

FIRE PERFORMANCE OF FIBRE-REINFORCED POLYMER COMPOSITES

A Good Practice Guide

Composites UK

Trade Association

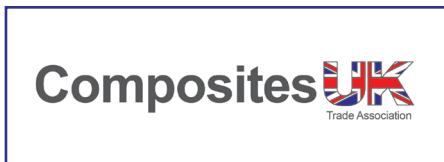
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1. INTRODUCTION

The fire performance of a composite component or structure is complex and accordingly, the knowledge base is constantly growing as new products arrive in the market place in response to growing demand. Despite the topic proving to be a “moving target”, there is a need to improve the understanding of how the fire performance of fibre reinforced polymer (FRP) composite components is specified by the engineer and buyer, and achieved by the manufacturer.

Note: Readers new to the subject may find Appendix A Glossary and Terminology a useful reference.

1.1 Scope

A composite material is composed of at least two materials, which combine to give properties superior to those of the individual components. This good practice guide refers primarily to FRP composites, usually with carbon, glass, aramid, basalt, polymer or natural fibres embedded in a polymer matrix. Ceramic and metal matrix composites are covered only briefly. Composites may also contain fillers, to modify its physical characteristics or its function, and may incorporate core materials and surface coatings, all of which affect the fire performance of the product.

The purpose of this guide is to provide a greater level of understanding of the requirements and solutions available when specifying or manufacturing FRP composite components, which need to provide a level of fire performance. It attempts to clarify the wide variety of material options, appropriate selection considerations, and the effects on fire performance in typical applications. It provides high level guidance on the standards and testing applicable to different applications, but does not provide a fully comprehensive list of standards for every product in every sector in every country. There is some guidance to formulators on approaches, but not detailed advice on how to enhance the fire, smoke and toxicity (FST) properties of a particular material.

Although aimed specifically at components manufactured using thermoset resin matrices, some of the information included herein can also be applied generally to thermoplastic materials and components as many of the referenced tests are generic and unless specifically mentioned therein will apply equally to both material types. The guide does not cover high temperature operational performance except for brief mentions.

1.2 Background

Since applications of FRP composite materials in marine and aerospace industries grew commercially in the 1950's, this technology was soon being transferred to other industries due to its ease of production and moulding of complex forms. However, in the majority of applications, the material was not utilised in applications requiring fire performance at this time.

Over the decades following, as with any new engineering material, hundreds of formulations were produced by an increasing number of manufacturers as they fine-tuned their base resin systems to enhance particular properties for each new application or process.

As demand for resins with improved fire performance grew, formulators tended to add ingredients to existing resin systems to improve fire performance, often resulting in reduced mechanical performance and frequently making the resin difficult to work with. These resins were also more expensive to manufacture.

As the application of composites spread into almost every sector of manufacturing, resins were produced with characteristics, including FST performance, for a specific industry/application/country. The majority of these are now readily available on the resins market but each has been formulated to pass the testing required to meet one particular FST specification.



Photo courtesy India Mart: MCC laminating Resins

1.3 Specification process

Specifiers and manufacturers share a responsibility for the safety of any structure they design or manufacture. Responsibilities are not only legal but may also be moral where the safety of life is at risk. No longer is it acceptable for a manufacturer to simply build to plan and deny any responsibility for the behaviour of a structure in a fire. As a specialist,

one will be expected to have some knowledge of the performance of the materials being proposed as part of a build in response to a specification or drawing supplied by others.

When a manufacturer receives an enquiry for any composite component a number of scenarios are possible:

1. There is no mention of a requirement for FST properties.
2. There is a requirement for fire performance, but no standard is quoted.
3. There is a particular requirement specified and codes, standards or other data are provided.

In the case of 1 above, it is possible that there is actually no need for any level of fire performance. The component may be required for use in water, for example, or in a location where there is either little chance of fire occurring, or where its failure as a result of a fire is not considered a high risk.

However, there will be clear cases when some level of fire performance is required, even though none is specified. In this case, one may argue that the manufacturer, being aware of this fact, has a duty to use materials that when combined to form the composite structure, provide an adequate level of protection even though it has not been specified. Ideally, the manufacturer will communicate with the specifier to determine what is desired, what standards might apply, and ultimately what level of protection against fire is demanded. This process may result in the manufacturer providing the buyer with, for example, options for different levels of protection.

In the case of 2 above, where there is a requirement but no standard is quoted, the buyer may use terms such as “required to be manufactured from FR materials” or “to have enhanced FST properties”, or even “to be manufactured from non-combustible materials”. In these cases, the buyer and/or specifier may lack knowledge of how to specify fire performance or of the international or other standards (regulatory or otherwise) that may apply to his particular product or component. In this event, it is essential both parties work together to firmly establish the correct specification prior to issuing an invitation to tender or responding with a quotation. A lack of knowledge on the part of at least one party is likely to result in a non-realistic price, leading to the product being manufactured using one or more generic “FR” rated materials which will not satisfy the relevant code or standard. In the event of a fire resulting in injury and/or financial loss, either or both parties could find themselves facing legal action for providing a product which does not meet legal requirements, or is unfit for purpose.

The third case above may appear to be the straightforward option. However, the buyer may provide information that is either irrelevant to a particular application / industry or may quote international or industry specific standards which are unfamiliar to the manufacturer. Often, quoted standards are not applicable to that particular product and it is left to the manufacturer to ascertain which standards are applicable and revert to the buyer for clarification or otherwise. The most often quoted requirement is for the use of “Class 0” or “Class 1” materials without providing any further information. In this instance, the manufacturer can easily take advantage of the buyer and follow his instructions precisely. The likely result however is a product that may not be fit for purpose and which, in the event of a fire, could leave both the buyer and manufacturer exposed to legal action.

A useful source of information is the manufacturer of the materials themselves. They will be able to advise on the suitability of their products for certain applications, and will be able to confirm, by the supply of test certificates, what tests have been undertaken and the results. The question becomes more complex when materials which may already have been tested alone are to be combined in one structure. It is very likely that test data for that particular combination of materials may not be available.

A logical approach to the decisions needed at the quotation stage is shown in flowchart format in Figure 1. A similar approach can be used by a specifier.



Photo courtesy Tom Royle: Jet fire test on riser protection system at Spadeadam

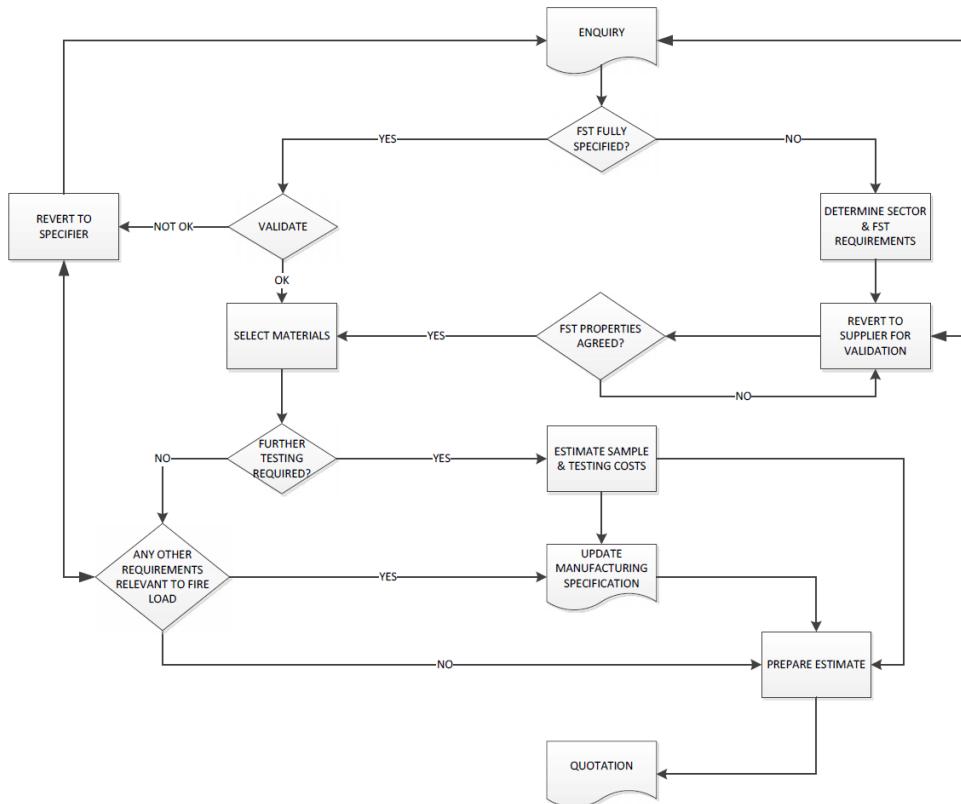


Figure 1: A logical approach to decision making at the specification / quotation stage.

2. WHAT ARE THE KEY CHARACTERISTICS WHICH DEFINE THE FIRE PERFORMANCE OF A COMPOSITE?

The fire performance of a composite component (i.e. a finished part that is manufactured from a fibre reinforced resin and which may also include a core material and a surface finish, such as gel coat or paint) is affected not only by the qualities of the resin, but also by the properties of all of the other materials which make up the laminate. Therefore, manufacturing a part using a fire retarded resin does not necessarily result in enhanced fire-retardant properties.

Thus, we will talk separately in Section 3 Materials and combinations thereof and Section 4 Methods of improving properties about the FST performance of resins, reinforcements and cores as well as the performance of the combined matrix/structure. Further details of the standards and tests which define these characteristics are given in Section 5 Standards and regulations for sectors. A description of the commonly used Cone Calorimeter test rig can be found in Section 6.3.

2.1 Reaction to fire & fire resistance

How materials and structures perform when exposed to a fire is often broken down into two measures:

- Reaction to fire - the measurement of how a material or system will contribute to the development and spread of a fire, particularly in the very early stages when evacuation of personnel may be crucial.
- Fire resistance - the measurement of the ability of a material or system to resist, and ideally prevent, the passage of fire from one distinct area to another.

These terms have been used extensively in several sectors and are now fully integrated into new fire testing standards, most notably but not exclusively, in the building and construction sector where all materials used now have to be classified according to Euroclasses which were introduced in 2000. (Further information on Euroclasses may be found in Section 5 Standards and regulations for sectors.)

2.1.1 Reaction to fire (fire growth)

This compares base materials' reactions to fire by exposing them to standardised test procedures which typically determine non-combustibility, calorific potential, ignitability or other burning characteristics. Standards have now been set for materials approved for use in different applications and whilst these are now harmonised within Europe for some sectors, some discontinuity and confusion remains in others.

2.1.2 Resistance to fire (fire compartmentation)

Definitions of this vary depending on the sector or application, but generally, the fire resistance of materials is determined by measuring their ability to withstand a standard fire, burner or furnace test for a specified period of time. Fire resistance tests can also be used to assess the retention of load-bearing integrity (e.g., stiffness, strength and creep resistance) of a structure during a fire and the residual mechanical properties following it. In most sectors, this measures the ability of a product or structure, commonly a wall or ceiling but also covering ventilation ducts and pipes, to withstand a harmonised fire test enabling its formal classification and therefore comparison with other similar products. In the construction sector, fire resistance is defined in BS 476-



Photo courtesy Fire Testing Technology; ISO 5658-2; IMO Resolution A.653(16); ASTM E1317; ASTM E1321
Spread of Flame Test Rig



Photo courtesy Warrington Fire

20:1987 'Fire tests on building materials and structures. Method for determination of the fire resistance of elements of construction (general principles)' as "the ability of an element of building construction to withstand exposure to a standard temperature, time and pressure regime without loss of its fire separating function or loadbearing function or both for a given time". Fire doors are categorised using a similar process and carry the same ratings as the partitions in which they sit.

Testing is usually undertaken using a large-scale furnace running a predetermined time temperature curve which is chosen according to the standard of compartmentation being tested. These tests will determine a number of characteristics of the product, typically: insulation, integrity and load carrying capacity. Ratings such as B15, A30, A60 result.

Whilst developed for the construction industry, these ratings have been adopted in other environments such as marine and offshore.

2.2 Non-combustibility

The term 'non-combustibility' is often misunderstood. Depending on the source of the definition, a material is generally defined as being non-combustible if:

- It does not burn when exposed to a fire, or
- It is incapable of igniting and burning when exposed to a fire, or
- It is not flammable, or
- It does not contain any organic material

Interestingly, some dictionary definitions also describe a non-combustible material as being "fire retardant", further adding to the confusion.

Fortunately, there are very well-defined tests to determine whether a material is non-combustible (in accordance with a particular standard or regulation) regardless of whether it comprises organic material or not. BS EN ISO 1182:2010 'Reaction to fire test - Non-combustibility test' is one such test accepted by European authorities concerned with the marine and offshore industries. Other sectors and countries may refer to other tests and/or may use standard tests but vary some of the test conditions to better suit their own particular requirements.



Photo courtesy Skyline Total Testing Solutions: ISO 1182 Non-Combustibility Test Rig

2.3 Ignitability

Ignitability is a measure of a material's ability to combust or support combustion due to its physical properties. Any material that is easily ignited may pose a significant fire risk depending on the application. Whereas ignitability is only one measure of a material's ability to resist burning, it is the most obvious one to aim to improve where a component may be exposed to high temperatures, or especially naked flames. Exposure to a naked flame may be caused by equipment located nearby, such as an industrial burner or flare stack, or perhaps an electrical fault. In some applications however, the greatest risk comes from fires started on purpose i.e. vandal attack. Wooden bridges, for example, have been badly damaged when subject to a fire started by placing a burning car tyre on the deck or up against a parapet.

A commonly referred to test for ignitability is BS 476-13:1987, ISO 5657:1986 'Fire tests on building materials and structures. Method of measuring the ignitability of products subjected to thermal irradiance', although there are many others.

2.4 Fuel load and heat release rate

The heat release rate (HRR) is the amount of heat generated by a fire and is typically measured as W/m^2 . It was first measured in the 70's by the commercial aircraft sector and several different methods were used until 1982 when the cone calorimeter was developed. This is still the most common test rig used today.

HRR is recognised as one of the most significant driving forces which determine the fire hazard. It is also understood that the higher the HRR the greater is the risk of production of toxic gases, smoke and other undesirable aspects of a fire. A test for HRR, as well as smoke production and mass loss rate, is defined in BS ISO 5660-1:2015 'Reaction-to-fire tests. Heat release, smoke production and mass loss rate. Heat release rate (cone calorimeter method) and smoke production rate (dynamic measurement)'.

The amount of flammable material that surrounds a fire, and is thus available to it as a source of fuel, is known as the fuel load. Larger fuel loads result in larger, longer lasting and more ferocious fires. Fuel load is sometimes measured as kg/m² where the weight is the equivalent weight of the fuel if it were to be wood. However, in Europe, the calorific value of the fuel combined with the amount of fuel present is now more commonly used as a base for definition. For example, a surface may be required to have a maximum gross calorific value (e.g. 45 MJ/m² as required under FTP Code rules for interior linings) according to its application and relevant code or standard. This would be determined by a test such as ISO 1716:2018 'Reaction to fire tests for products. Determination of the gross heat of combustion (calorific value)'.

2.5 Flame spread, surface flammability & fire propagation

Surfaces are often required to have low flame spread/surface flammability characteristics, and this is probably the most common requirement which will be specified for many different applications which are not fire partitions or divisions. Typically, tests expose a sample of the material to a combination of radiant heat and direct flame and measure the rate of spread of the flame front across the sample, as well as the distance covered after certain set periods of time. ISO 5658-2:2006 'Reaction to fire tests -- Spread of flame -- Part 2: Lateral spread on building and transport products in vertical configuration' is one such test. ASTM E162 - 16 'Standard test method for surface flammability of materials using a radiant heat energy source' is an American standard frequently seen quoted in Europe.

Such tests have been established for decades and test methods and test durations vary widely. When specifying this characteristic one needs to be especially careful to ensure that the quoted standard is relevant to the particular application. For example, there is little point quoting a standard where the test is conducted on a horizontal specimen if the application will use the material in a vertical plane. The test results will be meaningless and irrelevant for your application.

Fire propagation is a term used primarily in the building and construction industry and materials are tested to BS 476-6:1989+A1:2009 'Fire tests on building materials and structures. Method of test for fire propagation for products', are given a fire propagation index allowing specifiers to compare the performance of different products. However, there are numerous other fire propagation tests which have been developed for very specific applications such as cable ducts.

2.6 Melting behaviour / flaming droplets

Flaming droplets are known to be a very significant cause of spreading a fire and many standards now place limitations on the quantity of flaming droplets produced during a test. Such is their contribution to a fire that many codes demand a zero level of flaming droplet production. As a result, most fire tests for materials used for vertical and horizontal surfaces now include a measure of the number of flaming droplets that are produced during the fire test. In some instances, this relatively new measure has been incorporated by amendment into existing tests, such as that for surface spread of flame, for example.

2.7 Smoke & toxicity

As the breadth of applications of composites continue to grow, many products are being utilised in areas such as mass transit where risks to people on-board are reduced to an absolute minimum. Most unmodified resins, unlike metals, can burn because they are organic polymers; that is, their chemistry consists of at least one carbon compound. The combustion reaction, especially in the presence of other resin components, produces toxic by-products which pose a serious health risk when inhaled.

Statistically, loss of life more often results from exposure to smoke and toxic fumes than the fire itself.

Over time, resin additives and fire-resistant resin formulations have been developed to meet international and sector specific safety requirements for



Chongqing Gold Mechanical & Electrical Equipment Co.,Ltd: ISO 5658-2 IMO Spread of Flame Test Equipment



Photo courtesy Fire Testing Technology: ASTM D2843 Smoke Density Test Rig

control of FST. Today these more established solutions are being joined by newly emerging alternatives, such as inorganic resins and specially developed fibres which have improved FST properties.

None-the-less, the need to reduce the generation of smoke and toxic fumes remains a significant focus and numerous tests are available. ASTM D2483 ‘Density of Smoke from the Burning or Decomposition of Plastics’ and BS EN ISO 5659-2:2017 ‘Plastics, Smoke generation are two in common use. Determination of optical density by a single chamber test’, are typical tests, but there are many others. See Section 6.6. Always ensure that you use the most applicable test method and equipment to suit the particular application/sector.

2.8 Thermal insulation

Thermal insulation is the reduction of heat transfer (i.e. the transfer of thermal energy between objects of differing temperatures) between objects in thermal contact or in range of radiative influence. Heat flow is an inevitable consequence of contact between objects of different temperature.

Measurement of insulation value is straightforward and usually involves attaching thermocouples to both front and back faces of the material under test.

Composite materials offer the significant advantage over metals in that they are inherently better insulators. One practical advantage of this, when considering resistance to fire, is that the temperature of the non-fire side surface of the partition can be much lower than if the barrier or partition were to be manufactured from metal. This improves the safety of personnel in that compartment, and can reduce the risk of fire spread into that compartment.

Whilst understanding how heat is conducted through materials and combinations of materials is fundamental to determining how those materials perform during a fire, as can be seen already, that is only one part of a complex picture. The thermal properties of many common materials are not constant. For example, Kaowool and Rockwool conductivity changes by up to 5x as temperature increases to 800°C. In addition, behaviour of materials can be further affected by decomposition and phase changes.

2.9 Load bearing temperature envelope

Whilst some fire partitions only support their own weight, including perhaps minor items such as a TV, mirror, coat hooks, lighting or other equipment, some structures need to be load bearing. These are tested in a similar manner to non-loadbearing structures except that during the fire test, a continuous load is applied to the structure. This results in a more challenging test, especially for composite materials which soften at lower temperatures than metals.

For metal structures, limiting temperatures are applied which ensure that for the duration of the test, the temperature of the structure does not exceed a certain temperature, beyond which the material is deemed to have lost some of its structural strength and fails the test. For example, for aluminium, according to the FTP Code this temperature is deemed to be a rise of no more than 200°C.

For materials other than steel or aluminium, such as an FRP composite, the requirement is less clear and the maximum allowable temperature rise is set by the approval authority. This limiting temperature is most likely to be determined based on the heat deflection temperature (HDT) of the composite material. HDT is related to a fixed deformation defined by a standard and is affected by fillers and reinforcement. This defines the temperature at which the material will begin to lose structural integrity in a fire.

Glass transition temperature (T_g) is not the same as HDT. It is not defined by a single standard but essentially is the temperature region where the polymer transitions from a hard, glassy material to a soft, rubbery material. Hence, the glass transition temperature effectively defines the working temperature range of the material. Knowing its value is important in the design of most composite structures, especially those which are load bearing or which will be used in hotter climates or otherwise exposed to elevated temperatures.

3. MATERIALS & COMBINATIONS THEREOF

3.1 Combining materials

Materials manufacturers will be able to advise on the suitability of their products for certain applications, and will also be able to confirm, by the supply of test certificates, what tests have been undertaken, and what results were achieved.

Where the question becomes more complex is when materials which have been tested alone, are to be combined in one structure. It is very likely that test data for that particular combination of materials may not be available, not least because those materials may not have been sourced from one single manufacturer.

Every FRP composite component or structure is manufactured from a combination of materials, all of which react to fire in different ways.

- Resin
- Additives
- Reinforcements
- Core(s)
- Surface finishes and coatings

How each of these elements reacts will have some effect on how the overall matrix responds to fire, but even though individual components may have known properties, fire performance of a complete laminate or sandwich panel (including a core) is very difficult to predict and can usually only be determined by testing, although the overall value of thermal insulation of a complex panel can now be calculated using commonly used structural engineering software such as NASTRAN or Hyperworks.

Structures and components are often in contact with metals, whether they form part of a hybrid assembly or are simply the nuts and bolts used in the assembly. These items easily conduct heat and often also affect the way in which the composite element of the structure responds to the fire, causing hot spots and resulting in test failures.

3.2 Which is the fire side?

Composite structures or components are usually designed to withstand fire from one direction only. However, manufacturers should be aware that some codes and standards may demand that a structure be tested from both sides (in two separate tests).

3.3 Assembly and disassembly

Although consideration of how a structure may be assembled or disassembled is not obviously connected to its performance in a fire, it is always worthy of consideration during a design review.

For example, if a fire rated enclosure provides for access to its contents for inspection or maintenance, it should not be possible to replace the access hatch or other removable cover without guaranteeing that the fire integrity of the enclosure is re-established. Thus, loose fire seals/gaskets should be avoided and fixings should be captive.

3.4 Penetrations through structures

If there are to be any penetrations through a fire rated structure or component, perhaps for cables, pipes or linkages, check to ensure that the penetration will also be at least as resistant to the passage of smoke, flames, etc. as the partition itself. For some applications, proprietary fire rated seals and penetrations are available. In applications where the fire rating is non-standard, then it may still be possible to use suitably rated proprietary products. In all other instances it is likely that a small-scale fire test will be sufficient to demonstrate the suitability of the seal.

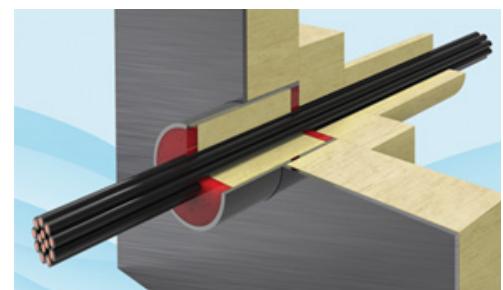


Photo courtesy STI Marine: Typical Cable Penetration using Fire Stop Putty

3.5 Fire and other loads

Fire is one of many load cases that any given structure may be exposed to. Designers need to be aware of any other loads resulting from external influences, whether static or dynamic, which may be likely to act simultaneously on the structure. This ensures that designer, specifier and manufacturer are well placed to determine whether further analysis of these effects, and how they might affect the particular structure in the event of a fire, is required.

4. METHODS OF IMPROVING PROPERTIES

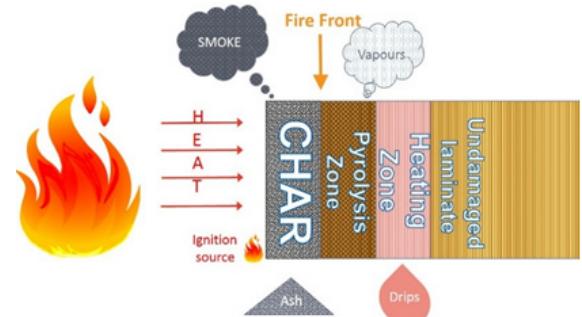
4.1 General principles

There is a very wide toolset for improving the fire performance of a composite product. Options include simple surface protection, choice of inherently good FST resins and reinforcements, and a plethora of fillers, additives and coatings to enhance specific materials behaviour when exposed to heat or flame.

4.1.1 Fire progression and combustion products

Fire typically attacks in a progressive fashion, heating up of the exposed surface, release of volatiles, ignition of those volatiles, progressive burning to peak heat release, and a die back phase through to fuel exhaustion and cool down.

- Heating (melting of thermoplastics)
- Pyrolysis and release of volatiles
- Ignition and flame spread
- Fire growth and penetration
- Char, smoke and ash creation
- Peak heat release
- Fuel exhaustion and die back
- Re-ignition risks



Progression of fire within a composite, courtesy of Nigel Keen.

4.1.2 Breaking the fire triangle

The palette of materials and solutions to address fire, smoke and toxicity performance in a composite product is extremely broad but there are four main strategies for preventing and controlling the ignitability, fire growth and flame spread in composite products:

- Reduce fuel availability by reducing the content of combustible materials.
- Cool, quench, reflect, trap or absorb heat.
- Create barriers, between fuel and heat, or between fuel and oxygen.
- Attack the fire plasma chemistry, preventing or modifying the combustion/oxidation reactions.

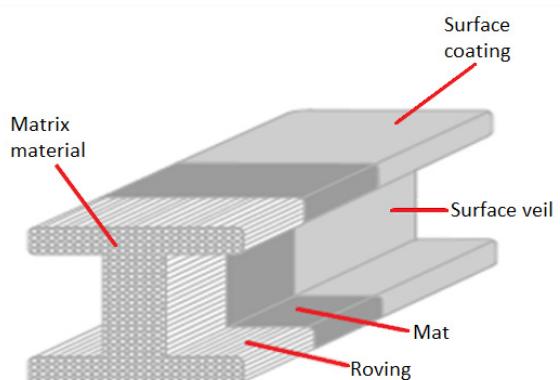


Fire triangle, courtesy of Nigel Keen.

4.2 Choosing FST solutions for your product

The key to correct choice of component materials and where they should be deployed in a product will depend on the end use, fire risk and the qualification requirements, standards and test protocols to be met.

- Final finishes, such as paint or lacquer.
- Surface films or veils.
- In mould surface layers.
- Intumescent layers (including specialist veils).
- Sacrificial ablative layers.
- Heat insulating core materials.
- Fillers for low combustible content.
- Inorganic reinforcing fibres.
- Fire retardant modified or inherently fire safe resins.



Layering of materials in a pultruded section showing where fire protection can be incorporated, courtesy of Nigel Keen.

A first consideration is whether the product has a safety critical structural role to play, is semi-structural, or is non-structural and can be deployed as a sacrificial or protective barrier.

This will determine whether there is a requirement for high-fibre volume fraction, or whether mechanical performance can be sacrificed, and polymer content minimised by deployment of fillers.

The second selection criterion centres around the likely fire scenario to be taken into account. The challenge may simply be reduced ignitability from a low heat flux source, such as a cigarette, match, or wind-blown burning ember, applied locally at one spot on the surface. At the other extreme the product may have to resist a very high heat flux over its entire surface for a long time AND maintain a level of structural integrity.

Finally, close consideration has to be given to the test regime to qualify the product. Will the product or components be tested for reaction to fire, fire growth tests, or fire resistance tests and how important are smoke and toxicity for the end application?

4.3 ‘Non-combustible’ composites

There are two families of composite materials that contain no organic content and can be considered non-combustible. These are ceramic matrix composites (CMCs) and metal matrix composites (MMCs). In these systems the matrix or binder holding the reinforcing fibres in shape is ceramic, or a metal. At one extreme these materials may be chosen for very high temperature applications, often replacing heavier metal components e.g. SiC/SiC and Ox/Ox materials are being deployed in the most advanced aero engines. In both cases the reinforcing fibre and matrix are made from the same materials, silicon carbide, and alumina respectively. These materials are expensive to produce and process, and their primary purpose is extreme high temperature performance, rather than fire resistance.

Metal matrix composites, such as alumina reinforced aluminium, or tungsten carbide fibres in titanium, are also applied mainly to stretch the operational performance into areas that metals alone cannot achieve. These materials, while intrinsically fire safe, are also usually too expensive to use solely for their FST properties.

At the other end of the performance spectrum, ceramics, deployed as water-based slurries and hardening via hydration reactions, can have various fibre reinforcements. They can be cement based, use gypsum or lime, or other ‘water glass’ ceramic chemistries. The fibre reinforcements can be ceramics like glass or basalt where fire safety is a primary concern. Glass-reinforced concrete is now the material of choice for applications such as tunnel linings.

Thermoplastic and natural fibres can also be deployed within ceramic matrices and composites and still have good fire performance, meeting limited combustibility test requirements. Some construction products use a cementitious matrix with natural fibres for their hygroscopic properties to manage humidity and act as passive heat regulators in buildings. Cement impregnated geotextile fabrics are deployed as drainage channels for irrigation, where the powder impregnated fabric can simply be draped into a prepared ditch or channel and sprayed with water to activate the cement. Blast and ballistic resistant panels use the high energy required to shatter brittle ceramics, combined with woven high tensile thermoplastic fibres, to both absorb shock and blast and prevent high velocity penetration.

4.4 Filled FST systems

The simplest and cheapest approach to enhancing fire, smoke and toxicity is to add an inorganic filler material to the composite. Filled resin systems work best in applications where cost is critical, and component strength and weight less so. In the simplest approach cheap inert filler, such as calcium carbonate, or even sand or crushed stone, displaces resin and fibre. This means there is less combustible material to burn, and much reduced smoke generation. Other inorganic fillers have a dual effect, or even act in multiple ways during fire progression. Fillers therefore are an important tool in the composites FST toolbox.

High levels of filler restrict the manufacturing processes available. The binder resin has to wet the higher surface area of both fibre AND filler in order to avoid porosity and maximise performance. This can limit choice of resin type. Resins for filled systems typically need to have low viscosity, often by being diluted, and potentially have high levels of volatile organic compounds (VOCs) and low resin solids content. This can lead to more restricted mechanical performance and reduced stiffness or reactivity. Alternatively, if high molecular weight solids must be maintained then high temperature processing may be required to reduce viscosity and allow flow and wetting during the component forming process. Filled systems, because of their low resin content may also be more brittle and more prone to water penetration and environmental attack and so may not be suitable in wet or some corrosive environments.

4.4.1 Inert fillers

In a non or semi-structural panel product, such as an enclosure or box where the fire risk is low and the application isn't safety critical, this may be the optimal solution. In this case the filler itself is essentially inert, rather than active. If the product is relatively thick in section, the relatively dense heavy filler may also act as a temporary heat sink, slowing ignition if it is from a small source. In a higher heat intensity scenario, however, inert fillers won't prevent the combustible materials in the composite from igniting and being burnt away. Good examples are very basic enclosures such as gas boxes made by hot press processes, where the bulk moulding compound may contain as little as 12-18% fibre and similarly low levels of resin binder. Cast composites products like engineered stone, cultured marble and onyx, and solid surface kitchen, bathroom and laboratory work surfaces have low to zero fibre, or small amounts of short fibre, maximising their use of fillers.

4.4.2 Hydrated mineral fillers

Many mineral fillers, both synthetic and natural, contain 'waters of hydration'. When hydrated fillers release this water vapour as steam, it both dilutes the combustible organic content in the gas phase and, because the reaction is endothermic, takes some heat out of the system, at least temporarily. One of the most useful FST fillers for composites is alumina trihydrate (ATH) where each molecule of ATH contains three molecules of water. This is released at temperatures from 180 to 250°C, which is safely above the processing temperature for most thermoset composites, but significantly below the decomposition and auto-ignition temperatures of many resin systems. There are a number of other hydrated fillers available as FST additives, such as magnesium dihydrate (MDH) often used in the plastic cables industry where processing temperatures are higher, but also usefully deployed in high temperature composite production processes, such as press-moulding, where they will form part of the filler package in sheet and bulk moulding compounds (SMC / BMC) used for higher temperature electrical applications.

Hydrated fillers are said to act mainly in the 'gas phase' of the fire process. In a fully developed fire, even calcium carbonate can help a little in this manner at high temperatures it decomposes (calcination) releasing carbon dioxide, another flame diluting gas and leaving behind calcium oxide.

Most hydrated fillers will decompose to their parent metal oxide, which can either form powdery ash, or at high temperatures these powders may react or fuse together with each other and with reinforcing fibres to create a more solid ceramic residue.

4.4.3 Catalytic fillers

Another family of FST filler additives is metal oxides. Many metal oxides act as catalysts, encouraging certain types of reaction between the VOCs generated as a component is exposed to heat. They can act to promote char formation, encouraging cyclic carbon-carbon reactions, trapping the carbon into insulating layers of soot, rather than allowing it to react exothermically with oxygen and be fuel for the flame. This is called 'condensed phase' catalysis. Alternatively, they can act more like the catalyst in a car exhaust, encouraging a cleaner burn and so reducing smoke and smoke toxicity.

Metal oxides can also be useful 'synergists'. In more complex FST systems, their catalytic effects can enhance the effectiveness of other additives. Zinc stannate, and zinc hydroxy stannate (ZHS) are good examples of this kind of filler. ZHS acts as a hydrated filler, a char promoter, and is also effective as a synergist in halogenated systems. Even simpler metal oxides used as primarily as pigments, such as titanium dioxide and iron oxides can have an effect on fire chemistry.

4.5 Resin and additive chemistry

In applications that require a high level of structural performance, or are weight critical, the use of fillers may not be a viable option. High stiffness applications generally need to maximise fibre loading and so typically a different strategy is required. Other applications preclude filler use because of the preferred manufacturing process, or for product aesthetic requirements, e.g. transparency. In these cases, we either look to the resin system to provide the required fire performance, or we look to protect the structural composite with sacrificial protective layers e.g. additional fire-retardant laminate, thermal insulation or a layer of intumescent/ablative material.

Some organic resin systems have intrinsically good fire performance. Phenolic and benzoxazine systems and furans have a highly aromatic resin chemistry, which readily creates a stable graphitic char with very little mass loss. Most common thermoset resin systems; polyesters, vinyl esters, epoxies and urethanes can all be tailored to include a degree of inherent

fire performance within the polymer structure. In addition, there is a whole swathe of liquid additives that can be introduced via blending at the liquid formulation stage to meet specific performance criteria.

Resin systems with a high aromatic content tend to be good char formers, but because they ‘burn badly’ can be very smoky, and often produce more toxic fire products e.g. higher levels of carbon monoxide.

Resin systems with highly aliphatic chemistry on the other hand tend to burn hotter and cleaner, which is an advantage when addressing smoke and toxicity requirements and they are often the resins of choice when using a filled system. For example, the use of dicyclopentadiene (DCPD) in a polyester resin backbone can give lower viscosity with reduced styrene monomer content, and is widely used in filled systems. Likewise, methyl methacrylate monomer can substitute styrene as the reactive diluent. While more flammable in liquid state its aliphatic chemistry gives a very clean burn. Its very low viscosity and excellent wetting of ATH fillers can provide a basis for cheap and effective, low smoke and low toxicity products.

Silicone based resin systems, such as reactive silanes and polysiloxanes, have a hybrid mix of organic carbon and silicone chemistry, and so can be deployed where low mass loss is required. They are useful as carriers for intumescent and filled systems, or where elastomeric properties are required at room temperature. At extreme temperatures they oxidise to a silica based crosslinked ceramic layer, which can be insulative and reflective even in a thin layer, or can bind and stabilise a foam. They can be highly effective in fire resistance tests deploying high heat fluxes that take temperatures above the point where graphite chars will themselves oxidise.

Fire retardant chemistries act either physically, as with the hydrated fillers already discussed, or chemically. Fire retardant additive chemistry can affect either the condensed phase, promoting char formation, or the gas phase, creating flame inhibiting reactions in the gas plasma phase. Chemically active species can either be added to existing resin systems as a blend, or reacted into the resin backbone as pre-cursor monomers, where in thermoset polymers they become crosslinked and will not leach.

4.5.1 Halogenated fire retardants

The most commonly used fire retardant additive reagents are the halogens, which operate in the gas phase as radical scavengers. Brominated additives are the most widespread and well known. Fluorinated systems tend to be expensive, and so are mainly used as thin protective surface films, for example printed polyvinylidene fluoride (PVDF) films are used to wrap composite components in aircraft interiors to provide decorative finishes and effective self-extinguishing performance.

Chlorinated thermoplastic polymers such as PVC are widely used in household electrical cabling for their good inherent self-extinguishing properties, and further enhanced with fillers and additives that promote charring. Chlorinated reactive species can be used in polyesters both as acids and glycols. Chlorinated plasticisers such as tris (2-chloroethyl) phosphate (TCCEP) are widely used as fire retarding plasticisers, added to normal resin systems to give low levels of self-extinguishing fire performance.

Halogenated compounds containing bromine, chlorine and fluorine release Cl[•], Br[•] and F[•] free radicals as they burn, and these ‘scavenge’ the combustion free radicals H[•] and OH[•] and larger organic fragment R[•]s, stopping chain reactions. The scavenging reactions are less exothermic than oxidation chain reactions, and reduce the heat generated. In a fire scenario, halogenated additives can be extremely cost and performance effective, at low levels of addition, particularly when combined with catalytic ‘synergists’ such as antimony trioxide (ATO).

However, there are increasing concerns about halogenated fire-retardant additives from an environmental and health and safety viewpoint. When some chemicals are used as blended additives in thermoplastics components, rather than reacted into the polymer backbone, they have the potential to leach or volatilise into the environment, where they can accumulate in fatty tissues and so enter the food chain. Certain brominated compounds are carcinogenic, while others are hormone mimics. The fire products from halogenated fire-retardant systems are both toxic and acidic, causing corrosion issues post fire. Glass fibre composites are being recycled by co-incineration in cement kilns in some countries, where the glass fibre and mineral fillers become part of the cement clinker, but materials containing halogenated fire retardants cannot be used in cement kilns as they result in products which are corrosive to steel reinforcement in concrete.

Industry is increasingly looking to replace halogenated additives, even the reactive monomers, because of associated or perceived environmental risks, and new legislation pressures. Materials developments are ongoing to ensure that new flame retardants satisfy REACH requirements.

4.5.2 Phosphorous fire retardants

Phosphorous additives are the second most widely used additive group. Like the halogens, phosphorous can be used as additives or incorporated into the polymer back bone. If the volatility is low the active group will remain in the condensed phase and promote char, but they can also volatilise into the gas phase and produce highly effective scavenging radicals $\text{HPO}_2\cdot$, $\text{PO}\cdot$, $\text{PO}_2\cdot$, and $\text{HPO}\cdot$, which can, in theory, be up to 5 times more effective at a molecule for molecule level than chlorine. Elemental red phosphorous, phosphonium compounds, phosphonates, phosphites and phosphates all find applications with different polymers, and they are key components in intumescent systems. They can work in both the gas and condensed phase. In the condensed phase they are very effectively used with polymers containing some oxygen and nitrogen, such as polyesters, epoxies and polyamides. With most of these thermal decomposition produces phosphoric acid, which can further react to release water, and create pyrophosphate structures, which themselves are effective char promoters.

Red phosphorous is a highly effective flame retardant as a dispersed solid in thermoplastics, but without encapsulation has the drawback that in high humidity conditions it can evolve the toxic gas phosphine. Phosphorous based plasticisers such as triphenyl phosphate (TPP) and tricresyl phosphate (TCP) volatilise at low temperatures, and can convey some self-extinguishing behaviours, but have limited effectivity at higher heat fluxes. Salts such as ammonium polyphosphate (APP) can be effective treatments for natural fibres and as a flame retardant in unsaturated polyesters and polypropylene, and metal salts such as aluminium phosphinate can usefully be deployed alongside other mineral fillers.

4.6 Intumescent systems

Intumescence is a special case of char formation, where the char is actively encouraged to expand by use of a chemical ‘blowing agent’ alongside active char forming additives and an adequate supply of a good carbon source. Intumescent systems are widely used to provide fireproof seals around doors and other penetrations and can expand up to several hundred times the original thickness.

A typical intumescent system may include a phosphorous compound such as ammonium polyphosphate (APP) and a carbon donor such as graphite particles or pentaerythritol and a sumpifiant such as melamine or melamine formaldehyde. These are incorporated in an organic binder, usually epoxy or methacrlate based system. The char can be further stabilised by the use of short glass or mineral fibres in nonwoven formats so that they can travel and strengthen the char, and low temperature glass frits and additives such as zinc borate that can fuse and stabilise the inorganic glassy char structures.

Passive fire protection coatings for structural steel elements are an example of these ‘composites’ and are often applied by spray to a primed surface. Intumescent systems can also be incorporated into the outer layers of a composite product, as a nonwoven veil, or as a coating or gelcoat, expanding rapidly to protect an underlying structural composite from heat, and retaining structural integrity.

Different formulations are used for application on conducting base materials, such as steel, and for use on an insulating material such as a FRP composite.

4.7 Insulation barriers and core materials

Composite materials are often deployed in ‘sandwich panel’ format, where stiffness is boosted by increasing thickness using lightweight core materials between structural laminates. This format can also be used to provide insulation against fire attack, in which case it is often advisable to choose core materials that have heat resistance and good fire performance. Natural materials like treated balsa or cork have inherently good fire performance, tending to burn very slowly, producing a protective char. Other commonly used thermoplastic foams, such as PVC, fire retardant treated polyurethanes and polyisocyanurate (PIR) foams may well pass simple plastic material fire tests, but might not be appropriate in a structural application, due to low melt temperatures, or the likelihood of smouldering. Cores that are suitable for fire barriers where burn through tests are required, include syntactic foams, e.g. glass microspheres in phenolic resin, or honeycombs made from Nomex, phenolic coated paper, or aluminium honeycomb.

4.8 Nanomaterials

At micron and sub-micron scale many materials are seen to have active effects at much smaller doses than similar materials in bulk or larger particle sizes. In part this is can be attributed to high surface areas, high aspect ratio morphology, or purity of active crystalline surface structures. Nanomaterials can often be created in-situ forming a separate network within

a polymer or be deposited on the surface of another formulation component. They primarily work by promoting char formation or changing char morphology. Additive types include montmorillonite (MMT), a naturally occurring aluminosilicate clay, and synthetic clays such as layered double hydroxides (LDH), metal oxides and hydroxide nano-particles. Carbonaceous nanoparticles such as carbon nanotubes, graphite, graphene and graphene oxide also show promise in thin coatings, and polyhedral oligomeric silsesquioxanes (POSS) show promise in creating intercalated silica networks rapidly creating insulating and reflective chars.

Nanomaterials are often functionally tailored to allow them to be dispersed effectively in various liquid carriers, directly into resin systems, including thermoplastic masterbatch concentrates. Other nanomaterials can be coated onto larger fillers, via sol-gel or even plasma deposition processes, enabling the formulator much safer and easier processing, eliminating at the product formulation stage the precautions required to handle 'dry' or 'pure' nanomaterials.

In general, these nanomaterials have to be used in combination with other fire-retardant systems as a booster, rather than as standalone wonder additives. While adoption is not widespread and these materials are often expensive, some of the simpler materials are made from common and inexpensive raw materials and are buying their way into FST formulations on merit, especially where using tiny doses allows retention of other critical properties for high performance applications.

As the market in these materials matures, the supply chain extends, and products become both easier to use, and available from multiple sources, we can expect these materials to play a bigger part in high performance FST formulations.

5. STANDARDS AND REGULATIONS FOR SECTORS

The high risk related to fire performance means that this area is extensively regulated to minimise the risk to people and property.

Major developments in standards often come about after a disaster, such as the International Convention for the Safety of Life at Sea (SOLAS), an international treaty originally adopted in 1914 in response to the Titanic disaster¹, the Offshore Installations (Safety Case) Regulations which came into force in 1992 after the Piper Alpha disaster², and the recent UK government review of building regulations and fire safety to make recommendations on the future regulatory system following the Grenfell Tower fire³.

Classification of materials and products and the resulting test requirements are very dependent on the risks to life, health and property in the application, and the time to evacuate. For example, if a car catches fire the driver will stop and the occupants will get out of the car, so tests for automotive are typically of short duration and not onerous. In comparison, a commercial, ocean-going vessel might catch fire in the middle of the ocean, two weeks sailing from port, so requirements are much more stringent.

There are a great many standards, codes and regulations pertaining to the performance of materials and products in fire situations. These come in four categories:

- Regulations and codes defining requirements which must be adhered to – usually sector specific
- Standards which describe test methods – sometimes sector specific, but often sector agnostic.
- Standards which describe how to categorise fire performance based on the results of tests
- Standards which provide more general guidance

Regulations, codes and standards providing general or categorisation / classification guidance typically refer to tests defined in other standards and/or include descriptions of tests which may be the same as, or modifications of, tests defined in other standards. Standards relating to buildings and the construction sector are the most extensive, and in many cases standards and tests developed for buildings are also used for applications in marine and rail.

Information on where to find codes and standards relating to fire performance of materials and products is in Appendix 2, with a list of around 100 of the most relevant standards used in sectors where FRP is common. The list is far from exhaustive. The standards listed there, and in this report generally, are current at March 2019, though some are under revision. It is essential always to check that the latest issue of the correct standard is being used.

¹History of SOLAS

<http://www.imo.org/en/KnowledgeCentre/ReferencesAndArchives/HistoryofSOLAS/Pages/default.aspx>

²Piper Alpha: Lessons Learnt, 2008 <https://oilandgasuk.co.uk/wp-content/uploads/2015/05/HS048.pdf>

³See Independent Review of Building Regulations and Fire Safety: final report

<https://www.gov.uk/government/publications/independent-review-of-building-regulations-and-fire-safety-final-report>

5.1 Construction and infrastructure

As can be seen from the list in Appendix 2, there are numerous fire performance standards related to construction applications. The BS 476 series, 'Fire tests on building materials and structures' form the backbone, covering reaction to fire and fire resistance. Many other standards have arisen over the years to cover specific applications, for example:

- Cladding
 - BS 8414-1:2015 'Fire performance of external cladding systems. Test method for non-loadbearing external cladding systems applied to the masonry face of a building'
 - BS 8414-2:2015 'Fire performance of external cladding systems. Test method for non-loadbearing external cladding systems fixed to and supported by a structural steel frame'
- Large scale room tests
 - ISO 9705-1:2016 'Reaction to fire tests -- Room corner test for wall and ceiling lining products -- Part 1: Test method for a small room configuration'
- Fire resistance tests for specific elements of the structure
 - BS EN 1364 series 'Fire resistance tests for non-loadbearing elements'
 - BS EN 1365 series 'Fire resistance tests for loadbearing elements'
- Fire resistance tests for discontinuities such as penetration and joint seals
 - BS EN 1366 series 'Fire resistance tests for service installations'
- Tests for doors, windows and building hardware
 - BS EN 1634-1:2014 'Fire resistance and smoke control tests for door and shutter assemblies, openable windows and elements of building hardware. Fire resistance test for door and shutter assemblies and openable windows'

Harmonised European classification for assessing construction products in the event of fire is defined in BS EN 13501 parts 1 and 2, where the results of several tests are used to classify a product:

5.1.1 Euroclass reaction to fire classification

Part 1, BS EN 13501-1:2019 'Fire classification of construction products and building elements. Classification using test data from reaction to fire tests' defines the 'Euroclass' classification and affects mainly surface covering materials, insulation materials, floor coverings, pipe insulation materials (and cables in Part 6). This compares results of tests for ignitability, flame spread, heat release, smoke production and propensity for producing flaming droplets/particles etc. It is required for CE marking, forming part of the requirements of the Construction Products Regulation 305/2011 (which replaced the Construction Products Directive, 89/106/EEC).

- There are seven Euroclass classification levels, from A1 to F. Products achieving A1 classification are defined as non-combustible. A2 is defined as having limited combustibility.
- There is a smoke classification of s1, s2 or s3. s1 is the highest level of performance and s3 is the lowest performance level. There are no smoke requirements for Class E products.
- There is also a classification of flaming droplets of d0, d1 or d2. d0 is the highest level of performance and d2 is the lowest performance level. There is no flaming droplet requirement for floorings.

As in some cases the nomenclature may be confused, it should be noted that the Euroclass classification is entirely different from the IMO fire resistance classes, e.g. A-30, B-15 (see section 6.7.2).

5.1.2 Fire resistance classification

Part 2, BS EN 13501-2:2016 'Fire classification of construction products and building elements. Classification using data from fire resistance tests, excluding ventilation services defines the classification for fire resistance, which is discussed further in section 6.7.1.

5.1.3 Bridges

‘Fibre-reinforced polymer bridges - guidance for designers’⁴ refers in section 4.6.8 ‘Fire Performance’ to BS 476-6:1989+A1:2009 Fire Propagation for Products, and BS 476-7:1997 Surface Spread of Flame, though noting that BS 476-7 does not consider emission of toxic smoke and gas. In section 5.1.1 ‘Basic Requirements’ it indicates that, where appropriate, bridges should be designed to consider accidental actions, including fire and explosions, in accordance with BS EN 1991-1-7:2006+A1:2014 ‘Eurocode 1. Actions on structures. General actions. Accidental actions’. BS EN 1991-1-7:2006+A1:2014 gives recommendations and guidance for safeguarding buildings and other civil engineering works against identifiable and unidentifiable accidental actions.



Foryd Harbour Bridge. Photo courtesy of AM Structures.

5.2 Rail

5.2.1 Harmonised rail standard

The rail industry has undergone an extensive pan-European project over the last twenty years or so, resulting in harmonisation of differing standards across Europe. BS EN 45545-2:2013+A1:2015 ‘Railway applications. Fire protection on railway vehicles. Requirements for fire behaviour of materials and components’ defines fire performance requirements for almost everything on a train. It was published in 2013 and became mandatory across Europe for rolling stock in 2018, though is under revision at the time of writing. The BS EN 45545 series replace BS 6853:1999 ‘Code of practice for fire precautions in the design and construction of passenger carrying trains’ which was withdrawn in 2016.

EN 45545-2 specifies the test methods, test conditions and reaction to fire performance requirements and classifies materials according to where they will be used, for which 26 “requirement sets” (R1 to R26) are identified. Each requirement has a corresponding series of test performance criteria with different thresholds for test parameters at three hazard levels (HL1, HL2, HL3). HL1 contains the lowest requirements and HL3 the highest, depending on factors such as how much the trains are in a tunnel, whether they are staffed, have two-stories or if people sleep on board.

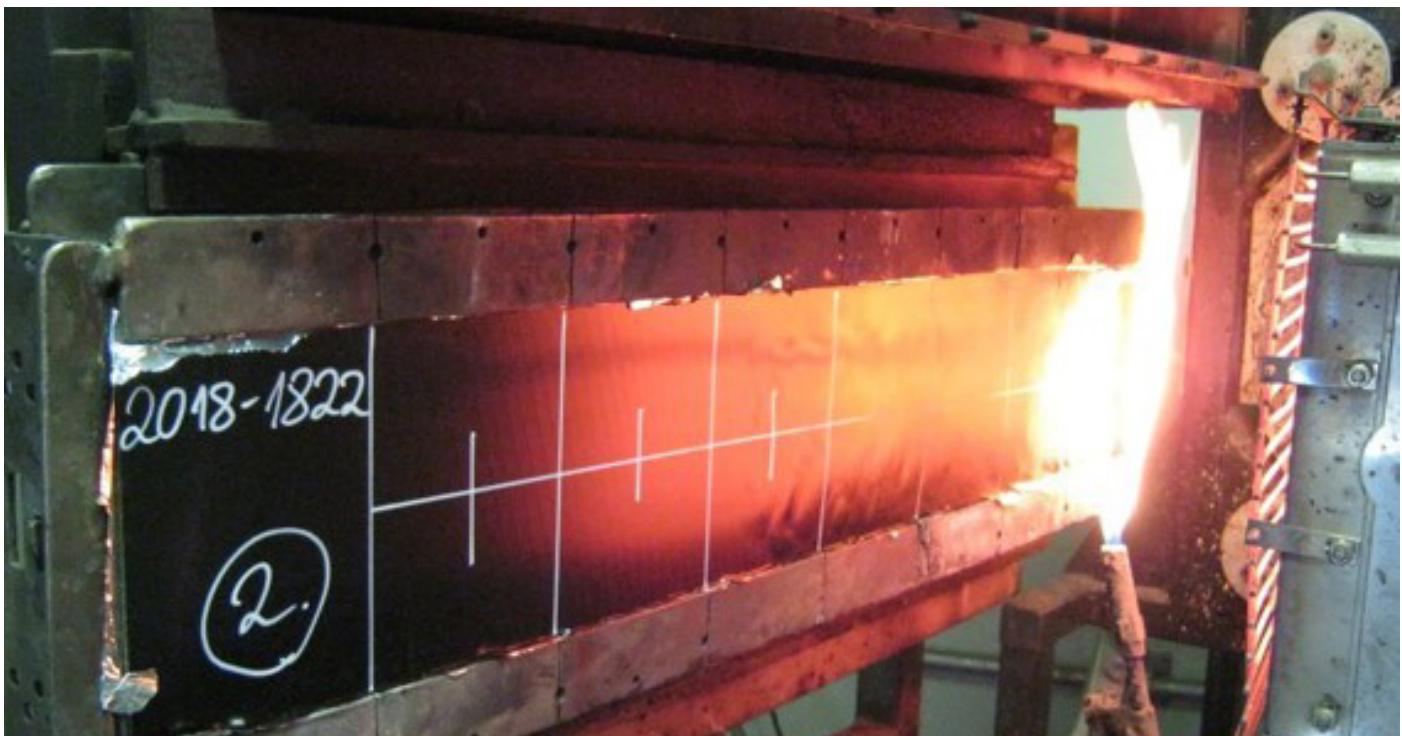
⁴ Fibre-reinforced polymer bridges - guidance for designers (C779) 2018, available at https://www.ciria.org/Resources/Free_publications/Fibre_reinforced_polymer_bridges.aspx

For example, R1 (interior surfaces) requires testing to:

- BS ISO 5658-2:2006+A1:2011 ‘Reaction to fire tests – Spread of Flame – Part 2: Lateral spread on building and transport products in vertical configuration’
- BS EN ISO 5659-2:2017 ‘Plastics, Smoke generation – Part 2: Determination of optical density by a single chamber test’
- BS ISO 5660-1:2015 ‘Reaction-to-fire tests. Heat release, smoke production and mass loss rate. Heat release rate (cone calorimeter method) and smoke production rate (dynamic measurement)’
- BS EN ISO 11925-2:2011 ‘Reaction to fire tests. Ignitability of products subjected to direct impingement of flame. Single-flame source test’ as a supplementary test if, when tested in accordance with ISO 5658-2, flaming droplets occur or test result is reported as unclassifiable.

A useful report by Fire Testing Technology details the fire test methods for EN 45545-2, with thresholds for the different hazard levels and tables linking test methods and standards to requirement sets.⁵.

Two new tests were published recently for railway applications: BS EN 16989:2018 tests fire behaviour for a complete seat. BS EN 17084:2018 measures toxicity of the products of combustion.



Evopreg PFC502 prepreg with polyfurfuryl alcohol resin achieves compliance with Hazard Level 3 (HL3), Requirement Sets R1 (interior surfaces) and R6 (passenger seat shells) of EN45545-2. Photo courtesy of Composites Evolution.

⁵ EN 45545-2:2013 New Fire Classifications and Fire Test Methods for the European Railway Industry, 2014-15, Fire Testing Technology Ltd. http://www.fire-testing.com/whitedragon/documents/file/Product%20Brochures/EN%2045545%20EU%20Railway%20Industry%202015_compressed.pdf. Note that aspects of this may be out of date when the revised version of EN 45545-2 is published.

5.2.2 Underground trains

Requirements for the London Underground are very stringent due to nature of the enclosed spaces and potentially longer time to evacuate. LUL S1085 'Fire Safety Performance of Materials - Stations and Tunnel Infrastructure' applies for combustibility, smoke and toxicity. LUL S1180 A9 'Standard for Rolling Stock' gives more general requirements and refers to BS 6853:1999 (now withdrawn), but has been amended to allow use of EN 45545-2. London Underground standards may be used by other underground train operators in UK.

5.3 Marine

Fire performance requirements for marine vessels vary enormously depending on the vessel type. Small leisure boats and inland waterway vessels have relatively less onerous fire requirements because the risk is lower, where they operate close to shore and / or have fewer passengers. Requirements for large ships are very stringent, as they may carry thousands of passengers and operate long distances from port. A full list of construction, maintenance and operation standards for different vessel types is available from the Maritime and Coastguard Agency (MCA), which is the UK government body responsible for marine regulations.⁶

Fire testing requirements for larger vessels are typically based on the International Maritime Organization (IMO) Resolution MSC 307(88) Annex 1 'International Code for Application of Fire Test Procedures' (FTP Code). The methodology is based on dividing the vessel into compartments with fire resisting divisions. (See section 6.7.2.) The FTP Code is also used in oil and gas and naval applications.



Figure 2: MS Queen Victoria. Photo S Job

5.3.1 Ocean going commercial ships

The IMO International Convention for the Safety of Life at Sea (SOLAS) specifies minimum standards for the safe construction, equipment and operation of passenger ships which carry more than 12 passengers or cargo ships of 300 gross tonnage and upwards and operate in international waters.

⁶ Construction, maintenance and operation standards

<https://www.gov.uk/topic/ships-cargoes/construction-maintenance-operation>

The IMO develops and adopts legislation, which is implemented by the flag states (government agencies such as MCA in UK) who may then delegate inspections and approvals to classification societies, such as Lloyd's Register and DNV-GL.⁷ Test houses for SOLAS applications must be approved by IMO.

SOLAS Chapter II-2 on fire protection requires structural materials to be non-combustible. This would prohibit the use of any composite with an organic polymer matrix. However, a regulation which came into force in 2002, Chapter II-2/17 for alternative design and arrangements (Regulation 17) allows for alternatives to the prescriptive requirements using a risk-based design approach to demonstrate equivalent safety. Regulation 17 approval can only be gained for a specific application on a specific vessel. It does not lead to a “type approval”.

In an attempt to move the subject forward and to have some composite materials on-board vessels as future case studies on which new rules can be based, IMO's working group covering fire protection (Sub-Committee on Ship Design and Construction) proposed ‘Interim guidelines for use of fibre reinforced plastic (FRP) elements within ship structures: Fire safety issues’, published in MSC.1/Circ.1574.⁸ These should be reviewed in four years in order to make any necessary amendments based on experience gained from using them, though at the time of writing, very few applications of the interim guidelines have resulted.

It should be noted that these interim guidelines are written for those approving the structures in accordance with Regulation 17, as a supplement to other MSC Circulars, rather than as a design specification / standard.⁹ The guidelines cover structures which do not contribute to global strength and may be removed without compromising the safety of the ship. They do not prohibit a fully composite ship, or ship with FRP primary structural elements, but the lack of guidelines means that such a vessel would be very difficult to assess. Appendix D of MSC.1/Circ.1574 describes the test requirements for FRP composite in some detail.

Some Regulation 17 assessments coordinated by Research Institute of Sweden (RISE) are available through E-LASS.¹⁰ E-LASS, European Network for Lightweight Applications at Sea, is a useful network and resource sharing the latest developments in this area.

There are several applications for composites in ships which are not subject to SOLAS Chapter II-2 non-combustibility requirements. Composites are already used in open decks, bathroom cubicles, deck lockers, lifeboats, radomes, pipework and internal architectural elements. Areas with good potential for replacement with FRP include guardrails, windscreens, supports, lighting columns, non-escape route staircases and lifeboat davits.

5.3.2 High speed craft code

High-speed craft is a special category of sea-going vessels that includes hovercraft, catamarans and hydrofoils. The International Code of Safety for High Speed Craft (HSC Code) allows for the use of composites in vessels capable of a certain speed.

In accordance with SOLAS Chapter 10 Reg. 1.3, “high-speed craft” are craft capable of a maximum speed, in metres per second (m/s), equal to or exceeding:

$$3.7 \times \Delta^0.1667$$

where Δ = volume of displacement in cubic metres corresponding to the design waterline, excluding craft of which the hull is supported clear above the water surface in non-displacement mode by aerodynamic forces generated by ground effect.

The HSC Code also makes reference to the FTP Code, and in particular to Parts 10 and 11 which relate specifically to high speed craft. The requirements are stringent but achievable and many vessels have been built to this code using composite structures.

⁷ See <http://www.imo.org/About/Membership/> and <http://www.imo.org/About/Pages/FAQs.aspx>.

⁸ MSC.1/Circ.1574 Interim guidelines for use of fibre reinforced plastic (FRP) elements within ship structures: Fire safety issues, IMO, June 2017 <https://e-lass.eu/media/2018/02/MSC.1-Circ.1574.pdf>

⁹ “The annexed Interim guidelines should be used as a supplement to the Guidelines for the approval of alternatives and equivalents as provided for in various IMO instruments (MSC.1/Circ.1455) and the Guidelines on alternative design and arrangements for fire safety (MSC.1/Circ.1002, as amended by MSC.1/Circ.1552) when approving FRP elements within ship structures.” MSC.1/Circ.1574, p.1

¹⁰ <https://e-lass.eu/archive/public-rise-coordinated-reg-17-assessments/>

5.3.3 Passenger ships / ferries

Passenger ships / ferries operating in domestic sea areas of the European Union (EU) are designed to Directive 2009/45/EC ‘on safety rules and standards for passenger ships’. This directive makes no allowance for structural FRP, requiring materials to be of “steel or another equivalent non-combustible material”.

This EU directive is often followed, but not mandatory, for vessels which sail only in one flag state’s national waters. Some flag states (such as Sweden, Denmark and Turkey) have allowed ferries to be built using structural FRP according to the HSC Code, though they do not meet the speed requirement, where they are operated within their own coastal waters.



One of 15 carbon fibre 39m, 32 knots, catamaran ferries. Photo courtesy of Sigmatek on behalf of Özata Shipyard, Turkey.

5.3.4 Inland navigation vessels

Vessels operating on inland waterways in the EU are covered by EUR-Lex 2006/87/EC: ‘Directive of the European Parliament and of the Council of 12 December 2006 laying down technical requirements for inland waterway vessels’ and ES-TRIN: ‘European Standard laying down Technical Requirements for Inland Navigation Vessels’. This allows for alternative materials for hulls, and “steel or another equivalent material” for bulkheads, walls and decks, except in high fire risk areas (e.g. engine rooms) where structural materials must be non-combustible. Fire regulations for these vessels are typically much lower than those required by SOLAS due to the environment in which they operate, and their inevitable nearness to shore.

5.3.5 Large yachts

Large yacht codes exist which allow for the use of structural composites for leisure yachts which carry up to 12 passengers and are 24m and over in load line length. (e.g. UK’s LY3) The fire requirements are not necessarily comparable to those in the HSC code. LY3 specifies its own standard which is essentially the same performance required in MGN 407, which can require a slightly higher performance than the HSC Code. MGN 407 simply seeks to reduce the number of fire tests for a given layup and extend the applicable range of fire performance of a given bulkhead / deck.

In 2010 the Red Ensign Group (UK with Crown Dependencies and UK Overseas Territories) developed a Passenger Yacht Code (PYC, currently 4th edition 2014) for leisure yachts which carry 13-36 passengers as an “equivalent arrangement” under SOLAS. At present this makes no allowance for structural FRP, requiring structural materials to be non-combustible.

5.3.6 Small vessels in commercial use

There are several UK codes of practice for different small commercial vessel types.¹¹ These typically allow for the use of FRP composites as long as they carry less than 12 passengers. In some cases, for workboats, special service personnel can be counted as crew rather than passengers.

MGN 280 (M) ‘Small Vessels in Commercial Use for Sport or Pleasure, Workboats and Pilot Boats – Alternative Construction Standards’ was written to harmonise several codes (known as the Blue, Yellow, Brown and Red codes). For workboats, this is superseded by the recently revised Brown Code, ‘Workboat Code Edition 2: The Safety of Small Workboats and Pilot Boats – A Code of Practice’.

The tests in these (Annex 9 of MGN 280, Appendix 9 of the Brown Code) are similar, essentially a 15-minute burn through test. The new workboat code allows that the burn through test may be waived if the construction complies with MGN 407 ‘Procedure for the testing of fire protection for use with composite and wooden constructions’.

5.4 Oil & gas

Composites have seen a range of applications in this sector, both onshore and offshore, due to their corrosion resistance, light weight and excellent insulation properties for fire protection.

Typical applications are:

- Fire and blast protection to valves and equipment (enclosures), structural steel and pipework (cladding)
- Piping for various services, including fire water
- Handrails, gratings, ladders and associated structures
- Flexible pipes, including risers
- Repair and reinforcement of corroded steel pipes, structural steel and concrete

Typically, different operators will have their own standards, specified in addition to common standards, and in some cases larger scale bespoke tests may have been devised.

¹¹ See <https://www.gov.uk/government/publications/small-craft-codes>

5.4.1 Fire and blast protection

Whereas a conventional fire in a building is more likely to be cellulosic, fires in oil and gas installations result from the burning of hydrocarbon fuels. Products designed to protect against hydrocarbon pool fires will be H rated (as compared to A or B rated products) and tests are defined within UL 1709 'Standard for Rapid Rise Fire Tests of Protection Materials for Structural Steel' or BS 476-20 'Fire tests on building materials and structures. Method for determination of the fire resistance of elements of construction (general principles)'. Further testing information is included in section 6.7.

Fires resulting from a source of high-pressure hydrocarbon gas are called jet fires due to the high velocity of the gas, and thus flame. Products to provide protection from these fires carry a J rating and testing is covered by BS ISO 22899-1:2007 'Determination of the resistance to jet fires of passive fire protection materials. General requirements'.

In some instances in the offshore industry ISO 22899-1 does not always represent a sufficiently severe scenario. However, simply increasing the heat flux may not produce a more onerous test. This is discussed in detail in a recent Health and Safety Executive review: RR1120 - A review of the applicability of the jet fire resistance test method to severe release scenarios.¹²

Real life scenarios may be complex. For example, an explosion may result in a blast wave, failure of control systems or active fire suppression systems, impacts from resulting projectiles, etc., as well as fire. Products carrying H or J ratings also frequently carry a maximum blast overpressure rating and it is important to fully understand the design scenarios for a particular installation prior to supplying suitable equipment. More information can be found in BS EN ISO 13702:2015 'Petroleum and natural gas industries. Control and mitigation of fires and explosions on offshore production installations. Requirements and guidelines'. Much of that guidance can also be applied to onshore installations.

Typically, process plant and machinery is protected by very specialised passive fire and explosion protection products whilst personnel protection relates more closely to the level of protection provided to passengers and personnel on-board commercial marine vessels, as described in section 5.3 above. Personnel accommodation for offshore personnel is nowadays always located away from process areas to reduce the risk of personnel being exposed to the more severe events.

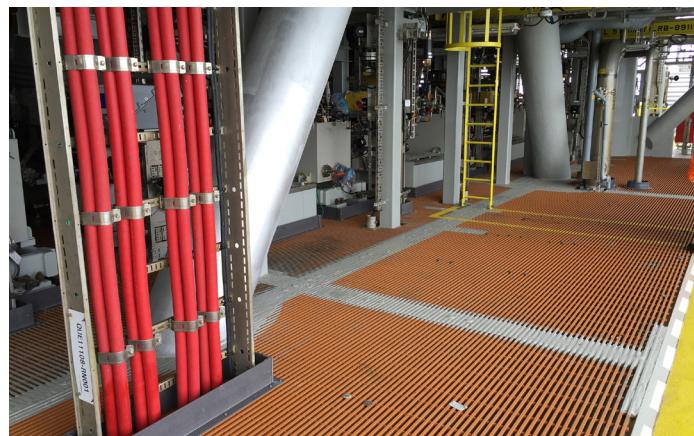
NORSOK M-501 'Surface preparation and protective coating' may be referred to for the application of spray-on passive fire protective coatings, such as intumescents.

5.4.2 Gratings and walkways

Fire rated gratings and other walkway systems are available as proprietary products and are widely used. Glass fibre / phenolic gratings for oil and gas applications can achieve Class 0 (A) to ASTM E84 'Standard test method for surface burning characteristics of building materials', though some may be Class 1, and can be classified self-extinguishing to ASTM D635 'Standard test method for rate of burning and/or extent and time of burning of plastics in a horizontal position'. Alternatively, they may be tested to BS476 parts 6 and 7 for flame spread / fire propagation.

In addition, a typical qualification approach for gratings requires them to be subjected to a standardised time-temperature curve for a cellulosic fire (e.g. ASTM E-119) for a period of 60 minutes, e.g. to achieve US Coast Guard

Level 2. However there has been discussion about whether using a cellulosic fire curve here is appropriate for the offshore scenario as a hydrocarbon fire will induce much faster degradation, such that while the gratings may pass the test to Level 2, they may not then be fit for pedestrian use. For more details see RR 950 'Preliminary fire testing of composite offshore pedestrian gratings'.¹³ Hence, these FRP gratings are not generally used for key escape routes due to uncertainty concerning their load bearing ability when in a fire scenario.



Phenolic grating installed on an offshore platform in the North Sea. Photo courtesy of NOV Fiber Glass Systems

¹² RR1120 - A review of the applicability of the jet fire resistance test method to severe release scenarios, Health and Safety Executive, 2017 <http://www.hse.gov.uk/research/rrhtm/rr1120.htm>

¹³ RR950 - Preliminary fire testing of composite offshore pedestrian gratings, Health and Safety Executive, 2012 <http://www.hse.gov.uk/research/rrpdf/rr950.pdf>

5.4.3 General guidance

Other applications are likely to require a comprehensive technical specification, often unique to the particular operator or facility owner.

Some classification societies have general design guidance for composite components such as, DNVGL-ST-C501 Edition: 2017-08. This does not give specific requirements for fire performance, but gives mainly qualitative guidance, including some guidance on evaluation of the properties of a composite component after a fire. It has a useful table on the effect of temperature on short term properties of FRP composites (Table 4-8, p.71). ¹⁴

5.5 Automotive

Fire standards for automotive are easier to achieve than those for most sectors, as evacuation times are minimal. FRP composites are widely used in interiors and brackets, and in higher value vehicles for body shell, chassis and other structural elements. They are also increasingly encroaching into traditional plastic or metal applications in drive train components in hot areas such as under bonnet ducting, exhaust systems and close to high performance brakes, and must meet performance standards required, including higher working temperature. Electric vehicles pose new challenges, especially in safe containment of high energy batteries.

Motor vehicles in the European Union are regulated by European Regulation (EC) No 661/2009 ‘concerning type-approval requirements for the general safety of motor vehicles, their trailers and systems, components and separate technical units intended therefore’. In Annex IV, this lists the relevant United Nations Economic Commission for Europe (UNECE) regulations by which vehicle manufacturers may obtain type-approval. Individual manufacturers may have their own additional requirements.

5.5.1 Interiors

ECE Regulation 118 ‘Uniform technical prescriptions concerning the burning behaviour and/or the capability to repel fuel or lubricant of materials used in the construction of certain categories of motor vehicles.’ (ECE 118) was initially based on European Directive 95/28/EC, which it superseded in 2014. It describes tests to define the burning rate in mm/min for both horizontal and vertical configuration and the melting behaviour of materials in the occupant compartments of motor vehicles. See sections 6.4 and 6.5.

ECE 118 allows for materials achieving an average critical heat flux at extinguishment (CFE) value greater or equal to 20 kW/m², when tested according to ISO 5658-2 (BS ISO 5658-2:2006+A1:2011 ‘Reaction to fire tests – Spread of Flame – Part 2: Lateral spread on building and transport products in vertical configuration’), to be deemed to comply in some circumstances instead of ECE 118 Annex 8.

5.5.2 Fuel tanks

ECE Regulation 34 ‘Uniform provisions concerning the approval of vehicles with regard to the prevention of fire risks’, Annex 5 - ‘Testing of fuel tanks made of a plastic material’ includes a pool fire test. A pan filled with fuel is ignited and moved under the tank, which is fixed as on the vehicle, where it is exposed to flame for two minutes. No leakage of fuel is allowed.

¹⁴ DNVGL-ST-C501 Edition: 2017-08, DNV GL, 2018

<https://rules.dnvg.com/docs/pdf/dnvg/st/2017-08/DNVGL-ST-C501.pdf>

5.5.3 Battery boxes

An emerging area is FRP composite battery boxes. There are currently no standards which provide tests specifically for incidents where thermal runaway occurs in lithium ion batteries, which can lead to fires or even explosions which need to be contained. An additional concern in cases of thermal runaway is the emission of highly toxic fluoride gases. This is clearly an area for development. For more information, see Larsson, et al, 'Toxic fluoride gas emissions from lithium-ion battery fires' where heat release and fluoride gas emissions were measured during battery fires for seven different types of commercial lithium-ion batteries.¹⁵



Battery box containing Li-ion cells, manufactured with PS200 prepreg, after a full thermal runaway 15-minute test. Internal temperature 1100°C, external face temperature 200°C. Photo courtesy of SHD Composite Materials Ltd.

5.6 Aerospace

Aircraft on the UK Register are required by the Civil Aviation Authority (CAA) to comply with CAP 747 'Mandatory Requirements for Airworthiness'.¹⁶ All aircraft that are covered by the European Union Aviation Safety Agency (EASA) requirements must meet the EASA standards. Other nations have their own requirements.¹⁷

EASA and most countries' airworthiness requirements are generally based on the US Federal Aviation Administration (FAA) Regulations (FARs). The FARs are part of Title 14 of the Code of Federal Regulations (CFR) and are comparable to the EASA Certification Specifications (CS). i.e. 14 CFR Part 25 'Airworthiness Standard: Transport Category Airplanes' (known as FAR 25) is comparable to EASA's CS-25 'Easy Access Rules for Large Aeroplanes'. It uses the same section numbering, but is not exactly the same. Differences are clarified online in the EASA Significant Standards Differences (SSD) between EASA and FAA airworthiness codes.¹⁸

The most relevant CSs are:

- CS-23 'Easy Access Rules for Normal, Utility, Aerobatic and Commuter Aeroplanes'
- CS-25 'Easy Access Rules for Large Aeroplanes'
- CS-27 'Easy Access Rules for Small Rotorcraft'
- CS-29 'Easy Access Rules for Large Rotorcraft'

Again, comparable numbering applies both between the CSs and in the FAR equivalents, with some differences. The rest of this section will refer to CS-25 as the most used of these.

These CSs need to be read in conjunction with other Acceptable Means of Compliance (AMC) and Guidance Material. AMC 20-29 'Composite Aircraft Structure' (Annex II to ED Decision 2010/003/R of 19/07/2010) is particularly important as a bespoke means for airworthiness certification for composite aircraft structures. For fire considerations the key section is 11b 'Fire protection, flammability and thermal issues'. EASA's AMC 20-29 is harmonised with FAA's AC 20-107B.

In addition, there may be "special conditions", which may be generic or related to specific aircraft models, listed in EASA Type Certificate Data Sheets. Often these special conditions are worked into the general rules over time.

In general, the requirements for structural parts in aircraft are based around equivalence to metals: "A composite design, including repair and alterations, should not decrease the existing level of safety relative to metallic structure." (AMC 20-29, 11b).

¹⁵ Larsson, F. et al. Toxic fluoride gas emissions from lithium-ion battery fires. *Scientific Reports* volume 7, Article number: 10018 (2017) <https://www.nature.com/articles/s41598-017-09784-z>

¹⁶ CAP 747 Mandatory Requirements for Airworthiness, Civil Aviation Authority <http://publicapps.caa.co.uk/modalapplication.aspx?catid=1&pagetype=65&appid=11&mode=detail&id=7980>

¹⁷ Links to other National Authorities can be found through the CAA.

<https://www.caa.co.uk/Commercial-industry/Aircraft/Airworthiness/Continuing-airworthiness/Airworthiness-Directives/>

¹⁸ EASA Significant Standards Differences (SSD) between EASA and FAA airworthiness codes

<https://www.easa.europa.eu/document-library/bilateral-agreements/eu-usa/easa-significant-standards-differences-ssd-between-cs-codes-and-faa-14-cfr-codes>

5.6.1 Aircraft test specifications

The main fire tests referred to in CS-25 (or FAR 25) are listed in Appendix F. The FAA Fire Test Handbook¹⁹ (FTH) contains descriptions of the tests in FAR 25 Appendix F and others, notably Chapter 12 'Powerplant Fire Penetration Test'. These are deemed to be the preferred acceptable test methods by the FAA.

The tests in CS-25 Appendix F (equivalent FTH chapters in brackets) are as follows:

- Part I (Chapters 1 to 4): Test criteria and procedures for showing compliance with 25.853, 25.855 or 25.869 (for interiors, cargo / baggage compartments and electrical system components). Includes burn tests for vertical, horizontal, 45° and 60° specimens. Flame time, burn length, and flaming time of drippings, if any, may be recorded.
- Part II (Chapter 7): Flammability of seat cushions. A modified gun type burner is applied for 2 minutes and the seat cushions are allowed to burn for a further 5 minutes. Burn length is measured and percentage weight loss must not exceed 10%.
- Part III (Chapter 8): Test method to determine flame penetration resistance of cargo compartment liners. Larger scale specimens simulate the cargo compartment sidewall or ceiling liner panel, with the flame being applied for a period of 5 minutes. The panels must not be penetrated during the test, and peak temperature 102mm above the panel must not exceed 204°C (400°F).
- Part IV (Chapter 5): Test method to determine the heat release rate from cabin materials exposed to radiant heat. Uses a modified version of ASTM E-906 'Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using a Thermopile Method'. The combustion products leaving the chamber are monitored in order to calculate the release rate of heat. The average total heat release must not exceed 65 kW mins/m², and the average peak heat release rate must not exceed 65 kW/m².
- Part V (Chapter 6): Test method to determine the smoke emission characteristics of cabin materials. The specimen is exposed to both radiant and direct flame heat sources in a chamber. Optical measurement is used to measure smoke density.
- Part VI (Chapter 23): Test method to determine the flammability and flame propagation characteristics of thermal/acoustic insulation materials. The specimen panel includes all the materials (including fixings, etc) used in the insulation. The panel must be self-extinguishing within three seconds.
- Part VII (Chapter 24): Test method to determine the burnthrough resistance of thermal/acoustic insulation materials. Test panels must not allow fire or flame penetration in less than 4 minutes or more than 2.27 W/cm² heat flux on the back face.

It is important to note that individual aircraft manufacturers have their own variants on testing. For example, Airbus and Boeing have more stringent requirements for smoke emission and toxic gases, which require additional tests to be carried out in conjunction with the smoke density test. Nadcap²⁰ is a cooperative, industry-managed approach to conformity assessment and continual improvement for aerospace and defence. Aerospace materials testing laboratories should be Nadcap accredited.

5.6.2 Interiors

All interior materials must be self-extinguishing according to applicable flammability tests (Part I). Seat cushions must meet the more onerous burner test in Part II. For aircraft with capacity for 20 or more passengers, interior ceiling and wall panels, partitions, galley structures, and cabin stowage must meet heat release and smoke emission tests (Parts IV and V). See CS 25.853. More stringent requirements for smoke emission and toxic gases required by aircraft manufacturers may apply as noted above.

Fire performance requirements for aircraft cabin interiors and therefore material solutions are similar to those for rail and mass transit interior products.

Cargo compartments are classified Class A, B, C, E or F, depending on fire detection, suppression, ventilation and ease of access as defined in CS 25.857. CS 25.855 describes requirements for these - in most cases they must meet a five-minute flame penetration test (Part III).

¹⁹ DOT/FAA/AR-00/42 Aircraft Materials Fire Test Handbook, FAA, regularly updated by chapter at <https://www.fire.tc.faa.gov/Handbook>. (Not to be confused with a report with the same reference number Thermal Decomposition Mechanism of 2,2-Bis-(4-Hydroxyphenyl)-1,1-Dichloroethylene-Based Polymers.)

²⁰ Nadcap was originally the National Aerospace and Defense Contractors Accreditation Program, but is now global. <https://p-r-i.org/nadcap/>

5.6.3 Fire containment

Containment is typically defined by a fire resistance test involving a 5-minute ('fire-resistant') or 15-minute ('fireproof') hydrocarbon burn through from a gun type burner. The focus here is containment by avoiding burn through, in contrast to the marine and oil and gas regulations which are concerned with limiting heat transfer and structural integrity. Further information can be found in section 6.7.4. Designated fire zones are defined for powerplant, nacelle areas and flammable fluid carrying components, separated by firewalls. See CS 25.1181 to 25.1183. CS 25.1191 and 25.1193 describe fireproof requirements for firewalls / shrouds, cowlings and nacelle skins.

Exterior fire protection issues associated with composite structure must include the effects of an exterior pool fire following a survivable crash landing. These considerations must be extended to wing and fuel tank structural integrity, e.g.: As related to crashworthiness, composite fuel tank structure must not fail or deform to the extent that fire becomes a greater hazard than with metal structure. AMC 20-29, 11b.

On the basis of equivalence to metallic structures, the test regime used for composite fuselage structures is that for the thermal insulation used for a metallic structure, i.e. CS-25 Appendix F, Parts VI and VII. According to CS 25.571 allowance needs to be made for latent fire which is not discovered, e.g. hidden under insulation. AMC 20-29 explains the damage tolerance philosophy.

Where a composite box or enclosure is proposed for containment of a presently unspecified risk, the process likely procedure to be followed is this:

- Define the fire threat. This would be done by the product supplier supplying the item which is the fire source.
- Meet the cabin safety and structural requirements when defining the fire resistance of the enclosure in accordance with the CSs.
- From a structures perspective (at a structural aircraft level), strength and stiffness would need to be addressed in accordance with damage tolerance considerations (AMC 20-29 Categories of damage), including considerations for the potential for latent fire.
- A useful reference temperature would be the glass transition temperature, T_g . A minimum 50°F margin would be required between the Maximum Operating Temperature (MOT) and T_g for the composite, and 30°F margin with respect to any adhesives used.
- This would typically apply to the structure around the composite box, i.e. the box, when subjected to the fire threat, would need to retain the fire so that the surrounding structure (load bearing structure) does not exceed the MOTs determined by the airframe designer (as dictated by material selection etc).
- Cabin safety requirements would also need to be met, e.g. toxicity, smoke density, etc.

5.6.4 Cabling

While traditional cabling is not in the scope of this guide, this is becoming relevant with the use of composite loom (stringing together multiple electrical control paths through a structure). According to CS 25.1713 cable insulation must be self-extinguishing according to the 60° burn test, as described in CS-25 Appendix F, Part I, and critical components must be 'fire-resistant'.

5.6.5 Battery boxes

As with automotive, tests for containment of fire in lithium ion battery boxes have not been clearly defined in specifications. (See section 5.5.3.)

In an incident involving an Ethiopian Airlines Boeing 787-800 at London Heathrow in 2013, thermal runaway failure of the lithium manganese dioxide battery in the emergency locator transmitter caused a fire which damaged the composite fuselage structure.²¹ Since then a Special Condition²² has been issued for consultation and Radio Technical Commission for Aeronautics (RTCA) Minimum Operational Performance Standards (MOPS)²³ have been published restricting explosion and toxic gas emissions for lithium batteries.

Composite battery boxes to provide containment of fire, blast and toxic gases may be a solution to some of those requirements, but so far there does not appear to be any specific guidance on this although Special Conditions have been produced referring to the required manufacturing standards for rechargeable and non-rechargeable lithium batteries.

5.7 Military

Military applications are not required to follow civilian rules, but fire performance will typically exceed the requirements for civilian applications. Bespoke tests are often required involving fire and blast. In comparison to offshore blasts, which are caused by igniting gas clouds, explosion tests for military applications normally use solid charge explosives which has much shorter blast wave profiles. Structures react completely differently to these blasts from those caused by igniting gas clouds, and this needs to be taken into account when designing the fire barrier.

Naval requirements tend to be the most severe. It is worth noting that the military requirement in the case of fire may be based on maintaining the validity of the platform as a base from which to operate, rather than simply allowing a safe time to evacuate.

Internationally, the NATO Standardization Office (NSO) has published covering standard STANAG 4602 'Assessment of reaction-to-fire of materials' Edition 2, which refers to guidance in AFAP-01 to 05:

- AFAP-01 Ed.:3 'NATO Reaction-To-Fire Tests for Materials - Policy for the Pre-Selection of Materials for Military Applications'. Refers to
 - ISO 1182 and IMO FTP Code Part 1 for non-combustibility
 - ISO 4589-2 for oxygen index (ignitability)
 - ISO 4589-3 for temperature index (flammability)
 - IMO FTP Code Part 7 for vertically supported textiles and films (and Parts 8 and 9 for furniture)
 - AFAP-2 to 05 as below
- AFAP-02 Ed.:3 'NATO Reaction-To-Fire Tests for Materials – Smoke Generation'
Based on ISO 5659-2, modified.
- AFAP-03 Ed.:3 'NATO Reaction-To-Fire Tests for Materials - Toxicity of Fire Effluents'
Refers to ISO 19701, ISO 19702, NF X 70-100-1 and SAFIR Final Report for sampling, analysis and testing of gases.²⁴
- AFAP-04 Ed.:3 'NATO Reaction-To-Fire Tests for Materials – Surface Spread of Flame'
Based on ISO 5658-2, modified and IMO FTP Code Part 5.
- AFAP-05 Ed.:3 'NATO Reaction-To-Fire Tests for Materials - Heat Release Rate'
Based on ISO 5660 Parts 1 and 2 modified. (Note that ISO 5660-2 is now withdrawn, having been incorporated in ISO 5660-1:2015.)

²¹ Aircraft Accident Report 2/2015 - Boeing B787-8, ET-AOP, 12 July 2013.

<https://www.gov.uk/aaib-reports/aircraft-accident-report-2-2015-boeing-b787-8-et-aop-12-july-2013>

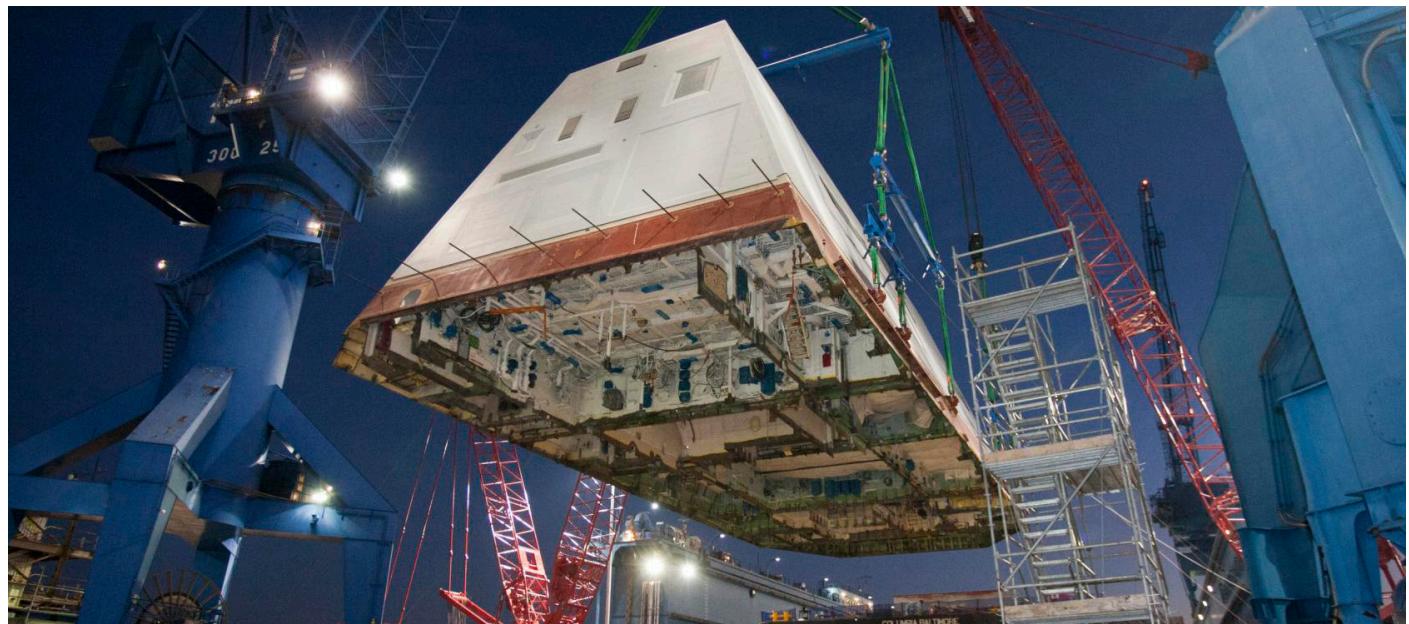
²² Special Condition on 'Non-rechargeable Lithium Battery Installations', EASA

<https://www.easa.europa.eu/document-library/product-certification-consultations/special-condition-%E2%80%98non-rechargeable-lithium>

²³ DO-311A - Minimum Operational Performance Standards for Rechargeable Lithium Batteries and Battery Systems, 2017 and DO-227A - Minimum Operational Performance Standards (MOPS) for Non-Rechargeable Lithium Batteries, 2017, RTCA. Available at https://my.rtca.org/nc_store

²⁴ SAFIR Final Report (Smoke Gas Analysis by Fourier Transform Infra-Red Spectroscopy, Tuula Hakkarainen, VTT Building Technology, 1999. <https://www.vtt.fi/inf/pdf/tiedotteet/1999/T1981.pdf> This formed the basis for the first version of ISO 19702.

UK naval applications generally refer to the Ministry of Defence (MOD) DEF STAN 07-247 Rev I2 'The Selection of Materials on the Basis of their Fire Characteristics' which uses a series of Defence Standards, British Standards and ISO test methods, similar to STANAG 4602. They will also often refer to Lloyd's Register approvals.



900t composite deckhouse of USS Zumwalt being lifted into position. Photo: US Navy

6. TESTING

Descriptions of a few representative tests are described below. Useful sources of further information include the Research Institutes of Sweden (RISE) website²⁵ and Firete.com²⁶ which have descriptions of many tests and other relevant information. Further sector specific comments on aircraft test specifications are in section 5.6.1.

Typically, samples will need to be conditioned in a controlled atmosphere for a defined duration before the test, as the temperature and moisture content will affect the result of the test. Careful preparation of small specimen pieces for testing is required as minor differences in e.g. edge sharpness, thickness or degree of cure can lead to significant variations in results. Several specimens are usually tested for small-scale tests, with specimen size defined in the relevant standard. An indicative (and less costly) test may require fewer specimens than are required for a complete (formal) test.

6.1 Non-combustibility

The primary test for non-combustibility is BS EN ISO 1182:2010 ‘Reaction to fire test - Non-combustibility test’. A cylindrical test specimen (45 mm diameter and 50 mm high) is placed inside a cylindrical furnace tube at 750°C. The furnace and specimen temperatures are measured continuously during the test. Potential combustion of the test specimen is registered as temperature rise and/or visible flames. Mass loss of the test specimen is calculated after the test. These parameters are used to decide if the product is non-combustible or not.

BS 476-4:1970 ‘Fire tests on building materials and structures. Non-combustibility test for materials’ has been superseded in Europe by BS EN ISO 1182, but it has not been withdrawn based on legitimate need for the standard within non-EU markets.

6.2 Ignitability

UL 94 ‘Standard for tests for flammability of plastic materials for parts in devices and appliances’ is intended for plastic parts in devices and appliances, but is often used for small polymeric samples to serve as a preliminary indication of ignitability / flammability.

The test specimen (125 mm x 13 mm. Max thickness 13 mm) is placed vertically in a test chamber. Cotton is placed under the specimen. The gas flame is applied for 10 seconds. The afterflame time is noted. When the flames have died out the gas flame is applied once more for 10 seconds. The afterflame time and afterglow time are noted and whether the material releases any flaming particles or drops which ignites the cotton under the specimen. The following test results are given in a report:

- Afterflame time for each specimen.
- Total afterflame time for the conditioned set.
- Afterflame time and afterglow time for each specimen after second gas flame application.
- If the material burns or glows to the specimen attachment.
- If the cotton is ignited.

Other standards testing ignitability include:

- BS 476-12:1991 ‘Fire tests on building materials and structures. Method of test for ignitability of products by direct flame impingement’.
- BS 476-13:1987, ISO 5657:1986 ‘Fire tests on building materials and structures. Method of measuring the ignitability of products subjected to thermal irradiance’
- ISO 5657:1997 ‘Reaction to fire tests -- Ignitability of building products using a radiant heat source.’

²⁵ <https://www.sp.se>, due to change to www.ri.se in 2019

²⁶ <http://www.firete.com/en/> has standards and test methods by sector, but appears not to have been updated for some years.

6.3 Fuel load and heat release rate

The cone calorimeter is the most important bench scale instrument in the field of fire testing, used in several tests including ISO 5660-1:2015 ‘Reaction-to-fire tests. Heat release, smoke production and mass loss rate. Heat release rate (cone calorimeter method) and smoke production rate (dynamic measurement)’.

A 100mm x 100mm sample is irradiated via the conical heater. The surface of the sample is heated and starts to emit pyrolysis gases that are ignited by a spark igniter. The emitted gases are collected in a hood and transported away through a ventilation system. Heat release rate (kW/m²) is determined by measuring oxygen concentration in the smoke and total heat release (MJ/m²) is calculated from that data. Mass loss (g/s) and effective net heat of combustion (MJ/kg) are both also measured, as are smoke production and levels of released toxic gases.

BS EN ISO 1716:2018 ‘Reaction to fire tests for products. Determination of the gross heat of combustion (calorific value)’ is one test that can define the calorific value, which is a way of measuring the available fuel load. A specimen of a particular mass is burned under standardized conditions at constant volume in an atmosphere of oxygen. This is done in a bomb calorimeter. The heat of combustion is calculated on the basis of the observed temperature rise, taking account of heat loss and the latent heat of vaporisation of water.

6.4 Flame spread, surface flammability and fire propagation

In flame spread tests, typically a defined flame, e.g. from a Bunsen burner, is applied to a sample for a short period, and the rate at which the specimen burns is calculated from the burnt distance divided by the time taken to burn.

ECE 118 ‘Uniform technical prescriptions concerning the burning behaviour and/or the capability to repel fuel or lubricant of materials used in the construction of certain categories of motor vehicles’ is used for automotive interiors, where a burning rate of below 100mm/minute may be required. Tests for vertical and horizontal configurations are described.

The horizontal burning rate tests in the following are technically equivalent or very similar, though the burn rate requirements for different applications will vary:

- ECE 118 Annex 6
- ISO 3795 (BS AU 169a:1992, ISO 3795:1989 ‘Method for determination of burning behaviour of interior materials for road vehicles, and tractors and machinery for agriculture and forestry’)
- Former European directive 95/28/CE annex IV (repealed by Regulation (EC) No 661/2009, though 661/2009 does not specify any fire / flammability tests except that it refers to the need for flammability testing of category M3 vehicles (buses)
- FMVSS 302 (US Federal Motor Vehicle Safety Standard ‘Flammability of interior materials’)

The vertical burning rate tests in the following are technically equivalent or very similar:

- ECE 118 Annex 8,
- ISO 6941 (BS EN ISO 6941:2003 ‘Textile fabrics. Burning behaviour. Measurement of flame spread properties of vertically oriented specimens’)
- Former European directive 95/28/CE annex VI (repealed as above)

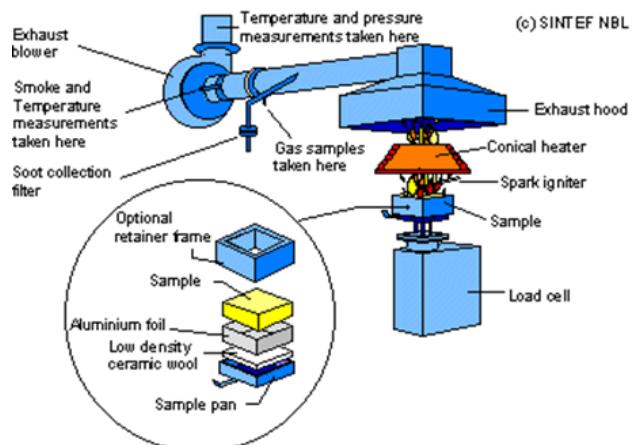


Figure 3: Cone calorimeter apparatus. SINTEF NBL

BS ISO 5658-2:2006+A1:2011 'Reaction to fire tests – Spread of Flame – Part 2: Lateral spread on building and transport products in vertical configuration' is different. Here the lateral flame spread is determined on vertically orientated specimens exposed to radiant heat, in addition to a small gas burner flame which acts as the pilot ignition source. The CFE-value (critical heat flux at extinguishment, in kW/m²) is the incident heat flux at the specimen surface at the point along its horizontal centreline where the flame ceases to advance. It is used in BS EN 45545-2 for trains and the same test procedure but with some additional measurements is used as the main flame spread test for interior linings in passenger ships under the IMO Resolution A.653(16).

The vertical burn tests (ISO 6941 and ISO 5658-2) place much harder requirements on the materials than the horizontal (ISO 3795) and there has been criticism of ISO 3795 and FMVSS 302 on this basis. A useful study from SP Technical Research Institute of Sweden describes this.²⁷



Figure 4: Filon G104 GFRP rofflight sheet achieves Class 1 to BS 476 Part 7 for surface spread of flame. Photo courtesy of Filon Products Ltd.

²⁷ A comparative study of test methods for assessment of fire safety performance of bus interior materials, Michael Försth. SP Technical Research Institute of Sweden, SP Arbetsrapport 2009:23, ISSN 0284-5172, Borås 2009

In BS 476-7:1997 'Fire tests on building materials and structures. Method of test to determine the classification of the surface spread of flame of products' the specimen is exposed to a radiant panel over a ten-minute test duration. A pilot flame is applied to the bottom corner of the specimen during the first minute of test. Classifications for flame spread are as shown in Table 1, where Class 1 is the highest classification with the slowest rate of spread.

Table 1: Classification of spread of flame according to BS 476-7:1997

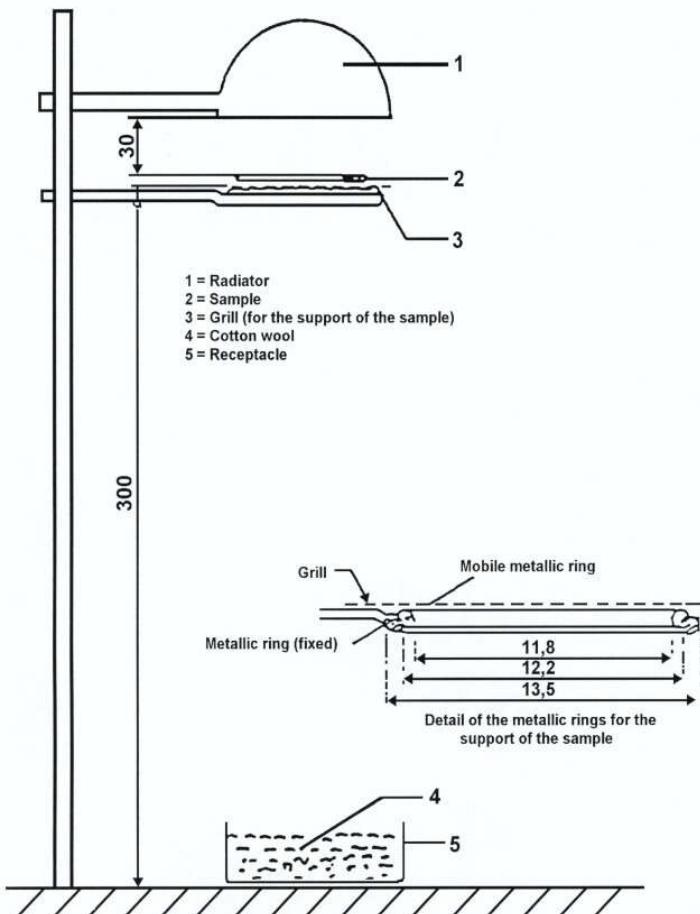
Classification	Spread of Flame at 1.5 minutes		Final Spread of Flame at 10 minutes	
	Limit (mm)	Limit for one specimen in sample (mm)	Limit (mm)	Limit for one specimen in sample (mm)
Class 1	165	165+25	165	165+25
Class 2	215	215+25	455	455+45
Class 3	265	265+25	710	710+75
Class 4	Exceeding the limits for class 3			

6.5 Melting behaviour / flaming droplets

In some cases, any melting behaviour may be observed over a period of exposure to a heat source, and any molten droplets, particularly if they are burning, are noted.

For example, in ECE 118 Annex 7 (automotive) a radiator is placed 30mm above the sample. A receptacle full of cotton wool is placed 300mm below the sample. During the first five minutes the radiator is moved away if the sample ignites, and replaced when the flame has extinguished. The test continues for a further five minutes with the radiator in place. The test report notes the fall of drops, if any, whether flaming or not, and whether ignition of the cotton wool has taken place (indicating burning droplets).

Flaming droplets are also observed in some spread of flame tests, e.g. BS ISO 5658-2, and the Euroclass classifies flaming droplets as described in 5.1.1.



Test to determine the melting behaviour of materials, ECE 118 Annex 7. Dimensions in mm

6.6 Smoke and toxicity

BS EN ISO 5659-2:2017 ‘Plastics, Smoke generation. Determination of optical density by a single chamber test’, determines optical density of smoke generation with Fourier transform infrared spectroscopy (FTIR) gas analysis techniques to detect specific toxic gases.

Specimens are 75 mm x 75 mm, up to 25 mm thick. The test sample is placed horizontally in a sealed chamber and exposed to a radiant heat source. Smoke is collected in the chamber and the optical density (transparency) is measured with a light source and a photo cell. A sample of smoke is taken from the chamber and analysed by FTIR analysis which can detect carbon monoxide, hydrochloric acid, hydrogen bromide, hydrogen fluoride, hydrogen cyanide, nitrous oxides and sulphur dioxide.

ISO 19702:2015 ‘Guidance for sampling and analysis of toxic gases and vapours in fire effluents using Fourier Transform Infrared (FTIR) spectroscopy’ gives specific guidance for sampling and analysis of toxic gases and vapours in fire effluents using FTIR spectroscopy. The first version of this standard was based on the results of the EU funded SAFIR project.²⁴

Other tests measuring smoke production and/or toxic gases include BS EN 17084:2018 (toxicity of the products of combustion); ASTM D2483 (smoke density); ASTM E-906 (smoke release using thermopile method); CS-25 Appendix F Part V /FAA Fire Test Handbook Chapter 6 (smoke emission for cabin materials, often accompanied by additional aircraft manufacturers tests for toxicity); AFAP-02 (modified ISO 5659-2); AFAP-03 (toxicity).

Smoke and toxic gases will often be measured alongside large scale tests.

6.7 Fire resistance: Passive fire protection and compartmentation

The insulating properties of a partition determine its ability to limit the spread of fire – compartmentation or containment – or to provide passive fire protection for structures or equipment. Tests cover cellulosic fire, hydrocarbon pool fire and jet fire and are carried out on large scale samples. Similar tests apply for construction, marine and oil & gas. Different “burn-through” tests are used for aircraft.

The fires most commonly considered are referred to in standards as cellulosic, i.e. at the level of intensity expected from the burning of wood, furnishings, etc. Hydrocarbon fires from the burning of fuels are more intense than cellulosic fires and the temperatures rises more rapidly.

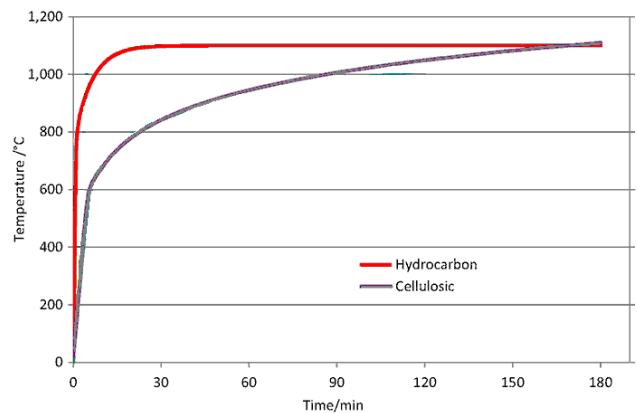


Figure 5: Time-temperature curves for cellulosic and hydrocarbon fires

Jet fires are the most severe fire scenario. They occur when a hydrocarbon gas or liquid fuel is expelled from an orifice, e.g. a leak in a pipe, at high pressure, giving rise to high convective and radiative heat fluxes and high erosive forces.

6.7.1 General fire resistance testing

The heating regimes used to test fire protection materials designed for cellulosic and hydrocarbon pool fires are set out in BS 476-20 ‘Fire tests on building materials and structures. Method for determination of the fire resistance of elements of construction (general principles)’, and others (including UL 1709, Eurocode 1). The time-temperature curves are slightly different. BS 476-20 provides a means of quantifying the ability of an element to withstand exposure to high temperatures, by setting criteria by which the loadbearing capacity (stability), the fire containment (integrity) and the thermal insulation can be assessed.

Testing involves a large-scale furnace running a predetermined time-temperature curve, as shown in Figure 5. The temperature of the unexposed surface is monitored using thermocouples. A load may be applied while the specimen is undergoing the test to assess the loadbearing integrity.

Depending on the application, several parameters need to be specified, including:

- Duration of exposure to maintain stability and integrity.
- Minimum duration of the insulation performance of the structure.
- Maximum and average permitted temperature rise of the unexposed surface (during the duration required for insulation performance).

Classification for fire resistance is defined in the European harmonised system for construction products. It uses the descriptors in Table 2: Classification for fire resistance according to BS EN 13501-2:2016 defined by BS EN 13501-2:2016.

Table 2: Classification for fire resistance according to BS EN 13501-2:2016

Letter	Description	Criteria
I	Insulation - The time it takes to produce an increase in temperature on the cold side, usually 140 °C.	Average temperature rise Maximum temperature rise
E	Integrity - The length of time the structural element retains its integrity against flames or hot gases.	Ignition of cotton pad Cracks and openings Occurrence of sustained flaming on the unexposed side
R	Load bearing capacity - The length of time that the relevant structural element is able to carry the current load in a normal fire development phase.	Limiting deformation Limiting rate of deformation
M	Mechanical action - The ability of the structural element to cope with mechanical impact in a standard fire.	Resistance to impact

So, for example, class REI 60 means that the structural element can resist fire for one hour with respect to load bearing capacity, integrity and insulation.

6.7.2 IMO FTP Code fire resistance class divisions

In the IMO FTP Code uses a different system (generally related to marine or offshore applications). The parameters in Table 3 apply. Additionally, a class H-0400 is often used, where 400 refers to the temperature limitation on the unexposed side.

Table 3: Parameters for fire testing for A, B and H class according to International Maritime Organization, FTP Code.

Criteria	A Class	B Class	H Class
Testing duration (to maintain stability / integrity)	60 min	30 min	120 min
Average permitted temperature rise on unexposed surface	140°C	140°C	140°C
Maximum permitted temperature rise on unexposed surface	180°C	225°C	180°C
Class description (number corresponds to minimum duration of insulation performance)	A-0, A-15, A-30, A-60	B-0, B-15	H-0, H-60, H-120

6.7.3 Jet fire

BS ISO 22899-1:2007 'Determination of the resistance to jet fires of passive fire protection materials. General requirements' provides an indication of how passive fire protection materials perform in a jet fire. It is designed to simulate the mechanical and thermal loads imparted to passive fire protection material by large scale jet fires. However, it cannot reproduce them all exactly and it is noted that the results of the jet fire test do not guarantee safety but may be used as elements of a fire risk assessment.

The test is conducted using 0.3 kg/sec sonic release of gas produced by a propane fuel system projected out of a standardized jet nozzle into a chamber, producing a fireball with an extended tail. High erosive forces are generated by the release of the sonic velocity gas jet 1m from the specimen.

Jet fire testing is typically carried out for 120 mins, with monitoring of the unexposed surface temperature as noted above, leading to class J-0, J-15, J-60, etc.

6.7.4 Aircraft fire penetration test

Aircraft compartmentation testing focuses on limiting burn-through, rather than heat transfer and structural integrity. Test specimens are actual or simulated aircraft hardware, typically 610 x 610mm though may vary. A modified gun-type oil burner fires a controlled flame for 5 minutes or 15 minutes. There must be no flame penetration or burning on the back side of the specimen.

Materials or parts are demonstrated to be “fireproof” by meeting requirements of this test for a flame exposure of 15 minutes, or “fire-resistant” with a flame exposure of 5 minutes. These tests are defined in BS ISO 2685:1998 ‘Aircraft. Environmental test procedure for airborne equipment. Resistance to fire in designated fire zones’ and in the FAA Fire Test Handbook, Chapter 12 ‘Powerplant Fire Penetration Test’. Individual primes may have their own versions.

An important recent change, following discussion over some years, is that propane burners may no longer be used for oil burner tests for aircraft. While a propane burner simulates the heat flux density and the temperature at the test article, it does not simulate a fire fuelled by representative fluids. As a result, testing with a propane burner may result in a less severe test than if a kerosene burner were used. See FAA Advisory Circular AC 20-135 with change.²⁸

6.8 Load bearing temperature envelope

Fire resistance is often required where the part is loaded as part of a structure. BS 476-21:1987 ‘Fire tests on building materials and structures. Methods for determination of the fire resistance of loadbearing elements of construction’ applies to this scenario, whereby beams, columns, floors, flat roofs or walls are tested with specified loading and restraint conditions, and subjected to heating and pressure conditions specified in BS 476-20:1987 ‘Fire tests on building materials and structures. Method for determination of the fire resistance of elements of construction (general principles)’.

Other tests covering this area include the BS EN 1365 series, ‘Fire resistance tests for loadbearing elements’, which specifically addresses balconies and walkways (part 5) and stairs (part 6).

In some marine applications where equivalence to steel is required, the determining factor for integrity of an FRP structure is identified as being related to heat deflection temperature (HDT). See section 2.9. In recognition of this, and particularly because the EU Directive 2009/45/EC on standards for passenger ships is applicable only to ships constructed of steel or equivalent materials, the MCA has produced MGN 407 (M+F) ‘Procedure for the Testing of Fire Protection for use with Composite and Wooden Constructions’. It focuses on ensuring that the FRP structure is not compromised by exceeding its heat deflection temperature and refers to ISO 75 and ISO 834:

- BS EN ISO 75-3:2004 ‘Plastics. Determination of temperature of deflection under load. High-strength thermosetting laminates and long-fibre-reinforced plastics’
- ISO 834-1:1999 ‘Fire-resistance tests – Elements of building construction, Part 1: General requirements.’

²⁸ Advisory Circular 20-135, Subject: Powerplant Installation and Propulsion System Component Fire Protection Test Methods, Standards, and Criteria, with Change 1, FAA, 2018.

https://www.faa.gov/regulations_policies/advisory_circulars/index.cfm/go/document.information/documentID/22194

6.9 Large scale tests

Most of the reaction to fire tests mentioned above are carried out on small coupons, but the fire resistance tests need to be carried out on large scale samples to be representative. Where whole structures, like a ship or a building, are concerned then often the wider design needs to be assessed for fire safety.

In some cases, large scale reaction to fire tests are also required, such as ISO 9705-1:2016 ‘Reaction to fire tests - Room corner test for wall and ceiling lining products - Part 1: Test method for a small room configuration’.

This evaluates the fire characteristics of a surface product in a room fire scenario. It is relevant to products or systems that can’t be tested at small scale, for example joint systems, materials with large irregularity, pipe insulation. The complete test uses at least 35 m² of material.

The test sample is mounted on the inside of the room, in the ceiling and on all the walls except for the wall with the door opening. A propane gas burner in one of the corners produces a heat release rate of 100 kW for 10 minutes, and then 300 kW for a further 10 minutes. Heat release rate (kW/m²), total heat release (MJ) and smoke production rate (m²/s) are measured. Flame spread and burning droplets or particles are observed visually. If flames emerge from the door opening, flashover is deemed to have occurred and the test is terminated. When necessary, toxic gases can also be measured using FTIR analysis.

The BS 8414 test methods were developed by the Building Research Establishment (BRE).

- BS 8414-1:2015+A1:2017 ‘Fire performance of external cladding systems. Test method for non-loadbearing external cladding systems applied to the masonry face of a building’
- BS 8414-2:2015+A1:2017 ‘Fire performance of external cladding systems. Test method for non-loadbearing external cladding systems fixed to and supported by a structural steel frame’

They evaluate whether a cladding system subject to fire breaking out of an opening, such as a window, will result in fire spreading excessively up the outside of the building and possibly re-entering at a higher level. The tests are performed on full-scale systems (rather than small-scale samples) in specialist laboratories and involve a 9 metre high demonstration wall incorporating joints, corner details, fixings, insulation, etc, to represent the whole system.

Bespoke large-scale tests may be designed for particular applications, for example SP Technical Research Institute of Sweden (now RISE) designed full scale fire tests to resemble possible fires in a RoPax (roll-on/roll-off passenger vessel) cabin. The objectives were two-fold; one aim was to study the fire development and the influence of sprinkler, ventilation and realistic cabin furnishings. The other aim was to evaluate the behaviour of a composite structure under realistic fire conditions, including with all active safety systems out of order.²⁹

6.10 Modelling, simulation and predictive behaviour

Small scale tests can provide some intrinsic materials data, such as time to ignition, calorific value, insulation properties, heat release rate etc. Computer models can extrapolate these properties to try and predict, for example, time to burn through, temperature rise on a back surface, time to collapse of a structure and the failure mode. Models can be used to ‘mimic’ or virtually test materials, e.g. cone calorimeter data can give a good indication of likely performance in larger scale tests, and so can be used to ‘screen’ candidate systems, prior to these larger scale and expensive validating tests.

Fire modelling is being used to predict fire chemistry within the plasma, right the way through to predicting transfer of heat, and flow of smoke through buildings and ships, in order to design fire safety systems, and even to simulate people behaviour in the face of fire and smoke and design safe evacuation pathways.

One such simulator is the NIST (USA National Institute of Standards and Technology) Fire Dynamics Simulator (FDS) which is a computational fluid dynamics (CFD) model of fire-driven fluid flow. The software solves numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow, with an emphasis on smoke and heat transport from fires.

²⁹ Large-scale fire tests in a passenger cabin, Arvidson, Axelsson & Hertzberg. SP Technical Research Institute of Sweden, SP Report 2008:33, ISBN 978-91-85829-50-7, ISSN 0284-5172

Modelling is often very helpful in the materials selection and design phase, and indicative or screening testing of specific materials combinations, not necessarily found in materials suppliers' literature, is often essential to provide data to model. Modelling, while it can provide confidence in a proposed system or concept, does not currently carry much weight with approval authorities and certification bodies, unless also backed by representative large or even full-scale tests.

6.11 Fire testing laboratories

There are several fire testing laboratories in the UK. The Fire Test Study Group³⁰ (FTSG) maintains a list of fire testing laboratories in the UK which undertake fire tests for building control purposes, though most cover other sectors as well, and there are several other testing laboratories which undertake fire testing relevant to FRP composites. The FTSG issues resolutions to clarify interpretation of standards and maintain consistency.

Testing laboratories must be accredited by the United Kingdom Accreditation Service³¹ (UKAS). On the UKAS website you can browse accredited organisations³² and view the schedule of accreditation for any laboratory, listing the tests they are accredited to undertake.

In several cases, testing laboratories also need to be accredited by sector regulatory bodies, such as IMO, FAA, EASA.

³⁰ <http://www.ftsg.co.uk>

³¹ <https://www.ukas.com/>

³² <https://www.ukas.com/browse-ukas-accredited-organisations/>

7. FUTURE TRENDS

Across all industrial sectors there are several driving forces and mega trends with direct effects on approaches to FST requirements for FRP materials. New fire safety hazards are emerging and new means to mitigate, control and regulate risks will need to be found.

7.1 Electrification of transport and mobility

The move away from fossil fuels towards a lower carbon, more sustainable economy is driving increased use of electricity to replace fossil fuels. This is occurring across the whole of the transport sector. Anything that currently moves, from gas powered ships, passenger jets, cars, buses, trucks, tractors, trains and wheelchairs, can benefit from weight reduction, and composites systems with the right FST credentials will play a key role.

In the air, electric passenger aircraft are already in design phases. Drone and UAV technology is being proposed for everything from the current surveillance and survey work, to parcel delivery, right up to autonomous air taxis. All are likely to be heavily reliant on new battery technology as well as using lightweight composites structures. Safe containment of thermal runaway battery fires is a key challenge facing the industry.

A stepping stone to full electric propulsion is fuel cell technology, where pressure cylinders to store and carry flammable gases like hydrogen, methane or butane on vehicles will be needed to feed fuel cells and clean electric/hybrid propulsion systems. These systems will need to be lightweight and robustly safety compliant including protection from external fire attack as well as from internal electrical failures.

Beyond that, electric actuators and motors, even wirelessly controlled, are replacing clunky hydraulic systems and electrical cabling, allowing all sorts of moving machinery and plant to move faster, require less power, and operate more safely.



FRP composite rear end of Wrightbus's hybrid electric New Routemaster bus.
Photo courtesy of Gurit.

Composite materials are pushing their way into hotter and hotter service temperature applications. In advanced modern aero engines fuel lines, electrical loom and fan blades are all being looked at, and the continuous service temperature envelope is key to this, but fire safety compliance is a must have. If the automotive industry is to realise its low emission targets then 'plastic' and composite components must replace heavier traditional materials in hot areas of the drive train, electric hub motors and components close to brakes or exhaust systems. Even the internal combustion engine itself is seeing more use of composite components in applications such as crank cases, sump and gearbox covers.

Clean nuclear power is another trend, and high temperature composites can provide key structural elements that are non-conductive and non-magnetic for use in future fusion reactors.

7.3 Reinforced thermoplastics

Thermoplastic composites are increasingly used in some demanding applications, especially where toughness and impact resistance are more important than simply stiffness. Thermoplastics also offer the possibility of simpler recycling or re-use options, provided the issues around FST additive contamination of secondary materials streams can be addressed.

Modern high-performance thermoplastics compete with the best thermosets in aerostructure applications, and some have inherently excellent FST performance, chemical resistance, and fatigue performance, meaning they have a strong future in oil and gas and offshore applications.

Current thermoplastic materials test regimes are mainly targeted at electrical applications, rather than structural ones, so new systems and test regimes will be needed to address some of these challenges.

At the other end of the spectrum, low-cost thermoplastic wood plastic composites, potentially using recycled thermoplastics, are replacing hardwood, and the option to improve performance and take these types of products into more demanding structural applications, requiring improved FST, is clear.

7.4 Environmental concerns, health and safety and end-of-life

Composite materials play a key role in saving energy and reducing carbon footprint in many of their application areas. These positive impacts must be set against potential negative impacts of using chemical products and petroleum derived plastics on the environment, or hazards during processing.

At the design stage thought must be put into how to re-use, recycle or recover materials at the end-of-life or during processing. Some additive systems can contaminate recycling streams, and so create a barrier to circular economy models.

Many very effective fire-retardant additives have health and safety issues for handling and processing, some have toxic fire products, and even some mineral filler extraction is less than environmentally friendly. While fire resistance is key to saving lives, it shouldn't be at severe environmental cost.



End of life aircraft scrap. Photo by Stella Job

Halogen chemistry and antimony tri-oxide synergist systems in TV casings and consumer products are being gradually replaced by newer phosphorous and nano-additive chemistries, some of which have not yet been through the same level of safety scrutiny as the established products.

As chemicals under investigation become less available or phased out, and the replacements more expensive or less effective there is a temptation to use not enough, or not use them. The consequence in some cases has been a reversal in safety, for example with more TV fires in US states that enforce the most rigorous criteria.

7.5 Sustainable materials sources

The plant world has developed interesting methods to preserve itself from fire, and chemicals refined from food crop waste streams are a useful source of next generation fire-resistant products. However even the plant world produces toxic products, such as natural creosote, and most wood smoke is very bad for human health.

Academics and industry continue to seek safer, effective fire additives, looking to bio-source rather than use petroleum chemistries for additives, bio-resins and reinforcements. Chemicals derived from sugar cane bagasse and cashew nut shell liquid have already successfully been used to replace petroleum derived resin systems in some aircraft interior products.

APPENDIX 1: GLOSSARY & TERMINOLOGY

AC	Advisory Circular
Aliphatic	(Of an organic compound) containing carbon and hydrogen joined together in straight chains, branched chains, or non-aromatic rings. It is one of two broad classes of hydrocarbons, the other being aromatic compounds.
AMC	Acceptable Means of Compliance
APP	Ammonium polyphosphate, used as a flame retardant and in intumescent systems
Aromatic	(Of an organic compound) containing a planar unsaturated ring of atoms which is stabilised by an interaction of the bonds forming the ring, and leads to good char formation, e.g. phenolics and furans
ASTM	American Society for Testing and Materials
ATH	Alumina trihydrate, commonly used hydrated filler for composites which releases water at high temperatures
ATO	Antimony trioxide, used as a catalytic synergist with halogenated fire retardants
Blast overpressure	The pressure on an object or structure caused by a shock wave over and above normal atmospheric pressure, typically caused by an explosion.
BMC	Bulk moulding compound, sometimes referred to as DMC, dough moulding compound
BRE	Building Research Establishment - a centre of building science in the UK
BSI	British Standards Institution - the national standards body of the UK
CAA	Civil Aviation Authority – the aviation authority of the UK
Calorific value or potential	Calorific energy which would be released by the complete combustion of a unit mass of a material - MJ/kg
Cellulosic	A cellulosic fire is one with a fuel source predominantly of cellulose (e.g. timber, paper, cotton). The flame temperature of a cellulosic fire is about half that of a hydrocarbon fire.
CFE	Critical heat flux at extinguishment
CFR	Code of Federal Regulations (USA)
CMCs	Ceramic matrix composites
Core	Used to thicken the laminate between structural skins, thus increasing its stiffness. Commonly made from low density materials.
CS	Certification Specifications (for airworthiness according to EASA)
DCPD	Dicyclopentadiene, used in unsaturated polyester resins
DIN	Deutsches Institut für Normung (German Institute of Standardisation)
EASA	European Union Aviation Safety Agency
E-LASS	European Network for Lightweight Applications at Sea
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
Fire resistance	The measurement of the ability of a material or system to resist, and ideally prevent, the passage of fire from one distinct area to another. Ratings are different according to different sectors / test methods
Fireproof	Able to withstand fire. Technically defined for aerospace as able to withstand a specified flame for 15 minutes without penetration.
Firewall	A structure designed to prevent a hazardous quantity of air, fluid, or flame from exiting a fire zone
Flag State	The jurisdiction under whose laws a merchant vessel is registered or licensed, deemed the nationality of the vessel. The flag state has the authority and responsibility to enforce regulations over vessels registered under its flag, including those relating to inspection, certification, and issuance of safety documents.

Flame / fire retardant	Chemicals which are added to manufactured materials to prevent or slow the further development of ignition by a variety of different physical and chemical methods. These terms tend to be used interchangeably, though there are some preferences, in particular, flame retardant is more common in relation to gas phase additives for thermoplastics, and fire retardant in relation to additive fillers in more complex systems. “Fire retardant” is also used for chemicals used in fighting fires. The same terms hyphenated can be used adjectively.
Flashover	The transition phase in the development of a contained fire in which surfaces exposed to the thermal radiation reach ignition temperature more or less simultaneously resulting in rapid fire spread
FMVSS	Federal Motor Vehicle Safety Standard (USA)
FR	Fire-resistant/ing / flame retardant / fire retardant / fire retarded / fire-rated / fibre reinforced, etc. Unclear and a best avoided term.
FRP	Fibre reinforced polymer
FST	Fire, smoke and toxicity
FTH	Fire Test Handbook – includes fire tests accepted by FAA
FTIR	Fourier Transform Infrared – a type of spectroscopy used for sampling and analysis of toxic gases and vapours
FTP Code	Fire Test Procedures - IMO fire testing code for international commercial ships
FTSG	Fire Test Study Group – a UK association concerned with fire testing and safety
Gel coat	A resin used to provide a hard-wearing quality finish on the outside of a laminate
HDT	Heat deflection temperature or heat distortion temperature - the temperature at which a polymer or plastic sample deforms under a specified load, defined for FRP composites by ISO 75
Heat flux	Rate of heat energy transferred per surface unit area - kW/m ²
HRR	Heat release rate - the rate at which fire releases energy, measured in watts (W)
HSC Code	International Code of Safety for High Speed Craft
Hydrocarbon	A hydrocarbon fire or pool fire, is a fire fuelled by hydrocarbon compounds (oil or gas).
Ignitability	The capability of a material to be ignited
IMO	International Maritime Organization - an agency of the United Nations, with 174 member states, responsible for the safety and security of international shipping and to prevent pollution from ships
Integrity	In this context, the integrity of a partition is its ability to prevent the passage of flame and/or smoke from the fire side of the partition through to the non-fire side for a period of time defined by the particular standard.
Intumescent	Material which expands when heated (up to several hundred times) to create an insulating char layer - widely used to provide fireproof seals around penetrations
ISO	International Organization for Standardization - a nonprofit organization that develops and publishes standards, with 162 national members
Laminate	The combination of a reinforcement and matrix, i.e. the composite
LDH	Layered double hydroxide - synthetic clay which can be used as a fire-retardant additive
Matrix	Material, usually a resin, which binds the reinforcement, usually a fibre, in a composite
MCA	Maritime and Coastguard Agency - UK authority for marine regulations
MDH	Magnesium di-hydrate - hydrated filler used as FST additive and high temperature
MMCs	Metal matrix composites
MMT	Montmorillonite - a naturally occurring alumino-silicate clay which can be used as a fire-retardant additive
MOD	Ministry of Defence (UK)
MOPS	Minimum Operational Performance Standards
Nadcap	Maritime Safety Committee of the IMO

NATO	A global, cooperative, industry-managed approach to conformity assessment and continual improvement for aerospace and defence (originally the National Aerospace and Defence Contractors Accreditation Program in USA, now global)
Nomex	A meta-aramid material developed in the 1960s by DuPont, with excellent thermal, chemical and radiation resistance for a polymer material
NORSOK	Family of standards developed by the Norwegian petroleum industry
NSO	NATO Standardization Office
OEM	Original equipment manufacturer
PIR	Polyisocyanurate - thermoset plastic typically produced as a foam and used as rigid thermal insulation
POSS	Polyhedral oligomeric silsesquioxanes - used in creating intercalated silica networks in insulating and reflective chars
PVC	Polyvinyl chloride - widely used in household electrical cabling for its good inherent self-extinguishing properties
PVDF	Polyvinylidene fluoride - may be used for decorative films, e.g. in aircraft interiors, where self-extinguishing performance is required
Pyrolysis	Thermal decomposition at elevated temperatures in an inert atmosphere (without oxygen)
Reinforcement	Usually in fibre form and added to the matrix to improve mechanical performance
RISE	Research Institute of Sweden
RTCA	Radio Technical Commission for Aeronautics
SAFIR	Smoke Gas Analysis by Fourier Transform Infra-Red Spectroscopy – a project which formed the basis for the first version of ISO 19702
SMC	Sheet moulding compound
SOLAS	International Convention for the Safety of Life at Sea - IMO regulations to specify minimum standards for the construction, equipment and operation of ships
Synergist	Chemical compound that increases the chemical activity of another compound when used with it
TCEP	Tris(2-chloroethyl) phosphate - fire retarding chlorinated plasticiser, added to resin systems to give low levels of self-extinguishing fire performance
TCP	Tricresyl phosphate - phosphorous based plasticiser with self-extinguishing behaviours, but limited effectivity at higher heat fluxes
T _g	Glass transition temperature - the temperature region where the polymer transitions from a hard, glassy material to a soft, rubbery material
Thermoplastic	A polymer that can be re-melted back to liquid form by the application of heat.
Thermoset	A polymer that is irreversibly hardened by chemical cross linking during the cure cycle
TPP	Triphenyl phosphate - phosphorous based plasticiser with self-extinguishing behaviours, but limited effectivity at higher heat fluxes
UAV	Unmanned air vehicle
UKAS	United Kingdom Accreditation Service for testing laboratories
UNECE	United Nations Economic Commission for Europe
VOC	Volatile organic compounds
Volatiles	Chemical elements or compounds which vaporise readily
ZHS	Zinc hydroxy stannate - hydrated filler, char promoter, also effective as a synergist in halogenated systems

APPENDIX 2: CODES AND STANDARDS

The list below includes most of the codes and standards used in UK relating to fire performance of materials and products which are used in sectors where FRP is common. Please note:

- The list is far from exhaustive.
- The standards listed there are current at March 2019, though some are under revision.
- Where a BS form of an EN or ISO standard exists, the prefix BS EN (and/or) ISO is used and the corresponding EN / ISO standard is not listed to avoid repetition.
- Some other national standards are listed where they are commonly referred to in UK.
- The sector columns indicate where evidence has been seen that the relevant standard has been used in that sector. These columns may not be complete.

Standards are constantly being updated. The status can be seen at the relevant website, with draft documents if the standard is under review, and information about the relevant technical committees reviewing the standard. It is essential always to check that the correct and most up-to-date standard is being used.

Where to find standards

Regulations, codes and standards can be found at the following websites at the time of writing:
(*= free to access)

- British Standards Institution (BSI) ³³
- International Organization for Standardization (ISO) ³⁴
- American Society for Testing and Materials (ASTM) ³⁵
- American National Standards Institute (ANSI) ³⁶
- * Building Regulations Approved Documents ³⁷
- * DNV GL Rules and Standards ³⁸
- DSTAN UK Defence Standardisation (DEFSTAN) Requires login ³⁹
- European Committee for Standardisation (CEN) ⁴⁰
- * European Union Aviation Safety Agency (EASA) ⁴¹
- * Federal Aviation Authority (FAA) through Electronic Code of Federal Regulations (e-CFR) with amendments incorporated ⁴²
- * International Maritime Organization FTP Code ⁴³
- * Maritime and Coastguard Agency (MCA) Construction, maintenance and operation standards ⁴⁴
- * NATO Standardization Document Database (STANAG) ⁴⁵
- Standards Norway (NORSOK) ⁴⁶
- UL ⁴⁷
- * United Nations Economic Commission for Europe (UNECE) Vehicle Regulations ⁴⁸

³³ <https://shop.bsigroup.com/>

³⁴ <https://www.iso.org/>

³⁵ <https://www.astm.org/Standard/standards-and-publications.html>

³⁶ <https://webstore.ansi.org>

³⁷ https://www.planningportal.co.uk/info/200135/approved_documents

³⁸ <https://rules.dnvgi.com/ServiceDocuments/dnvgi/#!/home>

³⁹ <https://www.dstan.mod.uk/StanMIS/Account/Login?ReturnUrl=%2fStanMIS%2f>

⁴⁰ <https://standards.cen.eu/dyn/www/f?p=CENWEB:105::RESET:::>

⁴¹ <https://www.easa.europa.eu/document-library/general-publications/easy-access-rules-large-aeroplanes-cs-25>

⁴² https://www.ecfr.gov/cgi-bin/text-idx?SID=9254aeeec94063ddfc8809b9f041e7f4&mc=true&tpl=/ecfrbrowse/Title14/14cfr25_main_02.tpl

⁴³ [http://www.imo.org/en/KnowledgeCentre/IndexofIMOResolutions/Maritime-Safety-Committee-\(MSC\)/Documents/ MSC.307\(88\).pdf](http://www.imo.org/en/KnowledgeCentre/IndexofIMOResolutions/Maritime-Safety-Committee-(MSC)/Documents/ MSC.307(88).pdf)

⁴⁴ <https://www.gov.uk/topic/ships-cargoes/construction-maintenance-operation>

⁴⁵ <https://nso.nato.int/nso/nsdd/listpromulg.html>

⁴⁶ <https://www.standard.no/en/>

⁴⁷ <https://standardscatalog.ul.com/>

⁴⁸ <https://www.unece.org/trans/main/wp29/wp29regs.html>

Note on numbering of standards:

The numbering of standards can be confusing. Some things to note include:

- i. In some cases, the standard number may be consistent across BS / EN / ISO, e.g. the combustibility test:
 - a. BS EN ISO 1182:2010 = EN ISO 1182:2010 = ISO 1182:2010
- In other cases that may not be the case, e.g.
 - b. BS EN ISO 1716:2018 'Reaction to fire tests for products. Determination of the gross heat of combustion (calorific value)' is completely different from BS EN 1716:1997 'Plastics piping systems. Polyethylene (PE) tapping tees. Test method for impact resistance of an assembled tapping tee.'
- ii. In some cases, a specification may refer to a standard with a specified date, which has been superseded or withdrawn. Or it may refer to a standard without specifying the date, which usually means that it refers to the latest (current) version of that standard, e.g. BS EN 45545-3:2013, related to fire protection on railway vehicles, refers to EN ISO 13943:2010, Fire safety — Vocabulary which has been superseded by BS EN ISO 13943:2017
- iii. For BS, EN, ISO standards, the number after the hyphen, if present, is the part number and the number after the colon is the year of publication, though there may have been corrections, or it may have been reviewed and confirmed after that date, e.g. BS 476-12:1991 is BS 476 Part 12, published 1991, with a corrigendum published in 2014, and it was last reviewed and confirmed 2017.
- iv. For ASTM standards, the number after the hyphen is the year (two digit) it was adopted or last revised. There may be a further letter if it has been revised again in the same year, e.g. ASTM E176 - 18a was revised a second time in 2018.

Table of codes and standards relevant to fire performance

This is not an exhaustive list. Revisions / dates correct at February 2019. Please see notes above.

Publication (confirm / add. date)	Body	Number	Title	Generic	Aero	Auto	Construction	Oil & Gas	Marine	Rail	Defence
2013	BSI	BS EN ISO 75-1:2013	Plastics. Determination of temperature of deflection under load. General test method	Y					Y		
2004	BSI	BS EN ISO 75-3:2004	Plastics. Determination of temperature of deflection under load. High-strength thermosetting laminates and long-fibre-reinforced plastics	Y					Y		
1992 (2003)	BSI	BS AU 169a:1992, ISO 3795:1989	Method for determination of burning behaviour of interior materials for road vehicles, and tractors and machinery for agriculture and forestry			Y					
2008 (2016)	BSI	BS EN ISO 291:2008	Plastics. Standard atmospheres for conditioning and testing	Y		Y		Y		Y	
2004 (2015)	BSI	BS 476-3:2004	Fire tests on building materials and structures. Classification and method of test for external fire exposure to roofs				Y				
1970 (2012)	BSI	BS 476-4:1970	Fire tests on building materials and structures. Non-combustibility test for materials				Y				
1989 (2015)	BSI	BS 476-6:1989+A1:2009	Fire tests on building materials and structures. Method of test for fire propagation for products				Y	Y	Y	Y	Y
1997 (2016)	BSI	BS 476-7:1997	Fire tests on building materials and structures. Method of test to determine the classification of the surface spread of flame of products				Y		Y	Y	Y
2009 (2013)	BSI	BS 476-10:2009	Fire tests on building materials and structures. Guide to the principles, selection, role and application of fire testing and their outputs				Y				
1982 (2017)	BSI	BS 476-11:1982	Fire tests on building materials and structures. Method for assessing the heat emission from building materials				Y				
1991 (2017)	BSI	BS 476-12:1991	Fire tests on building materials and structures. Method of test for ignitability of products by direct flame impingement				Y				

Publication (confirm / add. date)	Body	Number	Title	Generic	Aero	Auto	Construction	Oil & Gas	Marine	Rail	Defence
1987	BSI	BS 476-13:1987, ISO 5657:1986	Fire tests on building materials and structures. Method of measuring the ignitability of products subjected to thermal irradiance				Y				
1987 (2012)	BSI	BS 476-20:1987	Fire tests on building materials and structures. Method for determination of the fire resistance of elements of construction (general principles)				Y	Y			
1987 (2016)	BSI	BS 476-21:1987	Fire tests on building materials and structures. Methods for determination of the fire resistance of loadbearing elements of construction				Y				
1987 (2017)	BSI	BS 476-22:1987	Fire tests on building materials and structures. Method for determination of the fire resistance of non-loadbearing elements of construction				Y				
1987 (2016)	BSI	BS 476-23:1987	Fire tests on building materials and structures. Methods for determination of the contribution of components to the fire resistance of a structure				Y				
1987	BSI	BS 476-24:1987, ISO 6944:1985	Fire tests on building materials and structures. Method for determination of the fire resistance of ventilation ducts				Y				
1983 (2016)	BSI	BS 476-31.1:1983	Fire tests on building materials and structures. Methods for measuring smoke penetration through doorsets and shutter assemblies. Method of measurement under ambient temperature conditions				Y				
1989 (2017)	BSI	BS 476-32:1989	Fire tests on building materials and structures. Guide to full scale fire tests within buildings				Y				
1993	BSI	BS 476-33:1993, ISO 9705:1993	Fire tests on building materials and structures. Full-scale room test for surface products				Y				
2010	BSI	BS EN ISO 1182:2010	Reaction to fire test - Non-combustibility test	Y			Y		Y	Y	
2012	BSI	BS EN 1363-1:2012	Fire resistance tests. General requirements				Y			Y	

Publication (confirm / add. date)	Body	Number	Title	Generic	Aero	Auto	Construction	Oil & Gas	Marine	Rail	Defence
1999 (2018)	BSI	BS EN 1363-2:1999	Fire resistance tests. Alternative and additional procedures				Y			Y	
2015	BSI	BS EN 1364-1:2015	Fire resistance tests for non-loadbearing elements. Walls				Y			Y	
2018	BSI	BS EN 1364-2:2018	Fire resistance tests for non-loadbearing elements. Ceilings				Y			Y	
2012	BSI	BS EN 1365-1:2012	Fire resistance tests for loadbearing elements. Walls				Y				
2014	BSI	BS EN 1365-2:2014	Fire resistance tests for loadbearing elements. Floors and roofs				Y				
2000 (2018)	BSI	BS EN 1365-3:2000	Fire resistance tests for loadbearing elements. Beams				Y				
1999 (2018)	BSI	BS EN 1365-4:1999	Fire resistance tests for loadbearing elements. Columns				Y				
2004 (2018)	BSI	BS EN 1365-5:2004	Fire resistance tests for loadbearing elements. Balconies and walkways				Y				
2004	BSI	BS EN 1365-6:2004	Fire resistance tests for loadbearing elements. Stairs				Y				
2009	BSI	BS EN 1366-3:2009	Fire resistance tests for service installations. Penetration seals				Y				
2006 (2010)	BSI	BS EN 1366-4:2006+A1:2010	Fire resistance tests for service installations. Linear joint seals				Y				
2014 (2018)	BSI	BS EN 1634-1:2014+A1:2018	Fire resistance and smoke control tests for door and shutter assemblies, openable windows and elements of building hardware. Fire resistance test for door and shutter assemblies and openable windows				Y			Y	
2018	BSI	BS EN ISO 1716:2018	Reaction to fire tests for products. Determination of the gross heat of combustion (calorific value)	Y			Y		Y	Y	
2002	BSI	BS EN 1991-1-2:2002	Eurocode 1. Actions on structures. General actions. Actions on structures exposed to fire				Y				

Publication (confirm / add. date)	Body	Number	Title	Generic	Aero	Auto	Construction	Oil & Gas	Marine	Rail	Defence
2006 (2014)	BSI	BS EN 1991-1-7:2006+A1:2014	Eurocode 1. Actions on structures. General actions. Accidental actions				Y				
2015	BSI	BS ISO 2685:1998	Aircraft. Environmental test procedure for airborne equipment. Resistance to fire in designated fire zones		Y						
2011	BSI	BS EN 2824:2011	Aerospace series. Burning behaviour of non-metallic materials under the influence of radiating heat and flames. Determination of smoke density and gas components in the smoke of materials. Test equipment apparatus and media.		Y						
2011	BSI	BS EN 2825:2011	Aerospace series. Burning behaviour of non metallic materials under the influence of radiating heat and flames. Determination of smoke density.		Y						
2005 (2016)	BSI	BS 4422:2005	Fire. Vocabulary	Y							
2017	BSI	BS EN ISO 4589-2:2017	Plastics. Determination of burning behaviour by oxygen index. Ambient-temperature test	Y							Y
2017	BSI	BS EN ISO 4589-3:2017	Plastics. Determination of burning behaviour by oxygen index. Elevated-temperature test	Y							Y
2007	BSI	BS ISO 5658-2:2006+A1:2011	Reaction to fire tests – Spread of Flame – Part 2: Lateral spread on building and transport products in vertical configuration	Y		Y	Y		Y	Y	Y
2001 (2017)	BSI	BS ISO 5658-4:2001	Reaction to fire tests. Spread of flame. Intermediate-scale test of vertical spread of flame with vertically oriented specimen	Y			Y				
2017	BSI	BS EN ISO 5659-2:2017	Plastics, Smoke generation – Part 2: Determination of optical density by a single chamber test	Y	Y		Y		Y	Y	Y
2015	BSI	BS ISO 5660-1:2015	Reaction-to-fire tests. Heat release, smoke production and mass loss rate. Heat release rate (cone calorimeter method) and smoke production rate (dynamic measurement)	Y			Y		Y	Y	

Publication (confirm / add. date)	Body	Number	Title	Generic	Aero	Auto	Construction	Oil & Gas	Marine	Rail	Defence
2004	BSI	BS EN ISO 6941:2003	Textile fabrics. Burning behaviour. Measurement of flame spread properties of vertically oriented specimens	Y		Y					
2015	BSI	BS 8414-1:2015+A1:2017	Fire performance of external cladding systems. Test method for non-loadbearing external cladding systems applied to the masonry face of a building				Y				
2015	BSI	BS 8414-2:2015+A1:2017	Fire performance of external cladding systems. Test method for non-loadbearing external cladding systems fixed to and supported by a structural steel frame				Y				
2001	BSI	BS ISO TR 9705-2:2001	Reaction to fire tests. Full scale room tests for surface products. Technical background and guidance	Y			Y			Y	
2011	BSI	BS EN ISO 11925-2:2011	Reaction to fire tests. Ignitability of products subjected to direct impingement of flame. Single-flame source test	Y			Y			Y	
2014	BSI	BS EN 13381-1:2014	Test methods for determining the contribution to the fire resistance of structural members. Horizontal protective membranes				Y	Y			
2014	BSI	BS EN 13381-2:2014	Test methods for determining the contribution to the fire resistance of structural members. Vertical protective membranes				Y				
2013	BSI	BS EN 13381-4:2013	Test methods for determining the contribution to the fire resistance of structural members. Applied passive protection products to steel members				Y				
2013	BSI	BS EN 13381-8:2013	Test methods for determining the contribution to the fire resistance of structural members. Applied reactive protection to steel members				Y				

Publication (confirm / add. date)	Body	Number	Title	Generic	Aero	Auto	Construction	Oil & Gas	Marine	Rail	Defence
2008 (2016)	BSI	BS ISO 22899-1:2007	Determination of the resistance to jet fires of passive fire protection materials. General requirements					Y			
2009 (2014)	BSI	BS EN ISO 25762:2009	Plastics. Guidance on the assessment of the fire characteristics and fire performance of fibre-reinforced polymer composites	Y			Y				
2013 (2019)	BSI	BS ISO 30021:2013	Plastics. Burning behaviour. Intermediate-scale fire-resistance testing of fibre-reinforced polymer composites	Y			Y				
2013	BSI	BS EN 45545-1:2013	Railway applications. Fire protection on railway vehicles. General.							Y	
2013 (2015)	BSI	BS EN 45545-2:2013+A1:2015	Railway applications. Fire protection on railway vehicles. Requirements for fire behaviour of materials and components.							Y	
2013	BSI	BS EN 45545-3:2013	Railway applications. Fire protection on railway vehicles. Fire resistance requirements for fire barriers							Y	
2013	BSI	BS EN 45545-4:2013	Railway applications. Fire protection on railway vehicles. Fire safety requirements for rolling stock design.							Y	
2018	ASTM	ASTM D635 - 18	Standard test method for rate of burning and/or extent and time of burning of plastics in a horizontal position	Y				Y			
2018	ASTM	ASTM E84 - 18a	Standard test method for surface burning characteristics of building materials.	Y			Y				
2017	ASTM	ASTM E108 - 17	Standard test methods for fire tests of roof coverings.					Y			
2018	ASTM	ASTM E119 - 18ce1	Standard test methods for fire tests of building construction and materials.				Y				

Publication (confirm / add. date)	Body	Number	Title	Generic	Aero	Auto	Construction	Oil & Gas	Marine	Rail	Defence
2016	ASTM	ASTM E162 - 16	Standard test method for surface flammability of materials using a radiant heat energy source.				Y				
2018	ASTM	ASTM E176 - 18a	Standard terminology of fire standards	Y							
2018	ASTM	ASTM E662 - 18	Standard test method for specific optical density of smoke generated by solid materials.	Y			Y				
2016	ASTM	ASTM E1529 - 16e1	Standard test methods for determining effects of large hydrocarbon pool fires on structural members and assemblies					Y			
2018	ASTM	ASTM E2061 - 18	Standard guide for fire hazard assessment of rail transportation vehicles.							Y	
2018	ASTM	ASTM F3059 - 18	Standard specification for fiber-reinforced polymer (FRP) gratings used in marine construction and shipbuilding					Y	Y		
1976 (2016)	ISO	ISO 554:1976	Standard atmosphere for conditioning and/or testing – Specifications	Y					Y		
1999 (2015)	ISO	ISO 834-1:1999	Fire-resistance tests – Elements of building construction, Part 1: General requirements.				Y		Y	Y	
2009	ISO	ISO/TR 834-2:2009	Fire-resistance tests - Elements of building construction. Part 2: Guidance on measuring uniformity of furnace exposure on test samples				Y				
2012	ISO	ISO/TR 834-3:2012	Fire-resistance tests. Elements of building construction. Commentary on test method and guide to the application of the outputs from the fire-resistance test				Y				
2012	ISO	ISO 834-12:2012	Fire resistance tests. Elements of building construction. Specific requirements for separating elements evaluated on less than full scale furnaces								
1997 (2015)	ISO	ISO 5657:1997	Reaction to fire tests -- Ignitability of building products using a radiant heat source.				Y				

Publication (confirm / add. date)	Body	Number	Title	Generic	Aero	Auto	Construction	Oil & Gas	Marine	Rail	Defence
2016	ISO	ISO 9705-1:2016	Reaction to fire tests -- Room corner test for wall and ceiling lining products -- Part 1: Test method for a small room configuration	Y			Y		Y	Y	
2015	ISO	ISO 19702:2015	Guidance for sampling and analysis of toxic gases and vapours in fire effluents using Fourier Transform Infrared (FTIR) spectroscopy	Y					Y		Y
2013	Building regulations	Approved Document B (fire safety)	Building regulation in England covering fire safety matters within and around buildings. Vol 1: dwellinghouses Vol 2: buildings other than dwellinghouses				Y				
2010	EASA	AMC 20-29	Composite Aircraft Structure		Y						
2003 (2017)	EASA	CS-23	Easy Access Rules for Normal, Utility, Aerobatic and Commuter Aeroplanes		1						
2003 (2018)	EASA	CS-25	Easy Access Rules for Large Aeroplanes		1						
2003 (2018)	EASA	CS-27	Easy Access Rules for Small Rotorcraft		Y						
2003 (2018)	EASA	CS-29	Easy Access Rules for Large Rotorcraft		1						
1965 (2019)	FAA	14 CFR Part 25 ("FAR 25")	Airworthiness Standard: Transport Category Airplanes		1						
2009	FAA	AC 20-107B	Composite Aircraft Structure		Y						
2000 (2019)	FAA	DOT/FAA/AR-00/42	Aircraft Materials Fire Test Handbook		Y						
2010	IMO	MSC 307(88) Annex 1	International Code for Application of Fire Test Procedures Part 1 - Non combustibility Part 2 - Smoke and toxicity Part 3 - "A", "B" and "F" class divisions Part 4 - Fire door control systems Part 5 - Surface flammability Part 7 - Vertically supported textiles and films flammability Part 8 - Upholstered furniture Part 9 - Bedding component flammability Part 10 - Fire-restricting materials for high-speed craft Part 11 - Fire-resisting divisions of high-speed craft						Y		

Publication (confirm / add. date)	Body	Number	Title	Generic	Aero	Auto	Construction	Oil & Gas	Marine	Rail	Defence
2010	NATO	AFAP-05 Ed.:3	NATO Reaction-To-Fire Tests for Materials - Heat Release Rate								Y
2006	AFNOR	NF X 70-100-1	Fire tests - Analysis of gaseous effluents - Part 1 : methods for analysing gases stemming from thermal degradation - Essais de comportement au feu	Y						Y	Y
2017	NFPA	NFPA 58	Liquefied petroleum gas code					Y			
2012	NORSOK	NORSOK M-501	Surface preparation and protective coating - Edition 6					Y			
2013	UL	UL 94 edition 6	Standard for tests for flammability of plastic materials for parts in devices and appliances	Y						Y	
2011	UL	UL 263 edition 14	Standard for Fire Tests of Building Construction and Materials	Y			Y	Y			
2017	UL	UL 1709 edition 5	Standard for Rapid Rise Fire Tests of Protection Materials for Structural Steel				Y	Y			
2015	UNECE	ECE Regulation 34, Rev.3	Uniform provisions concerning the approval of vehicles with regard to the prevention of fire risks. Annex 5 - Testing of fuel tanks made of a plastic material.			Y					
2018	UNECE	ECE Regulation 118, Rev.2	Uniform technical prescriptions concerning the burning behaviour and/or the capability to repel fuel or lubricant of materials used in the construction of certain categories of motor vehicles.			Y					