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DISSEMINATION, STANDARDISATION AND REVIEWS

Thick Composites

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ABSTRACT

The complex requirements and physical magnitude of many engineering structures for use in transportation (road, sea and air), bridges, buildings, electrical, nuclear, chemical plant and off-shore applications requires versatile materials that can be tailored to meet demanding service conditions. Composite materials offer the user/designer the flexibility and the range of properties (i.e. mechanical, thermal and electrical) to meet many of these requirements. These materials have tended to be used for aerospace and marine applications involving thin membrane structures, but in recent years their use in large thick structures, often complex in shape, has expanded. The wide range of processing routes, fibre types and formats (two- and three-dimensional architecture), and resin matrices provides the means of producing thick complex engineering structures suitable for use in safety critical applications and hostile environments, such as infrastructure for bridges and off-shore platforms.

This report reviews key issues relating to the design, manufacture and utilisation of thick composites, highlighting issues that need to be resolved or better understood in order for these materials to fulfil their full market potential. These issues include processing, testing (including standardisation), design and analysis, non-destructive evaluation, environmental durability, impact and fire resistance. The report describes a variety of low- and high-cost applications and the potential for expansion in these areas.

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1. INTRODUCTION

The wide range of properties (i.e. mechanical, thermal and electrical) obtainable using polymer matrix composites (PMCs) and the ability to produce thick, complex engineering structures using these materials has resulted in a steady increase in the use of PMCs in safety critical applications. These materials have tended to be used for their weight reduction and corrosion resistance qualities. The use of these materials has mainly involved thin membrane structures, but in recent years their use in large thick structures (i.e. greater than 20 mm thick), often complex in shape, has expanded, particularly for use in aerospace/defence, transportation (road, sea and air), bridges, buildings, electrical, nuclear, sewerage (water treatment) and chemical plant, and off-shore applications.

Composites pose significant problems to designers and maintenance engineers due to their complexity, and hence a number of technical issues need to be considered when using composite materials in large secondary and primary load-bearing structures. This report reviews issues relating to thick composites that need to be resolved or better understood in order for these materials to fulfil their full market potential. Issues considered in this report include processing, testing (including standardisation), design and analysis, inspection, environmental durability and impact resistance.

The report is divided into eight (8) sections (including Section 1, Introduction). Section 2 considers engineering applications involving thick composite sections. Section 3 examines various manufacturing processes for producing thick laminated components/structures in terms of cost and shape considerations, thickness limitations, material suitability and non-destructive evaluation (NDE). Mechanical testing of thick-sections and associated standards are considered in Section 4. Consideration is given to the applicability of existing techniques, which are being used to characterise thin laminates.

Section 5 considers three-dimensional analysis requirements for thick laminated composite structures. Durability, impact resistance and flammability issues are considered in Section 6. A brief discussion and concluding remarks are presented in Section 7. The report concludes with recommendations for future research and development work (Section 8).

2 APPLICATIONS

This section examines industries/applications where thick composites are currently being used or being considered for use in the future.

2.1 PROCESS PLANT

The chemical plant, water purification and sewerage industries are major users of composite materials, investing large amounts of capital per annum in plant and equipment manufactured from these materials. Composite materials offer the industries an extremely wide range of corrosion resistance products, low maintenance costs, and greater flexibility in component design, than is available with conventional materials. Glass fibre-reinforced plastic (GRP) pipes and tanks have been in-service since the early 1960's in chemical and sewerage plants (see Figure 1). Many of these structures have been installed underground. During the same decade, steel underground gasoline tanks were replaced by composite equivalents because the former were prone to leakage and corrosion. GRP components are highly competitive with those manufactured from stainless steel or other materials.

Figure 1: Chemical plant containing GRP storage vessels and pipework.

GRP is being used to produce large complex components, such as storage tanks, pressure vessels (Figure 2), pipes and stacks. Storage vessels up to 25 metres in length and 6 metres in diameter with wall-thickness in excess of 50 mm have been produced. These structures invariably contain a variety of features (e.g. openings and branches) for connecting, supporting and inspection of the structure. GRP vessels are being used to store hazardous and corrosive fluids (e.g. acids, solvents and gasoline). Operating temperatures and pressures range from 0 to 110 °C and 0 to 10 bar absolute (see [1-5]).

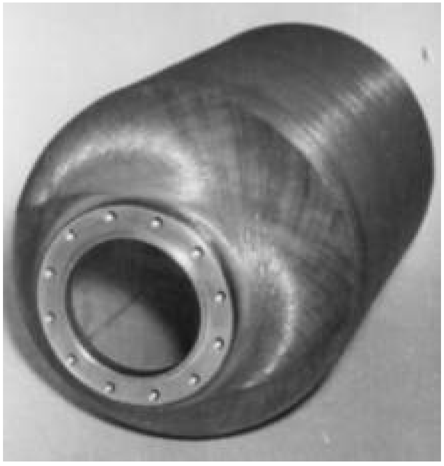

Figure 2: Filament wound vessel with end fitting.

The production of storage tanks, pressure vessels and pipework systems in GRP does not require high capital investment. Consequently, there are a large number of small suppliers servicing the chemical plant, water purification and sewerage industries without the technical, engineering and quality assurance/quality control that larger suppliers are able to direct towards their products. Although, national and international standards bodies have been addressing this issue for sometime, there is still an immediate need to provide readily accessible, user-friendly guidance for material selection, testing and design of thick GRP structures for use in hostile service conditions.

2.2 OFF-SHORE OIL

The motivation within the Off-shore Industry to obtain wider approval for the use of GRP has been linked to the historical problems associated with metallic materials in salt water service and the need to improve safety and cost efficiency. Compared with conventional materials such as high alloy stainless steels, these materials offer improved corrosion resistance (i.e. immunity to electrochemical corrosion mechanisms that attacks metals) and weight savings. GRP pipes can offer weight savings up to 60% compared to carbon steel, while costs are comparable with carbon steel and cheaper than stainless steel or similar metal alloys. The lower density of these materials allows for easier construction and handling, particularly as these structures can be of considerable size. A list of applications are given below:

- High pressure and drill pipes, tubing, downhole tools, pump risers, caissons, tethers for tension leg platforms and subsea flowlines.

- Piping systems; fire protection panels; walkways and flooring; partition walls; tanks and vessels; fire, blast and impact equipment enclosures; cable ladders and trays; corrosion protection; lifeboats; buoys and floats.

NB. Although a number of the components listed above may be considered as thin structures, the second group includes thick constructions.

Figure 3: Off-shore oil drilling platform.

Legislation relating to the Off-shore Industry, prior to 1990, inhibited the use of GRP materials because their fire resistance was deemed inadequate. Subsequent changes to the legislation following the Piper Alpha disaster, in an effort to improve safety, have resulted in an increased use of these materials in off-shore drilling platforms (Figure 3). Thick laminates have a superior retention of structural integrity in a fire than conventional materials. GRP pipes circulating seawater have been able to survive for 2 hours within a hydrocarbon fire at 1100 °C. Fire resistance of composite laminates will be discussed further in Section 6.3.

The uptake of composites in the Off-shore Industry has been slower than might have been expected considering the advantages (i.e. light weight, corrosion and fire resistance) these materials offer. There is insufficient quantitative information about the effect of long-term exposure of the marine environment on the mechanical properties of the types of composite structures used in off-shore oil/gas installations. Design factors have been based on data obtained from tests conducted on flat plate coupons rather than actual structures used in the field (see Section 6.3). There is a tendency to apply the same design factors regardless of the material construction or manufacturing process (e.g. design codes BS 4994 [3], BS 5480-2 [4], BS 6464 [5] and Eurocomp [6]). The design factor for strength is the order of 10.

It is envisaged that self-propelled off-shore platforms will be used in the near future for launching satellites into orbit. Mobile semi-submersible oil platforms will need to be light, robust and flexible, and capable of withstanding hurricane force winds and buffetings from massive waves. The technology adopted for these structures can be expected to spin-off into floating airports, pier facilities and power plants. The potential for PMCs in this sector could be considerable.

2.3 MARINE STRUCTURES

GRP is used extensively throughout the marine industry in the construction of leisure boats, commercial transport and naval vessels (e.g. mine-counter measure vessels (MCMV)), lifeboats, submersibles, etc [1-2, 7-9]. High performance, weight critical hulls are being fabricated using these materials. The preference for using GRP in hull construction of MCMVs (i.e. minesweepers or mine-hunters) can be attributed to a reduction in structural weight, improved resistance to corrosion and fire, enhanced stealth and good fatigue resistance of these materials. Composites can be made acoustically transparent, thus providing vessels with stealth. GRP also offers improved protection against high-velocity projectiles (including small arms fire and larger calibre cannon shell) compared with conventional materials (see Section 2.4). These structures often consist of thick curved sections with top-hat stiffeners (See Figure 5). Composite sections for MCMVs of the order of 160 mm thick have been produced. Details of design requirements are presented in references [7-8]. GRP and other composites are being considered for pier facilities and floating airports.

Figure 4: HMS Sandown mine countermeasure vessel (courtesy of Vosper Thornycroft).

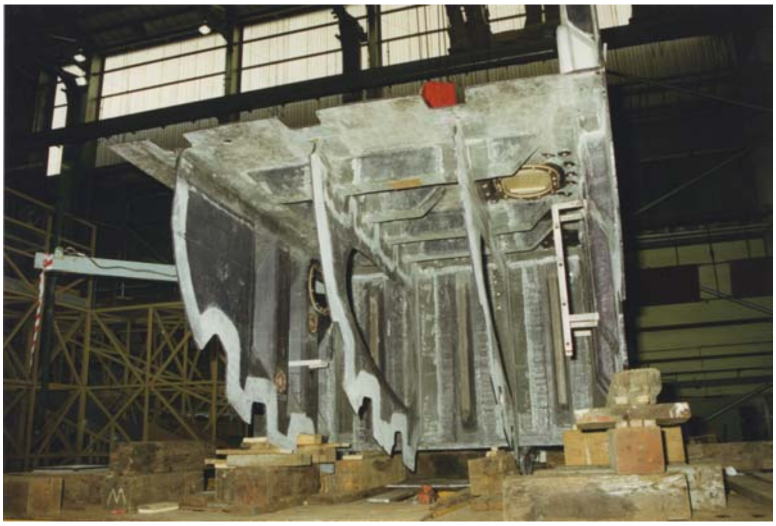

Figure 5: GRP hull construction (courtesy of Vosper Thornycroft).

Carbon fibre-reinforced plastics (CFRPs) are now being used in the construction of hulls for manned and unmanned submersible vessels for deep-sea exploration and research. The use of these materials has led to a substantial increase in working depths of submersible vessels, which is necessary if underwater exploration is to progress. The Office of Naval Research (Arlington, USA) has recently produced a composite storage capsule, which provides a hydrostatic pressure resistant dry environment [9]. The project involved the manufacture of a thick thermoset hangar door (65 mm thick) and spherical thermoplastic hull sections. Two- and three-dimensional woven fabrics and braided reinforced structures were fabricated using resin transfer moulding. Composites are also being used in the secondary structures of submersibles (e.g. internal decks and bulkheads). Future work will not only concentrate on structural performance, particular under hydrostatic pressure in fresh or salt water environments, but also on fire and impact resistance, and electrical and magnetic properties.

2.4 ARMOURED VEHICLES

Light weight armour (ballistic) panels are now being used to protect vehicles and ships against armour piercing rounds, high-powered rifles, hand and machine gun bullets, and incendiary and fragmentation weapons. The armour panels are manufactured using glass, carbon or other fibres, and thermoset and thermoplastic polymeric materials. Work carried out by the Defence Evaluation and Research Agency (DERA), United Kingdom, in 1992 demonstrated the efficacy of using thick composite panels (i.e. one square metre in area and up to 60 mm thick) in providing ballistic protection and for producing primary load-bearing structures. This work considered the use of RTM for panel manufacture with the eventual objective of producing Europe's first composite armoured fighting vehicle.

To maximise the mechanical properties of the plate armour and increase production rates, many of the mouldings used non-crimp fabrics (NCFs). These materials were stitched bonded rather than woven. The result was a highly conformable fabric, which achieved good mechanical properties. The materials were high areal weight. A major problem was the difficulty in mould closure when using a thick reinforcement pack. It was also observed that quadriaxial non-crimp fabrics presented a high resistance to resin flow in the TT direction. This resulted in dry areas near the centre of the panels. Impregnation was generally better with biaxial fabrics.

Figure 6: ACAVP vehicle (courtesy of DERA).

The Advanced Composite Armoured Vehicle Platform (ACAVP) programme {10] has shown that thick composite materials are a viable alternative to metal structures (Figure 6). Consequently, complete platforms can be manufactured using composites, rather than the less than satisfactory approach that has often been adopted of part-by-part substitution [10]. Recent publicity by the Ministry of Defence has indicated that the next generation of army tanks will consist primarily of composite materials.

Light weight composite armour plating is particularly suited for protecting vehicles that require speed and manoeuvrability, such as police vehicles and patrol boats. A fully armoured automotive shell (i.e. roof, side panels, gas tank, floor panel and engine compartment) can be fabricated using composite materials. In addition to high stiffness, high strength and excellent impact resistance, composite materials can provide excellent resistance to abrasion, cutting, moisture and chemical attack. These materials are also known to have a low dielectric constant, which is essential for avoiding radar detection (i.e. inherently radar transparent). A number of fibre systems including aramid, polyethylene, carbon and glass fibres are being considered for ballistic and impact applications. Future work will need to consider mechanical and physical merits of the different systems, along with associated manufacture and assembly costs and joining technologies.

2.5 AEROSPACE

The use of composite materials in the aerospace industry is wide spread and covers a time span from the 1940's to the present. The composite industry, however, is relatively immature as developments were initially slow. Since 1970, there has been a rapid increase in the development and use of composite materials, replacing conventional materials in defence aircraft. Most modern defence aircraft have substantial amounts of composites distributed both internally and externally, but primarily restricted to secondary loading structures. In contrast, the use of composite materials in civilian aircraft, especially in primary structures, has lagged behind. The current generation of commercial airliners, however, contain a large number of thick composite components, including wing skins, tail fins, spars and ribs (Figure 7). Sections in excess of 50 mm thick are being fabricated using CFRP.

Figure 7: Airbus UK composite wingbox section.

Aerostructures pose significant problems to designers and maintenance engineers due to their complexity, and hence a number of technical issues need to be considered when using composite materials in large secondary and primary aircraft structures. These issues include: processing and tooling, dimensional stability, tolerances, surface quality, impact resistance, durability (i.e. fatigue and environment), maintenance and repairability, thermal properties, non-destructive inspection and joining technologies. Although these issues apply to both thin and thick composite structures and joints, there are no procedures or guidelines as to the design, manufacture and testing of thick composite sections under representative service conditions.

The extensive application of composites has seen the emergence of durability problems specific to these materials. These problems are associated with in-service environmental conditions and handling procedures (including. maintenance, repair and modifications). Durability is a serious issue from both a health and safety aspect and in terms of economic costs. The repair or replacement of a deteriorated part is both labour and capital intensive. Composite parts are very expensive and due to "parts integration" are often very large. Airlines are reluctant to hold spare parts because of the cost of purchase and storage space. These problems can be expected to escalate as aircraft size increases.

Subsonic civil aircraft operate in temperatures ranging from –55 °C to +80 °C. The top skin surface temperatures of parked aircraft have been known to reach 105 °C. Concorde when cruising operated with a fuselage and general skin temperature of about 90 °C to 100 °C. Supersonic civil aircraft of the future will be exposed to temperatures ranging from –55 °C to +177 °C (350 °F) with excursions to 204 °C (400 °F) under stress with associated rapid temperature changes (ie thermal spiking). The synergism of moisture, long term exposure at elevated or sub-ambient temperatures, thermal cycling and thermal spiking, and applied mechanical stress needs to be fully understood. In addition, galvanic reactions between composite and metallic parts can cause corrosion and progressive disbonding of composite skins from aluminium honeycomb cores.

Although the above-mentioned issues can be associated equally with both thin and thick composite materials, their effects on structural performance can be expected to depend on material thickness. At present, there is insufficient data to derive realistic design allowances to account for deterioration in structural performance due to these effects.

2.6 CIVIL INFRASTRUCTURE

The use of composite materials for civil infrastructure (e.g. foot and traffic-bearing bridges, and electrical power transmission towers) has steadily increased. There are a number of government funded civil infrastructure renewal/replacement initiatives, particularly in the USA. Across the globe, advanced age and poor maintenance have led to the deterioration, and in some cases collapse of bridges. Natural disasters, such as earthquakes, floods and hurricanes have aggravated the situation. It was estimated in 1993 that between 150 and 200 bridges in the USA suffer partial or complete collapse per year. The cost of rehabilitating bridges in the USA was estimated at that time to be £60 billion. Similar levels of expenditure could now be expected for Europe. Many of the road and train bridges within the UK and Europe are suffering from age combined with the weakening effects of ever increasing traffic loads.

On a cost basis, composite materials can compete with steel and concrete constructions and offer a number of advantages including: light weight, corrosion resistance, ease of transport and rapid construction with minimal disruption to traffic. Composite materials are seen as particularly suited to portable bridge construction and for replacement of ageing infrastructure. Examples of bridge constructions that have composite primary load-bearing structures are listed below.

(i) Fibreline Bridge (Kolding, Denmark) – A 40 metre long, 3 metres wide crossing for pedestrians, bicycles and motorcycles designed to support a 500kg/m^2 load. The total weight of the bridge deck is 12 metric tons. The bridge consists of thick glass fibre-reinforced polyester pultruded sections joined with metal clamps and bolts. The light weight composite enabled rapid construction of the bridge (18 night-time hours), thus minimising disruption to traffic. The bridge is supported from a support tower (18.5 metre high) that is bolted to a concrete foundation (Figure 8). In-built sensors (strain-gauges) are being used to measure stress and deformation in various elements of the bridge due to mechanical and thermal loads.

(ii) Salmon River Highway Bridges (Kemptown, Nova Scotia) – Two fibre-reinforced bridges, each consisting of two 31-metre spans, were constructed in 1995 for the Nova Scotia Department of Transportation and Communications (Canada).

(iii) Lockheed Martin Palo Alto Research Laboratories have assembled a 10 metre long, 6 metres wide (one quarter full scale) bridge manufactured from GRP. The structure weighs 10,000 kg and is capable of withstanding 52,700 kg load (equivalent to the weight of an 18 wheel truck).

(iv) A composite bridge is being planned for carrying significant truck traffic across the Delaware River. The bridge, which is expected to last over 75 years, is to consist of three continuous spans, and have horizontal curvature and super-elevation. This represents an advance in service requirements and design complexity from the simply supported span bridges manufactured from GRP that now carry light traffic across the Delaware River. The GRP deck will be designed with transverse joints.

Future efforts in this area will be directed towards conceptual design with composite materials (extending current design to curved structures and spans in excess of 50 metres), panel-to-panel connections (bonded and bolted thick joints), fatigue and environmental resistance, serviceability (health monitoring and structural inspection). Chemical resistance and durability testing programmes will need to include ultra violet radiation, heat, humidity, salt water, diesel fuel and acid rain. It is also envisaged, that there will be substantial expansion in other areas of composite construction including: buildings, railway stations, entertainment stadiums, and electrical power pylons and towers. In addition to mechanical properties, future supportive programmes will need to consider issues relating to electrical and thermal properties of composite materials.

Figure 8: Fibreline Bridge (Kolding, Denmark).

3. MANUFACTURE AND INSPECTION OF THICK LAMINATES

This section presents an overview of commonly used manufacturing processes that are capable of producing thick laminated components/structures. Processing routes covered include autoclave moulding, filament winding, contact-moulding, resin injection processes, resin infusion and pultrusion. Consideration is given to fabrication effects, such as residual stresses, material non-uniformity, wrinkling, exothermic reactions, compaction and porosity that warrant special attention.

3.1 INTRODUCTION

Fabrication of thick composite laminates (20 mm or greater) is often difficult, with process-induced (i.e. residual) stresses becoming increasingly important as the thickness is increased. Residual stresses can have a significant effect on the engineering properties of laminated structures by inducing warpage, fibre buckling, matrix microcracking and delaminations. These stresses arise from resin chemical shrinkage, as a result of curing and differences in thermal contraction between adjacent plies on cooling the laminate from the cure temperature. The net effect is that the strength properties of the laminate are diminished.

There is a major drive to develop on-line (real-time) cure monitoring techniques and predictive models that are capable of providing reliable information on the physical state of the composite material in the process environment. Controlling the state of cure is critical to ensuring optimum end-use performance, thereby reducing production costs and scrap rates. The relationship between the degree of cure through the laminate thickness and the physical and mechanical properties in thick composite sections is of particular commercial interest. Establishing validated models that relate process variables (i.e. applied pressure and heat input) to cure-induced residual stresses and strains, non-uniform cure distributions, glass-transition temperature and part thickness is seen as a high priority. Work is proceeding in the use of sensors in composites for measuring degree of cure.

3.2 AUTOCLAVE MOULDING

Autoclave processing can be adapted to produce laminated structures in a wide range of geometries and sizes. The technique, which has been used to manufacture large panels for military and civil aircraft wings, is compatible with most thermoset and thermoplastic resin systems, fibre types and fibre formats. The high quality products that result using this processing route is often off-set by high production costs. Autoclave processing is costly in terms of feedstock, capital investment, auxiliary materials, labour requirements and processing time.

Autoclave processing often involves an intermediate temperature stage to avoid excessive heat generation caused by exothermic chemical reaction of the matrix. If dissipation of liberated heat through thermal conduction is slow, then the internal temperature may be elevated to levels that induce irreversible thermal damage. The risk of heat damage to the matrix increases with laminate thickness. A second concern relates to the complex temperature and degree of cure gradients that develop in thick-sections during the curing process. These gradients may induce a non-uniform state of cure through the laminate thickness, which can result in poor laminate consolidation, leading to undesirable fibre volume fractions and entrapped volatiles or voids.

3.3 FILAMENT WINDING

The strength-to weight ratio offered by filament wound glass fibre-reinforced plastics makes this material/fabrication route a very attractive alternative to steel or titanium for producing large thick-walled structures, such as hulls for deep submergence vehicles, underground chemical and fuel storage tanks and pipe constructions. The flexibility of the technique has enabled manufacturers to produce large and complex shapes, such as rail carriages, drive shafts, and gun barrels along with pipes, risings and casings for off-shore applications. Structures 9 to 10 metres in diameter, 25 metres in length with wall thickness of 150 mm can be produced using this manufacturing process. Fibre-reinforced plastic (e.g. glass/polyester) underground gasoline storage tanks have been known to maintain their structural integrity and resist the corrosive effects of soil, moisture and petroleum over 30 years, and longer.

The filament winding process permits high fibre to resin ratios, and hence the resultant product has the highest strength-to-weight ratio obtainable in any composite structure. Fibre volume fractions of 0.6 to 0.7 are achievable with this technique. The technique tends to be used with thermoset resins (e.g. epoxies and polyester resins), although success has been achieved using thermoplastics. Good wet out and consolidation are more difficult to achieve with thermoplastic composites. The technique is compatible with most fibre types, although glass fibre-reinforcement is the most widely used with this processing route. Liners (e.g. gel coatings, elastomeric materials, etc.) can be used to protect the inner and outer surfaces of filament wound structures. Residual stresses induced during the cure process can have a significant effect on the mechanical performance of thick filament wound components.

3.4 CONTACT-MOULDING

Contact moulded structures may not be as strong as an equivalent filament wound structure, however "hand lay-up" and spray-up are the most widely used methods for manufacturing large thick-walled composite structures. Contact moulding techniques can be used to produce complex shapes, such as nozzles, elbows, conical sections, and complete tanks and pipes. The resultant structures are particularly suited to operating in highly corrosive environments. The process of manufacturing thick composite sections is however slow, as only a maximum thickness of 12 plies or 15 mm can be applied at any one time. No further plies are laid "until the heat has gone from the system (typically 1 hour)". This is to avoid damage to the composite resulting from temperature rise due to exothermic reactions. Excessive exothermic heat generation can cause fuming or even plant fires.

Another concern, mainly associated with the manufacture of thick components, is the possibility of resin shrinkage, which can be high. The composite industry has tended to produce in-house guidelines or codes of practice, which outline procedures for hand lay-up and spray-up of thick composite sections. The major disadvantage of contact moulding techniques are the low fibre volume fractions (typically 0.20 to 0.35) and hence the low mechanical properties. The technique is labour intensive and provision must be made for the large variability in material properties as a consequence. Final product quality and thickness are very sensitive to operator technique.

3.5 RESIN INJECTION PROCESSES

Resin transfer moulding (RTM) and structural reaction injection moulding (SRIM) have been developed with the aim of producing large, complex and highly integrated composite components for high performance applications. These techniques offer substantial time and cost savings compared with autoclave and hand lay-up processing methods. The two processing methods are compatible with a wide range of resin systems (including epoxies, phenolics, polyesters vinyl esters, bismaleimides). It is possible to produce thick composite sections (100 mm in thickness) containing bosses, ribs and metal inserts

Recent developments have seen the introduction of computerised controlled, closed-mould processing that can be used to manufacture large and complex fibreglass parts in far shorter times than the traditional labour-intensive, open-mould process. Boat hulls that required 8 to 12 hours can be fabricated in an hour. The technology is similar to that of RTM, but differs in that the new technique uses light weight composite moulds instead of heavy metal tools and the process is fully automated. Thin fibreglass moulds replace the heavy metal tools and water in the pressure vessel supports the mould and serves as a heat source. The technique has been used to manufacture 7 metre length boat hulls. Processing variables, such as temperature, pressure, viscosity, flow rates, etc. during lamination process are computer controlled.

3.6 RESIN INFUSION

Resin infusion under flexible tooling (RIFT) can be used to produce large structural components. The process is compatible with polyester; vinyl ester and epoxy resin systems and most conventional woven or stitched fabrics. The technique offers relatively low tooling costs for high performance components (i.e. high fibre content), a more uniform microstructure and lower void content compared with hand lamination.

A number of problems associated with processing have been encountered. Uneven flow may result in dry (i.e. unimpregnated) areas and thus very high and expensive scrap rates. Delamination of components is usually associated with thick components where exothermic heat generation is excessive. This problem may be overcome using either a slower cure schedule or another resin system.

3.7 PULTRUSION

Pultrusion is an automated processing technique for producing continuous sections of reinforced plastics where the orientation of the fibre reinforcement is predominantly axial. The reinforced fibre materials (or reinforcement "pack") are in the form of continuous strands (rovings) or plies (random mats, stitched fabrics, bi-directional reinforcements and surface veils). Pultrusions can be run dry, employing prepreg thermosets or thermoplastics, or wet (i.e. being impregnated with liquid matrix resin).

A wide variety of solid and hollow profiles (e.g. I-beams, L-channels, tubes, angles, rods and sheets, etc.) can be produced, typically ranging from 2 to 30 metres in length. Line speeds of 1 m/min are possible using current techniques. It should be noted, that the rate of cure is influenced by profile section thickness and there is at least a theoretical limit on the maximum production speed for a particular profile at a particular matrix/reinforcement specification. Temperature control is critical because the product must be fully cured prior to exiting the pultrusion die. The maximum thickness of solid sections obtainable is typically 40 mm.

3.8 QUALITY ASSURANCE AND INSPECTION

The issue of quality control, and hence inspection of thick composite sections is critical to the acceptance of these materials for usage in primary and secondary loading applications. Information on the structural integrity of the finished product is needed in order to verify material conformance to user specifications and acceptance standards, and safety regulations. NDE techniques regularly used for production include visual, ultrasonic C-scan and X-radiography inspection. Techniques, such as thermography, shearography and acoustic emission, are being developed for future use in production and in-service inspection.

The most widely used technique for assessing the structural integrity of a composite is ultrasonic C-scan inspection. The technique can be used to detect a variety of production type defects (e.g. delaminations, voids and porosity, resin starved and resin rich areas) in both thin and thick (40 to 50 mm) laminates manufactured from continuous aligned and woven fabric reinforcement. Detection of defects with ill-defined boundaries (or interfaces with surrounding substrate material) is difficult, particularly as the laminate thickness increases. Detection of defects is further exacerbated in non-crimped fabrics (NCFs), where the material is highly heterogeneous, and hence is highly dispersive/attenuative to ultrasonic signals. X-radiography is frequently used to evaluate bonding of inserts in laminate panels and honeycomb core to skin bonds in sandwich panels. Detection of debonds becomes more difficult with increasing laminate thickness.

4. MECHANICAL TESTING AND STANDARDISATION

The general perception has been to associate through-thickness (TT) properties with thick composites, whereas in fact an equally important issue relates to the measurement of in-plane (intralaminar) properties and the effect of physical size of test specimens on measured data. Measurement of in-plane properties of thick sections can pose considerable problems from a testing perspective unless scaling effects are understood. Currently, there are no standard test methods available that provide guidance on testing of thick composite sections.

The approach generally adopted has been to use existing standards, developed for testing small laboratory-scale specimens, with non-standard (i.e. larger) specimen geometries. However, thick laminated sections pose particular problems in relation to mechanical testing, as the large size of the test pieces often requires high load capacity testing facilities, which are not readily accessible for most organisations. The lack of suitable test methods has resulted in a shortage of reliable engineering data for large structural applications. This section evaluates mechanical test methods for characterising both in-plane and TT elastic and strength properties in relation to their suitability for testing thick-sections. Tension, compression, shear and flexural test methods are assessed, along with multiaxial testing methods.

4.1 IN-PLANE TESTING

4.1.1 Tension

Conventional tensile test procedures tend to be used for measuring the stiffness and strength properties of thick composite sections. ISO 527 (Parts 4 and 5) [11-12] specifies methods and specimen geometries for determining the tensile properties for continuous aligned, random mat, woven fabric and multidirectional laminates. ISO 527-4 allows for 10 mm thick isotropic and orthotropic laminates. There is no general consensus within the composite industry as to the preferred specimen width or length.

An apparent scale effect has been observed by a number of researchers for unidirectional, angle-ply, cross-ply and quasi-isotropic lay-ups [13-15]. In these studies, failure loads and strains are shown to decrease with increasing laminate thickness with laminate stiffness appearing insensitive to changes in laminate thickness. These studies however, tend to overlook the effects of manufacturing technique and conditions, loading arrangement and the ply stacking sequence of the laminate. In a recent study, Sutherland et al [16] concluded that changes in specimen thickness had no substantial effect on tensile strength or stiffness of unidirectional carbon and glass fibre-reinforced epoxy systems. The authors also observed [17] that tensile strength of woven fabric laminates tended to decrease with increasing laminate thickness. The reduction however, was attributed to the effects of scale of production rather than a genuine size effect (i.e. lower quality specimens are obtained when a thicker laminate is produced). It was concluded that manufacturing variations were the main reason for observed thickness effect and that manufacturing processes for coupon specimens should closely mirror those used to produce the composite structure.

The presence of interlaminar tensile (peel) and shear stresses at the free edges of a laminate may be sufficient to cause local matrix and interfacial cracking, and edge delamination. Frequently, these stresses and strains induce failure in the laminate. The magnitudes of the stress gradients present at the free edges of a laminate are dependent on the laminate stacking sequence and the level of sub-laminate scaling. Sub-laminates consist of 1 or more layers of the same fibre orientation stacked together. The tensile strength of $[0°_n/90°_n]_S$ cross-ply laminates can be expected to decrease as a result of increasing **n** the number of plies within the 0° and 90° sub-laminates (i.e. thicker sub-laminates). This is because the tensile stresses at the free edges of the laminate increase with increasing sub-laminate ply thickness.

Large specimens are manifestly more difficult to test than small laboratory-scale coupon specimens since larger lateral loads are required to grip the larger specimens to prevent slippage. Stress concentrations in the vicinity of the end tabs, resulting from the gripping fixture, can be expected to increase with laminate thickness, leading to an apparent reduction in tensile strength. Failure commonly occurs in the vicinity of the end tabs where the end tabs terminate and gauge-section begins. For the above reasons, tensile strength dependence on laminate thickness cannot be accurately modelled using simple statistical models based on Weibull distributions of flaw densities and the weakest link approach or by fracture mechanics models.

4.1.2 Compression

There is no in-plane compressive test methods specifically developed for loading sections in excess of 10 mm in thickness. BS EN ISO 14126 [18] specifies methods and specimen geometries suitable for determining the compressive properties of continuous aligned, random mat, woven fabric and multidirectional laminates. The standard allows for 10 mm thick material. Particle-filled and short fibre (less than 1 mm in length) reinforced plastics are covered by ISO 604 [19].

The longitudinal modulus and in-plane Poisson's ratios for these materials are insensitive to specimen thickness, however experimental data has shown that compressive strength decreases with increasing thickness for unidirectional glass and carbon fibre-reinforced laminates [20-22]. Failure commonly occurs in the vicinity of the end tabs. Camponeschi [20-22] attributes this reduction in strength to compression fixture restraint effects, which according to the author can be explained in terms of TT Poisson's expansion that occurs in thick laminates (i.e. difference between the TT expansion of the gauge-section and the TT expansion within the fixture grips is the effective gauge-section expansion). This expansion results in fibre curvature where the specimen exits the clamping blocks or gripping fixture. The effective gauge-section expansion increases with increasing thickness, and hence fibre curvature also increases. The larger fibre curvature results in increasing buckling forces, and hence the lower compressive strengths observed for thick composite sections. If the end effects are minimised then variations in specimen thickness should have minimal effect on the measured compressive properties.

4.1.3 Shear

Considerable experimental and analytical effort has been expended in the development of in-plane shear test methods. One of the principal difficulties has been to produce a uniform state of pure shear in specimens. The difficulty of inducing pure shear increases with increasing anisotropy and inhomogeneity of the material. As these characteristics increase, the complex stress states arising at or near the loading zones become more dominant, particularly for continuous unidirectional laminates containing high modulus and high strength fibres. In these materials, it is difficult to obtain adequate regions of uniform shear stress free of extraneous stress components within the specimen, even if the production of the specimen and test alignment are perfect. In addition, extraneous tensile and compressive stress components have a marked effect of shear strength of these materials. Tensile stresses induce premature failure, whereas compressive stresses delay the onset of failure. The

difficulties in producing a state of pure shear in composite specimens are compounded when the material thickness is increased.
The general approach has been to extrapolate data from tests conducted on thin laminates (i.e. 2 to 5 mm in thickness) to thick structures. The most commonly used test methods for the determination of shear properties are as follows: (i) uniaxial tension of a ±45° laminate (BS EN ISO 14129 [23]) or 10° off-axis laminate; (ii) two-rail and three-rail shear tests (ASTM D 4255 [24]); (iii) V-notched beam (or Iosipescu) test (ASTM D 5379 [25]); (iv) plate twist test (ISO 15310 [26]); and (v) torsion of a thin-walled circular tube (ASTM D 5448 [27]).

The effects of laminate thickness associated with tensile testing of composite laminates apply to both the ±45° and 10° off-axis shear methods, and to the two- and three-rail shear tests (see Section 4.1.1). It has been reported that strength measured using the ±45° tension test is dependent on the number of layers, or shearing interfaces, in the specimen [28].

The plate twist test, which was initially developed to measure the shear modulus of plywood (ASTM D 3044 [29]), has proved satisfactory for measuring shear moduli ranging from 0.29 GPa (chopped glass-fibre reinforced polyurethane) to 88.2 GPa (steel). The test method is unsuitable for determining in-plane shear strength. ISO 15310 recommends a standard plate specimen 150 mm x 150 mm and a length to thickness ratio ≥ 35. There is insufficient data to assess the suitability of the test method for use with thick-sections, however from a testing perspective there is a practical limit as to the maximum size of specimen that can be tested (i.e. approximately 10 mm thick panels).

In the case of the V-notched beam geometry, the stress state induced in the specimen can be expected to become less uniform with increasing laminate thickness with compressive stresses increasing as the laminate thickness is increased. The ASTM test fixture is not designed for testing thick material (> 10 mm thick) and has been observed to deform at high loads.

From an applied mechanics viewpoint, torsion of thin-walled circular tubes is the most desirable method for shear characterisation. Thick-walled cylindrical specimens however, can be tested provided the TT shear gradient is negligible. To ensure a uniform shear stress field, the specimen should have a gauge-length to diameter (L/D) ratio > 1 and a wall-thickness to diameter (h/D) ratio of 0.02, or less (i.e. h = 20 mm and D = 1 m) [14].

Testing thick structures requires considerably large specimens and suitable test equipment to accommodate these structures. Increasing the wall thickness, whilst maintaining all other dimensions constant, results in a significant stress gradient across the tube wall, and a reduction in shear strength. Cylindrical wound tubes are suitable for characterising static, creep and fatigue behaviour of composite materials in tension, compression and shear. The test geometry is also suitable for assessing mixed-mode behaviour (i.e. shear + tension and shear + compression).

4.1.4 Flexure

BS EN ISO 14125 [30] specifies methods for determining the flexural properties of fibre-reinforced plastic composites under three-point and four-point bend loading. The method is suitable for use with all fibre types and fibre formats, and allows for non-standard test geometries. It is possible to use these methods for testing of 25 to 40 mm thick laminated beams using the scaling rules given in the standard. The limitation being the load capacity and physical size of the test machine required for testing large structures. The recommended span for 25 mm and 40 mm thick GRP beams loaded in three-point bend are 500 mm and 800 mm, respectively.

4.2 THROUGH-THICKNESS TESTING

The National Physical Laboratory (NPL) and Defence Evaluation and Research Agency (DERA) have developed test methods for determining TT tension and compression properties (i.e. modulus, strength and failure strain) [14, 31-32]. These methods are suitable for use with a wide range of composite material, and are subject to further validation work in order for their adoption as national and international standards. TT testing is easier for "thick" laminates (< 20 mm thick) compared with thin laminates. There are existing standards for measuring interlaminar shear properties (e.g. short beam shear and V-notched beam methods). The UK proposal for a double-notched shear test for determining interlaminar shear strength has been submitted for an ISO (international standards organisation) ballot as a new work item (NWI). Work has been carried out at NPL to assess the suitability of a number of test methods for characterising TT fatigue performance of composite materials in tension, compression and shear [31]. This section briefly examines test methods suitable for characterising TT material properties.

4.2.1 Tension

There are two contrasting methods and several associated geometries, which can be employed in the measurement of TT tension (i.e. direct and indirect tensile loading). The direct method introduces tensile load to the specimen via adhesively bonded bars or through grips (see Figures 9 and 10). The indirect method aims to induce TT tension, in significantly curved specimens by the application of bending moments. The load is introduced via the specimen lever arms, in either tension or flexure (Figure 11). Indirect methods (e.g. C-section) tend to produce mixed mode failure, and not TT tension. In-plane tensile methods identified in international standard ISO 527-5 (specimen length of 250 mm with a 150 mm gauge-length) are unsuitable for adaptation to TT tensile testing due to manufacturing difficulties and costs associated with producing such thick composite sections (250 mm).

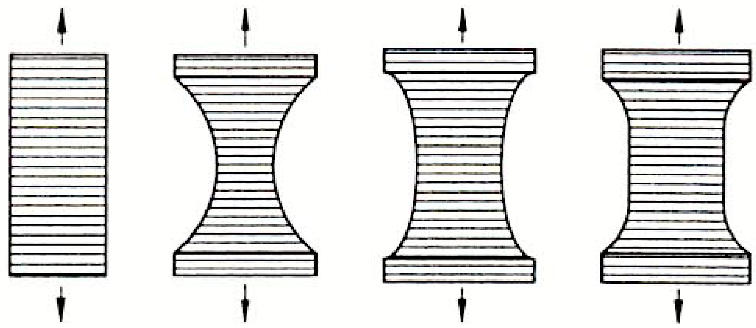

Figure 9: Schematic of direct TT tensile test methods
From left to right: Parallel sided, circular, elliptical and RARDE specimens.

The preferred approach is to directly load parallel sided short blocks or waisted (circular, elliptical or RARDE configurations) with a thickness-wise dimension of 20 to 40 mm. Parallel-sided short blocks (20 to 40 mm thick with a 15 mm square cross-section) are suitable for measuring TT elastic modulus $\mathbf{E}_{zz}$ and Poisson's ratios ν_{zx} and ν_{zy}. Load is introduced via reusable aluminium or stainless steel loading bars, which are bonded to the ends using a high strength epoxy adhesive. Biaxial strain gauges, measuring axial and transverse strains, are used to determine modulus and Poisson's ratios. This specimen is unsuitable for determining TT tensile strength owing to the high probability of bond failure in tension.

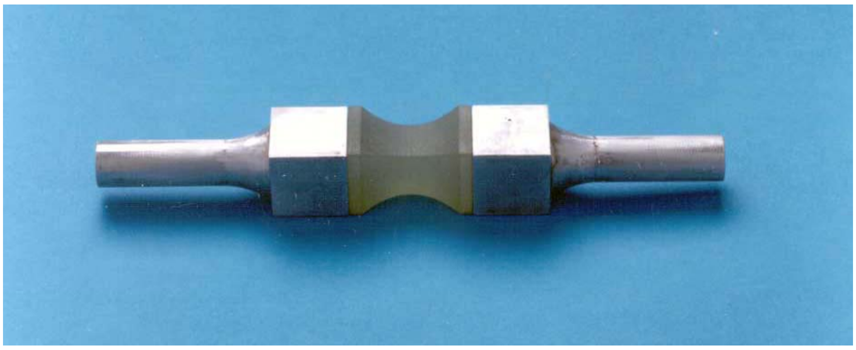

Figure 10: Circular waisted TT tensile specimen with adhesively bonded loading rods.

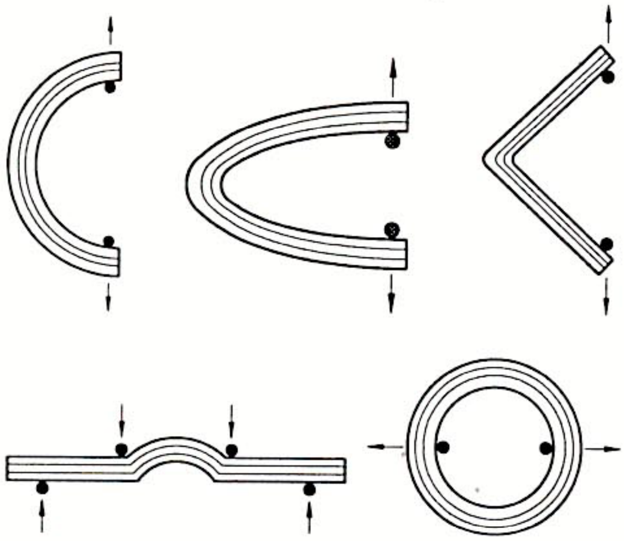

Figure 11: Schematic of indirect TT tensile test methods
Clockwise from top: C-sections, closed ring and hump back specimens.

The RARDE specimen can be used to measure TT tensile elastic and strength properties. The specimen is 40 mm thick with 25 mm square ends. The gauge-section is 12 mm long, with a rectangular cross-section of 10 mm (Y-Z plane) x 16 mm (X-Z plane). Specimens with an elliptical profile (Figure9) have been successfully used to measure TT elastic and strength properties of unidirectional carbon/epoxy. The elliptical specimen is smaller than the RARDE specimen (i.e. 17 mm thick). Specimen loading and strain measurement in both cases is identical to that employed for parallel-sided specimens.

Circular or plain waisted short block specimens (Figure 9) can only provide TT strength data. Specimens have 25 mm square ends, a gauge-section 32 mm long, with a cross-section approximately 16 mm square at the specimen mid-section. The large radius of curvature (30 mm) ensures that the stress concentration at the specimen mid-section is close to unity. TT tensile strength values tend to be higher than those measured using the RARDE specimen.

4.2.2 Compression

The basic configurations identified for TT tension are also suitable for compression. Testing consists of short blocks (waisted or parallel sided) end loaded in compression between flat, parallel platens with close fitting recesses to reduce lateral movement of the specimen. A four-pillar die set is used to maintain uniform compression loading [33]. Specimen preparation and strain measurement for each method is identical to that used for the tension tests. For TT compression, the parallel sided, circular or plain waisted, and RARDE short block geometries are suitable for determining the TT elastic properties or TT strength, or both respectively. Parallel-sided short block specimens are unsuitable for strength measurement in compression owing to the presence of high stress concentrations at the specimen ends, which frequently leads to premature failure. Celanese, IITRI and end loaded test methods specified in BS EN ISO 14126 are unsuitable for characterising in-plane compression behaviour owing to the difficulty in obtaining material of the required thickness. Trials involving these specimens proved unsatisfactory due to the sensitivity of the specimen to premature failure during handling or testing.

4.2.3 Shear

A multitude of shear tests are available [14, 28, 31-32], of which a number are potentially suitable for measuring TT shear properties, namely: (i) short beam shear (BS EN ISO 14130 [34]); (ii) V-notched beam (ASTM D 5379); and (iii) double notched shear (ASTM D 3846 [35]). The short beam shear test is limited to the TT shear strength determination of brittle unidirectional laminated materials. The double-notched shear test, although only suited to measuring TT shear strength, is applicable to a wider range of materials. The V-notched beam test is suitable for determining the TT shear modulus ($\mathbf{G}_{xz}$ and $\mathbf{G}_{yz}$) and strength ($\mathbf{S}_{xz}$ and $\mathbf{S}_{yz}$) properties of most composite materials, providing a suitable shear failure occurs.

4.3 MULTIAXIAL TESTING

This section will examine multiaxial testing methods that can be used for characterising thick composite materials. Two- and three-dimensional methods will be considered. These tests are important in the development of reliable three-dimensional numerical (finite element analysis) modelling, design and analysis, and failure theories for thick composite structures. Multiaxial testing, which can be used to identify actual material strengths and failure mechanisms under representative service conditions, is often used simply on the grounds that there is insufficient confidence in three-dimensional failure analysis. There are two distinctively different methods of inducing multiaxial loads/displacements in composite materials (see below) [36].

4.3.1 Lineal Test Techniques

Testing consists of applying loads/displacements along the primary, mutually orthogonal coordinate axes of lineal test specimens (i.e. rectangular plates, cubes or two- and three-dimensional cruciforms). Specimens are loaded using either planar biaxial or triaxial loading frames. Servo-hydraulic actuators or screw-driven test frames are used to apply load(s) to the test specimen. Special end tabs and support fixtures are required for loading and constraining the test specimens. Both biaxial and triaxial test machines require sophisticated control systems for controlling and monitoring loads and displacements of the test specimen throughout the duration of a test. These controls are used to avoid unwanted eccentric loading conditions, thus ensuring inappropriate failure mechanisms or failures outside the instrumented gauge-section do not occur. Extreme care is required in order to prevent undesirable end and edge effects and stress concentrators.

4.3.2 Cylindrical Test Techniques

This method consists of loading cylindrical specimens either in tension, compression and/or shear. There are a numerous biaxial test facilities capable of applying combined axial (tension or compression) and torsional twisting loads (about the longitudinal axis) to the cylindrical test specimens. Triaxial machines, which are similar to biaxial test machines, have the additional facility of being able to induce a pressure gradient across the cylindrical wall of the test specimen by applying either external, internal or both external and internal pressure. Triaxial test machines are well suited for testing filament wound structures, such as pressure vessels and pipes. Cylindrical specimens are free of edge effects due to the hoop continuity of the test geometry. However, end effects and the potential problem of structural instability (or buckling) can have a significant effect on test results and failure mechanisms. Specimen design and loading fixtures need special consideration in order to eliminate the adverse effects of these two factors.

A significant amount of work has been directed towards developing test methods and standards for assessing the performance of pressure vessels and pipe sections (see [1, 37-38]). ASTM D 2992 [39] specifies procedures for determining the long-term cyclic and static hydrostatic strength of a composite pipe. According to Ellyin and Marten [38], ASTM D 2922 specifies a worst-case scenario rather than typical conditions experienced by composite pipes for example in oil fields.

4.4 DISCUSSION AND RECOMMENDATIONS FOR FUTURE WORK

Considerable development work is still required to provide test methods suitable for measuring the mechanical properties of thick composite sections under static, dynamic (i.e. fatigue and impact) and creep loading conditions. Table 1 presents methods for measuring in-plane and TT elastic and strength properties of thick composites.

Table 1: Test Methods for Determining Input Design/Analysis Data

Material Property	Standard/Test Method
Elastic Properties	**m.d = multidirectional, u.d = unidirectional**
In-plane (E_{xx}, E_{yy}, ν_{xy})	Tension - BS EN ISO 527-4 (m.d)/BS EN ISO 527-5 (u.d)
Through-thickness (E_{zz}, ν_{xz}, ν_{YZ})	T-T tension and compression-NPL draft procedures
In-plane shear (G_{xy})	±45° tension method - BS EN ISO 14129 (u.d)*
Through-thickness shear (G_{xz}, G_{yz})	V-notched beam test - ASTM D 5379
Strength Properties	**m.d = multidirectional, u.d = unidirectional**
In-plane tension (S_{xx}^T S_{yy}^T)	Tensile - BS EN ISO 527-4 (m.d)/BS EN ISO 527-5 (u.d)
Through-thickness tension (S_{zz}^T)	Through-thickness tension - NPL draft procedure
In-plane compression (S_{xx}^C, S_{yy}^C)	Compression - BS EN ISO 14126
Through-thickness compression (S_{zz}^C)	Through-thickness compression - NPL draft
In-plane shear (S_{xy})	±45° tension method - BS EN ISO 14129 (u.d)
Through-thickness (S_{xz}, S_{yz})	V-notched beam method - ASTM D 5379 (u.d)

Symbols: E = modulus of elasticity, G - shear modulus, ν = Poisson's ratio, S = strength
Subscripts: xx, yy and xy denote in-plane properties, xz, yz and zz denote through-thickness properties
* Plate twist method - ISO 15310 (simple test for measuring shear modulus only)

5. THREE-DIMENSIONAL ANALYSIS

This section of the report presents the three-dimensional (3-D) analysis required for characterising the stress-strain behaviour of thick composites under uniaxial and multiaxial loading conditions. Laminate theory is briefly described along with comments on underlying assumptions [36, 41].

5.1 UNIDIRECTIONAL LAMINATES

In order to analyse a multidirectional 3-D laminate, it is necessary to initially examine the elastic behaviour of a single unidirectional lamina. From this initial point, a logical progression can be made to the prediction of macromechanical behaviour of a laminate. Although, the properties of a lamina on a microscopic scale are inherently heterogeneous and variable from point to point, on a macroscopic scale the lamina may be considered as a homogeneous anisotropic layer. The lamina properties are uniform in any given direction and are dependent on the properties of the lamina constituents. Behaviour of the constituents is considered to be linear-elastic to failure. Constituents are also considered to be homogeneous and isotropic. Furthermore, the analysis assumes that there are no defects (e.g. voids) present within the composite structure and there is perfect interfacial bonding between fibre and matrix.

In general, the state of stress at a point in a body can be described by the nine components of the stress tensor $\boldsymbol{\sigma}_{ij}$. Correspondingly, the strain tensor $\boldsymbol{\varepsilon}_{ij}$ also has nine components. The linear relationship between stress and strain can be expressed as:

$$\sigma_{ij} = E_{ijkl}\varepsilon_{ij} \tag{1}$$

where the components of the fourth-order tensor, $\mathbf{E}_{ijkl}$, is known as the stiffness tensor (i.e. elastic constants).

The stress-strain relation given in Equation (1) can be expressed in the inverted form as:

$$\varepsilon_{ij} = C_{ijkl}\sigma_{ij} \tag{2}$$

where $\mathbf{C}_{ijkl}$ is known as the compliance tensor.

For orthotropic unidirectional lamina, the 81 components of the fourth-order tensor $\mathbf{C}_{ijkl}$ reduce to 36 of which only 21 components are independent. The relationships given by Equations (1) and (2) reduce to the following form:

$$\sigma_{ij} = Q_{ij}\varepsilon_{ij} \tag{3}$$

and

$$\varepsilon_{ij} = C_{ij}\sigma_{ij} \tag{4}$$

where $\boldsymbol{\sigma}_{ij}$ are the stress components, $\boldsymbol{\varepsilon}_{ij}$ the strain components, $\mathbf{Q}_{ij}$ is the stiffness matrix and C_{ij} is the compliance (i.e. inverse stiffness matrix).

The expanded stress-strain relationship given by Equation (4) for an orthotropic unidirectional lamina is shown below.

$$\begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \gamma_{23} \\ \gamma_{31} \\ \gamma_{12} \end{Bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{33} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \tau_{23} \\ \tau_{31} \\ \tau_{12} \end{Bmatrix} \quad (5)$$

The above relationship can be rewritten in terms of nine independent elastic material constants $\mathbf{E_{11}}$, $\mathbf{E_{22}}$, $\mathbf{E_{33}}$, $\mathbf{G_{12}}$, $\mathbf{G_{13}}$, $\mathbf{G_{23}}$, ν_{12}, ν_{13} and ν_{23} as follows:

$$\begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \gamma_{23} \\ \gamma_{31} \\ \gamma_{12} \end{Bmatrix} = \begin{bmatrix} \frac{1}{E_{11}} & -\frac{\nu_{21}}{E_{22}} & -\frac{\nu_{31}}{E_{33}} & 0 & 0 & 0 \\ -\frac{\nu_{12}}{E_{11}} & \frac{1}{E_{22}} & -\frac{\nu_{32}}{E_{33}} & 0 & 0 & 0 \\ -\frac{\nu_{13}}{E_{11}} & -\frac{\nu_{23}}{E_{22}} & \frac{1}{E_{33}} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{23}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{31}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}} \end{bmatrix} \begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \tau_{23} \\ \tau_{31} \\ \tau_{12} \end{Bmatrix} \quad (6)$$

For orthotropic materials the following reciprocal relationships must be satisfied.

$$\frac{\nu_{12}}{E_{11}} = \frac{\nu_{21}}{E_{22}}, \quad \frac{\nu_{13}}{E_{11}} = \frac{\nu_{31}}{E_{33}}, \quad \frac{\nu_{23}}{E_{22}} = \frac{\nu_{32}}{E_{33}} \quad (7)$$

5.2 ORIENTED ORTHOTROPIC LAMINATES

For oriented balanced and symmetric laminates loaded in the x-, y- or z-direction, the stress-strain relationship is as follows:

$$\begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \gamma_{23} \\ \gamma_{31} \\ \gamma_{12} \end{Bmatrix} = \begin{bmatrix} \bar{C}_{11} & \bar{C}_{12} & \bar{C}_{13} & 0 & 0 & 0 \\ \bar{C}_{12} & \bar{C}_{22} & \bar{C}_{23} & 0 & 0 & 0 \\ \bar{C}_{13} & \bar{C}_{23} & \bar{C}_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & \bar{C}_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & \bar{C}_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & \bar{C}_{66} \end{bmatrix} \begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \tau_{23} \\ \tau_{31} \\ \tau_{12} \end{Bmatrix} \tag{8}$$

The stress-strain relationship can be rewritten in terms of the effective engineering elastic constants $\mathbf{E_{xx}}$, $\mathbf{E_{yy}}$, $\mathbf{E_{zz}}$, $\mathbf{G_{xy}}$, $\mathbf{G_{xz}}$, $\mathbf{G_{yz}}$, $\nu_{xy}\nu_{xz}$ and ν_{yz} as follows.

$$\begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ \gamma_{yz} \\ \gamma_{zx} \\ \gamma_{xy} \end{Bmatrix} = \begin{bmatrix} \frac{1}{E_{xx}} & -\frac{\nu_{yx}}{E_{yy}} & -\frac{\nu_{zx}}{E_{zz}} & 0 & 0 & 0 \\ -\frac{\nu_{xy}}{E_{xx}} & \frac{1}{E_{yy}} & -\frac{\nu_{zy}}{E_{zz}} & 0 & 0 & 0 \\ -\frac{\nu_{xz}}{E_{xx}} & -\frac{\nu_{yz}}{E_{yy}} & \frac{1}{E_{zz}} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{yz}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{zx}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{xy}} \end{bmatrix} \begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \tau_{yz} \\ \tau_{zx} \\ \tau_{xy} \end{Bmatrix} \tag{9}$$

The following reciprocal relationships must be satisfied.

$$\frac{\nu_{xy}}{E_{xx}} = \frac{\nu_{yx}}{E_{yy}}, \quad \frac{\nu_{xz}}{E_{xx}} = \frac{\nu_{zx}}{E_{zz}}, \quad \frac{\nu_{yz}}{E_{yy}} = \frac{\nu_{zy}}{E_{zz}} \tag{10}$$

5.3 DISCUSSION AND RECOMMENDATIONS FOR FUTURE WORK

The above analysis applies to balanced and symmetric laminates. For unbalanced and asymmetric laminates, the analysis is modified to include coefficients of mutual influence and Chentsov's coefficients (for further details see [40]). Although the analysis does not account for non-linear material behaviour, or thermal and moisture effects, it can be readily modified to account for hygrothermal induced stresses and strains [41]. The nine independent elastic properties $\mathbf{E_{11}}$, $\mathbf{E_{22}}$, $\mathbf{E_{33}}$, $\mathbf{G_{12}}$, $\mathbf{G_{13}}$, $\mathbf{G_{23}}$, ν_{12}, ν_{13} and ν_{23} can be determined experimentally (see Section 4) or calculated using micromechanics formulations, such as those used in CoDA (Composite Design and Analysis) preliminary design software, developed by the NPL.

The analysis in CoDA could readily be modified to enable three-dimensional elastic property prediction and to facilitate 3-D failure analysis for balanced and symmetric laminates. Although, it may be more appropriate to include the formulation in finite element analysis (FEA).

6. ENVIRONMENTAL AND IMPACT RESISTANCE, AND FLAMMABILITY

Thick sections take a longer time to degrade under hostile environments or exposed to fire, and exhibit greater impact resistance in comparison to thin sections. The large timescales involved for thick composites exposed to moisture to reach equilibrium, even under accelerated testing conditions, can be impractical, and hence the use of relatively thin specimens to determine the "through-the-thickness" moisture diffusion coefficient. The question arises as to the reliability or relevance of using thin coupon data for predicting long-term behaviour of large thick structures. Similar questions arise in relation to flammability and impact tests. This section examines the issues of environmental durability, impact resistance and flammability in relation to thick composite sections.

6.1 ENVIRONMENTAL DURABILITY

6.1.1 Coupon Tests

Prolonged, or even short term, exposure to aqueous environments can cause irreversible changes in the chemical and physical properties of fibre-reinforced polymer composites, particularly at elevated temperatures. These changes often compromise the load carrying properties of the material with the level of degradation increasing as moisture content increases. Reductions in stiffness and strength, and changes in thermo-mechanical behaviour can often be linked directly to the amount of moisture absorbed. The combined effect of heat and humidity can induce thermal blistering in thick laminate sections. Resistance to thermal blistering is a function of the moisture content; heat up rate and the thickness of the part.

A review of test methodologies and standards [42] revealed that the general approach to accelerated ageing of fibre-reinforced polymer composites is to expose laminated structures to severe test conditions, often well in excess of actual service conditions. In hot/humid environments (e.g. 70°C and 85% relative humidity (RH)) it may take 10-15 years for a thick composite structure to reach a state of moisture equilibrium or saturation. This condition, however, is even more difficult to achieve under milder and more realistic conditions than those employed to accelerate moisture conditioning. The issue arises as to the applicability of thin coupon durability data for predicting environmental degradation of thick composite sections.

The two main types of basic moisture conditioning are: (i) fixed conditioning, where a test specimen is exposed to a conditioning environment for a specified time; and (ii) equilibrium conditioning, where a specimen is exposed until the material reaches equilibrium with the conditioning environment. The first technique is routinely employed for screening purposes. This approach results in non-uniform moisture distribution through the thickness of the test specimen (particularly thick-sections). In principle, test data obtained from specimens conditioned in this manner are only considered suitable for comparing different batches of the same material or for quality control tests. This approach, however, is widely used for generating engineering data. Ideally, comparative studies of water absorption properties of materials should be carried out only using the equilibrium moisture content of polymeric materials exposed to identical conditions. Comparisons between composite systems with different moisture absorption characteristics are possible if the materials are conditioned to equilibrium. The thicker the material the longer the time required to reach equilibrium, hence the use of relatively thin specimens to determine the "through-the-thickness" moisture diffusion coefficient. The large timescales involved, even under accelerated testing conditions, can make this approach impractical.

The International standard BS EN ISO 62 [43] describes a procedure for determining the moisture absorption properties and/or diffusion coefficients in the "through-the-thickness" direction of flat and curved solid plastics. BS EN ISO 62 is suitable for use with polymer and composite specimens. The method can be applied to vapour exposure and liquid immersion. A major disadvantage with many tests is that the test piece is conditioned unstressed in the required environment and then tested. Failure to account for the combined effect of stress and environment will frequently result in an overestimation. This is particularly pertinent to flexural loading conditions where highly stressed surfaces are vulnerable to attack. Standard methods, therefore, need to have the widest possible applicability and be capable of representing actual service conditions.

The CEN (Comité Européen de Normalisation) working group on engineering use of pultruded composites has initiated a study item to identify the minimum testing necessary to account for the effect of both vapours (e.g. moisture) and liquid (e.g. chemicals and water) environments. Methods for producing equilibrium saturation are now currently being discussed, but there is a strong industrial demand for fixed exposure times that are more applicable to industrial timescales and costs. Difficulties arise in selecting suitable exposure times for all materials, due to the time dependence on thickness and material. A recent development has been the CEN standard for underground glass fibre-reinforced plastic (GRP) tanks for the non-pressurized storage of liquid petroleum based fuels. The standard accounts for exposure to both the liquid fuel and the vapour.

6.1.2 Product Testing

Combined stress and environmental conditions are used in some product test methods. ASTM D 3681 [44] and BS 5480 (Part 2) [45] are used by industry to determine the chemical resistance of glass fibre-reinforced pipes. Testing consists of exposing the interior of a pipe section to a corrosive solution while the pipe is subjected to a compressive deflection until the structure fails. The test is carried at several deflections and the time-to-failure is measured for each test. The long-term chemical resistance of the pipe is obtained by extrapolating to 50 years the log-log linear regression line for the initial strain level. This test is appropriate to structures buried underground, such as sewer pipes or gasoline tanks, which will experience a constant strain throughout the life of the structure. A self-stressing fixture can be used to apply a constant displacement. Alternatively, a constant load, often in the form of a dead weight, is applied to the pipe section and the creep behaviour is monitored. Time-to-failure is plotted either as a function of stress or as a function of initial strain. This test is appropriate to above ground pipes. It is quite common for creep tests under adverse environmental conditions to be carried out using standard test coupons (i.e. flexure and tension coupons).

6.1.3 Design/Analysis

It should be possible to characterise environmental (i.e. moisture) ageing effects, although roughly, on the mechanical properties of thick composite structures. The approach described below could be implemented in FEA and non-FEA software packages (e.g. CoDA).

Step 1 Determine tensile, compressive and shear elastic and strength properties for different levels of moisture content/glass-transition temperatures.

Step 2 Determine the moisture absorption kinetics and equilibrium (i.e. diffusion coefficients, $\mathbf{D}_{xx}$, $\mathbf{D}_{yy}$ and $\mathbf{D}_{zz}$, and saturation weight gain $\mathbf{M}_{\infty}$) by absorption tests on coupon specimens in a controlled environment.

Step 3 Determine the time-sequential moisture distribution in the composite structure.

Step 4 Determine the time-sequential distribution of mechanical properties with moisture content of the composite structure from **Steps 1 to 3**.

Step 5 Determine time-sequential stress and strain distributions with applied load within the composite structure.

Step 6 Apply suitable failure criteria to each point within the structural element to determine failure onset and progressive failure (i.e. ply by ply).

Semi-empirical formulations could possibly be used to relate mechanical property degradation with moisture content [46]. This would reduce the amount of testing required for generating design data. Future work should examine through the use of case studies as to the implementation of the approach as mentioned above. If successful, this approach could be used for a wide range of chemical environments.

6.2 IMPACT RESISTANCE

Increasing laminate thickness tends to improve damage resistance. Similarly, impact resistance of sandwich structures is generally improved by using thicker or denser core materials. The efficacy of using thick composite in providing impact protection and for producing primary load-bearing has led the Ministry of Defence to announce that the next generation of armoured personnel vehicles and tanks will consist primarily of composite materials (see Section 2.4). Previous work has shown that residual compressive strength and delamination propagation of impact damaged panels was insensitive to panel thickness over the range of 5 mm to 25 mm. The reason being that the flexural deformation is generally negligible compared with TT shear deformation for thick laminates. A thick laminate behaves as a semi-infinite body [47]. Localised damage in the form of fibre breakage and crushing can be expected to occur within the vicinity of impact.

For carbon fibre-reinforced laminates, the threshold force required to initiate impact damage needs to be increased by a factor of approximately 3 each time the laminate thickness is doubled. Increasing the laminate thickness from 2 mm to 60 mm (typical armour plating thickness) would result in a 164-fold increase in the threshold force.

It is recommended that future work focus on impact resistance of non-aerospace materials, curved and joined structures, and defect criticality under uniaxial and multiaxial static, fatigue and creep loading conditions. Defect criticality should take into account the presence of stress concentrations (e.g. cut-outs, ply drops and bond ends) and environmental effects. Damage characterisation/modelling is still far from satisfactory, particularly for non-aerospace materials. From a design perspective, there is a need to establish mathematical relationships between impact force/energy and residual mechanical properties and resultant damage. It may be possible to use a fracture mechanics approach to predict impact resistance.

6.3 FLAMMABILITY

Thick laminates have a superior retention of integrity in a fire than conventional materials. An oil-fed fire in an engine room of a Hunt Class MCMV lasted several hours with temperatures sufficient to melt aluminium fittings and to cause severe laminate charring to a depth of several millimetres [48]. The mechanical properties of remaining thickness of shell and bulkhead laminate was virtually unimpaired and the paint on the reverse side was not discoloured. There is scope for hybrid construction consisting of steel (i.e. framing) and GRP (thick laminates or sandwich panels), which would offer high stiffness and strength retention and provide good heat insulation at elevated temperatures. Although the performance of these hybrid steel/composite structures under load in severe fire conditions is now being considered, further work is required to provide the necessary confidence in the use of these structures in safety critical marine and off-shore applications. GRP pipework systems have been shown to remain intact during fire simulations an added bonus when considering firewater mains and sprinkling systems for off-shore platforms.

Most resin systems burn easily, emitting toxic gases and smoke. One solution is to include fire resistant additives. The use of fire retardants has only partially solved the problem of flammability. The problem of reducing smoke and toxic gases has been more difficult to solve. One of the more promising class of materials are phenolic resin based GRPs, which are intrinsically fire resistant and emit low levels of gases and smoke. These materials are particularly suitable for internal bulkheads and decks in ships, submarines and off-shore platforms. The low thermal conductivity of GRP will limit the wall temperatures and hence reduce damage in adjoining compartments. This can be an important component in limiting the spread of a fire. The potential market for fire-resistant composites has been estimated at £300 million for the transport, marine, electrical and construction sectors and with further potential in the aviation industry. Many of these applications will involve large thick composite sections.

7. DISCUSSION AND CONCLUDING REMARKS

The general consensus is that variations in material (particularly strength) properties due to laminate thickness can primarily be attributed to differences in processing. Thicker laminates require longer curing cycles in order to achieve complete cure. Increasing the rate of cure may reduce the cure cycle time, but at the expense of material performance. Internal stresses developed during processing can result in defect formation (e.g. voids, delaminations and microcracks). Excessive porosity adversely affects strength properties (particularly matrix dominated properties), and environmental and fatigue resistance. Fast cure rates, involving steep heating and cooling rates, will result in high process induced residual stresses. Slowing the process down to minimise, if not eliminate, process induced residual stresses means increased production costs, although scrap rates are reduced.

Thickness effects can be minimised by optimising the cure cycle and by controlling processing variables, such as temperature, pressure, viscosity, flow rates, etc. Cure simulation/modelling could play an important part in understanding and controlling the cure kinetics and degree of cure at any point in the composite at any time during the cure cycle. The development of cure processing models and monitoring procedures are needed to optimise material properties, prevent process-induced failures and most importantly reduce costs.

As previously mentioned, considerable development work is still required to provide test methods/standards and predictive models for determining the behaviour of thick composite structures (with and without damage) under multiaxial loading conditions. This work would be expected to address NDE inspection of thick sections/structures, environmental effects, impact and fire resistance, and the size of structurally critical/significant defects. Validated design procedures and safety margins need to be established for curved (i.e. pressure vessels and pipes), hybrid (metallic and composite) and joined structures (i.e. bonded and bolted). The review highlighted the need for reliable data pertaining to thick composite materials, particularly for non-aerospace applications. Future work needs to rectify this weakness; especially as there is a large market potential for these materials.

8. RECOMMENDATIONS FOR FUTURE WORK

The review has identified a number of areas that require further investigation and standardisation in relation to cure processing and inspection of thick composite structures. Recommendations for future work are given below.

Processing and Quality Assurance

- Development of real-time cure monitoring techniques and standards (i.e. ultrasonics, dielectric, infrared, nuclear magnetic resonance and optic fibre) for on-line processing for both composite laminates and bonded composite structures. Future work will need to account for different material systems and processing routes, and the use of sensors located within the component.
- Development of validated models, which relate processing parameters to cure kinetics, resin shrinkage, laminate thickness, glass-transition temperature, stress development and material performance.
- Development of techniques (e.g. Moiré and electronic speckle pattern interferometry) and for measuring process induced TT laminate/residual stresses and strain distributions in thick laminate sections and joined structures.
- Extension of NDE techniques (e.g. ultrasonic C-scan and X-radiography) to the inspection of thick composite sections (i.e. laminates, sandwich structures and bonded and bolted systems).
- Method(s) of evaluating residual stresses and through-thickness cure gradients.

Thick Composite Properties

- Development of in-plane and TT tension, compression and shear (including torsion of cylinders) test methods/standards suitable for characterising composite behaviour under static, creep and fatigue loading conditions. This work would need to be extended to elevated temperatures and hostile environments, and include defect criticality for various production type defects.
- Test methods/standards and failure criteria for multiaxial (i.e. biaxial and triaxial) loading of lineal and thick-walled cylindrical specimens. This work would need to include static, creep, fatigue and hydrostatic loading conditions and environmental conditions (including acids, solvents, fuel, salt water, elevated temperature, etc.), and be extended to include composite component testing.
- Test methods/standards for assessing the behaviour of bolted and bonded composite sections with and without defects (i.e. criticality) for various loading and environmental conditions (see above).

- Impact and high rate test methods/standards and predictive models for damage initiation and propagation.
- Development of fire test methods/standards and models for composite materials and structures (to include bonded and bolted systems). The assessment would need to consider the effect of additives (e.g. fire retardants) on short- and long-term performance, and cure processing of composite materials. An assessment of structural integrity of fire damaged composite structures would include loaded structures.
- Reliable design procedures for monolithic and joined composite structures to account for degradation due to mechanical loading, environmental factors, fire and impact.

Development of predictive models/design procedures for monolithic and joined composites would need to consider non-linear material behaviour, effect of fibre format/architecture (e.g. discontinuous and continuous, random and aligned, and 2-D and 3-D woven fabrics), hygrothermal effects, edge effects and blocking or grouping of lamina of identical fibre orientation. The models will need to account for fibre, matrix and interface failure modes, and be applicable to both in-plane and out-of-plane multiaxial loading conditions.

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REFERENCES

1. Design and Manufacture of Composite Structures, Eckold, G., Woodhead Publishing Limited, United Kingdom, 1994.
2. Designing with Plastics and Composites: A Handbook, Rosato, D.V., DiMattia, D.P. and Rosato, D.V., Van Nostrand Reinhold, 1991.
3. BS 4994, Design of Construction Vessels and Tanks in Reinforced Plastics.
4. BS 5480-2, Specification for Glass Reinforced Plastics (GRP) Pipes and Fittings for Use for Water Supply and Sewerage. Part 2: Design and Performance Requirements.
5. BS 6464 Specification for reinforced plastics pipes, fittings and joints for process plants.
6. Structural Design of Composites, Eurocomp Design Code and Handbook, Editor Clarke, J.L., E and FN Spon, 1996.
7. Design of Marine Structures in Composite Materials, Smith, C.S., Elsevier Applied Science, 1990.
8. Handbook of Polymer Composites for Engineers, Editor Holloway, L., Woodhead Publishing Limited, 1994.
9. Kelly, J.J., Leon, G.F., Hall, J.C. and Woodhall, C., "Reliable Design and Fabrication Composite High Performance Marine Structures", Volume VI, Proceedings of 10th[h] International Conference on Composite Materials, Whistler, British Colombia, Canada, Wood head Publishing Ltd, 1995.
10. French, M.A., "ACAVP – Europe's First Composite Armoured Fighting Vehicle", ECCM 9 Proceedings, Brighton, United Kingdom, 2000.
11. ISO 527-4, Plastics – Determination of Tensile Properties. Part 4: Test Conditions for Isotropic and Orthotropic Fibre-Reinforced Plastic Composites".
12. ISO 527-5, Plastics – Determination of Tensile Properties. Part 5: Test Conditions for Unidirectional Fibre-Reinforced Plastic Composites".
13. Niklewicz, J., "Review on Existing Status of Size Effects", NPL Measurement Note CMMT(MN) 022, 1998.
14. "Mechanical Testing of Advanced Fibre Composites", Editor Hodgkinson, J.M., Woodhead Publishing Limited, 2000.
15. Sutherland, L.S., Shenoi, R.A. and Lewis, S.M., "Size and Scale Effects in Composites: I. Literature Review, Composites Science and Technology, 59(2), 1999, pp. 209-220.
16. Sutherland, L.S., Shenoi, R.A. and Lewis, S.M., "Size and Scale Effects in Composites: II. Unidirectional Laminates", Composites Science and Technology, 59(2), 1999, pp. 221-233.
17. Sutherland, L.S., Shenoi, R.A. and Lewis, S.M., "Size and Scale Effects in Composites: III. Woven Roving Laminates", Composites Science and Technology, 59(2), 1999, pp. 235-251.
18. BS EN ISO 14126, "Fibre-Reinforced Plastic Composites - Determination of Compressive Properties in the In-plane Direction".
19. ISO 604, "Plastics – Determination of Compressive Properties".

20. Camponeschi, E.T., Jr., "Compression of Composite Materials: A Review", Composites Materials: Fatigue and Fracture (3rd Volume), ASTM STP 1110, Editor O'Brien, T.K., American Society for Testing and Materials, Philadelphia, 1991, pp 439-456.
21. Camponeschi, E.T., Jr., "Compression Testing of Thick Composite Materials", Composites Materials: Fatigue and Fracture (3rd Volume), ASTM STP 1110, Editor O'Brien, T.K., American Society for Testing and Materials, Philadelphia, 1991, pp 550-578.
22. Camponeschi, E.T., Jr., "Compression Response of Thick-Section Composite Materials", DTRC-SME-90/60, David Taylor Research Center, Bathesda, Marylands 20084-5000, USA, 1990.
23. BS EN ISO 14129, "Fibre-Reinforced Plastic Composites - Determination of the In-Plane Shear Stress/Strain, Including the In-Plane Modulus, by the ±45° Tension Test Method".
24. ASTM D 4255, "Standard Guide for Testing In-Plane Shear Properties of Composite Laminates, Volume 15.03, ASTM Standards, 2000, pp 209-219.
25. ASTM D 5379, "Standard Test Method for Shear Properties of Composite Materials by the V-Notched Beam Method", Volume 15.03, ASTM Standards, 2000, pp 241-253.
26. ISO 15310 "Fibre-Reinforced Plastic Composites – Determination of In-Plane Shear Modulus by the Plate Twist Method".
27. ASTM D 5448, "Standard Test Method for Inplane Shear Properties of Hoop Wound Polymer Matrix Composite Cylinders", Volume 15.03, ASTM Standards, 2000, pp 254-265.
28. Sims, G.D., "Harmonised Standards for mechanical Testing of Composites", Plastics, Rubber and Composites, Volume 28, Number 9, 1999, pp 409-415.
29. ASTM D 3044, "Standard Test Method for Shear Modulus of Wood-Based Structural Panels", Volume 4.10, ASTM Standards, 2000, pp 436-438.
30. BS EN ISO 14125 "Fibre-Reinforced Plastic Composites – Determination of Flexural Properties".
31. Broughton, W.R. and Sims, G.D., "An Overview of Through-Thickness Test Methods for Polymer Matrix Composites", NPL Report DMM(A)148. 1994.
32. Lodeiro, M.J., Broughton, W.R. and Sims, G.D., "Understanding Limitations of Through-Thickness Test Methods", Plastics, Rubber and Composites, Volume 28, Number 9, 1999, pp 416-424.
33. Through-Thickness Testing of Polymer Matrix Composites, NPL Measurement Note MATC(MN) 06, 2001.
34. BS EN ISO 14130, "Fibre-Reinforced Plastic Composites – Determination of Apparent Interlaminar Shear Strength by Short-Beam Method".
35. ASTM D 3846, "Standard Test Method for In-Plane Shear of Reinforced Plastics", Volume 8.02, ASTM Standards, 2000, pp 471-473.
36. Military Handbook Polymer Matrix Composites, Volume 3 – Materials Usage, Design and Analysis, MIL-HDBK-17-1E.
37. Tanopols'kii, Yu.M. and Kincis, T., "Static Test Methods for Composites", Translated and Edited by Lubin, G., Van Nostrand Reinhold Company Inc., 1984.
38. Ellyin, F. and Martens, M., "Biaxial Fatigue Behaviour of a Multidirectional Filament-Wound Glass-Fiber/Epoxy Pipe", Composites Science and technology, Volume 61, 2001, pp 491-502.
39. ASTM D D 2992, "Standard Practice for Obtaining Hydrostatic or Pressure Design Basis for "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe and Fittings, Volume 8.02, ASTM Standards, 2001, pp 325-335.
40. Jones, R.M., "Mechanics of Composite Materials", Hemisphere Publishing Corporation, 1975.

41. Whitcomb, J. and Noh, J., "Concise Derivation of Formulas for 3D Sublaminate Homogenization", Journal of Composite Materials, Volume 34, Number 06, 2000, pp 523-535.
42. Broughton, W.R, Lodeiro, M.J., Maudgal, S. and Sims, G.D., "Review of Test Methods and Standards for Assessing Long-Term Performance of Polymer Matrix Composites", NPL Report CMMT(A) 94, 1998.
43. BS EN ISO 62, Plastics - Determination of Water Absorption.
44. ASTM D 3681 "Standard Test Method for Chemical Resistance of "Fibreglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe in a Deflected Condition", Volume 8.04, ASTM Standards, 2001, pp 483-489.
45. BS5480-2, "Specification for Glass Reinforced Plastics (GRP) Pipes and Fittings for Use for water Supply and Sewerage. Part 2: Design and Performance Requirements".
46. Broughton, W.R., "Analytical Models for Assessing Environmental Degradation of Unidirectional and Cross-Ply Laminates", NPL Report MATC(A) 1, 2001.
47. "Impact Behaviour of Fibre-Reinforced Composite Materials and Structures", Editors Reid, S.R. and Zhou, G., CRC Press, Woodhead Publishing Ltd, Cambridge, UK, 2000.
48. Smith, C.S., "Design of Marine Structures in Composite Materials", Elsevier Applied Science, 1990.