $2/3^{\text{rds}}$ of hydraulic pressure, followed by stabilisation under ambient conditions, conditioning at -50°C , further cycling for 5,000 cycles, re-stabilisation under ambient conditions and 30 cycles at ambient. The two “fatigued” cylinders are then burst tested, when the pass is a failure pressure of 1.6 x the hydraulic test pressure. The damage tolerance test requires two cuts (one longitudinal, 1 transverse) to be machined by a 1 mm thick, ~ 20 mm diameter cutter. Each cut should be half the wall thickness with the length of the base of the cut or “gouge” five times the wall thickness. One cylinder is burst tested, with a 2 x operating pressure pass requirement, and one cylinder pressured cycled to survive 1,000 cycles from ambient pressure to operating pressure.

6.10.3 Summary

For these applications, cyclic loading is normally limited to the final product or sub-component (e.g. plain pipe). Material fatigue level data is only high-lighted in the DNV approvals.

6. 1 FLAMMABILITY

6.11.1 Pressure Vessels -prEN 13121

Part 3 of prEN13121 has limited information indicating that “if required/specified” then external layers should be modified to have the appropriate surface spread of flame characteristics. No values or test methods are given, although, it is noted that there may be local or national fire regulations that have to be met.

6.11.2 Other Documents

(a) GRP piping offshore – ISO/DIS 14692: The coverage of fire is quite comprehensive due to the initial focus of this standard on applications off-shore in the petroleum and gas sectors. The terms fire endurance and fire reaction are used, which are the equivalent of the reaction to fire and fire resistance terms in EN 13501 produced under the Construction Products Directive. Fire endurance covers ability to perform under fire conditions, while fire reaction covers material related aspects (e.g. time to ignition, flame spread, etc.).

A comprehensive fire classification scheme is used, based on three aspects for fire endurance, A-service function, B- fire type and C – performance (e.g. leakage or weepage). A xxx code gives the duration that the pipe is qualified to perform. Two additional codes cover fire reaction, D for heat release and E for smoke and toxicity. The test methods and criteria for codes D and E follow IMO (International Maritime Organisation) Resolutions (i.e. procedures). The approach, described fully in Part 3 – Annex F) is now more sophisticated than the “must be non-combustible” initial requirement that prevented the application of GRP in situations where it has positive advantages due to a combination of properties (i.e. light weight, corrosion resistance and low thermal conductivity) related to application, threat and performance requirements. Annex F proposes 6 codes representing generic applications, which may gain some permanence as “standard” grades.

(b) Water tanks – BS EN 13280: Not covered.

(c) DNV High Speed and Light Craft: Fire retardant resins only referenced regarding use in lifeboats, when an oxygen index test must be passed with a minimum value of 23.

(d) Lloyd’s Register: The fire performance is controlled by a separate part of the regulations, which has material categories of *non-combustible* (does not burn or emit below 750°C), *steel or equivalent* (includes well insulated composite) and *alternative forms of construction* (can also be demonstrated to give steel-like performance when insulated etc.). Fire retardant additives are allowed, but no warning is included to check that other properties (e.g. mechanical) are not degraded.

(e) FRP Lighting Columns – prEN 40-7: Not covered

(f) EUROCOMP Design Guide: Complexity of design is highlighted in Design Guide Part, with more detailed discussion in Handbook Part, related to BS fire standards, such as BS 476. It is likely that this discussion needs to be updated to take account of fire standards, EN 13501, now supporting the Construction Products Directive in Europe. The design aspects include a much wider brief than purely, material properties (e.g. protection, containment). Although the behaviour is closer to the charring behaviour of wood (c.f. buckling/melting of metal sections), the FRP sections tend to be thinner than an equivalent timber design, so that information on residual properties is more important. For pultruded profiles see Section 6.11.3.

(g) Wrapped Gas Cylinders - EN 12245: Filled cylinder (water or air at operating pressure) tested in horizontal and 45°C positions, on top of a wood fire, or at the surface of the liquid for a hydrocarbon fire. Cylinders must not burst, but can leak. Testing is continued until the cylinders are empty or pressure release valve ceases to function.

6.11.3 Summary

Fire performance is often highlighted as an issue for polymer composites, particularly when the requirement is for a “non-combustible material” that prevented composites being specified initially for off-shore applications. However, with better understanding of the different resins or additives available, the use of intumescent coatings, the advantage of high glass-fibre content and low thermal conductivity the use of composites off-shore and in other critical areas, such as light transport is possible. Successful experience has been achieved in practical circumstances, such as, the good response of the high glass-fibre content minesweeper bulkheads during an extensive engine fire [14]. This will be aided by use of EN fire standards that provide a framework that can be applied elsewhere. For example, NPL has recently negotiated with the EU fire regulators on behalf of CEN TC249/Sc2/WG6 a variation of the Single Burning Item (SBI) test (prEN 13823) that will allow pultruded profiles to use the same test and classification procedures as other construction products.

6.12 STATIC ELECTRICITY

6.12.1 Pressure Vessels -prEN 13121

If the build-up of static electricity will cause problems, prEN 13121 suggests that the resistivity should be less than 10^6 ohms as measured by ISO 3915.

6.12.2 Other documents

(a) GRP piping offshore – ISO/DIS 14692: This aspects is dealt with in considerable depth (Annex G, Part 3), even compared with fire performance, which may reflect the less advanced state of the knowledge of static electricity. Several risks are identified including:

- atmospheric electrical fields (lightning strike),
- flow inside pipe (normally OK, unless low conductivity (e.g. kerosene) or a mist,
- mechanical wrapping (low risk),
- escaping mist or sprays,
- spark or brush discharge
- combined circumstances.

In general, in the absence of identified high risks, an upper limit of resistance to earth of 10^8 ohms is acceptable. The standard identifies cases when the pipe itself should be conductive, by for example, including a network of conducting filaments within the pipe wall, using a conductive resin or an external conductive paint. Finally, recommendations on earthing procedures (e.g. lowest points, where fluid can be trapped, etc.) are given. Both IMO resolution A 753 and BS 5958 are referenced.

(b) Water tank – EN 13280: Not covered

(c) DNV High Speed and Light Craft: Not covered.

(d) Lloyd’s Register: Not covered

(e) FRP Lighting Columns – prEN 40-7: Not covered.

(f) EUROCOMP Design Guide: Not covered.

(g) Wrapped Gas Cylinders - EN 12245: Not covered.

6.12.3 Summary

Interest, at present, is restricted to pipe and vessels used in the chemical and oil processing industries, in particular within the off-shore industry.

6.13 PRODUCTION CONTROL

6.13.1 Pressure Vessels - prEN 13121

Several aspects are considered in this standard including:

- documentation,
- handling, storage, packaging and delivery,
- training of staff,
- quality control system.

The quality control level applied is based on a risk assessment of requirements affecting both structural integrity (design, materials of construction, workmanship, service loads, etc.) and consequence of failure (social, environmental, economic, etc.). Three levels are identified, QC1, QC2 and QC3, which are dependent on the following factors:

- | | |
|--------------------------|---|
| • pressure loading | • product flammability |
| • operating conditions | • toxic content |
| • geometry of complexity | • estimated service life |
| • tank capacity | • material properties and operating environment |
| • design temperature | |

These levels control the level of documents required:

- technical documentation
- records and documentation requirements for raw materials
- manufacturing documentation
- quality control tests, records and documentation

with QC1 being the highest requirements. For example, production tests coupons are only needed under QC1 if advanced design properties are used. The requirements are specific covering 31 different aspects in total. Additional consideration is required if any special circumstances apply (e.g. earthquakes, storage of particularly dangerous products).

Because the material is formed at the same time as the product, it is important that a full production control system is instigated. The quality control is set at three levels depending on the pressure, temperature, geometric complexity, etc. involved. The approach given is:

- Inspection includes permissible defects, which are set separately for the inner (process) laminate (essentially none), structural laminate and outer (non-process) laminate,
- Check on tolerances, smooth contours and thickness changes ($\geq 6/1$ ramps),
- A survey of cure is carried out of the inner and outer surfaces using the Barcol hardness test, with thermoplastic linings checked by spark testing,
- Hydraulic pressure test at ambient temperature and vacuum tests,
- Thickness check, which must be not more than 10% below specification or 3 mm, whichever is the lower value,
- Coupon testing, which can either be on cut-outs or test plates produced at the same time as the vessel. For round sections that are difficult to test, physical checks on the laminate thickness, orientation and construction, weight of glass-fibre and lap-shear strength may give a good indication of laminate strength.

Instructions are also given for prototype testing and on-site built tanks/vessels. The works requirements define separate areas for raw material storage, preparation of resins, preparation of reinforcement, laminating, welding, assembly and grinding. Factory production control is covered in Part 3, which requires the manufacturer to keep records for five years (see EN 10204).

6.13.2 Other documents

(a) GRP piping offshore – ISO/DIS 14692: A significant point included is the requirements for the invitation to tender that the user should supply that fully describes the intended use (e.g. media to be carried, minimum and maximum temperatures, etc.). This is important in view of the amount of “design for purpose” that is involved in these products. In addition, there is given a full list of quality control aspects to be considered, such as storage of raw materials, training and certification of workforce including inspectors and maintenance of production records for at least five years. No specific production factory conditions required.

(b) Water tanks – BS EN 13280: No requirement other than type testing.

(c) DNV High Speed and Light Craft: Comprehensively covered under storage of raw materials, manufacturing conditions, production procedures and workmanship, manual lamination, spray moulding, secondary bonding and quality control. Points to be noted include:

- manufacturing conditions to be at $\geq 18^{\circ}\text{C}$ for 24 hours before lamination commences and then to be maintained within $\pm 3^{\circ}\text{C}$ within each 24 hrs.,
- RH should be less than 80% to avoid condensation, or above 40% for spray moulding,
- surfaces for secondary bonding should be ground if cured for > 5 days, or >1 day for resins with wax additions,
- warning to avoid “excessive” heat generation during cure,
- cure should be for 48 hours at $\geq 18^{\circ}\text{C}$, or shorter period at a higher temperature.

(d) Lloyd's Register: General requirements for good practice, including use of ISO 9000. Moulding shop requirements are above 16°C and normally less than 25°C, and below 70% RH. Importantly, all aspects of production are at all times open to inspection by LR Surveyors. Further details are given of the fabrication process (e.g. gel-coats 0.5 mm thick with specified first reinforcement layer, CSM between woven layers (i.e. ILSS < than 13.8 MPa) and for spray laminating the fibre length must always be greater than 25 mm, and > 35 mm for structural parts). Following lamination, a minimum of 12 hours is recommended for ambient cures (or manufacturer's recommendations used), also to achieve a Barcol hardness of > 20 before removal from the mould and above 35 before removal outside the controlled environment.

(e) FRP Lighting Columns – prEN 40-7: Type approval can be by testing or calculation, with re-testing if there significant (undefined) changes in raw materials or the production process, which could change (undefined) the finished product.

(f) EUROCOMP Design Guide: General discussion of good practice with some specific details (e.g. workshop at $\geq 17^{\circ}\text{C}$, or as directed by resin manufacturer). No mention of laminator requirements. Requirements for gel coat thickness (i.e. ~ 500 microns, but all within 400 to 600 microns) with permission needed to use double gelcoats.

(g) Wrapped Gas Cylinders - EN 12245: Requirement for visual, dimensional and water capacity checks for 10% of production, but no requirements given for approval other than given on design drawings. Pressure test for 100% of production, with burst tests for 1 cylinder per batch and cyclic pressure test for 1 cylinder per 5 batches.

6.13.3 Summary

Some consistency exists for production control of principally wet process routes (e.g. hand lay-up, spray lay-up, filament-winding, resin injection). Other aspects, such as, type testing are increasingly well covered.

6.14 CURE ASSESSMENT

6.14.1 Pressure Vessels -prEN 13121

The assessment of cure during the manufacturing process (see clause 15.6.2) is undertaken via Barcol hardness to establish that the resin "has reached its appropriate level of cure". Measurement of the base-line Barcol hardness value was a requirement under Part 1 on Raw Materials. It is not clear what value the check is when the requirement is to achieve 80% of the Barcol harness, which is not a direct value of the degree of cure (c.f. as for Tg). There is also in some cases (not clearly identified) the need to undertake an acetone test, whereby the surface is checked for tackiness after a cloth soaked in acetone has been laid on the surface for 3 mins. An absence of tackiness is considered to confirm satisfactory cure.

6.14.2 Other documents

(a) GRP piping offshore – ISO/DIS 14692: Required to check 1% of production cure using the same technique as used in qualification. Criteria are that Tg (by one of two methods) should be 90% of qualification value in $^{\circ}\text{C}$, styrene content less than 2%, or Barcol hardness less than 90%

of minimum qualification value. As with other assessment criteria, production since the last successful test results must be scrapped, but a re-test facility is available.

(b) Water tanks – BS EN 13280: Type testing or re-testing requires the DTUL to be measured.

(c) DNV High Speed and Light Craft: Only controlled in resin approval.

(d) Lloyd's Register: Barcol hardness as noted in previous section

(e) FRP Lighting Columns – prEN 40-7: Covered only via requirement for maintaining Barcol hardness and DTUL values but limited type testing requirement or traveller coupons.

(f) EUROCOMP Design Guide Importance of obtaining full cure noted but no specific requirement.

(g) Wrapped Gas Cylinders - EN 12245: Not covered.

6.14.3 Summary

Barcol hardness still most frequently referenced. However, as noted elsewhere Barcol hardness, as for Tg and DTUL, are not direct measures of the degree of cure. On-line monitoring has not developed sufficiently, although a new NPL programme is aimed at encouraging industrial adoption through a research and demonstration programme on these techniques. These techniques will be more applicable as manufacturers move to more automated and/or closed mould processes, such as RTM, filament winding and pultrusion [15].

6.15 NON-DESTRUCTIVE TESTING

6.15.1 Pressure Vessels -prEN 13121

Non-destructive testing is limited to Barcol hardness survey of the inner and outer surfaces to ensure resin has “reached the appropriate level of cure”.

6.15.2 Other documents

(a) GRP piping offshore – ISO/DIS 14692: NDE only considered via a cross-reference to NORISK M-622, which includes radiography and acoustic emission as available methods. More detailed information is given on NDE techniques for detecting in-service details.

(b) Water tanks – BS EN 13280: Not covered

(c) DNV High Speed and Light Craft: Not covered.

(d) Lloyd's Register: Ultrasonic gauges recommended for checking thickness, which should be calibrated on identical laminate samples. No other techniques mentioned.

(e) FRP Lighting Columns – prEN 40-7: Not covered.

(f) EUROCOMP Design Guide: Techniques listed with potential application to bonded joints.

(g) Wrapped Gas Cylinders - EN 12245: Not covered.

6.15.3 Summary

Application of NDE techniques are little developed outside of the aerospace industry, where C-scan ultrasonics predominates. An important encouragement to a greater use will be through providing traceable procedures [6] for defect detection with guidance on the criticality of detected manufacturing or in-service damage.

6.16 TOLERANCES

6.16.1 Pressure Vessels -prEN 13121

This aspect is not covered in prEN13121

6.16.2 Other documents

(a) GRP piping offshore – ISO/DIS 14692: Tolerances, minimum only, are given for wall thickness that vary with pipe diameter as follows:

- below 600 mm diameter – lower of 3 mm or 60% of wall thickness
- 600 mm – 1200 mm diameter – lower of 4.5 mm or 40% of wall thickness
- greater than 1200 mm diameter - lower of 6 mm or 25% of wall thickness

(b) Water tank – EN 13280: Requires panel length, breadth and flange height to be within ± 1 mm, squareness within ± 1.5 mm on diagonals, flange angle within $\pm 1^\circ$, and flange bolt holes diameter, pitch and line-of-centres, ± 0.5 mm.

Table 19 illustrates well the different tolerances achieved through using different process routes. Matched tools give a tighter tolerance with small differences for thin panels, but significantly better (x 4) for thicker panels (> 12 mm). The detailed data provides useful reference data.

Table 20: Tolerances for flange and diaphragm thickness as per EN 13280.

Nominal Thickness, mm	Moulding from open mould, mm	Moulding from closed mould, mm	Moulding from matched moulds, mm
< 1.5	+ 0.50, -0.25	± 0.20	± 0.18
1.5 to < 3	± 0.75	± 0.30	± 0.20
3 to < 6	± 1.1	± 0.50	± 0.30
6 to < 12	± 1.5	± 0.75	± 0.40
12 to < 25	± 2.0	± 1.40	± 0.50
25 and greater	± 3.0	± 1.90	± 0.65

(c) DNV High Speed and Light Craft: No specific dimensional requirements.

(d) Lloyd's Register: No specific dimensional requirements, except as under production control.

(e) FRP Lighting Columns – prEN 40-7: Two aspects are covered, wall thickness – which must not vary by more than $\pm 20\%$ at any particular cross-section, and straightness – less than 3 mm deviation using a 1 m straight edge. The straightness can also be assessed for the full length of the column. The thickness control appears generous as buckling performance is dependent on the thickness.

(f) EUROCOMP Design Guide: Tolerances are given, but this must be taken as general guidance as it applies to all unspecified products. Width and height, straightness and squareness are all set at slightly greater than 0.1% of the dimension. Flatness is set similarly at 3 mm over a 1 metre length.

(g) Wrapped Gas Cylinders - EN 12245: Dimensions, weights, capacities checked for 10% of production against drawings but no criteria given in the standard. For the burst test, the failure pressure must be greater than 80%, and not more than 120%, of the minimum pressure found in the qualification tests.

(c) Summary

In most product areas, appropriate procedures are being developed that provides an improved and demonstrated ability to control production quality.

6.17 DEFECTS

6.17.1 Pressure Vessels -prEN 13121

Table 15.6 in prEN 13121-3 lists 15 defects types with different acceptance criteria for the inner process shell (thermoplastic liner only), structural laminate layers and outer (non-process surface). For the structural laminate layers, no defects are allowed except resin dry spots (maximum 10 per m^2 with a total area not greater than 100 m^2) and entrapped air (less than 1.5 mm diameter and not more than 2 per 100 mm^2).

6.17.2 Other documents

(a) GRP piping offshore – ISO/DIS 14692: A comprehensive list, in Part 4, includes basic design errors and general aspects of process control (e.g. inadequate cure, visible defects) and transport and handling damage. Defects are brought together in this Part of the standard with tables each for those occurring during fabrication, handling and storage; during operation, with a summary table of all defects with corrective action at each. In most cases the prescribed corrective action is repair for minor defects and replacement for major defects. There appears to be no definition of “minor” and “major” defects.

(b) Water tanks – BS EN 13280: Defects levels are covered by the requirement for internal surfaces to be “smooth, even texture, and free from imperfections that may distract from performance”. All cut edges in contact with water shall be sealed by the resin used for the inner tank surface. Bolt holes must be drilled at the manufacturer's premises (i.e. not on site).

- (c) DNV High Speed and Light Craft: Only covered with regard to ensuring adequate compaction of the reinforcement and removal of voidage.
- (d) Lloyd's Register: Minor cosmetic faults can be repaired using an agreed procedure, but must be reported to Surveyor. For major structural repairs a full plan must be prepared and agreed with LR.
- (e) FRP Lighting Columns – prEN 40-7: No specific defect requirements except that the column and brackets shall have a smooth finish with a suitable coating that prevents fibre break-out, which is applied after sealing cut edges.
- (f) EUROCOMP Design Guide: Little specific requirements except that voidage should be less than 5% by volume.
- (g) Wrapped Gas Cylinders - prEN 12245: Required that internal and external surfaces are free from defects, which could affect safe working of finished cylinders, but no details are included.

6.17.3 Summary

Some commonality is developing, but there is a need for agreed definitions and some increased research into the relationship between the defect and its effect (i.e. criticality of the defect, and repair action required). The pultrusion standard, prEN 13706 includes a longer list of similar defects, based on an equivalent ASTM standard. A new joint NPL/AEAT project is aimed at developing assessment procedures for defect criticality.

6.18 APPROVAL OF LAMINATORS

6.18.1 Pressure Vessels -prEN 13121

In Annex E of prEN 13121-3 are given the requirements for approval of hand laminators, which are based on fabrication of a three test items (a flat panel, a seam joint and a branch joint). Approval is based on undertaking standard tensile and shear tests for comparison with the original qualification values for the flat plate only, and visual against defect levels in Section 6.17, Barcol hardness, volume fraction and fibre arrangement, following resin burn-off, for all three specimens. Re-approval is required after two years or if there is a period of six months or more inactivity.

6.18.2 Other documents

- (a) GRP piping offshore – ISO/DIS 14692: Required for workshop staff and inspectors and procedures related to TWI approval certificates CSWIP-GRP-1 and 2 published in 1996 specifically on installation of composite pipes.
- (b) Water tanks – BS EN 13280: Not covered.
- (c) DNV High Speed and Light Craft: Lamination required by “skilled operators”, but no details given of approval procedure.

(d) Lloyd's Register: Laminators required to be "trained and qualified to the level required by the quality plan", but no details given.

(e) FRP Lighting Columns – prEN 40-7: No requirement for process control or staff qualification.

(f) EUROCOMP Design Guide: Not covered.

(g) Wrapped Gas Cylinders - EN 12245: Not covered.

6.18.3 Summary

The most useful document is prEN 13121 in providing a full assessment procedure that can be undertaken periodically. In the longer term, however, in formal courses and qualifications are required, as planned by SEECOM and the Polymer National Training Organisation as noted in a recent *Foresight* study of the UK polymer composites industry [15].

6.19 HANDLING, STORAGE AND PACKAGING

6.19.1 Pressure Vessels -prEN 13121

As most haulage and installation firms will be more familiar with steel tanks, it is important that the requirements of reinforced plastics are clearly identified. Part 4 of EN13121 has good coverage of the special needs for handling of RP vessels and tanks. This covers:

- the correct handling using specified lifting points and procedures (see detailed drawings in annex A),
- the need to avoid impacts,
- the need to spread loads by using flat woven webbing slings or non-metallic ropes (i.e. non metallic straps), avoidance of abrasion (as a relatively soft material).

Further instructions are given on installation in either the vertical or horizontal mode as appropriate to the vessel design. As previously, if a flat-bottomed vessel placed directly on the ground, it must be free from local pressure points (i.e. stones) so a bedding material is often recommended. Support surfaces should be fall within 2 mm per metre with a maximum deviation of 5 mm with a maximum vertical deviation of the vessel of 0.5°. Horizontally supported vessels on saddles etc. should avoid uneven or local loads as with the shipping requirements.

Other aspects such as bolting, attachment of flanges and pipework must also avoid overstressing due to lack of support or over-tightening of bolts. No limits are given on bolting torques, other than following manufacturers recommendations. A check list is included in Annex C.

6.19.2 Other documents

(a) GRP piping offshore – ISO/DIS 14692: Extensive information given in Part 4 regarding the installation of the pipework system, which is the approach necessary (cf production of pipe lengths). Consequently, the majority of the information refers to the fabrication of joints, and

their inspection, in order to produce the required pipework system. Warnings are included on the susceptibility of GRP piping to damage from “impact, sharp edges or scratching” and the need to avoid use of “chains, wire ropes and clamps” for lifting. Stacking procedures for pipe lengths are given.

(b) Water tanks – EN 12380: Water tanks has a similar level ground requirement, to pressure vessels, of 2 mm in 1 m, but a slightly different maximum of 6 mm in any 6 metres measured laterally or diagonally. For a suspended floor or beams, the combined deflection of the supported full tank shall be less than 1/500th of the span.

(c) DNV High Speed and Light Craft: Not covered.

(d) Lloyd’s Register: Not covered except by minimum Barcol hardness of 35 to be achieved before removal from the controlled environment. In practice there will be an extensive fitting out period of the final craft.

(e) FRP Lighting Columns – prEN 40-7: Not covered.

(f) EUROCOMP Design Guide: General guidance given.

(g) Wrapped Gas Cylinders - EN 12245: Not covered.

6.19.3 Summary

The detail provided by the pipe and pressure vessel standards should be applied more widely as the relative softness, low failure strains, local damage potential need to be highlighted in all applications. In particular, haulers, installers etc. need to be advised of the differences of GRP vessels compared to the more usually handled steel components.

6.20 MAINTENANCE AND REPAIR

6.20.1 Pressure Vessels -prEN 13121

Annex E of EN13121 covers “*Guidance notes for maintenance*” under the following sections:

- general
 - highlights need for “instructions” to be available for each following item.
 - monitoring controlled by user using appropriate standards and statutory regulations.
- service conditions
 - materials and design are “design specific”, indicating that they should not be used for another purpose without proof of conformity and any special measures needed identified, including variation in working pressures, rate of flow and emptying etc.
- cleaning and servicing
 - trained operators, vessels properly emptied and isolated from rest of system, requirements of personal protective equipment and safety equipment met, liquids and waste to be properly controlled.

repairing and replacing

- equipment out of service, choice of repair should consider availability, safety and economy, temporary repairs need special monitoring, repairs by manufacture at their plant or using similar conditions on-site, repair should use accepted procedures for laminating, etc. (but source not stated).

inspection and test

- user's inspection in accordance with specified maintenance procedures, visual inspections especially for general state, impact damage, erosion/ablation, inspect before and after pressure tests.
- tests can include acoustic emission, pressure tests and spark testing of liners.

documentation

- inspection shall be recorded and kept until vessel is decommissioned.

While this is all acceptable, there is little that is specifically for reinforced plastic vessels, except by inclusion, as no references are given to trained laminators, standard procedures for repair etc.

6.20.2 Other documents

(a) GRP piping offshore – ISO/DIS 14692: Need for repair procedures to be agreed No detailed instructions included.

(b) Water tanks – EN 12380: Not covered.

(c) DNV High Speed And Light Craft: Not covered.

(d) Lloyd's Register: Not covered

(e) FRP Lighting Columns – prEN 40-7: Not covered.

(f) EUROCOMP Design Guide: Need for agreed procedures highlighted and confirmation by test. Guidance on surface preparation (e.g. abrasion and a suitable chemical primer) and need for adequate curing are included. As well as general advice on cleaning and painting, specific details are included (e.g. cracks up to 0.5 mm can be filled with an epoxy solution for at least 50 mm past the end of cracks). Also advice given against the use of burn-off and paint-strippers containing methylene dichloride.

(g) Wrapped Gas Cylinders - EN 12245: Not covered.

6.20.3 Summary

An important area where progress is being made in providing the level of information and confidence needed, particularly by asset owners. An area where good practice can be beneficially applied more widely. The GRP minesweepers, again, demonstrate that structural repairs are possible as when a new bow section was bonded on following a major collision [14]. A previous DTI project at PERA researched this area [16].

7. SUMMARY

This report has reviewed the development and implementation of the materials infrastructure supporting the development and use of composite material products. These products cover a wide range of applications and approaches. Product design is increasingly moving from a prescriptive-based approach to a performance-based approach. The earlier availability of these design codes was highlighted as an important requirement for the UK polymer composites industry [15].

It has been shown that many of the required facets are being developed as the industry matures, so that, constituent material supply and generation of property data can be undertaken according to international standards. These standards are increasingly supplied with the essential precision data that is necessary for supporting free trade and product liability requirements. Provision of precision data for new test methods has been an important aspect of many NPL projects, both national and international. The NPL research programmes on composite materials have been clearly focussed on supplying this infrastructure and has many contributed. on several levels in a planned and progressive manner.

Several aspects, as detailed in Section 6, are increasingly covered by procedures as documented in the product codes and standards reviewed. Particular, aspects to note related to polymer matrix composites are the needs for:-

- consistency in defining allowable service temperatures,
- agreed procedures for chemical performance,
- simplified material qualification procedures,

In the area of laminate mechanical properties [1], the approach and conditions represented in the BS EN ISO standards allow them to replace the CRAG informal recommendations [7], and ultimately the aerospace standards for generic properties.

Other areas that would aid the adoption of polymer composites in new applications includes:-

- recognition of implementation of handling, maintenance and repair requirements,
- improved NDE techniques,
- agreed defect assessment procedures,
- improved procedures for cure assessment,
- recognition of implementation procedures for defects, tolerances and quality control.

These facets show that the industry has moved away from its “bucket and brush” and back-street image, with many significant products made in composites with structural and other requirements outside of the glamour areas of aerospace and Formula 1 racing. These other applications include pressure vessels, process piping, wind-turbine blades and minesweepers. All aspects are summarised in the chart given below.

TOPIC	SUMMARY
Constituent materials	A satisfactory basis exists in ISO series for test and specification purposes, which is being developed further.
Laminate test methods	Established EN ISO series is being applied as new or revised documents are produced. The mechanical tests, harmonised with ASTM, can replace CRAG test methods.
Materials properties - default	Limited data that compares fairly well between different sources. EUROCOMP has most (manufacturers) data. Other sources need to be referenced for full databases.
Materials properties - measured	Wide variation in requirements but including normally tensile strength and modulus.
Temperature capability	Important property controlling service temperature capability, but alternative methods for Tg/DTUL gives rise to in-consistencies.
Water absorption	ISO 62, or similar procedures, used for both basic data and for application orientated data (e.g. water tanks).
Chemical resistance	Important property for many applications (+ good specific properties). Need for agreed universal procedures, based on ISO 175/prEN 13121.
Impact resistance	Material level tests follows ISO 6603, or similar, with expected application relevant tests of final products.
Creep behaviour	In products of relevance, centered around product testing for qualification, with material tests or defaults for design.
Fatigue and damage behaviour	Similar to creep situation.
Flammability	Initial negative industry response as combustible, now replaced by wider and more enlightened use meeting individual requirements.
Static electricity	Mainly of interest in off-shore industry, where ISO/DIS 14629 has most comprehensive information.
Production control	Some consistency developing for wet resin production facilities. Type testing is developing well that demonstrates commitment to high and consistent quality.
Cure assessment	Still mainly dependent on Barcol hardness, but expected that increase in automated, closed mould production will encourage use of other techniques.
Non-destructive testing	Limited use and requirements outside extensive use of C-scan ultrasonics for assessing high performance composites.
Tolerances	In most product area this issue is being covered, which will demonstrate to purchasers commitment to quality.
Defects	Some commonality of approach but agreement needed on definitions and procedures for assessment of defect critically.
Approval of laminators	Practical scheme given in prEN 13121 but national approval schemes to be encouraged.
Handling, storage and packaging	Guidance in prEN 13121 should be applied more widely to make installers and users aware of possibilities of handling damage.
Repair and maintenance	Agreed procedures need to be developed on a universal basis, together with specific product considerations

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All BSI, EN and ISO standards, including copies of draft standards available for public comment, are available from BSI Customer Services, 389 Chiswick High Road, London W4 4AL. (Tel + 44 (0) 20 8996 9001).

Annex B STANDARDS FOR FIBRE REINFORCED PLASTICS

Reinforcing fibres and fibre products - Test methods and specifications

ISO 1887: Glass fibre – size content

ISO 1888: Glass fibre – density

ISO 2078: Glass fibre - designation yarns

ISO 3341: Glass fibre – breaking force – yarn

ISO 10119: Carbon fibre – density

ISO 10548: Carbon fibre – size content

ISO 10618: Carbon fibre – breaking force – yarn

ISO 11566: Carbon fibre – breaking force – single filament

ISO 11567: Carbon fibre – diameter

ISO 13002: Carbon fibre – Designation system for filament yarns

ISO 1889: all fibres – linear density

ISO 1890 all fibres – twist

BS 4045:1966. Specification for epoxide resin pre-impregnated glass fibre fabrics.

ISO 9291. Textile glass reinforced plastics – rovings – preparation of unidirectional plats by winding. (being replaced by ISO 1268)

BS ISO 10371:1993. Fibre reinforced plastics. Braided tapes for composite materials reinforcement. Basis for a specification.

BS EN 13003:1999. Para-aramid fibre filament yarns.

ISO/DIS 15039. Textile glass rovings – determination of solubility of sizing

ISO/DIS 15100. Plastics – reinforcement fibres – chopped strands – determination of bulk density

Moulding compound / pre-impregnates – test methods and specifications

prEN yyyyy: Reinforced plastics composites – Specifications for thermoset moulding compounds (SMC, BMC, DMC)

prEN yyyyy: Determination of flowability

prEN 2833: Aerospace: Reinforced Plastics – Glass fibre pre-impregnates

ISO 9782. Plastics; reinforced moulding compounds and prepreps; Determination of apparent volatile matter content.

ISO 10352. Fibre reinforced plastics Moulding compounds and prepreps – Determination of mass per unit area.

ISO 11667. Fibre reinforced plastics – moulding compounds and preregs – Determination of resin, reinforced fibre and mineral filler content – Dissolution methods.

ISO 12115. Fibre reinforced plastics – thermosetting moulding compounds and preregs – determination of flowability, maturation and shelf life.

ISO 12114 – Fibre reinforced plastics – thermosetting moulding compounds and preregs – determination of cure characteristics

BS EN 12575:1998. Plastics. Thermosetting moulding compounds. Determination of the degree of fibre wet out in SMC.

prEN 13677: Reinforced Plastics Composites – specifications for thermoplastic moulding compounds (GMT)

ISO 15034: Preregs – resin flow

ISO 15040: Preregs – cure time

Resin systems

BS 3532:1990. Specification for unsaturated polyester resin systems for low pressure fibre reinforced plastics.

Many other standards for unreinforced thermoplastic and thermoset resins applicable (www.bsi-global.com)

Fibre reinforced plastics (or polymer matrix composites)

BS 6564-3:1990. Polytetrafluoroethylene (PTFE) materials and products. Specification for E-glass fibre filled PTFE.

Laminated materials – Mechanical property tests

BS EN ISO 75-3:1996. Plastics. Determination of temperature of deflection under load. High-strength thermosetting laminates and long-fibre-reinforced plastics

BS EN ISO 527 – Part 1 Plastics – Determination of tensile properties – General principles

BS EN ISO 527 – Part 4: Determination of tensile properties – Test conditions for isotropic and orthotropic fibre-reinforced plastic composites

BS EN ISO 527-5: Plastics. Determination of tensile properties. Test conditions for unidirectional fibre-reinforced plastic composites

ISO 72. Textile glass reinforced plastics; determination of loss on ignition

ISO 1268: Fibre reinforced plastics – test plate manufacturing methods

ISO 2818: Plastics – Preparation of specimens by machining

ISO 3597. Textile glass reinforced plastics; Determination of mechanical properties on rods made of roving reinforced resin (Parts 1-4)

ISO 4899 Textile glass reinforced thermosetting plastics; properties and test methods.

ISO 10350-2: Plastics – acquisition and presentation of comparable single-point data – Part 2: long fibre reinforced plastics

ISO/FDIS 13003: Fibre reinforced plastic composites – determination of fatigue properties under cyclic loading

BS EN ISO 14125: Fibre-reinforced plastics composites – determination of flexural properties

BS EN ISO 14126: Fibre reinforced plastic composites – determination of the in-plane compression strength

ISO/DIS 14127. Composites – determination of resin, fibre and void content of composites reinforced with carbon fibre

BS EN ISO 14129: Fibre reinforced plastic composites – Determination of the in-plane shear stress/shear strain, including the in-plane shear modulus and strength by the $\pm 45^\circ$ tension test method

BS EN ISO 14130: Fibre reinforced plastic composites – determination of apparent interlaminar shear strength by short-beam method

ISO 15024: standard test method for Mode I Interlaminar fracture toughness G_{Ic} of unidirectional fibre reinforced polymer matrix composites

ISO 15310: Fibre reinforced plastic composites – determination of in-plane shear modulus by plate twist

Thermal analysis test methods

ISO 6721: Plastics – Determination of dynamic mechanical properties

ISO 11357: Plastics - Differential scanning calorimetry

Final Products –Test method and Product Standards

BS EN 1013-2:1999. Light transmitting profiled plastics sheeting for single skin roofing. Specific requirements and test methods for sheets of glass fibre reinforced polyester resin (GRP).

BS 4154:1985. Corrugated plastics translucent sheets from thermo-setting polyester resin (glass fibre reinforced).

BS 5480:1990. Specification for glass fibre reinforced plastics (GRP) pipes and fittings for water supply or sewerage.

ISO 7370. Glass fibre reinforced thermosetting plastics (GRP) pipes and fittings; nominal diameters, specified diameters and standard lengths.

ISO/FDIS 7432 Glass reinforced thermosetting plastics (GRP) pipes and fittings-test methods to prove the design of locked socket and spigot joints

BS 7491. Glass fibre reinforced plastics cisterns for cold water storage

ISO/DIS 7509 Plastics piping systems – glass reinforced thermosetting plastics (GRP) pipes – determination of time to failure under sustained internal pressure

ISO 7510. Plastics piping systems- glass reinforced plastics (GRP) components

ISO 7511. Plastics piping systems – glass reinforced thermosetting plastics (GRP) pipes and fittings – test methods to prove the leaktightness of the wall under short-term internal pressure.

ISO 7684. Plastics piping systems – glass reinforced thermosetting plastics (GRP) pipes – determination of the creep factor under dry conditions.

ISO 7685. Plastics piping systems - glass reinforced thermosetting plastics (GRP) pipes – determination of initial specific ring stiffness.

ISO/DIS 8483 glass reinforced thermosetting plastics (GRP) pipes and fittings – test methods to prove the design of bolted flange joints.

ISO/DIS 8513. Plastics piping systems - glass reinforced thermosetting plastics (GRP) pipes – determination of initial longitudinal tensile properties.

ISO 8521 Plastics piping systems - glass reinforced thermosetting plastics (GRP) pipes – determination of the apparent initial circumferential tensile strength.

ISO/DIS 8533. glass reinforced thermosetting plastics (GRP) pipes and fittings – test methods to prove the design of cemented or wrapped joints.

ISO/DIS 8639 Glass reinforced thermosetting plastics (GRP) – test methods for leaktightness and resistance to damage of flexible and reduced-articulation joints.

ISO 10466. Plastics piping systems - glass reinforced thermosetting plastics (GRP) pipes – test method to prove the resistance to initial ring deflection.

ISO/DIS 10467. Plastics piping systems for pressure and non-pressure sewerage – glass reinforced thermosetting plastics (GRP) based on unsaturated polyester (UP) resin.

ISO/DIS 10468 plastics piping systems - glass reinforced thermosetting plastics (GRP) pipes – determination of the long-term specific creep stiffness under wet conditions and calculation of the wet creep factor.

ISO/DIS 10471. Plastics piping systems - glass reinforced thermosetting plastics (GRP) pipes – determination of the long-term ultimate bending strain and the long-term ultimate relative ring deflection under wet conditions.

ISO/DIS 10639. Plastics piping systems for water supply with or without pressure – glass reinforced plastics (GRP) based on unsaturated polyester (UP) resin.

ISO 10928. Plastics piping systems - glass reinforced thermosetting plastics (GRP) pipes and fittings – methods for regression analysis and their use.

ISO 10952. Plastics piping systems - glass reinforced thermosetting plastics (GRP) pipes and fittings – determination of the resistance to chemical attack from the inside of a section in a deflected condition

prEN 13706: Fibre reinforced plastics – Specification for pultruded profiles

prEN 13923. Filament-wound GRP pressure vessels. Materials, design, manufacture and testing

ISO/DIS 14692:2000, *Petroleum and natural gas industries - GRP piping (4 Parts)*

ISO/DIS 14828. Plastics piping systems - glass reinforced thermosetting plastics (GRP) pipes – determination of the long-term specific ring relaxation stiffness under wet conditioned and calculation of the wet relaxation factor

Further information available from

www.npl.co.uk/cog/index.html

www.bsi-global.com

www.iso.ch