Guideline for the use of FRP in superstructures on passenger ships

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Date : August 2016
Project name : COMPASS – COMposite superstructures for large PASsenger Ships

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DANISH MARITIME AUTHORITY

1 Preface

This guideline was prepared as part of the research project COMPASS which was sponsored by the Danish Maritime Fund (Den Maritime Fond) and the Maritime Reconversion Fund (Den Maritime Omstillingspulje). The project was carried out in a partnership between Danish Institute of Fire and security Technology (DBI) and the Technical University of Denmark (DTU), Department of Civil Engineering and Department of Mechanical Engineering.

The scope of the COMPASS project was to demonstrate how an existing passenger ferry may be refurbished substituting parts of the existing superstructure with polymer composite materials.

The present guideline was requested by the Danish Maritime Authority (Søfartsstyrelsen) as a means in their continuing effort to provide guidance to the maritime industry in Denmark. As such, the content is aimed at authorities as well as naval architects, ship component manufacturers and shipyards.

2 Introduction

Passenger ships and other ships assigned to the SOLAS rules [IMO, 2014] are normally designed with steel as the predominant construction material. This is due to the fact that the prescriptive rules of SOLAS originate from a ship construction tradition where steel was the only applicable material (after the phase-out of timber).

Since 2002 the SOLAS rules have included “Regulation 17” which is the official acceptance of so-called “alternative designs and arrangements” for fire safety. In theory, this would also enable the use of alternative materials like FRP (Fibre Reinforced Polymer) for substitution of steel. Though, in practice it has been challenging for both industry and authorities to adopt. There is a pronounced need for both applicable design tools and practical experience demonstrating that the use of FRP provides a sufficient level of safety and is also economically feasible.

Figure 1 illustrates the strength-to-weight ratio of fibre composites (carbon and glass fibre) compared to steel and aluminium. The potential weight saving is often used as the primary argument for using FRP components since it may potentially reduce the fuel consumption or increase the tonnage. Moreover, polymer composite materials are usually deemed to be more weather resistant than steel, thus reducing the maintenance costs during the lifetime of the component.

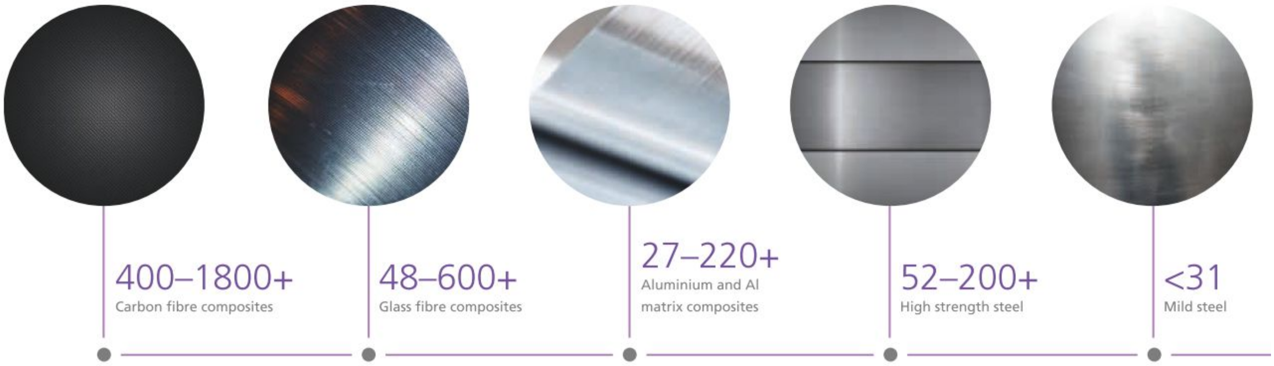

Figure 1: Strenght-to-weight ratio of selected materials (kN*m/kg) [Lloyd's, 2015]

Often the term “FRP” is used a bit misleading as a general term covering a range of components that are only partly made from FRP materials. It should be emphasised that an FRP is basically just a composite made of polymer matrix reinforced with a fibre material (e.g. glass, carbon or aramid) [Wiki, 2016]. For use as, for example, part of the load-bearing structure of a ship, two (or more) layers of FRP materials may be combined with a light and stiff core (e.g. PVC foam or balsa) to produce a relatively strong and light sandwich panel.

To this day there are no superstructures made out of composites on passenger ships or other SOLAS ships partly due to different impeding challenges (Figure 2) but mainly because there has not yet been a real application to provide in praxis proof of the benefits of the proposed concept. This lack of data in turn discourages the ship design stakeholders to adopt novel concepts.

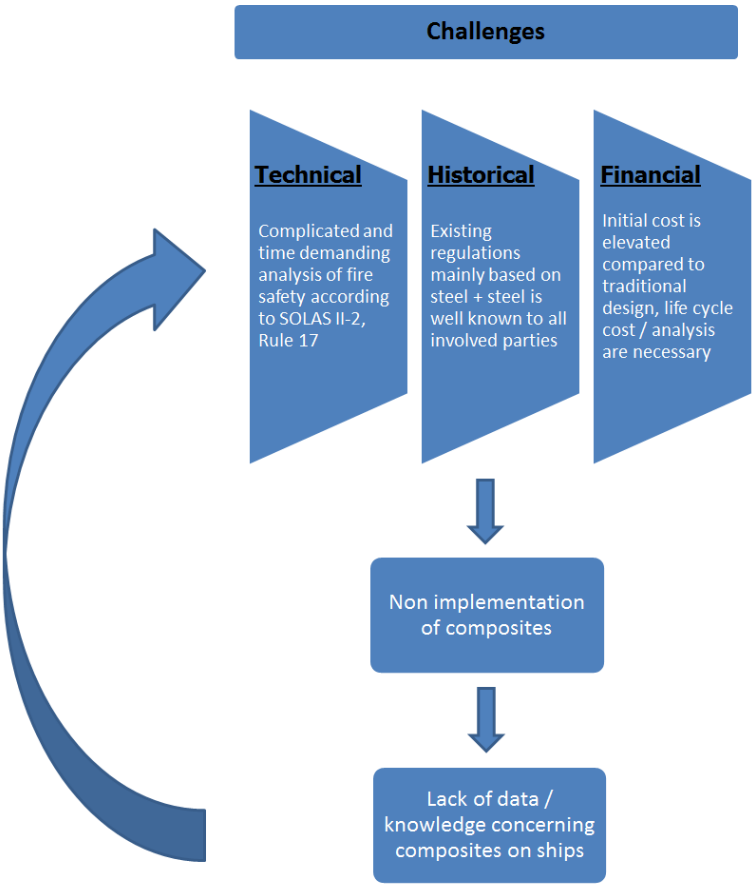

Figure 2: Challenges associated with the implementation of composites on SOLAS ships

The main concern about using FRP in ships is often identified to be the impact on the fire safety of the ship [Lightship, 2015], thus influencing the safety of passengers and crew, safety of the ship and the risk to environment. Construction products based on conventional FRP materials lose their strength at a relatively low temperature compared to steel [Mouritz, 2006], thus making them more sensitive to the high temperatures caused by a fire. Moreover, since the matrix of most commercial FRP materials and the most core materials for sandwich panels are combustible they can potentially contribute to the fire and produce additional smoke. The poor fire properties may to some extent be met by adding a protective layer (e.g. insulating wool or boards). But instead of trying to design "an FRP component with steel properties" the goal should be a more holistic design approach that uses all relevant features of the ship and its fire safety measures. That said, FRP's are not generic materials. Even though they are often combustible, products that are almost non-combustible do exist. This is important to keep in mind when assessing a specific design.

Parallel to the fire safety issue there is also a need for applicable structural solutions where the advantages of FRP materials are utilised while its disadvantages are compensated. Load-bearing and fire separating bulkheads, for example, behave completely different when made with FRP/foam core sandwich panels compared to a conventional steel bulkhead [COMPASS, 2016a]. Also the joints between steel structure and any FRP component are identified as an area where more research is still needed to produce applicable solutions [Lightship, 2015].

A special challenge when switching from prescriptive-based design to performance-based design is that the prescriptive rules are based on "history" and some interpretation of which solutions are "sufficiently safe". The safety level induced by these rules is not quantified. This was acknowledged and expressed in SAFEDOR, a major research project on risk-based ship design:

> "*Compliance with prescriptive regulations implies absolute trust that the minimum safety level implicit in them is deemed to be appropriate for the type of vessel and operation intended; unfortunately this often proves to be conjecture." (*…) "*Knowledge of the actual safety level provision within prescriptive rules is missing*." [Papanikolaou, 2009].

Recently, several research projects have been working with the use of FRP materials for ship construction or more generally on risk-based design of ships. All projects add pieces to the large puzzle of knowledge that is needed before the new material technologies achieve a general acceptance for large passenger ships.

The purpose of this guideline is to give an introduction to the issues which must be addressed when using FRP for ship construction. The Guideline does not provide a complete recipe for the use of FRP SOLAS ship superstructures. More material research and experience with fire safety engineering methods in real ship design is needed before it is possible to produce a streamlined and fully workable "best practice" Guideline.

3 Cost-efficiency when using FRP instead of steel

In this passage an attempt has been made to list the parties involved and the different costs that are associated with the task of designing/retrofitting the superstructure of a ship using composite materials.

It is evident that despite the advantages that composite materials possess, the most important criterion that governs their implementation on commercial shipping is the potential for cost reduction or, alternatively, the potential increase of profit during the ship's life cycle for the majority, if not for all, of the involved stake holders [Job, 2015]. To this end, a detailed life cycle cost and life cycle assessment study has to be performed for the given ship that satisfies the interests of the involved parties and at the same time does not violate the existing design and operational constraints [Stopford, 2009]. This task is crucial and has to be carried out in depth otherwise the risk of having a non-profitable solution or complications during the ship's life cycle increases.

Due to this fact the only available life cycle cost assessments come from feasibility studies conducted under the scope of research projects. Two notable examples of such analyses are the life cycle cost assessment performed for the passenger ship STENA Hollandica and for the Norwegian Gem cruiser. Both analyses have been performed under the scope of the LASS research programs [Evegren, 2011a], [CSC project]. Results indicated that the accumulated cost for the steel version exceeded those of the composite one after only 4 years for the case of STENA Hollandica. For the case of the Norwegian Gem two alternative designs for the superstructure were considered. The first one consisted of adding 86 additional cabins in the superstructure while the second one focused on the reduction of fuel consumption by reducing the draught of the vessel. The results indicated that 2.5 years and 5.9 years were required respectively to reach the break-even point. Unfortunately, only partial data from these assessments are publicly available.

Several of the life cycle costs are influenced or stem from the technical, historical and financial challenges listed in the figure above, both directly and indirectly. An example of an effective life cycle cost scheme is presented below (Figure 3) [Dhillon, 2010]. It must be noted that the designer may perform these steps in sequence, out of sequence or simultaneously as he sees fit. To better understand how cost groups are affected, the major challenges that have been identified are mentioned. For each step only the items applicable to the design/retrofitting of a composite superstructure have been listed.

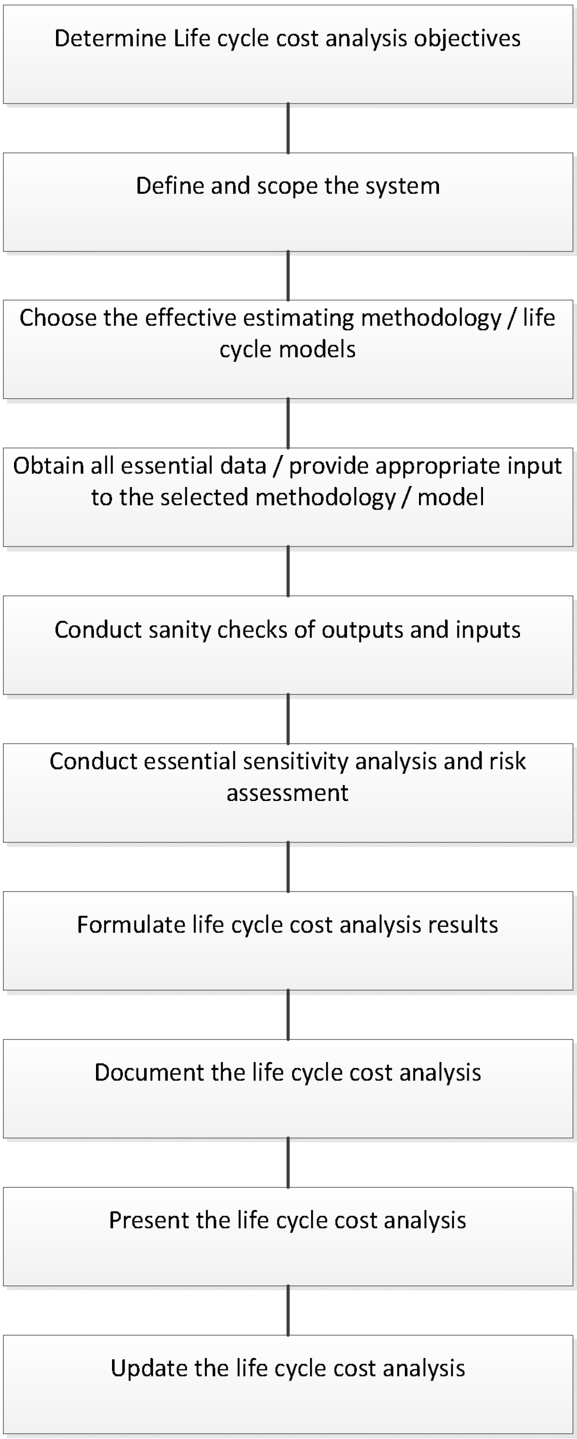

Figure 3: Effective life cycle cost scheme [Dhillon 2010]

3.1.1 Life cycle cost analysis steps

Determine life cycle cost analysis objectives: The first step is to clearly define the purpose of the life cycle cost analysis. For the composite superstructure case the most relevant types of life cycle cost analyses are: comparative analysis i.e. new/retrofitted superstructure versus traditional/existing steel one and LCC estimate i.e. to support decisions and budget requirements

Define and scope the system: This step is crucial for a meaningful LCC analysis and deals with the design constraints and objectives. Typically, due to the complexity of this step, the best approach is considered to carefully assess the similarities and differences of an analogous system. Items that provide to this step are linked to performance parameters (e.g. service range, speed, payload, thrust, etc.), technical parameters (size, engine power, materials, design architecture, etc.) and schedule parameters (conceptual, design production, operating and disposal phases)

Choose the effective estimating methodology / life cycle models: The selection of the methodology / models is dependent on the type of analysis that will be conducted and the system itself, most of the times more than one type of methodology have to be combined to perform the analysis. Some LCC models that are relevant are parametric models and analogous models.

Obtain all essential data / provide appropriate input to the selected methodology / model: This step is challenging as a significant number of data might not be available to the analyst. Moreover, the fact that comprehensive databases do not exist for the majority of parameters associated with the LCC, the analyst will have to rely in word of mouth information which might be erroneous or incomplete.

Conduct sanity checks of outputs and inputs: The analyst needs to assure himself that no fatal inaccuracies or logic flaws exist that would render the analysis useless. To this end the inputs and outputs have to be checked multiple times for consistency, accuracy, validity and completeness.

Conduct essential sensitivity analysis and risk assessment: As the name of the step implies sensitivity analyses are to be performed by changing the range cost estimates. The risk and uncertainty that result from the sensitivity analysis are assessed at the same step

Formulate life cycle cost analysis results: Having defined all necessary prerequisites for the given case the life cycle analysis is performed and the results reviewed and assessed to identify critical factors which drive the LCC.

Update the life cycle cost analysis: Update will be required as the system is further definitized and therefore additional perturbations may be necessary.

3.1.2 Life cycle cost breakdown

The life cycle cost as mentioned earlier can be a very complicated task with several variables that have proven hard, if not impossible, to quantify accurately. Moreover, considering that technological advancements are being made at an exponential rate and that the world economy is more than ever influenced by geopolitical changes and the political agenda, it is obvious that the fields involved in the life cycle cost are far from static but change over time at different rates along with their interdependency and their governing criteria. The main cost groups identified as part of a life cycle cost study are presented and commented below.

Acquisition cost: The acquisition cost is the most evident of all cost groups. This fact has led to the misconception of considering the minimisation of the acquisition cost as the sole criterion for the cost effectiveness of a design. However, this is far from the truth. The acquisition cost includes the following cost groups:

Research: Research of composite materials has increased significantly in the past years and it is expected to increase further in the following years.

Designing: The design of a composite superstructure is more complicated and challenging compared to its steel counterpart; this is partly due to the nature of the materials themselves. However, the main reason that the design is more challenging and time consuming is associated with the fact that the predominantly existing regulations are based on steel and not on composite materials. This, in combination with the fact that there is a general lack of knowledge about composites in different parties in the field, has led to the development of regulations which require very complicated and time demanding analyses in order to be met.

Raw Material: Composite materials are more expensive than steel. The cost related with the acquisition of the raw materials varies with the type of materials and the supplier. However, following the price trends of composites it is expected that the material costs will continue to decrease thanks to the introduction of high-end processes and the new technological developments in resin systems, fibre reinforcements and production methods.

Production: There exists a variety of different production methods for composites, such as hand layup, vacuum bagging, vacuum assisted resin transfer moulding, pultrusion to name but a few. It must be taken into consideration that the production method greatly affects the quality and performance of the end product, and, as expected, the more advanced techniques are the ones that are the costlier as the infrastructure and equipment costs are elevated compared to simpler ones.

Testing: It is expected that the regulatory bodies and the authorities will require an increased number of tests compared to steel structures.

Construction: The costs related with construction are hard to quantify a priori as they are unavoidably tied to the design at hand. Additionally, the level of automation, the existing infrastructure, the experience and the practice followed by the composite manufacturer that will undertake the construction task will greatly affect the construction cost.

Operations costs: The operations costs associated with the composite superstructure are expected to be drastically reduced compared to the traditional steel design. This can be achieved either by reducing the fuel consumption as the composite solution will be lighter but more importantly by increasing the number of passengers on the passenger ship. The ship's stakeholders have to choose the solution that is more profitable for them based on the calculated fuel consumption, the expected oil price change during the ship's service life and the estimated number of passengers that the ship route will serve. In the case of retrofitting there are additional constraints imposed by the original design that should be taken into consideration as for example the design draught, the engine's optimum operational points, the propeller efficiency and others. In the case of new design, it might be possible to further reduce the operational and acquisition costs by optimising the design. Examples of how additional cost reduction can be achieved compared to traditional steel designs might be installing smaller engines than what would be the case for the steel counterpart, decreasing the amount of ballast needed for the stability which reduces maintenance costs and/or optimising the tank space to account for the desired fuel and ballast capacity.

Product distribution cost: Material handling is a key parameter to ensure that the desired performance of composites is reached. Depending on the materials selected, different shelf lives and handling are needed. This may necessitate special infrastructures for the suitable storage of materials and segregated workshops during production where for example the humidity, temperature and level of contamination can be controlled. The transportation costs are once again case dependant and the transportation of the composite parts to the site where the steel construction lies is necessary. However, it is expected that the handling of composite parts will be significantly faster and easier compared to steel ones due to the fact that they are significantly lighter.

Software cost: There is a plethora of different software tools that can be used to optimise the analysis, design, production, operation and monitoring of structures. Modern software already includes composite materials or offer additional plug-ins and support to enable these features in software that were not initially included. The added cost associated with the software acquisition is considered to be minor.

Maintenance cost: The maintenance cost is expected to be reduced compared to the steel superstructure. This is because unlike metals, composite materials are corrosion resistant and exhibit prolonged fatigue life. These attributes are very appealing to ship operators as corrosion and cracking are the most commonly found defects in steel structures.

Test and equipment cost: The equipment required for testing already exists in research centres, so the additional cost for the acquisition of testing equipment will most likely be part of an investment strategy of these centres. The support equipment cost inflicts multiple parties such as consultants, producers and the regulatory bodies for example due to the fact that the material properties, failure mechanisms, damage tolerance and production and inspection method

Training cost: It is expected that all parties involved in the composite superstructure design, production, operation and decommission phases will have to undergo training so that all phases can be carried out efficiently and safely

Technical data cost: By the term “technical data” is meant the technical description of an item adequate for supporting an acquisition strategy, production, and engineering and logistics support. The description defines the required design configuration or performance requirements, and procedures required to ensure adequacy of item performance. It consists of applicable technical data such as models, drawings, associated lists, specifications, standards, patterns, performance requirements, quality assurance provisions etc.

Supply support cost: This group is associated with the spares, the inventory and material support needed for the composite superstructure. Due to the lack of data and what the repair strategy that will be followed is, it is unknown how these compare to the steel superstructure case.

Retirement and disposal cost: Disposal of composite materials has been assumed to be a complicated and expensive procedure. However, the scrapping of one of the Danish standard flex 300 ships has proved that scrapping of a composite ship can be completed fast and with little cost [Hellbratt, 2002]. Additionally, recent technological advances on the field of composites recycling offer the possibility to reuse materials and therefore further decrease the disposal cost by selling the composite part for recycling.

4 The legislative basis

4.1 SOLAS

The most relevant set of regulations and guidelines is as included in the IMO SOLAS Convention (The International Convention for the Safety of Life at Sea) [IMO, 2014].

The SOLAS Convention is entered into force through "Technical Regulation Notice B from the DMA" [DMA, 2011]. Notice B is described in more detail in chapter 4.3.

As relevant for the use of FRP in ship design SOLAS is, among others, applicable for passenger ships engaged on international voyages.

SOLAS consists of a number of chapters with regard to maritime safety. As shortly explained in the following, the use of FRP composites (combustible materials, smoke and toxicity, etc.) will challenge 'Chapter II-2: Construction – Fire protection, fire detection and fire extinction'.

Chapter II-2 provides a set of prescriptive regulations, and certain fire safety objectives and functional requirements are to be met to obtain required fire safety.

A fundamental fire safety concept is to restrict the use of combustible materials and require ships to be built of steel or equivalent non-combustible materials.

Attention is given to the following selected SOLAS definitions:

- *Combustible material* is any material other than a non-combustible material. [Ch. II-2 A, Reg. 3.15]
- *Non-combustible material* is s off flammable vapours in sufficient quantity for self-ignition when heated to approximately 750 °C, this being determined in accordance with the Fire Test Procedures Code. [Ch. II-2 A, Reg. 3.33]
- *Steel or other equivalent material* means any non-combustible material which, by itself or due to insulation provided, has structural and integrity properties equivalent to steel at the end of the applicable exposure to the standard fire test (e.g. aluminium alloy with appropriate insulation). [Ch. II-2 A, Reg. 3.43]

Regarding structural integrity attention is given to the following SOLAS requirements:

- The purpose of this regulation is to maintain structural integrity of the ship, preventing partial or whole collapse of the ship structures due to strength deterioration by heat. For this purpose, material used in the ships' structure shall ensure that the structural integrity is not degraded due to fire. [Ch. II-2 C, Reg. 11.1]
- The hull, superstructures, structural bulkheads, decks and deckhouses shall be constructed of steel or other equivalent material. [Ch. II-2 C, Reg. 11.2]

Fire safety objectives shall be achieved by ensuring compliance with prescriptive requirements, or by alternative design and arrangements.

Chapter II-2, Regulation 17 (Part F) is an option to apply for acceptance of an alternative fire safety design and arrangements.

Alternative design and arrangements are solutions that deviate from the prescriptive requirements of the SOLAS regulations, but are suitable to satisfy the intent of the respective regulations. Such designs and arrangements, defined as ‘equivalent solutions’ in SOLAS I.5, include a wide range of measures, such as alternative shipboard structures and systems based on novel or unique designs, as well as traditional shipboard structures and systems that are installed in alternative arrangements or configurations.

The purpose of regulation 17 is to provide a methodology for alternative design and arrangements for fire safety.

When fire safety design or arrangements deviate from the prescriptive requirements of this chapter, engineering analysis, evaluation and approval of the alternative design and arrangements shall be carried out in accordance with this regulation.

The engineering analysis shall be prepared and submitted to the Administration, based on the guidelines developed by the Organization, and shall include a minimum of elements. The ship type must be determinate, and its prescriptive requirements which will not comply. The required fire safety performance criteria should be identified for the corresponding fire and explosion hazards. And finally, the description of the alternative design with its technical justification should be included.

As Regulation 17 doesn’t focus on the fire safety, a dedicated circular has been published: The MSC/Circ. 1002 which is described later.

Attention is given to the following regarding alternative design and arrangements:

- Fire safety design and arrangements may deviate from the prescriptive requirements set out in parts B, C, D, E or G, provided that the design and arrangements meet the fire safety objectives and the functional requirements. [Ch. II-2 F, Reg. 17.2.1]
- When fire safety design or arrangements deviate from the prescriptive requirements of this chapter, engineering analysis, evaluation and approval of the alternative design and arrangements shall be carried out in accordance with this regulation. [Ch. II-2 F, Reg. 17.2.2]
- The engineering analysis shall demonstrate that the alternative design and arrangements provide an equivalent level of safety to the prescriptive requirements. [Ch. II-2 F, Reg. 17.3]

In addition to the above, attention is also given to the following general option:

- *Equivalents.* Where the present regulations require that a particular fitting, material, appliance or apparatus, or type thereof, shall be fitted or carried in a ship, or that any particular provision shall be made, the Administration may allow any other fitting, material, appliance or apparatus, or type thereof, to be fitted or carried, or any other provision to be made in that ship, if it is satisfied by trail thereof or otherwise that such fitting, material, appliance or apparatus, or type thereof, or provision, is at least as effective as that required by the present regulations. [Ch. I A, Reg. 5(a)]

  Any Administration which so allows, in substitution, a fitting, material, appliance or apparatus, or type thereof, or provision, shall communicate to the Organization particulars thereof together with a report on any trails made and the Organization shall circulate such particulars to other Contracting Governments for the information of their officers. [Ch. I A, Reg. 5(b)]

4.2 IMO Documents

4.2.1 Guidelines on alternative design and arrangements for fire safety

The IMO guideline MSC/Circ.1002 – "Guidelines on alternative design and arrangements for fire safety" [IMO, 2001] provides further guidance on SOLAS Chapter II-2 Regulation 17.
Regulation 17 is giving reference to this guideline which includes how to carry out an engineering analysis.

When an Administration approves alternative design and arrangements for fire safety, this shall be documented and reported to IMO for circulation to the Member Governments.

4.2.2 Guidelines for the approval of alternatives and equivalents as provided for in various IMO instruments

The IMO guideline MSC.1/Circ.1455 – "Guidelines for the approval of alternatives and equivalents as provided for in various IMO instruments" [IMO, 2013] is not only focused on fire safety, but more generally dealing with a structured process on approving alternative and/or equivalent designs.

A complete superstructure in FRP composites will affect other aspects of safety than those related to fire, for which reason this guideline should also be considered in such projects.

When an Administration approves alternative and/or equivalent design, this shall be documented and reported to IMO for circulation to the Member Governments.

4.2.3 Interim guidelines for use of fibre reinforced plastic (FRP) elements within ship structures: Fire safety issues

SDC 2/WP.5 – "Interim guidelines for use of fibre reinforced plastic (FRP) elements within ship structures: Fire safety issues" [IMO, 2015] is an interim IMO guideline and should be used as a supplement to guidelines MSC/Circ.1002 and MSC/Circ.1455. Note that it is a Draft MSC Circular - Preliminary document only.

The guideline is intended to facilitate the safe use of FRP composites in ship building, taken into account the material particularities. The guideline has been developed to provide support for Administrations to ensure that fire safety evaluation of FRP composite structures can be made in a consistent way by any flag State.

4.2.4 FTP Code – International Code for Application of Fire Test Procedures

The FTP Code [IMO, 2012] is applicable for the products which are required to be tested, evaluated and approved in accordance with the FTP Code as referenced in the SOLAS Convention.

The FTP Code provides international requirements for laboratory testing, type approval and fire test procedures for the:

- Non-combustibility test
- Smoke and toxicity test
- Test for "A", "B" and "F" class divisions

- Test for fire door control systems
- Test for surface flammability
- Test for primary deck coverings
- Test for vertically supported textiles and films
- Test for upholstered furniture
- Test for bedding components
- Test for fire-restricting materials for high-speed craft
- Test for fire-restricting divisions of high-speed craft.

4.2.5 FSS Code – International Code for Fire Safety Systems

The FSS Code [IMO, 2000a] is applicable to fire safety systems as referred to in SOLAS Chapter II-2.

The FSS Code details the specifications for items such as:

- International shore connections
- Personnel protection
- Fire extinguishers
- Fixed gas fire-extinguishing systems
- Fixed foam fire-extinguishing systems
- Fixed pressure water-spraying and water mist fire-extinguishing systems
- Automatic sprinkler, fire detection and fire alarm systems
- Fixed fire detection and fire alarm systems
- Sample extraction smoke detection systems
- Low-location lighting systems
- Fixed emergency fire pumps
- Arrangement of means of escape
- Fixed deck foam systems
- Inert gas systems
- Fixed hydrocarbon gas detection system.

4.3 EU Directive / Notice D from the DMA

Regarding passenger vessels engaged on domestic voyages the relevant set of regulations and guidelines is as included in the DIRECTIVE 2009/45/EC – on safety rules and standards for passenger ships.

The Directive is entered into force through "Technical Regulation Notice D from the DMA" [DMA, 2011].

With reference to *'Article 3(2)(a)(iii)'* the Directive does not apply to: Vessels constructed in materials other than steel or equivalent.

It is not the intention of the Directive to allow whole vessels or larger parts of a vessel to be constructed in materials other than steel or equivalent.
However, the Directive includes an option to apply for acceptance of an alternative design and arrangements with specific reference to SOLAS Chapter II-2 Part F (Regulation 17).

Attention is given to the following:

- The fire safety objectives must be achieved by ensuring compliance with the prescriptive requirements specified in this chapter or by alternative design and arrangements which comply with Part F of the revised Chapter II-2 of SOLAS 1974. [Ch. II-2 A, Reg. 1.3]

In addition to the above attention is also given to the following general option:

- *Equivalents.* Where the present regulations require that a particular fitting, material, appliance or apparatus, or type thereof, shall be fitted or carried in a ship, or that any particular provision shall be made, the Administration of the flag State may allow any other fitting, material, appliance or apparatus, or type thereof, to be fitted or carried, or any other provision to be made in that ship, if it is satisfied by trail thereof or otherwise that such fitting, material, appliance or apparatus, or type thereof, or provision, is at least as effective as that required by the present regulations, and that it is, furthermore, acceptable to the government of the host States that the ship intends to visit. [Ch. I, Reg. 8.4]

  Any such equivalent shall be handled as stated in the Directive, e.g. notification of the Commission.

  Within six months from the notification, the Commission will decide on whether the equivalent is acceptable or not.

4.4 Evacuation management at sea

Evacuation management is an important tool when an alternative design or arrangement is to be implemented in a ship design. In case of fire (or collision, grounding, etc.) the incident may develop to a scenario where the ship has to be abandoned.

Like regarding "fire safety", the most relevant set of regulations and guidelines covering an evacuation situation is as included in SOLAS.

General attention is given to Chapter II-2 (Part D - Escape and Part E - Operational requirements) and Chapter III (Life-saving).

The requirements for arrangement of a ship and the requirements for qualifications of the crew are quite comprehensive. The following should only be considered as a very simplified description with regard to evacuation of a passenger ship.

Notification

- In case of a "situation" the crew and passengers are to be notified. This requires the arrangement of a general emergency alarm system (GA) and a public address system (PA).
- Means shall be provided for two-way communication between emergency control stations, muster and embarkation stations and strategic positions on board.

Means of escape

- Safe escape routes shall be provided. Normally, at least two widely separated and ready means of escape shall be provided from all spaces or groups of spaces.

- In the design process of a ship, escape routes shall be evaluated by an evacuation analysis.

Muster and embarkation

- Muster and embarkation stations shall be provided. Muster and embarkation stations shall be readily accessible from accommodation and work areas.
- The sounding of the general alarm is the signal for summoning passengers and crew to muster stations. At the muster stations the crew can assist and give instructions and safety briefings to the passengers.
- From the muster stations the passengers and crew can continue to embarkation stations and board relevant lifeboats or life crafts and leave the ship.

Operational readiness

- There shall be a sufficient number of trained persons on board for mustering and assisting untrained persons.
- Each passenger ship shall have procedures in place for locating and rescuing passengers trapped in their staterooms.
- Muster list and emergency instructions shall be prepared. The muster list shall include the duties assigned to members of the crew in relation to passengers in case of emergency, e.g. keeping order in the passageways and on the stairways.

Qualifications, training and drills

- On-board training and drills (e.g. fire drills and abandon ship drill) to take place. Every crew member with assigned emergency duties shall be familiar with these duties before a voyage begins.
- A training manual shall be provided in each crew mess room and recreation room or in each crew cabin.
- Crew to be qualified in compliance with the STCW Convention [IMO, 1978]. This includes specific training requirements, such as training in crew management.

Decision support system

- A decision support system (for masters of passenger ships) for emergency management shall be provided on the navigation bridge.

Life-saving appliances

- All life-saving appliances and arrangements shall comply with the applicable requirements of the LSA Code [IMO, 1996].

5 Fire Safety Engineering in ship design

5.1 The basics of Fire safety engineering

In recent years, steps have been taken by some IMO member states to gain acceptance of so-called "alternative designs" for ships which are assigned to the SOLAS rules. Alternative designs are designs which to some extent deviate from the prescriptive requirements defined in SOLAS and the legislative basis as defined in chapter II-2, regulation 17 (hereafter denoted "Regulation 17").

The general principle of justification of a fire safety design by qualitative or quantitative evaluation is usually referred to as "Fire Safety Engineering" (FSE). The discipline has developed for land-based structures in the past 30 years and has been accepted by the industry in many countries all over the world. There are deviations from one country to another on how to perform an FSE but there is consensus that a full FSE is basically about proving that the Required Safe Egress Time (RSET) is shorter than the Available Safe Egress Time (ASET).

An FSE analysis may be performed as a "full FSE" analysis or a "comparative" analysis depending on the identified risks and overall goal. This is described more thoroughly in chapter 5.4.

As illustrated in Figure 4, the choice between different analysis tools should be based on a qualitative evaluation of the complexity and novelty of the specific ship design.

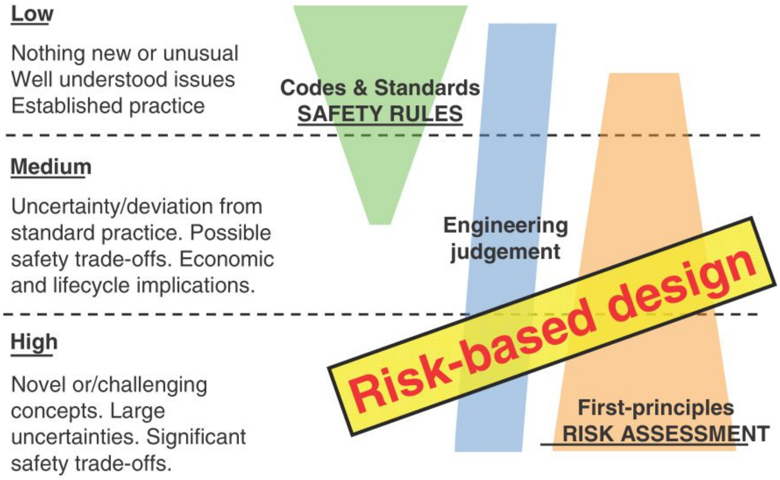

Figure 4: Risk based design and innovation [Papanikolaou, 2009]

The FSE tools which are used for land-based structures are generally based on generic physics, chemistry and fluid dynamics. The same tools may be used for fire safety evaluation of a ship design. Off course, attention must be given to all input parameters and if empirical models are used it must be checked whether all limitations of the model are met. Certain aspects associated with land based structures and how these could be adapted for FSE of SOLAS vessels are given in the following.

RSET is usually the time required to evacuate the building. The evacuation time is the sum of warning time, reaction time, decision time and moving time (walking and queuing). The moving time may be calculated by using simple back-of-the-envelope calculations or by using advanced computer models where the interaction between individuals is taken into account.

Establishing the evacuation time for individuals on a ship is a bit more complicated than from a land-based structure since they cannot just walk out of a door at ground level to be safe.

Two methods to analyse the evacuation time are described in MSC.1/Circ.1238 "Guidelines for evacuation analysis for new and existing passenger ships" [IMO, 2007a]; 1) a simplified evacuation analysis and 2) an advanced evacuation analysis. It is noted that the choice between the simplified and the advanced method is governed by the complexity of the vessel.

ASET is the time at which conditions (smoke, heat etc.) in the building become harmful to individuals without sufficient protection. The development of a fire and the movement of smoke may be estimated with various numerical tools. The rather complicated geometry in large passenger ships (e.g. long corridors and openings between decks) probably requires the use of advanced CFD (Computational Fluid Dynamics) models.

The timelines of ASET and RSET are illustrated in Figure 5.

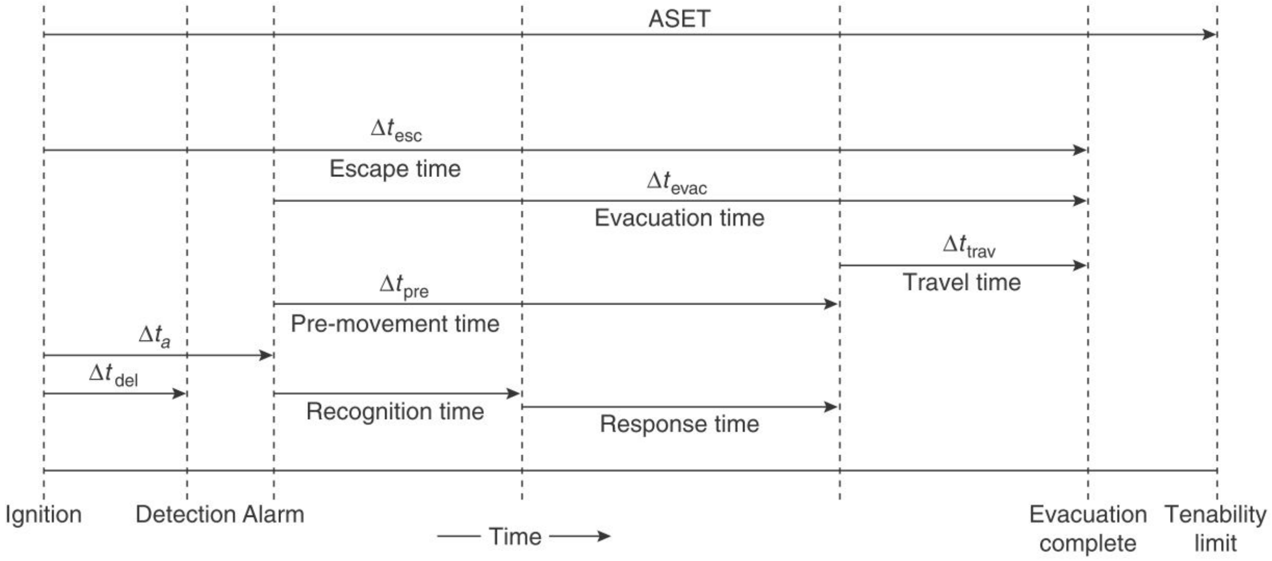

Figure 5: Time line for RSET (denoted "Escape time") and ASET [Fire Protection Handbook, 20th edition, NFPA, 2008]

Before an FSE analysis is performed the design team must initially determine the failure criteria. In relation to ASET the failure criteria are often a set of tenability limits, that is, conditions related to visibility, temperature, radiation etc. which are harmful to individuals. Failure criteria may also be associated with the safety of rescue personnel or damages to the environment or to ship structures. Off course, damages to ship structures may have an impact on the other criteria.

In principle, an FSE analysis is a holistic evaluation where all aspects of the specific structure are taken into account. This approach is difficult to deal with for the manufacturers of ship components since their production lines are very industrialised and optimised which means they can probably not make significant changes to their products from one ship project to another. Moreover, they may not even know the entire ship design upon production. Development of standardised products which are pre-accepted for a whole category of vessels may be the only profitable way to supply components for the ship yards.

In order to make Regulation 17 practically and economically useful for commercial use in the ship construction industry, a modular approach must be developed and accepted. This may be done by identifying a set of relevant parameters which needs to be documented for a certain component (not limited to fire properties). Then, the designer will be able to build a vessel by adding the modular components and add its parameters to the overall analysis of fire safety, stability, manoeuvrability etc. The process may require that all prescriptive requirements are eliminated.

5.2 Risk based design

As previously described, the IMO document MSC/Circ. 1455 should be used for the design and approval process of alternative designs or arrangements (that is, design or arrangements which deviate from the prescriptive solutions). The document calls for a comprehensive risk assessment but does not give any suggestions on how to perform the risk assessment. Nor does it provide any risk evaluation criteria, e.g. "acceptable loss of human lives per ship year". The document only suggests a framework for the corporation between stakeholders and the exchange of information between design team and approval body. Therefore, specific tools and acceptance criteria must be found elsewhere.

The research project SAFEDOR which was finalised in 2009 carried out an extensive work on risk based design and operation of ships. The project developed tools and methods for the design process and provided worked case examples. A regulatory framework was also suggested which was later adopted by IMO as MSC/Circ. 1455.

The present sub-chapter is mainly based on the work from SAFEDOR.

The SAFEDOR project used the following definition of Risk Based Design (RBD) [Papanikolaou, 2009]:

> *RBD is a formalised methodology that integrates systematically risk assessment in the design process with prevention/reduction of risk embedded as a design objective, alongside "conventional" design objectives.*

With "risk" being a new design objective, a new scope is added to the design process:

$R_{Design} \leq R_{Acceptable}$

R_{Design} is the risk associated with the considered ship or system. The three predominant hazards are fire, flooding and collision. Consequences are associated to the passengers/crew, to the ship or to the environment.
$R_{Acceptable}$ is the acceptable risk level defined as either an absolute risk or a relative risk.

An "absolute risk level" is defined by IMO risk acceptance criteria.

A "relative risk level" is defined by a reference design based on the prescriptive regulations. The use of a relative risk level is often referred to as "comparative analysis" where the design objective is to achieve "safety equivalence".

The difference between absolute risk (full FSE analysis) and relative risk evaluation (comparative approach) is described in chapter 5.4.

In order to determine the risk level for a specific ship design, an analysis may be done where the Fire Safety Engineering methodology is combined with probabilistic methods to examine variations of input parameters and failure scenarios.

The ultimate result of an analysis may be a theoretical number of fatalities per year in service. Whether or not the calculated risk level is acceptable is basically a political matter. A suggestion for acceptance criteria is given by IMO in MSC 83/INF.2 (see Table 1).

Decision parameter		Acceptance criteria	
		Lower bound for ALARP region	Upper bound for ALARP region
		Negligible (broadly acceptable) fatality risk per year	Maximum tolerable fatality risk per year
Individual risk	to crew member	10^{-6}	10^{-3}
	to passenger	10^{-6}	10^{-4}
	to third parties, member of public ashore	10^{-6}	10^{-4}
	target values for new ships	10^{-6}	Above values to be reduced by one order of magnitude
Societal risk	To groups of above persons	To be derived by using economic parameters as per MSC 72/16	

Table 1: Quantitative risk evaluation upper and lower bounds. Reproduced from [IMO, 2007b]

The acceptance criteria in Table 1 are defined as a lower bound and an upper bound for the "ALARP region". ALARP (As Low As Reasonably Practicable) is a commonly used approach to evaluate whether a specific risk level is sufficiently low. Often, the bounds are presented in an F-N diagram as illustrated in Figure 6.

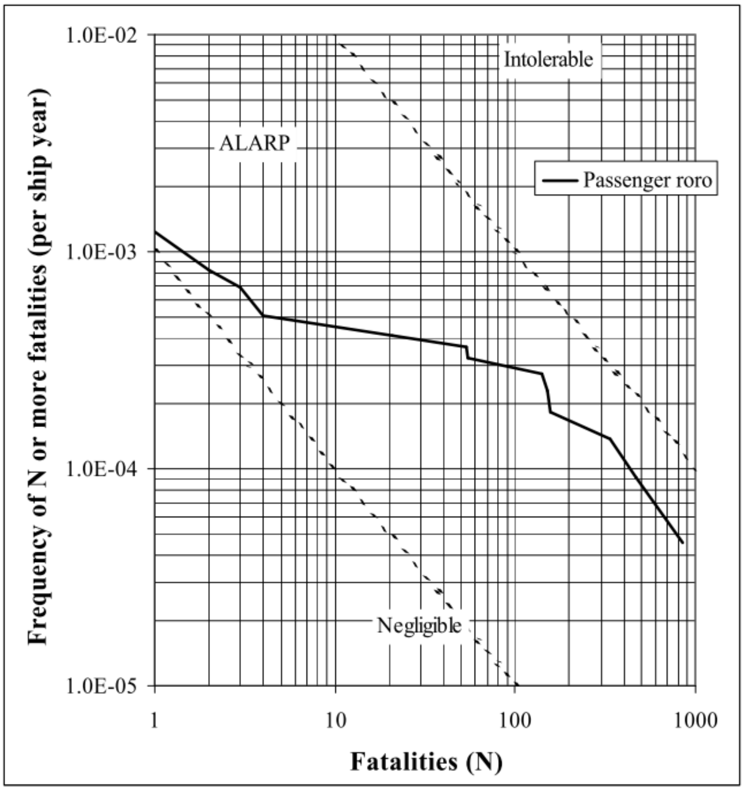

Figure 6: Historic F-N diagram for passenger ro/ro ships, shown together with risk acceptance criteria. Data from 1989-1998. (Data source: LMIS). [IMO, 2000b]

It can be argued, however, that the F -N diagram does not reflect the fact that society is more likely to accept a high number of incidents with a low number of fatalities compared to a low number of incidents with a high number of incidents, which might need to be taken into account. Therefore, the design team should consider lowering the bounds for fatalities above 10.

5.3 Alternative Design and Arrangements

5.3.1 Guidelines on alternative design and arrangements for fire safety (MSC/Circ. 1002)

The engineering analysis used to show that the alternative design and arrangements provide the equivalent level of safety to the prescriptive requirements of SOLAS chapter II-2, should follow an established approach to fire safety design. [IMO, 2001] *states that "This approach should be based on sound fire science and engineering practice incorporating widely accepted methods, empirical data, calculations, correlations and computer models as contained in engineering textbooks and technical literature."*

"A design team acceptable to the Administration should be established by the owner, builder or designer and may include, as the alternative design and arrangements demand, a representative of the owner, builder or designer, and experts having the necessary knowledge and experience in fire safety, design, and/or operation as necessary for the specific evaluation at hand.

"The design team should conduct a preliminary analysis to develop the conceptual design in qualitative terms. This includes a clear definition of the scope of the alternative design and arrangements and the regulations which affect the design but also a clear understanding of the objectives and functional requirements of the regulations and the development of fire scenarios, and trial alternative designs." [IMO, 2001]

After the design in qualitative terms, a quantitative analysis should be done in order to evaluate possible trial alternative designs using quantitative engineering analysis. This consists of the specification of design fires, development of performance criteria based upon the performance of an acceptable prescriptive design and evaluation of the trial alternative designs against the agreed performance criteria. From this step the final alternative design and arrangements are selected and the entire quantitative analysis is documented in a report.

5.3.1.1 Preliminary analysis in qualitative terms

The preliminary analysis firstly consists of the development of fire scenarios. This process can be broken down into four areas. The first step is the identification of fire hazards (ignition sources, contact with potential fuels, initial fuels, secondary fuels, extension potential, target locations, critical factors and relevant statistical data). The second step is the enumeration of fire hazards, grouped in three incident classes: localised, major, or catastrophic. From this, a selection process should identify a range of incidents which cover the largest and most probable range of enumerated fire hazards. During this third step, a demonstration of equivalent performance during the major incidents should adequately demonstrate the design's equivalence for all lesser incidents and provide the commensurate level of safety. The last step is the specification of design fire scenarios including a qualitative description of the design fire (e.g., ignition source, fuel first ignited, location, etc.), description of the vessel, compartment of origin, fire protection systems installed, number of occupants, physical and mental status of occupants, and available means of escape.

At this point in the analysis, one or more trial alternative designs should be developed so that it can be compared against the developed performance criteria.

The key results of the preliminary analysis should include a secured agreement from all parties to the design objectives and engineering evaluation, specified design fire scenario acceptable to all parties and a trial alternative design acceptable to all parties.

5.3.1.2 Quantitative analysis

For each of the identified fire hazards, a range of fire scenarios should be developed. Because the alternative design approach is based on a comparison against the regulatory prescribed design, the quantification can often be simplified. In certain cases, live fire testing and experimentation may be necessary to properly predict the fire characteristics.

The required performances of the trial alternative designs are specified numerically in the form of performance criteria.

These performance criteria could fall within one or more of the following areas:

- Life safety criteria
- Criteria for damage to ship structure and related systems
- Criteria for damage to the environment

Each selected trial alternative design should be analysed against the selected design fire scenarios to demonstrate that it meets the performance criteria with the agreed safety margin, which in turn demonstrates equivalence to the prescriptive design.

The final alternative design and arrangements should be selected from the trial alternative designs that meet the selected performance criteria and safety margins.

5.4 Comparative study vs. full FSE analysis

Since the revision of the SOLAS Convention relating to fire safety in 2002, various projects have been conducted to study the options for applying Regulation 17 "Alternative design and arrangements" of Ch. II-2.

Several approaches have emerged, with the following as the main ones:

A. "Comparative study": An approach that aims to stay as close as possible to the prescriptive regulations by making conservative equivalences in terms of passive protection compared to an equivalent prescriptive design. The goal is to achieve a level of safety similar to a prescriptive steel design. The analysis may be limited to a component level. For more information the reader is referred to [Evegren, 2011b].

B. "Full fire safety engineering (FSE) analysis": An approach that aims to adapt the protection to the level of risk in a given compartment, combining both active and passive protection. The goal is to achieve a sufficient level of safety. Since no absolute sufficient risk level is defined in SOLAS (e.g. no. of deaths/hours of service), the risk level must be agreed upon with the authorities prior to the analysis. For more information the reader is referred to [Gutierrez, 2013]. Until an official absolute risk level is decided in IMO, the risk level of a prescriptive ship design may be used as the safety level that is deemed to be sufficient.

As both approaches have been developed in the sense of the Regulation 17 - Ch. II-2 of the SOLAS, they follow its requirements but some differences should be noticed.

During the preliminary analysis in qualitative terms, the considered alternative design is basically different. Indeed, in the case of the comparative study, even if an FRD60 construction does not achieve the requirement on non-combustibility it may fulfil the SOLAS requirements on fire resistance for an A-60 division. Whereas in the case of the FSE analysis, the SOLAS requirements on fire resistance for an A-60 division might not be fulfilled, but the FSE analysis may show that the level of fire safety of the alternative design is at least as effective as the prescriptive design when all aspects of the ship's fire safety is taken into account.

The other noticeable difference is during the analysis in quantitative terms. During the step called "Estimation of the fire risk on the alternative design", the comparative study is almost the same than during the estimation of the fire risk on the prescriptive design (the additional work is taking into account the effects of the smoke for the evacuation).

In the case of the FSE analysis, the work is much heavier. For instance, a series of fire scenarios may be evaluated (e.g. by numerical modelling), while ensuring that the Computational Fluid Dynamic software has been validated.

The following diagram shows the main difference between the two different approaches.

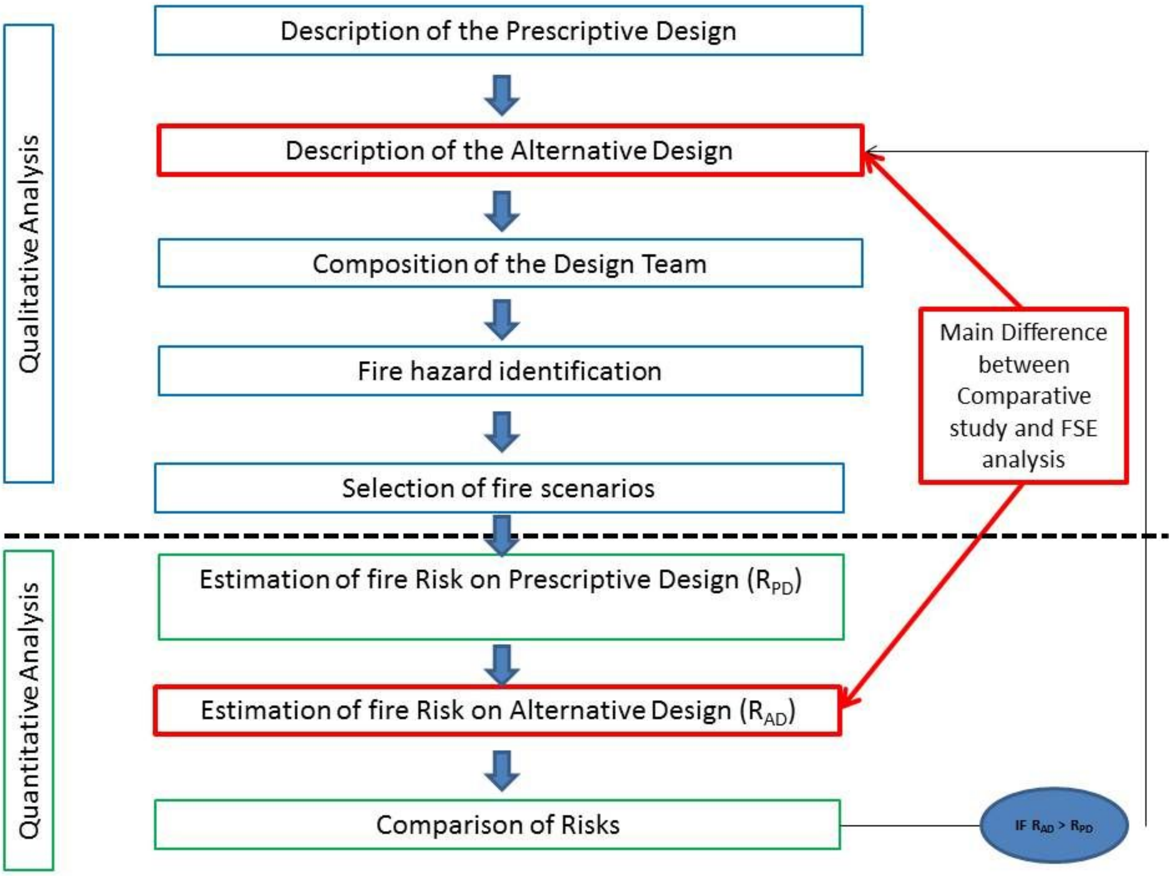

Figure 7: Procedure of the regulation 17 of the SOLAS convention

To explain the main difference between the comparative study and the FSE analysis, the following figure shows the example of the procedure of Regulation 17 analysis for a bulkhead.

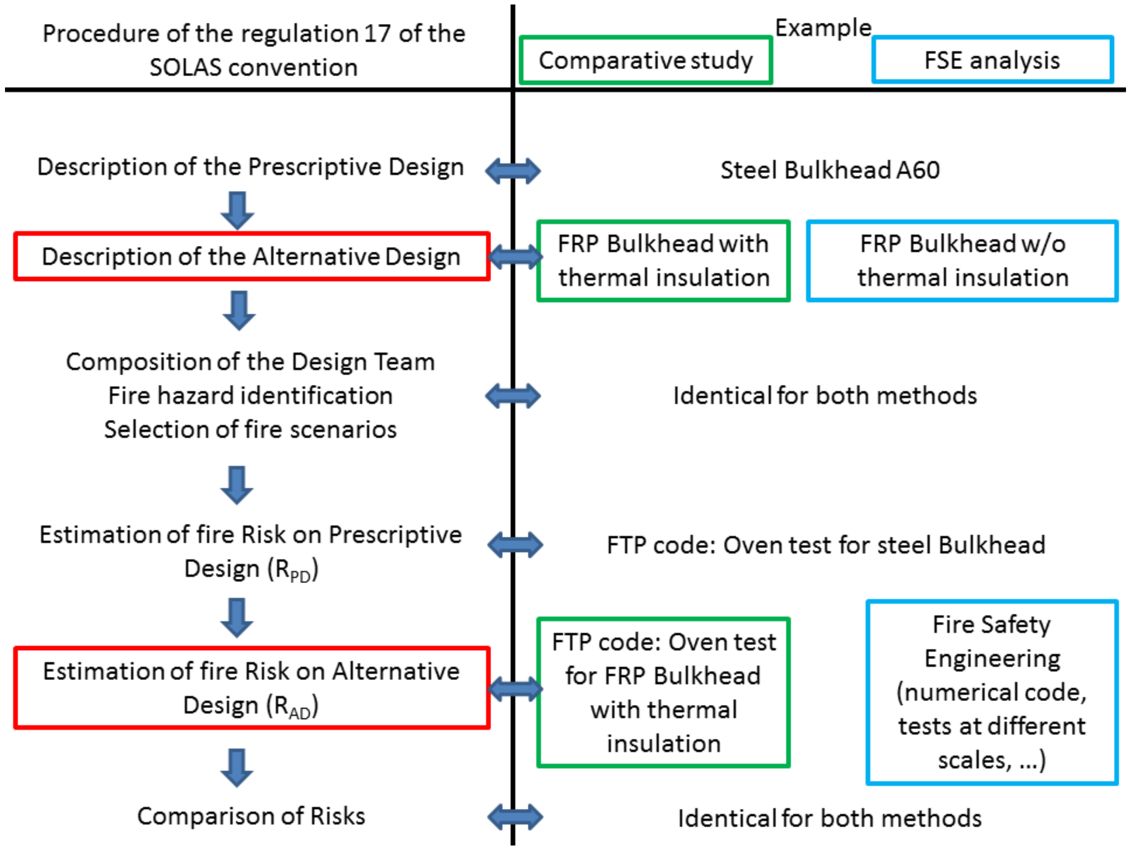

Figure 8: Comparison of the application of the procedure of the regulation 17 of the SOLAS convention for a bulkhead, following both methods: Comparative study and FSE analysis.

The following table shows the Pros and Cons of the two different approaches described in the first paragraph.

	Pros	**Cons**
Comparative study	• Approach is relatively simple • The task is reduced to a well-known prescriptive case • Sufficient to conduct tests in order to verify that the new criteria are fully complied with • May be limited to component analysis	• Principle of equivalence adopted should be conservative • If too conservative, there are too many opportunities to penalize composite construction compared to steel, by applying protection that is not actually necessary in all cases (will add to the cost and weight of the structure and reduce the benefit of using composites.)
FSE analysis	• Potentially reduce the cost and weight of the protection to be used by matching it to the level of risk • Increased freedom of design	• The risk acceptance level is not yet pre-defined and must be agreed upon with the authorities prior to the analysis • It is often necessary to include the entire system (ship) – or subsystem – in the analysis which makes the analysis complicated and time consuming • More difficult to implement in the beginning of the design process

Table 2: Pros and cons of the two main approaches of the application of the Regulation 17

6 Fire safety issues related to FRP

The most concerning issue when it comes to introducing polymer composite materials in SOLAS ships is their behaviour in the case of fire as, unlike metals, composites are combustible and at temperatures above 300-400 °C they will ignite and if no actions are taken they will eventually burn. In addition, most matrix types used in FRP composites soften in moderate temperatures (100-200 °C) which greatly affects the matrix dominated mechanical properties and the structural integrity. Therefore, in reality, the safe operating temperature range is defined by the softening temperature and not the ignition temperature.

Much effort has been devoted to studying the fire behaviour of composites and significant advancements have been made in understanding and improving their performance. This has led to the development of novel material systems, manufacturing and design methods throughout the years to better suit the desired performance criteria. Still, despite recent advancements there are several questions left unanswered and the experience gained from real field applications fall short compared to metallic materials that have been extensively used since the 19th century in industrial applications.

The sentence "behaviour in the case of fire" is used to describe the sum of all related aspects of composite materials both during and after a fire incident; these aspects can be categorized as follows.

Obviously, it is not possible to design a certain FRP component with the exact same properties as a similar steel component. If steel and FRP should be compared at all, it is important to identify exactly which properties of the steel component is vital for the specific use and hence should be implemented in the FRP component. To prove an equivalent level of safety – for the selected relevant criteria – it is necessary to consider the component as part of a "system". Not as single separated materials.

Reaction to fire
This aspect affects the early stages of fire (from the ignition to the flashover point) and deals with the flammability and combustion properties of the materials, important properties that fall in this category are the smoke toxicity, the heat release rate, time to ignition, flame spread and oxygen index.

Fire resistance
This defines the ability of a component/structure to contain the fire and prevent further spreading of the fire in adjacent areas as well as the ability to retain the structural integrity in the case of fire. Heat insulation, burn through resistance and the structural performance, during and post fire, are part of the fire resistance.

This guideline does not thoroughly address all aspects of fire safety related to the use of FRP materials (e.g. smoke toxicity). The main focus is on the structural properties of composites in fire and the expected structural performance of composite components.

6.1 Reaction to fire

"Reaction to fire" is a term which is traditionally used to express how much a given construction product contributes with energy to a fire and how much smoke it produces. The energy contribution from surfaces is a critical factor in the development of a fire and has an impact on the magnitude of the fire. Smoke production affects evacuating individuals and rescue personnel by reduced visibility and by exposure of toxic substances. Therefore, reaction to fire of construction products is regulated in the prescriptive codes for both land-based structures and ships.

As opposed to steel, FRP products are combustible and thereby release energy when exposed to heat. That stated, FRP is not a generic product group and the reaction to fire properties may differ significantly from one product to another.

Requirements on reaction to fire are first of all associated with the internal and external surfaces which are directly exposed to heat in the early stages of a fire. In some applications, also load-bearing structures are assigned to requirements on reaction to fire even though they may be protected by non-combustible fire protection systems. The three applications – internal surfaces, external surfaces and load-bearing structures – are described separately below.

6.1.1 Internal surfaces

Development of a fire in a room is mainly controlled by ventilation conditions (supply of fresh air) and the amount of accessible combustible materials in surrounding structures (linings on walls, floors and roofs) and interior (furniture and stock).

Especially internal linings are traditionally deemed to have a significant impact on the time from ignition to flashover in a room is reached. Therefore, the prescriptive requirements – for both ships and land-based structures – restrict the energy contribution from linings.

The use of FRP sandwich panels in ships will most likely require the use of passive fire protection. Therefore, there may not be any FRP panels which are directly exposed to fire in a room. FRP protected with a passive fire protection system will of course be exposed to heat in case of a long-lasting fire but will not contribute in the initial stages where evacuation is taking place.

At a certain stage in the fire development, the passive fire protection will fail either when the heat has conducted through the materials or because the system simply collapses. By then, the FRP panel will be exposed to critical temperatures which will lead to the release of energy and smoke. If properly accounted for in the fire safety strategy it may not be critical to the safety of passengers and staff since the area on fire is no longer in use for evacuation.

Further research and development may make it possible – from a structural point of view – to design a passenger ship with non-protected FRP panels for internal surfaces. In that case, it is probably necessary to restrict the energy and smoke contribution from the surface of the FRP panel by choosing materials (matrix, fibre, and core) with limited combustibility.

6.1.2 External surfaces

The non-corrosive properties of FRPs make them an attractive alternative for the external components of a ship where salty water and shifting weather conditions call for regular painting of steel parts. But if a design includes FRPs, which are directly exposed in case of fire, much care must be taken when assessing the impact on the fire safety.

When a fire develops inside a ship structure it may at some point reach a stage where it emerges from the windows and thereby exposes the external components of the ship to heat and flames. If combustible materials are used for the external surfaces there is a risk of ignition and self-sustained external fire spreading on the surfaces. This may pose a risk of both vertical and horizontal fire spread between different fire compartments in the ship. Moreover, it may expose evacuees assembling at outer decks to heat and smoke.

The fire properties of an FRP (and core materials if sandwich panels are used) may be improved to some extent by adding different flame retardants to the polymer matrix and by using non-combustible fibres. Though, depending on the attained fire properties and the extent of FRP, it may be necessary to apply a fire protection system to the external FRP components of the ship.

Fire protection systems are traditionally categorised as either "passive" or "active".

Passive systems include measures where the FRP is covered with non-combustible insulation or boards with a certain fire resistance. It may also be intumescent paintings which swell and create an insulating layer when heated.

Active systems may be drenchers (water sprinklers) applied to the external surfaces of the ship.

Research from SP has shown that selected passive and active protection systems are both able to prevent self-sustained flaming along the FRP surface [Evegren, 2016]. Before any protection system is applied to a ship, the system must be tested with a fire exposure that is comparable to the exposure from an expected real fire.

Of course, it must be considered whether the selected protection system is capable of resisting the harsh conditions from salty water and weathering.

6.1.3 Load-bearing structures

The reaction to fire properties of load-bearing structures is not directly connected to the "resistance to fire properties" of the structure. That is, a non-combustible panel may have a low resistance to fire. On the other hand, a combustible panel may have a high resistance to fire.

It may be argued that sufficient reaction and resistance to fire of a given component may both be achieved by protecting the component with a passive fire protection system. Though, using non-combustible materials may under the right circumstances build extra robustness into the load-bearing structures.

Recent large-scale fire tests have indicated that the combustible materials of an FRP bulkhead will not ignite if the bulkhead is protected with non-combustible fire insulation to obtain 60 minutes fire resistance [COMPASS, 2016a].

6.2 Resistance to fire

Fire resistance is a general term that usually covers three different fire properties; structural stability, heat insulation and integrity (flames, hot air, smoke). When evaluating the use of a certain component as part of a ship design it is important to be aware of the difference between the three properties.

In land-based structures it is normal procedure to evaluate and prescribe structural stability separately from insulation and integrity. For example, a building may have a requirement of 120 minutes structural stability in case of fire while the fire divisions only have a 60 minutes requirement for insulation and integrity. And, if columns are used as part of the load-bearing structure, there will probably be a requirement on structural stability while requirements on insulation and integrity are not relevant.

In SOLAS and the FTP Code there is no distinction between structural stability, insulation and integrity in case of fire. Components are always tested as fire divisions only. Both A-class and B-class divisions are evaluated by measuring the temperature rise and observing any flaming on the non-exposed side when exposed to the standard fire curve. There are no separate criteria for components that are only load-bearing. Though, there is a requirement in the FTP Code, annex 1, part 3, ch. 3.3, that the structural core of load-bearing divisions of aluminium alloy shall not have an average temperature rise of more than 200 °C. Moreover, it is stated that the Administration shall decide the allowed temperature rise if the structural core is other than steel and aluminium alloy.

The decision not to have a requirement for the structural core of steel divisions is probably based on an assumption that the temperature of the core will not reach a level where the steel loses strength as long as the average temperature rise on the non-exposed side is below 140 °C which is the criterion for both A-class and B-class divisions.

The prescriptive requirements in SOLAS are based on a maximum of 60 minutes fire resistance. Tests have proved that 60 minutes fire resistance is possible to achieve for a loaded FRP sandwich bulkhead simply by applying a sufficient layer of fire insulation on the exposed side [COMPASS, 2016a].

An important question that has been raised by certain IMO member states during the discussion about introducing FRP on board SOLAS ships is; what happens when the fire lasts for much more than 60 minutes?

The fire at the Norman Atlantic in 2015 is an example of how a fire may run out of control while the weather conditions make evacuation of passengers and crew almost impossible. Even though the fire was raging throughout the inside of the ship people were waiting in relative safety on the sun deck. It took about 24 hours to evacuate all people with helicopters.

It is with long-lasting fires like this in mind that IMO Subcommittee on Ship Design and Construction (SDC) discussed the proposed guideline on FRP in ship structures. Fires like the one on the Norman Atlantic indicate that traditional steel ships designed according to SOLAS have an additional built-in safety that is not quantified by the tests performed according to the FTP Code. The additional safety is sometimes referred to as "implicit robustness" since it is not quantified in any IMO document.

The implicit robustness may partly be an indirect result of the way steel ships are designed where the coefficient of utilisation of the steel is relatively low. Another important factor is that the temperature development in real fires is usually far from the standard fire curve used for testing according to the FTP Code. Figure 9 shows three examples (the curves A, B and C) of calculated parametric temperature curves compared to the standard fire curve (ISO834). The parametric fire curves are based on fire load, ventilation conditions and heat loss to the surroundings and they are close to what is measured in real fires. The example illustrates how the temperature decreases while the fire load is consumed. Though, the temperature in a certain room may be kept on a high level as long as the fire spreads throughout adjacent rooms and hot smoke is moving from one room to another. But the temperature is not likely to keep increasing like the standard fire curve.

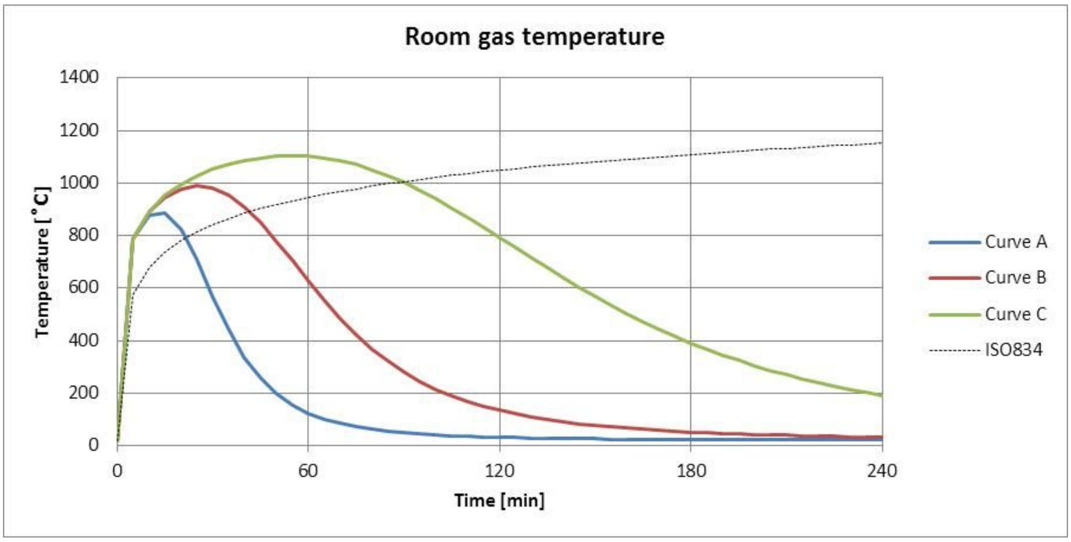

Figure 9: Example of room temperature curves for fully-developed fires

If a fire lasts for several hours a steel bulkhead will most likely reach a temperature of several hundred °C even though it is fire insulated, and the temperature rise criteria in the FTP Code will be exceeded. But steel does not lose significant strength before it reaches 400-500 °C [Eurocode, 2005] and the utilisation of steel capacity in ship structures may be relatively low [DNV, 2014]. Therefore, the steel structure will often last through a full burnout of a ship without collapse of the structure.

During the annual IMO meetings multiple nations in IMO have expressed concern on whether a ship built using a significant amount of FRP will show an equivalent robustness during long-lasting fires. The strength of an FRP sandwich panel is highly dependent on the strength of the skins and the bond between skins and core. Therefore, the sandwich panel may collapse when the temperature of the fire exposed FRP skin reaches 80-100 °C which is the glass transition temperature. This may happen without any temperature increase on the non-exposed side since the sandwich core acts as an insulator.

Several recent research projects have indicated that double-skin (skin-core-skin) FRP sandwich panels do not hold extra fire resistance beyond the time provided by the fire insulation system [Evegren, 2016][COMPASS, 2016a].

As an alternative to the double-skin panels, a non-insulated triple-skin (skin-core-skin-core-skin) FRP sandwich panel has been fire tested [Evegren, 2016]. The idea is that the first skin and core on the fire exposed side is "sacrificed" and acts as an insulator that protects the remainder of the panel. Of course, the panel must be designed to carry the design load without the fire exposed skin and core. The test showed that the panel was able to stand the FRD-60 criteria for 90 minutes.

No matter if the fire resistance of a specific component – and maybe the entire structure – is achieved by adding fire insulation, by designing with sacrificial layers or by other measures the ultimate performance of the component and structure must be quantified to be accounted for in the ship's fire safety strategy. If the strategy requires the fire resistance to be more than 60 minutes then the design must comply with that; even if 24 hours of structural fire resistance is required to achieve a sufficient fire safety level.

Quantifying resistance to fire (far) beyond 60 minutes opens multiple questions. Especially thermal exposure, duration of the test, and load conditions are essential questions to answer as they are not predefined by any test standard.

6.3 Progressive failure of the FRP structure

Metallic and composite materials exhibit different physical, chemical and mechanical properties. In addition to these, the failure mechanisms that govern the behaviour of these materials are inherently different.
In general, depending on the layup and type of loading, most composites are designed in such a way so as to fail in a progressive manner and to provide damage tolerance. The same principle applies to the design of composites against fire.

A SOLAS ship is divided into different fire zones which are prescribed by the regulations based on the location and function of each space. Depending on the fire zone the combination of insulation and structural member (i.e. deck, bulkhead or pillar) should satisfy the prescribed performance criteria whose goal is to contain the fire from spreading to other areas for a specific time (e.g. FRD-60, FRD-30 etc.).
During this time and possibly for more time the structural component is gradually exposed to heat from the side exposed to the fire.

The mechanisms of failure for FRP exposed to one-sided thermal loading and structural loading is by default progressive, meaning that there is a gradual degradation of the mechanical properties of the plies/core with increasing time and temperature starting from the exposed side and gradually propagating through the thickness of the panel to the other side [Mouritz, 2006]. Gradually the load bearing capacity of the components is reduced proportionally to the extent of softening/damage due to fire until the point where the existing load cannot be carried from these. If the fire is left unattended then it will spread affecting multiple components up to the point that the accumulated damage will lead either to partial or total loss of the structural integrity of load bearing elements which will eventually lead to the failure of the superstructure.

A progressive failure analysis of a structure due to fire is a challenging task as it is multidisciplinary and heavily dependent on the case at study. There are numerous factors that affect the fire safety which are interdependent and changing both in relation to the temperature but also in relation to the duration of the fire.

Such factors are:

- the type and location of fire,
- the available fire load,
- the existing passive fire protection
- the existence and type of active fire detection and firefighting systems
- the oxygen content in and the airtightness of the room,
- the loading and support of the structure,
- the ambient temperature and others

The following diagram (Figure 10) shows the relation between these. The overall scheme presented below does not differ between the steel and the composite case, what changes, though, is the impact of each factor depending on the material. The cornerstones of the diagram are the fire growth and development, the behaviour of the structure and the safety of the people on board.

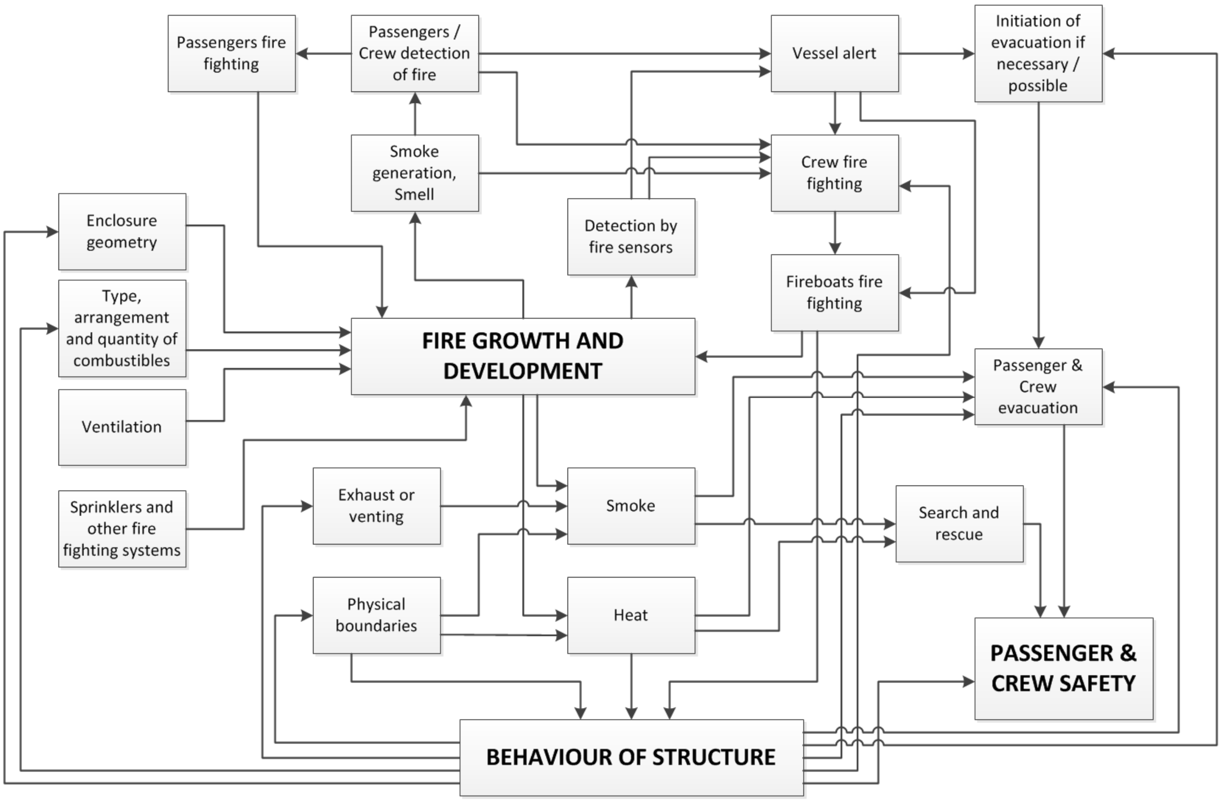

Figure 10: Relation of different factors to the fire growth, structural integrity and finally passenger and crew safety [Bennets, 2002]

With the above diagram as a starting point, the following measures are suggested that will delay, if not entirely prevent progressive failure of the structure. It is assumed that the minimum requirements dictated by the regulations, classification societies and the authorities are met for each field.

6.3.1 Passive and active firefighting, firefighting techniques

Additional fire insulation and firefighting systems can be installed in areas that are deemed critical. Unlike steel that have good heat conducting properties, composites are not good conductors of heat. This means that the fire is less likely to spread through conduction to other compartments and that boundary cooling (from the un-exposed side) is not necessary, allowing for more localised and therefore more efficient firefighting approaches. Considering this, the crew will have to be aware of the basic fire behaviour characteristics of composite and trained in how to deal with such fires.

6.3.2 Suitable material selection, additives

There exist advanced matrix systems which allow for higher temperature and thermal loading [Horrocks, 2008]. These systems can be partially introduced in critical areas or in areas where the installation of fire insulation is not possible such as on the outer side of the superstructure. One other aspect that would impede the heat transfer is the selection of core materials that produce char once burnt. The char acts as an insulating barrier partially shielding the remaining, core materials.

6.3.3 Larger safety / reserve factors

The load bearing components can be resized or redesigned in such a way to provide a larger factor of safety. This can be achieved both by increasing the size/stiffness of typical sandwich panels or by introducing different design concepts. Such examples are given below:

- Increasing the core thickness and / or increasing the number of layers in the skin of the sandwich structure.
- Using corrugated sandwich panels
- Using stiffeners on both sides of the sandwich panel where possible.
- Using a triple sandwich concept

6.3.4 Adequate supporting to account for failure of a structural element, load redirection

One of the basic principles during the design of loadbearing structures is to distribute the load in multiple components. This principle allows for load redistribution to the intact / less damaged elements in case of failure. Bearing this in mind a more fail safe approach can be adopted by correctly positioning supporting pillars or more structural bulkheads around critical locations. It must be emphasised once again that due to the low heat conductivity of composite materials the damage caused by high thermal load tends to be localised, hence fire spread in the surrounding structure is slow. Therefore, depending on the area and intensity of the fire event, it is possible to have only local damages which do not affect the global performance of the structure.

6.3.5 Segregated “safe houses” for crew and passenger protection

There have been incidents on steel ships where the fire had spread to a significant part of the structure impeding the evacuation of the people onboard. In addition, weather conditions might not allow for the use of the means of rescue during the incident, further complicating the evacuation procedure. To ensure passenger and crew safety it is possible to design a segregated area which will be designed to provide a safe haven until a rescue operation is possible. The location, arrangement and provided level of safety is to be designed based on fire engineering studies and may even be introduced as a regulation requirement for composite ships assigned to the SOLAS rules [IMO, 2014].

7 Joints between steel structure and FRP superstructure

7.1.1 Introduction

One of the most critical issues that has to be dealt with for the implementation of composites in metallic structures is how to join these dissimilar materials [Shokolnikov, 2014]. This has been the subject of research and has concerned designers and engineers in automotive aerospace and naval applications.

In principle, joints between metallic and composite materials can be divided into three main categories based on the means that are used to join the different components together. These categories are adhesive bonding, mechanical fastening and hybrid joints which consist of a combination of the aforementioned methods. Each of these joining techniques present different advantages and disadvantages and the most appropriate method will depend on application and service requirements. A short description of each method is given in the following.

Adhesive bonding
Adhesive bonding, as the name implies, relies on the use of polymeric adhesives which undergo a chemical or physical reaction for the formation of the joint. Advancements in material sciences have led to the development of high strength and tough adhesives which are well suited for load bearing joints. The main advantages associated with this technique are weight reduction and uniform load transfer through the bond line [Weitzenbock, 2012]. On the other hand, inspection and disassembly becomes problematic and, if not properly configured, environmental degradation will decrease their durability over time

Mechanically fastened joints
This type of joints incorporated the use of fastening components such as bolts and rivets and originates from the joining of metallic components. The advantages of mechanically fastened joints are that inspection, assembly and disassembly is straightforward and that analysis and design of such types of joints is in general less complicated compared to the adhesive solution. Disadvantages include increased weight, the need to drill holes in the components, and the introduction of stress concentrations where the fasteners are positioned

Hybrid Joints
Hybrid joints represent a combination of the aforementioned joining techniques and are designed in such a way so that the adhesive and the fasteners act in a complimentary fashion to each other. However, in the maritime industry hybrid bonded-bolted joints are not in fact designed for hybrid action where one joining method improves the performance of the other. On the contrary, they are used to provide a fail-safe-mode where one joining method takes over when the other fails [Da Silva, 2011]. This approach is favoured due to the complexity of the loading experienced during service and to account for infrequent inspection periods in a very aggressive environment. Based on the few existing applications bonded-bolted connections consist of adhesively bonded parts combined with vertical members that limit potential movement both in plane and out of plane directions. This may include bolts, studs or metal strips that are welded or bolted in place. Additionally, by the choice of suitable adhesive or/and sealing materials this type of joints can provide corrosion protection by prohibiting galvanic corrosion.

7.1.2 Hybrid joints for marine applications

It must be stated that any of the aforementioned joining techniques can be employed provided they are suitably designed to account for the operational conditions and loading the structure encounters during service. It is deemed however, that the hybrid joint approach is more appealing in naval applications.

This design provides a more fail safe mode as the adhesive is the one carrying the shear, and ensures a uniform load transfer through the joint loading during service. The bolts compensate for the poor adhesive strength against peeling stresses that might be present. In the event of fire the adhesive will soften when being critically heated. In that case there is reserve strength in the joint from the bolts. Another advantage of the hybrid bolted-bonded joint is that bolted connections consist of a proven joining method, therefore, the issue of predicting long-term performance is avoided which is one of the major concerns associated with the bonded joints and the lack of data from joints of these types operating in marine applications. On the other hand this approach is more costly than the other two as the substrate preparation, fabrication and inspection costs are increased.

7.1.3 Design Considerations

In general the following aspects have to be carefully considered:

Joint strength: The joint should present strength equal to or greater than the strength of the individual components. In addition, the joint should be designed in such a way to account for the loading it will be subjected to during operational conditions i.e. tension, shear, compression, bending etc.

Joint stiffness: Depending on the application the desirable stiffness differs. In the case of the joint located at the superstructure, it is deemed that an average stiffness is desirable, with the joint representing a stiffness transition region between the steel substrate and the composite counterpart. In addition, this approach reduces the loading transmitted from the underlying steel structure to the composite counterpart.

Water tightness: Depending on the location of the joint, water tightness is desirable, as is the case with joints located at the external side of the superstructure. In addition, in the case of adhesive joints and hybrid joints additional measures might be necessary to protect the adhesive from environmental ageing.

Manufacturing/installation: A suitable design would allow for easy installation and fabrication of the joint. One appealing approach is to manufacture the joint along with the composite structure including the steel substrate and to subsequently weld the steel to the steel substructure.
Elevated temperature performance: Once again the joint should exhibit strength equal to or greater than the individual components and in the event of fire to maintain functionality for the period prescribed by the regulations (e.g. FRD-60) or by a fire safety engineering analysis. Special considerations should be given to the fire protection of the joint as well as protection from possible heat conduction from the steel substrate.

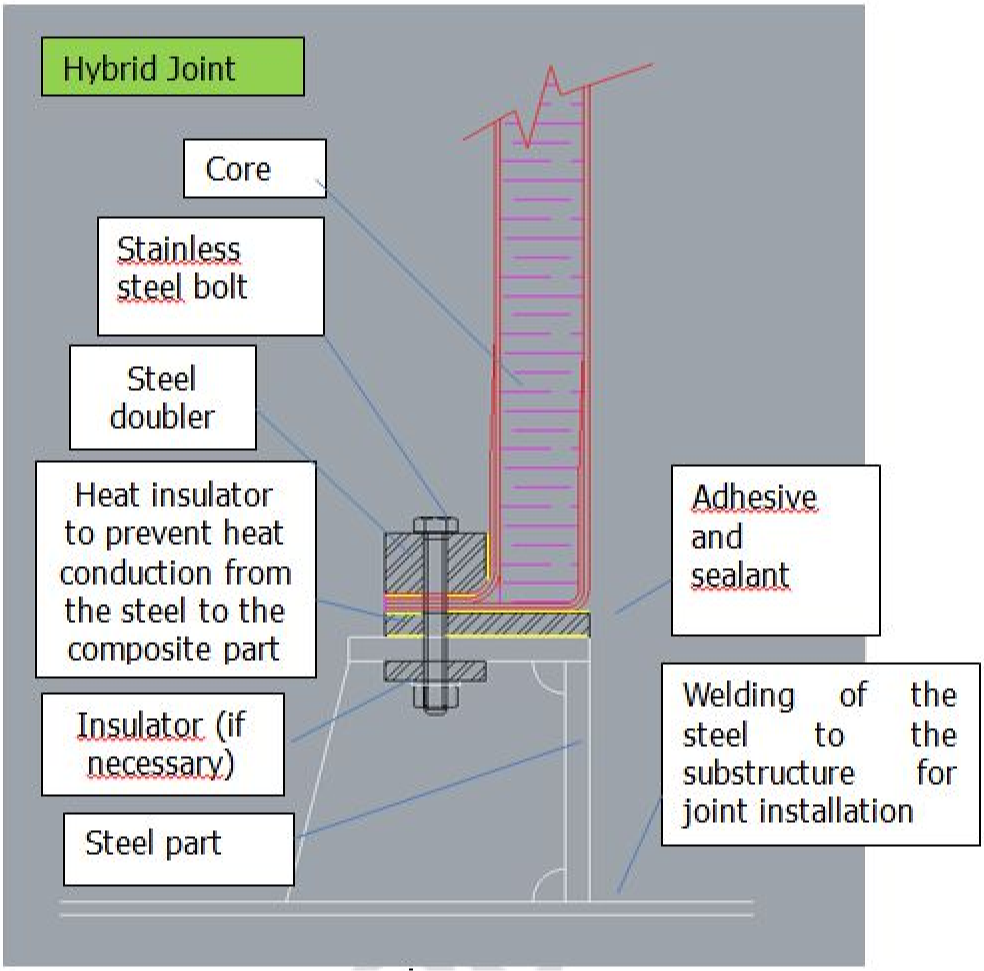

Figure 11: Cross section of hybrid joint example

7.1.4 Insulation strategies for steel/FRP joint

This section concerns the numerically and theoretically, but not experimentally, validated study of the steel/FRP interfacial temperatures in the case of a fire occurring in the room located below the deck on which the FRP panels are fixed, and heat being transferred to the joint by conduction through the construction.

Certified A60 steel bulkheads experience a maximum temperature rise on their unexposed side of 140 °C after 60 minutes of exposure to standard fire. Such a temperature will severely damage the mechanical integrity of the FRP materials, which should therefore be protected. The present section analyses protection strategies against heat for the steel/FRP joint, and the effect of different materials.

In the COMPASS project, a simple heat transfer model was used as design tool, as it allowed easy and quick investigation of several types of insulation strategies and materials. The geometry of the joint was reproduced in COMSOL Multiphysics and material properties taken from existing standards and best knowledge. The full extent of the calculation can be found in [COMPASS, 2016b]. Main conclusions are reproduced herein as an example of a decision tool.

It is emphasized that the investigation has been performed for a situation of 60 minutes exposure to standard ISO 834 time-temperature curve.

The insulation configuration depends on the position of the joint. Figure 12 depicts two different insulation configurations, namely for the case where the joint is located inside the superstructure and for the case where the joint is located at the superstructure side. For the latter there is no insulation at the external side or at the steel side structure below.

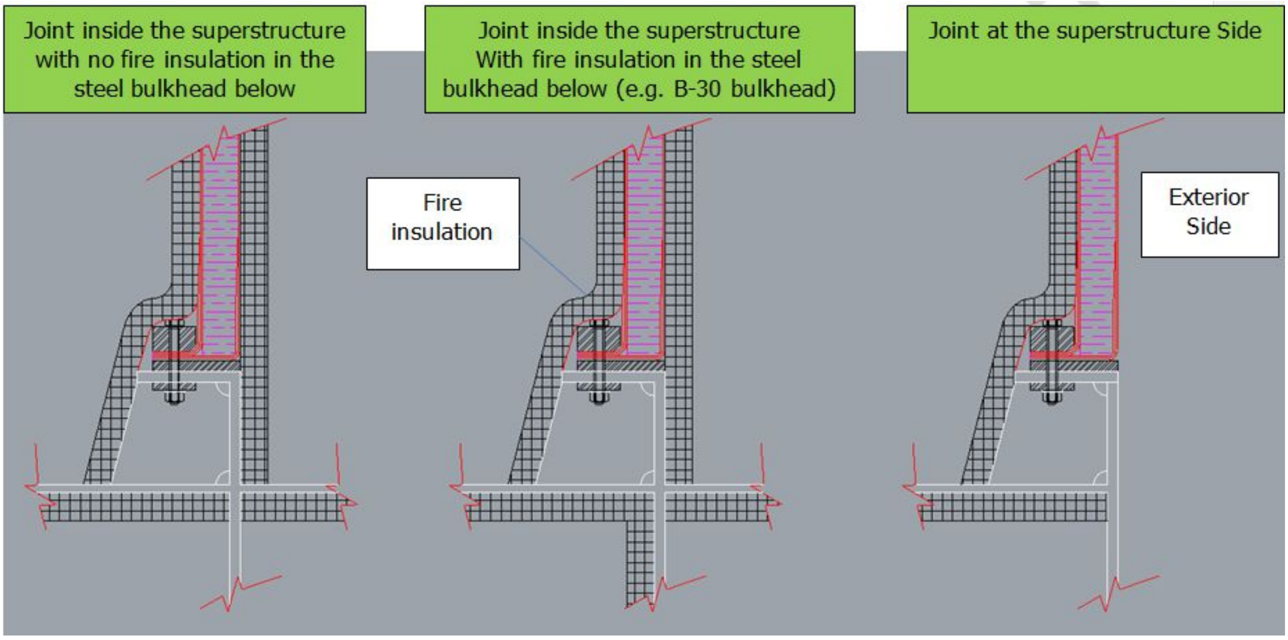

Figure 12: Examples of different passive protection configurations

The critical temperature has been set at 45 °C, which is 20 °C below the Heat Deflection Temperature (HDT) of most polymers.

The calculation showed that with standard fire insulation (30 mm mineral wool) of the deck below the joint as the only insulation, temperature at steel/FRP interface strongly depends on initial conditions. For the most commonly expected air temperature (15 °C or less) the standard configuration is suitable with maximum temperatures of 47 °C. As shown on Figure 13, hotter days can lead to higher temperatures. It is difficult to estimate how hot the materials can get, especially considering radiation from the sun, so the standard solution is considered unsafe.

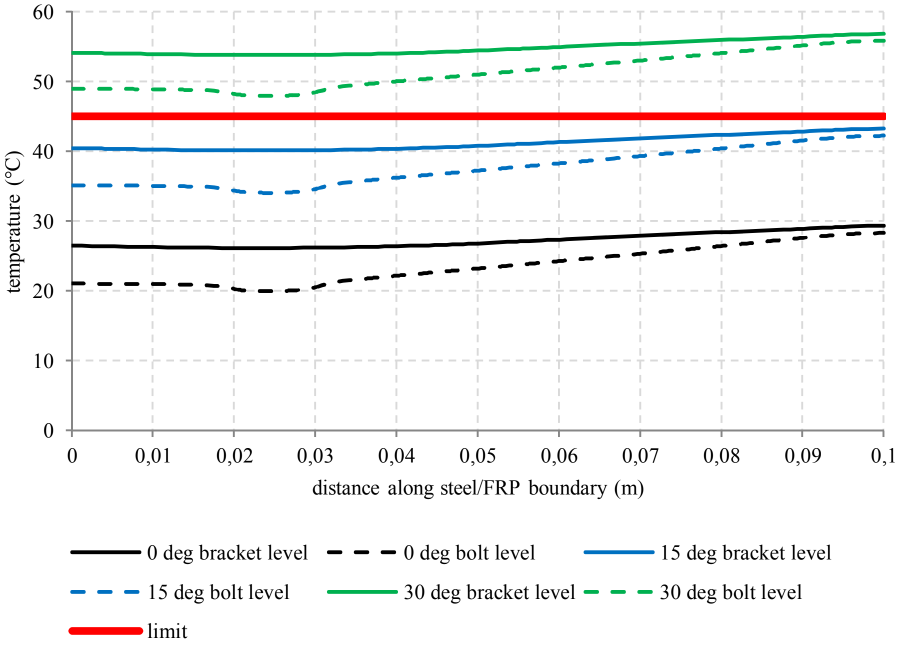

Figure 13: Temperature for 1 h of exposure to heat along steel/FRP interface for different initial temperatures

The joint should benefit from additional protection. Two different strategies are proposed:

- Thicker steel deck insulation;
- Placing an insulator separating steel and FRP.

The first solution is easy to implement, does not modify standard building procedures, and allows keeping a rather simple joint structure. The second solution is potentially cheaper to apply, but requires more detailed work and adds a layer to consider when analysing the mechanics and shear transferring ability of the joint construction.

Investigation has been performed on a selection of candidate materials for joint insulator. Concrete, gypsum, wood, and a fantasy material with desired relevant properties have been considered. Results are presented in Figure 14.

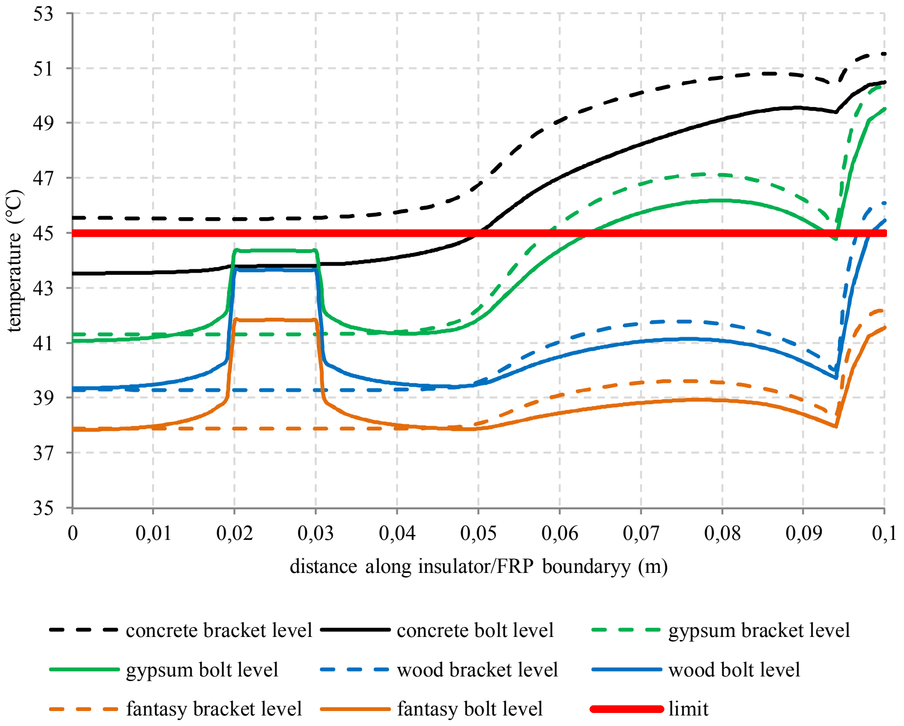

Figure 14: Computed temperatures at the insulator/FRP interface for selected insulator materials

The most promising material was wood. The entire insulator/FRP interface remains below the critical temperature of 45 °C. The fantasy material shows that a combination of low thermal conductivity, high heat capacity and high density is desirable for a good insulator.

As illustrated above, two different strategies can be followed to achieve a satisfying level of insulation against fire for the steel/FRP joint.

The first approach is to use an increased thickness of mineral wool to insulate the deck below. The proper insulation thickness should be determined with respect to the conditions of application and specifications of the design.

The second approach is to integrate an insulator between steel and FRP. The thickness of the insulator must be calculated to suit the design objectives, and wood has been identified as the most promising material with respect to temperature development. The choice of wood must be validated against structural criteria and life cycle at sea. The insulator solution must be validated structurally since it impacts the shear transfer ability of the joint.

Numerical modelling is indeed a fast and easy way to obtain results and perform parametric studies. The present results should, however, be regarded qualitatively as no experimental validation of the design has been performed so far.

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Appendix I – Relevant FSE literature

The MSC/Circ. 1002 guidelines states that the fire safety engineering approach should be "based on sound fire science and engineering practice incorporating widely accepted methods, empirical data, calculations, correlations and computer models as contained in engineering textbooks and technical literature." There are literally thousands of technical resources that may be of use in a particular fire safety design. Therefore, it is very important that fire safety engineers and other members of the design team determine the acceptability of the sources and methodologies used for the particular applications in which they are used. When determining the validity of the resources used, it is helpful to know the process through which the document was developed, reviewed and validated. For example, many codes and standards are developed under an open consensus process conducted by recognized professional societies, codes making organizations or governmental bodies. Other technical references are subject to a peer review process, such as many of the technical and engineering journals available. Also, engineering handbooks and textbooks provide widely recognized and technically solid information and calculation methods.

Additional guidance on selection of technical references and resources, along with lists of subject specific literature, can be found in:

a. *The SFPE Engineering Guide to Performance-Based Fire Protection Analysis and Design of Buildings*, Society of Fire Protection Engineers and National Fire Protection Association, 1999.
b. ISO/TR 13387-1 through 13387-8, *"Fire safety engineering"*, International Standards Organization, 1999.

Other important references include:

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