Firefighting in large FRP composite cruise ships

Fredrik Falkman

Department of Fire Safety Engineering and Systems Safety
Lund University, Sweden

Brandteknik och Riskhantering
Lunds tekniska högskola
Lunds universitet

Report 5396, Lund 2012

Firefighting in large FRP composite cruise ships

Author:
Fredrik Falkman

Supervisors:
Franz Evegren
Stefan Svensson

Lund 2012

Firefighting in large FRP composite cruise ships

Fredrik Falkman

Report 5396
ISSN: 1402-3504
ISRN: LUTVDG/TVBB--5396--SE

Number of pages: 80
Illustrations: 22

Keywords:
Fire, fighting, firefighting, FRP, cruise, ship.

Sökord:
Brand, brandbekämpning, släckinsats, FRP, kryssningsfartyg, fartyg.

Abstract:

Thanks to amendments of the regulations governing safety of ships on international voyages, ship-builders are given the possibility to design large merchant ships in novel light-weight materials such as Fibre Reinforced Polymer (FRP) composite.

As a part of a collaborative risk assessment, this report investigates the implications of using this new material for the personal risks of firefighting crew and for the effectiveness and efficiency of the firefighting organization. Furthermore, it investigates how current routines and equipment may be adjusted so they are suitable for large FRP cruise ships.

Through a study of literature, interviews, and a comparison of relative risk, the author draws the conclusion that firefighting can be done at least as safe, effective and efficient in the novel lightweight FRP design, as in the prescriptive steel and aluminum design, if adjustments are made to the current firefighting routines and equipment.

Brandteknik och Riskhantering
Lunds tekniska högskola
Lunds universitet
Box 118
221 00 Lund

brand@brand.lth.se
http://www.brand.lth.se

Telefon: 046 - 222 73 60
Telefax: 046 - 222 46 12

Department of Fire Safety Engineering
and Systems Safety
Lund University
P.O. Box 118
SE-221 00 Lund
Sweden

brand@brand.lth.se
http://www.brand.lth.se/english

Telephone: +46 46 222 73 60
Fax: +46 46 222 46 12

"Speed is safety"

Abstract

Thanks to amendments of the regulations governing safety of ships on international voyages, ship-builders are given the possibility to design large merchant ships in novel light-weight materials such as Fibre Reinforced Polymer (FRP) composite.

As a part of a collaborative risk assessment, this report investigates the implications of using this new material for the personal risks of firefighting crew and for the effectiveness and efficiency of the firefighting organization. Furthermore, it investigates how current routines and equipment may be adjusted so they are suitable for large FRP cruise ships.

Through a study of literature, interviews, and a comparison of relative risk, the author draws the conclusion that firefighting can be done at least as safe, effective and efficient in the novel lightweight FRP design, as in the prescriptive steel and aluminum design, if adjustments are made to the current firefighting routines and equipment.

Abstrakt

Tack vare korrigeringarna i regelverket som styr säkerhetfen för fartyg på internationella farvatten, ges skeppsbyggare möjligheten att konstruera storskaliga handelsfartyg i nya lättviktsmaterial, såsom Fibre Reinforced Polymer (FRP) komposit.

Som en del i ett kollaborativt riskanalysarbete, undersöker denna rapport vilka konsekvenser införandet av detta nya material får för brandbekämparnas personrisk och brandbekämpnings-organisationens effektivitet. Vidare undersöks hur nuvarande brandbekämpningsrutiner och utrustning kan anpassas för att vara lämpliga ombord på stora FRP-kryssningsfartyg.

Genom litteraturtudie, intervjuer och en relativ risk-jämförelse, drar författaren slutsatsen att att brandbekämpning kan göras minst lika säkert och effektivt i den nya FRP-designen, som i den preskriptiva stål-och-aluminiumdesignen. Det krävs dock justeringar i nuvarande rutiner och utrustning för att uppnå detta.

Contents

1 Abbreviations, definitions and nomenclature

Below, a number of abbreviations and terms are defined, which are used throughout the report.

1.1 Abbreviations

ALARP	As Low As Reasonably Practicable
CE	Cutting Extinguisher
BA	Breathing Apparatus
BESST	Breakthrough in European Ship and Shipbuilding Technologies
FRP	Fibre Reinforced Polymer
FN	Fog Nail
FTP	Fire Test Procedures
HSC	High Speed Craft
HRR	Heat Release Rate
IMO	International Maritime Organization
ISM	International Safety Management
LCA	Life Cycle Analysis
MTO	Man-Technique-Organization
RO-RO	Roll On – Roll Off
RR	Relative Risk
SOLAS	Safety Of Life At Sea
TIC	Thermal Imaging Camera

1.2 Definitions and nomenclature

BA-team	As a part of the firefighting squads, the BA-teams are equipped with Breathing Apparatuses and firefighters' outfits, with the purpose of being able to work in conditions that are harmful to humans.
Ceiling Jet	Horizontal flame phenomenon along a ceiling caused by a fire plume that reaches it.
Displacement	Total weight of a ship, including cargo and full fuel tanks.
Flashover	The rapid transition to a state of total surface involvement in a fire of combustible materials within an enclosure.
Fully Developed Fire	All combustible surface areas inside an enclosure have been ignited and are steadily producing pyrolysis gases that are fueling the fire.
Heat Release Rate	Fire effect (firepower), denoted by $\dot{Q}$ (kW).
Inboard fires	Fire scenarios that take place in the interior of the structure, for instance in cabins, restaurants, cinemas, machinery spaces, et cetera.
Outboard fires	Fire scenarios that take place on the exterior of the ship, for instance on sun-deck, balconies, along the hull, et cetera.
Structural Collapse	In this report the terms *Structural Collapse* or *Structural Failure* refers to when a load-bearing part of a structure is rendered incapable of bearing its prescribed load, thus collapsing if under load. It does not refer to the whole process (deformations et cetera.) leading up to the collapse.

2 Introduction and objectives

Below follows a short introduction to the report. The report's main objectives are also presented.

2.1 Introduction

The introduction of novel lightweight Fibre Reinforced Polymer (FRP) composite constructions in the international maritime industry was made possible in 2002, when the fire safety chapter of SOLAS opened up for performance-based design. Such a design must be at least as safe as a design achieving all the prescriptive requirements, shown through a fire risk assessment. SP Fire Technology in Borås coordinated such an assessment for a ship with a large FRP composite superstructure. A need to investigate implications for firefighting efforts on board these ships was identified in the process.

This report is credited as a Bachelor Thesis at the department of fire safety engineering and systems safety at Lund University. It aims to investigate the novel design's implications for firefighting efforts on board large scale cruise ships.

2.2 Objectives

The report has the following objectives:

- Investigate the FRP composite design's implications for firefighters' personal risk.
- Investigate the FRP composite design's implications for the firefighting organization's effectiveness and efficiency.
- Make recommendations on how to adopt current firefighting routines so that they are suitable for an FRP composite environment.

3 Problem description and background

This chapter aims to provide further background and detail as to why this report has been composed.

3.1 Background

The EU project BESST - Breakthrough in European Ship and Shipbuilding Technologies is a research collaboration aiming to further develop European shipbuilding industry's competitive advantage on the global market. Life Cycle Analysis (LCA) has shown that shipping companies can increase profits by investing in a lightweight ship design, as the higher initial cost is repaid by increased payload capacity or reduced fuel consumption. Load-bearing structures on board large ships are traditionally built in steel, which is strong and cost effective in the construction phase but heavy. By replacing parts of the structure with a more lightweight design profits can be maximized, even though initial investment costs are higher (Hertzberg, 2009).

3.2 SOLAS – Safety Of Life At Sea

Large scale merchant ships are traditionally constructed in steel and this is also the material current regulations are based upon. In 1929 the first edition of SOLAS - Safety Of Life At Sea was published. Amended many times since, this is still the valid regulation dictating what is permitted in regards to safety on board merchant ships. In 2002, Regulation 17 was introduced in the fire safety chapter (Chapter II-2) of SOLAS, permitting design of non-prescriptive fire protection if it is proven that the fire safety is equal or better than implied by the prescriptive fire safety requirements. Prior to this date there was also a possibility of circumventing prescriptive design specifications through Regulation 5 in Chapter I. However, going down the latter path is impractical as it is based on consideration from the Flag State, creating many potential problems such as need of approval from a new Flag State if the ship should need to be reflagged (Evegren, 2010) (IMO, 2009).

3.3 The FRP composite construction

In order to achieve light weight, Fibre Reinforced Polymer (FRP) composite has been used since the 1970s on Navy crafts. An FRP composite is a sandwich type construction generally consisting of two laminates on each side of a light core, creating one stiff panel. Typically, the laminates are made of glass or carbon fibre bonded together by a resin, while the core is a PVC polymer or a lightweight wood such as balsa, as seen in Figure 1. The FRP composite panels are often suitably stiffened with T-joint stiffeners to increase its load-bearing capacity. This type of construction enables the panels to bear loads not only perpendicularly but also laterally, making them practical for constructing both decks and bulkheads (Evegren, 2010).

Figure 1. Illustration of an FRP Composite with its laminates on each side of a lightweight core (Evegren, 2010).

However, These FRP panels introduce new complications with regards to fire safety on board since they are combustible. Tests have shown that when exposed to a fire and the laminate on the exposed side reaches a critical temperature, the FRP composite will delaminate and start to lose its load-bearing capabilities. The temperature at which this happens depends on what type of resin is used. Polyester or a phenolic polymer mix are commonly used resins and they will have lost their bonding capabilities at around 130°C and 200°C respectively (Hertzberg, 2009). As the construction gets heated further, more load-bearing capacity is lost and eventually the structure will collapse after 60 – 140 minutes of sustained fully developed fire (More detailed information on this time-span can be found in chapter 6.3.2). In order to provide sufficient protection from fire, all interior FRP composite surfaces will be insulated. SOLAS Regulation II-2/11-2 states that load-bearing structures shall be built in *Steel or other equivalent material* (IMO, 2009). With additional safety measures, such as the added insulation, a ship with FRP composite structures can be designed with equivalent fire safety (Evegren, 2010). Figure 2 shows an FRP composite with a T-joint and insulation.

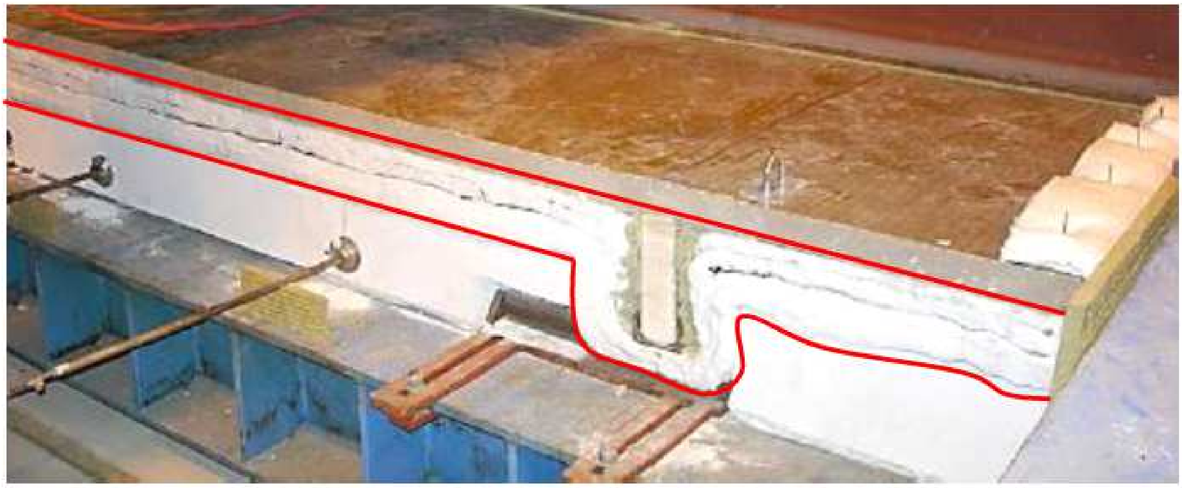


Figure 2. Insulation fitted to an FRP composite construction marked in red (Evegren, 2010).

3.4 Application case: The Norwegian Future

In September 2009, the BESST project was set a sail. In order to build ships of novel designs with the help of SOLAS Regulation 17, a comprehensive risk assessment is performed as part of this project. The risk assessment involves several collaborates and is put together by SP in Borås. Performing a screening of potential hazards with the novel design (SP, 2012), a need to review and perhaps adopt firefighting routines was discovered. This is where this thesis comes into the picture; it is to be a part of the risk assessment for the BESST project.

While the scope of the BESST project is to create a holistic package for FRP ships in general, a method for reaching that goal is performing case studies of virtual ship designs. The BESST project includes three such case studies, one of which is the redesign of the Norwegian Gem (Figure 3) into the Norwegian Future with five uppermost decks constructed in FRP composite. The writing of this report is based upon this application case. Since the BESST project is the first of its kind where the design of large merchant ships in FRP composite is studied, it is likely to have some impact in setting the standard for how these ships will be built and operated in the future.

Figure 3. The Norwegian Gem (Evegren, 2010).

The Norwegian Gem is a 295m long cruise ship built in 2007 by Meyer Werft in Germany. It is capable of accommodating around 2400 passengers and 1150 crew members. Onboard the Gem, the five uppermost decks constructed in steel and aluminum were replaced in the virtual design by a superstructure built in FRP composite, highlighted in Figure 4. The redesign resulted in 1200 tons of weight savings. However, since the FRP superstructure does not contribute to global hull strength, the resulted loss of strength required engineers to reinforce the remaining steel hull with around 400 tons of steel, thus making the final weight savings 800 tons. This in turn meant that the engineers could add approximately one third of a deck, consisting of 100 extra cabins plus some recreational areas and crew space. The novel design of the ship resulted in an added capability of around 200 passengers while hull strength, fuel consumption, displacement and stability all remained the same (Evegren, Hertzberg, & Rahm, 2011).

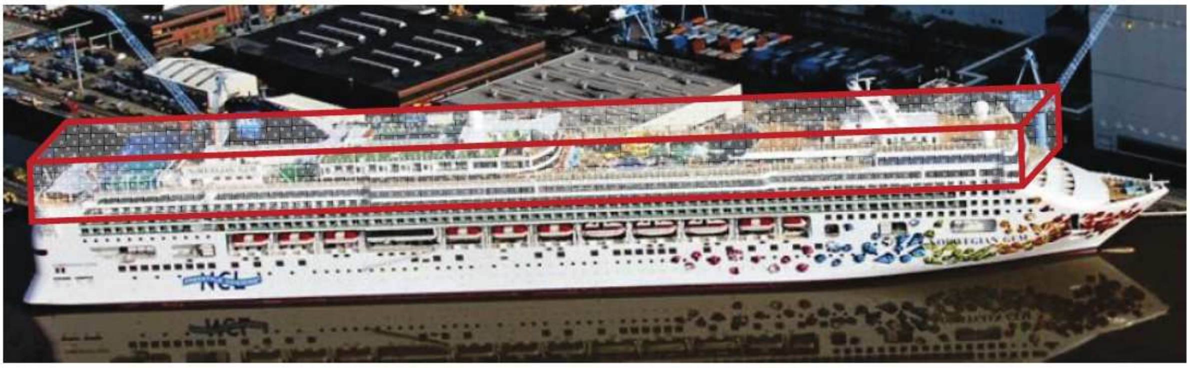


Figure 4. Norwegian Gem, with the five uppermost redesigned decks marked in red (Evegren, 2010).

In this novel virtual design, all load-bearing bulkheads and decks were replaced with FRP composite in the five uppermost decks. But what does this mean? Figure 5 shows a schematic top-down overview of a deck with cabin compartments on board the Norwegian Gem. The red lines in the figure make out the load-bearing structures and thus what is redesigned in FRP composite. As seen in the figure, not all parts of the ship's interior are load-bearing. At an interval of 34-45 meters apart, main vertical zones can be seen. These are large load-bearing bulkheads that also make out fire zones (main vertical zones). All other red lines are also load-bearing, such as the hull and several other parts.

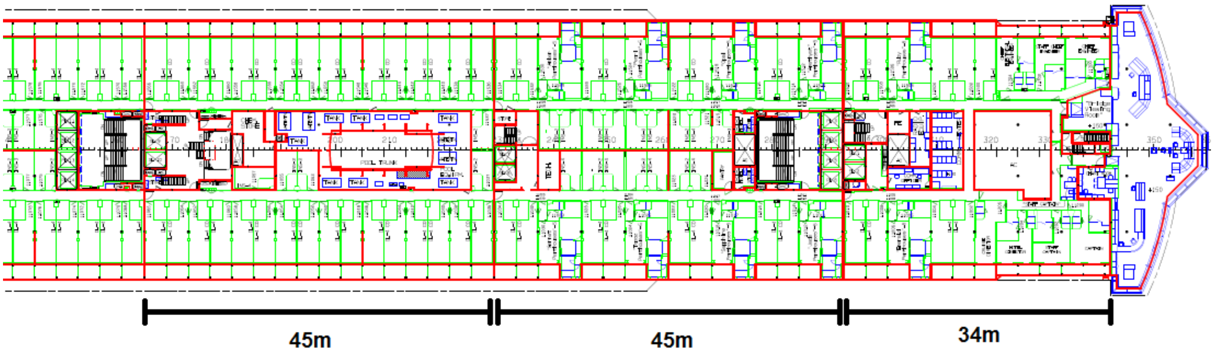


Figure 5. Top-down perspective of a deck with cabins on board the Norwegian Gem. Red lines indicate load-bearing parts of the structure (Evegren, 2010).

To picture how a cabin area on board this type of ship is constructed, many similarities can be drawn to a typical office space. One can imagine a larger area on a deck where the boundaries are two bulkheads and both sides of the hull in the horizontal plane. In the vertical axis the boundaries are determined by the deck and the bottom side of the above deck. Into this volume several cabin modules are inserted. Above the cabin modules is a void space between the ceiling of the modules and the bottom of the deck above. There is also to some extent a void space between the cabins, as well as between the cabins and the bulkheads. The following figure 6, illustrates the construction schematically.

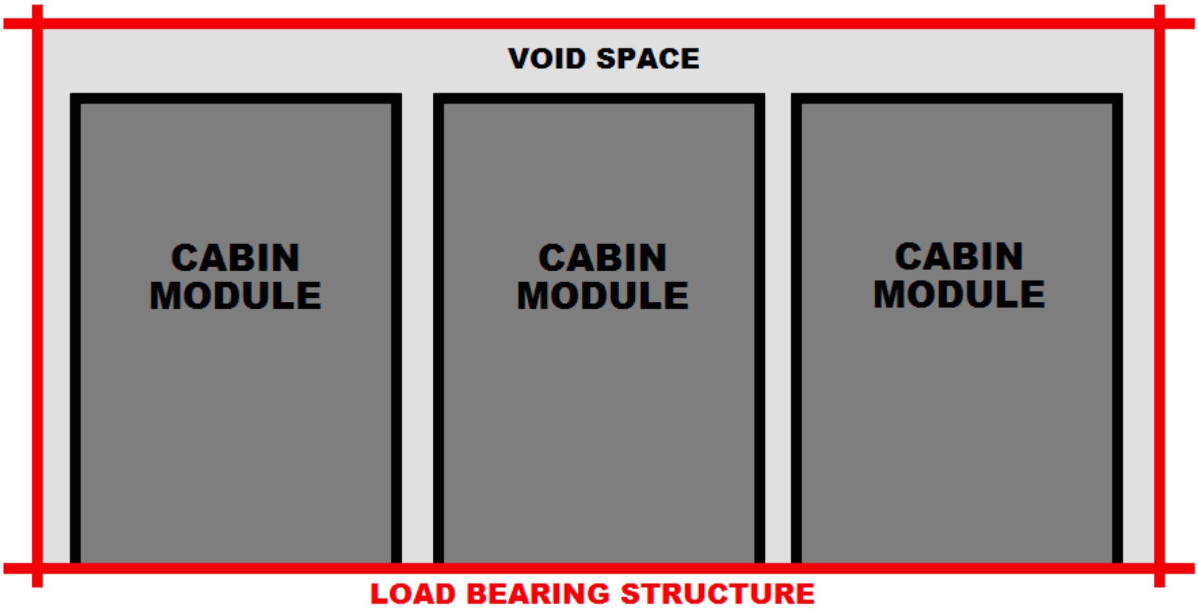


Figure 6. Schematic view of cabin modules in an FRP composite design.

Much like in an office building this void space is used for wiring, ventilation, plumbing et cetera. As of now the novel design does not change these interior modules, it affects only the load-bearing structure such as described above. However, in the future there shall hopefully also be more lightweight cabin modules available on the market.

According to SOLAS II-2/11, main vertical fire zones and decks shall be constructed in class A-60. This means that the barrier shall be able to withstand a standardized fire load for 60 minutes without the unexposed side reaching 140°C on average across the surface and must not have any local maximum temperatures above 180°C. It is also required that the barrier is *capable of preventing passage of smoke and flame to the end of the standard fire test*. However, it should be noted that due to the nature of the test, this does not mean that the barrier necessarily is 100% intact, as the test itself permits a certain amount of structural integrity loss. For more information about the tests, review the Fire Test Procedures Code, by the International Maritime Organization (IMO, 1998).

Due to its high thermal resistance, the novel design is likely to contain the fire in this area between bulkheads and decks better than steel – until the point in time a collapse occurs (Evegren, 2010). A steel bulkhead or deck will have the tendency to transport heat away from the fire source, possibly igniting secondary fires in adjacent spaces and in joints and intersections in the construction. The FRP composite is in itself a good thermal insulator and combined with the added insulation to both sides, it creates a strong barrier for fire containment. However, the novel design also has its setbacks. In case of a prolonged and severe fire, the structure's load-bearing capabilities will deteriorate thus resulting in risk of structural collapses.

With regards to passenger safety on board it is believed that the conditions for evacuation in the novel design may be equally good or better than in a prescriptive design. 60 minutes is regarded as enough time for passengers to get alerted, perceive danger and move to a safe area on board (Evegren, 2010), thus potentially benefiting from the better fire containment while not being subjected to any structural collapses.

However, the novel design may imply added danger for firefighting crew when considering the risk of structural collapses. Although steel starts to deteriorate at 400-500°C, incidents such as the fire on board the Scandinavian Star (Almersjö, o.a., 1993) have shown that fires can rage on board steel passenger ships for days without causing total structural collapse. The novel design would be susceptible to such problems if a fire is not hindered.

4 Method and limitations

This chapter presents the methods and limitations for the report.

4.1 Method

The report was based on literature studies and interviews. When sufficient data was acquired, an analytical discussion was performed.

The analysis of implications toward firefighters' personal risk was done by a comparison of relative risk. Onboard fire scenarios that can be regarded detrimental, unobtrusive or beneficial (to firefighters' personal risks) were inventoried, with consideration of novel firefighting strategies and materiel taken into account.

When the scenarios here been identified a ratio of how common they are, was assessed based on the ice-berg model. This allows for a relative risk comparison of how much the (more frequent) beneficial scenarios must increase firefighters' safety in order for them to make up for the (less frequent) detrimental scenarios. For instance, if the beneficial scenarios outnumber the detrimental ones 5:1, this implies that the safety increase in each beneficial scenario must equal at least 20% of the increase to firefighters' personal risk caused by one detrimental scenario.

Performing a fully quantitative risk analysis for this type of question is not really applicable and would be associated with great uncertainties. The method used in the report does not attempt to deliver an exact figure of relative risk e.g. $P(A)=0.8*P(B)$. However, the objective is to answer a question such as *whether* $P(A)\leq P(B)$*?*

4.2 Limitations and assumptions

The limitations to the report are the following:

- The report is mainly aimed towards the types of ships similar to the application case Norwegian Future, which is described in chapter 3.4. This indicates a large cruise ship with the uppermost passenger decks constructed in FRP composite. It may not be applicable to cargo or RO-RO ships for example due to differences in fire load and geometry.
- The report is aimed towards ships with the type of organization described in subchapter 5.1, which implies that rather large firefighting resources are available for rapid deployment. The report is based on the assumption that at least around 30 personnel are assigned to firefighting squads. Should the amount of available firefighting crew fall short of this number, the results of the report may not be applicable.
- Residual value after a fire is not taken into account.
- Passenger safety is not discussed.

Since certain details regarding the final construction are not yet fully decided upon, some parameters will have to be assumed to be able to move forward with the analysis in this report. Such details are:

- Amount of insulation that protects FRP panels from fire. The base design of the Norwegian Future is that all load carrying decks and bulkheads are insulated sufficiently to withstand a standardized fire test for 60 minutes. However, there is also a possibility that there may be less insulation in specific areas. Such areas could for instance be where the fire risk is deemed lower or where the FRP composite is not required to bear heavy loads, such as the uppermost deck or balconies et cetera.

- Which safety measures are to be installed to protect the outboard spaces and the exterior of the hull. Outer layers that are either non-combustible or has low flame spread characteristics, or drenchers (outboard sprinklers), or a combination of both are currently considered at the point in time this report is composed.

5 Literature and interview findings

Below all key literature and interview findings are presented.

5.1 Onboard firefighting organization

How firefighting organizations are managed and operated was surveyed by interviews and screening of regulations. The findings were summarized in a schematic overview and a timeline of events that normally take place in the event of a fire alarm. Furthermore, differences between merchant and navy fleet firefighting strategies are presented, as well as information about training and equipment.

5.1.1 Firefighting organization schematic overview

It was found that regulations governing how the firefighting organization is to be managed are performance based. Further information can be found in Appendix B.2. This means that organizations may differ between shipping companies and ships et cetera. Figure 7 displays an overview of how a firefighting organization generally is set up on board large cruise ships. It was compiled with the assistance of Håkan Warnemyr (Warnemyr, 2012) at MSB Revinge College and Gabor Szemler at the maritime fire safety department of the Swedish Transport Agency (Swedish Flag).

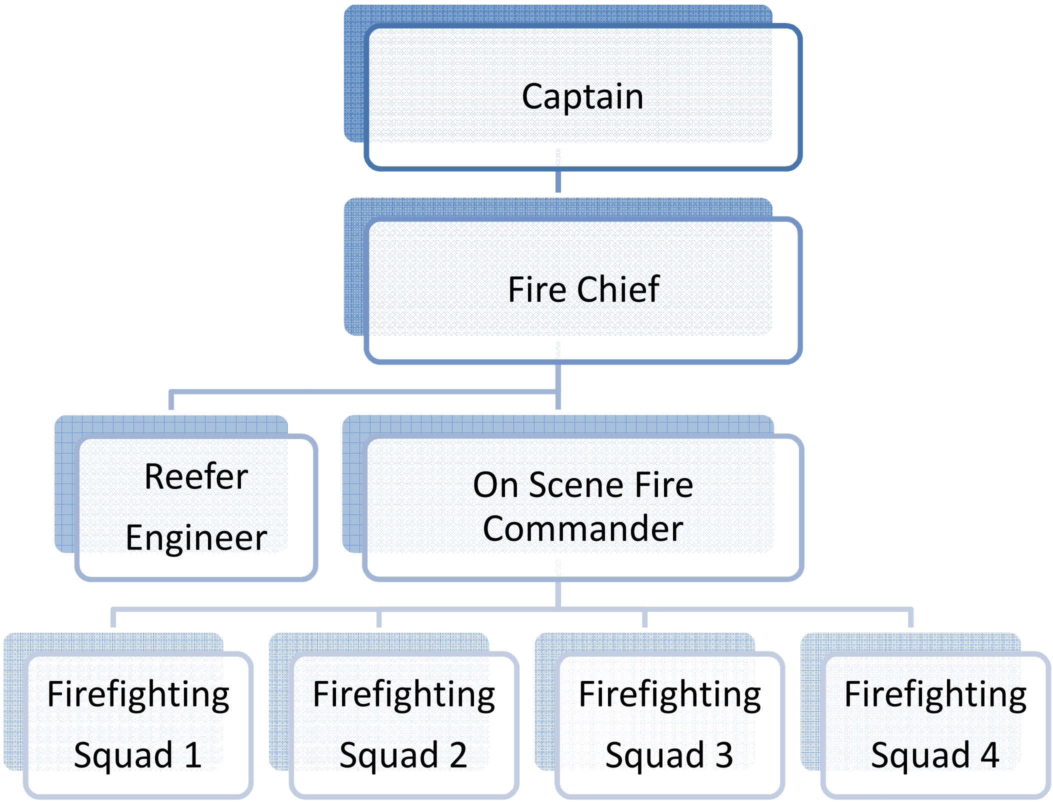


Figure 7. Schematic overview of onboard firefighting organization

The captain on board is always the commanding officer and ultimately in charge of all onboard operations. The Fire Chief is in charge of firefighting operations and is a position normally appointed to the Chief Engineer. The Reefer Engineer is in charge of managing ventilation systems on board and the On Scene Fire Commander has operative command at the site of fire. Additional crew is also available to assist the Captain, Fire Chief, Reefer Engineer and On Scene Fire Commander. The number of Firefighting Squads, and also the amount in men in each squad, may vary on different ships but generally a squad consists of around ten to twentyfive men, of which four or six are designated BA-team members. In addition to this "core" firefighting organization, all crew members have a designated task to perform in case of a fire on board such as ensuring compartments are closed, assisting passengers, et cetera.

5.1.2 Firefighting routines timeline

The general procedure of how the firefighting organization responds to a fire alarm on board was inventoried. The timeline was compiled with the assistance of Håkan Warnemyr (Warnemyr, 2012) at MSB Revinge College and Gabor Szemler at the maritime fire safety department of the Swedish Transport Agency (Swedish Flag).

In case a fire is detected, the following is assumed to occur on board a large cruise ship:

1. Bridge receives the alarm
2. Bridge executes the following:
    a. Security staff on duty or similar are sent to alarm location to acknowledge whether the alarm is true or false. If possible they put out a potential fire with first effort means such as fire extinguishers, blankets et cetera.
    b. The "First Firefighter", if such exists, is notified to collect firefighting equipment and move to location to perform a first effort with BAs in case there is too much smoke for staff without BA to be effective.
    c. Mobilization of firefighting organization with
        i. Notification to the Fire Chief and assembly of firefighting squads.
        ii. Notification to Reefer Engineers to man the fire control room, from which ventilation can be controlled.
3. If first efforts by Security staff and, if applicable, First Firefighter are ineffective, firefighting squads will:
    a. Activate sprinklers if they are manually operated and are not yet switched on.
    b. Combat the fire with the aid of BAs.
    c. Perform boundary cooling and monitoring of adjacent spaces to hinder fire propagation.
4. If firefighting efforts are still ineffective, passengers will be asked to go to muster stations.
5. If firefighting efforts are still ineffective, the order will be given to abandon ship.

Note1: Main events marked by numbers indicate a likely timeline, but sub-events marked a,b,c, or i,ii are not necessarily in any particular order and may be considered more or less simultaneous

Note2: The exact chain of events is not necessarily in this particular order as it may depend on the situation and differ depending on what the Captain or the Fire Chief deems appropriate. Event No4 may for instance occur already when the alarm has just been received at the Bridge, if deemed necessary.

5.1.3 Navy firefighting routines

Consultation with Mårten Ribbing, Fire Safety Engineer and Head of the Ships' Fire Safety Department at the Naval Warfare Centre in Karlskrona indicates that firefighting onboard Swedish Navy ships is performed much in a similar manner to civilian ships.

The main differences are:

- Many Swedish Navy ships have access to modern firefighting equipment such as Cutting Extinguishers and Fog Nails.
- Firefighters are likely to have better local knowledge of all onboard compartments.
- Subsequent better understanding of fire scenarios, fire development and knowledge of specific risks in the different compartments.
- Slightly quicker response-time and a higher level of training are likely.

A summary of the Navy's general method is presented below:

- *Incident extinguishment and rising of alarm. He or she who discovers the fire attempts to put out the fire and raises the alarm.*
- *1st Effort after one minute. Two pre-designated seamen attempts to put out the fire and seals the compartment. They are equipped with flame retardant clothing and escape hoods.*
- *2nd Effort after two minutes. Two pre-designated seamen ensures the compartment is sealed and performs outer measures such as deployment of fixed systems, boundary cooling, Fog Nails or Cutting Extinguishers, depending on the circumstances.*
- *BA-team Efforts after five minutes." Smoke diving group" of 2+1, On Scene Commander and pump attendant performs reentry, rescue of personnel and extinguishment of fire. When the situation is under control, they start preparing for retrieval of important functions.*
- *Retrieval of important functions is initially performed by crew with BA's to get all systems operational as quick as possible.*

5.1.4 Requirements for enlisting in a firefighting squad on board

It was found that no additional certification or training than *Basic Safety* is required by SOLAS for a crew member to enroll in a firefighting squad. This is the same certificate required by all seamen on any ship, no matter what function they have on board. Firefighting commanders (Fire Chief and On Scene Commander) are required to have an *Advanced Firefighting* certificate. More detailed information can be found in Appendix B.1.1.

5.1.5 Periodical onboard drills and training

Once a seaman has enlisted to the core firefighting organization on board, he or she will start to train with them. As required by Regulation III/30 in SOLAS, fire drills are performed once a week on all passenger ships. However, each crew member is obligated to attend only a minimum of one drill per month. What the fire drills are required to contain is specified in SOLAS Regulation III/19-3.4 and can be found in Appendix B.1.2.

In summary, the regulation requires only a crew gathering at muster stations where all relevant equipment subsequently is checked for function. No theoretical or practical firefighting exercises are actually required by the regulation.

5.1.6 Firefighting equipment

In all spaces on board, hoses are installed in a manner that always ensures coverage from two separate sources simultaneously, ensuring there is water supply available if a fire should start right at a hose station, as required by SOLAS Regulation II-2/10.2.1.5. In addition to this there are handheld fire extinguishers at regular intervals. Firefighters are issued with “standard” firefighting equipment that is collected from the squads’ respective assembly stations. The specific equipment available may vary slightly on different ships and shipping companies, but includes tools for breaking and entry, additional hoses and connections et cetera (Warnemyr, 2012). It will also always include firefighters’ outfits and Breathing Apparatuses (BA) and often one or more Thermal Imaging Cameras are available. The minimum number of outfits and BAs available on board is regulated by SOLAS II-2/10-10. Standard issue equipment does not include Fog Nails or Cutting Extinguishers.

5.2 FRP composite properties in fire situations

Several in-house tests of FRP composite panels were performed at SP Borås at the point in time this report was composed. It was thus not possible to refer to a report at the time, but it is SP’s intent to release a public report when all results have been summarized. The tested FRP composite panels were regarded to be of similar construction to the ones that are to be used on large cruise ships with the uppermost decks constructed in lightweight materials. The panels were weighted with rather substantial loads, which were believed to correspond to the actual load bearing capacity required in an actual ship construction.

24 large scale tests of both insulated and un-insulated FRP composite panels and constructions, performed at four different institutes were also reviewed (Gutierrez, o.a., 2005) (Hertzberg, Axelsson, & Arvidson, 2008) (SP, 2012) (Lattimer, Oulette, & Sorathia, 2004) (Potter, 2002). Furthermore, an incident report was of relevance to this topic (Allison, Marchand, & Morchat, 1991). In the following sections, the findings of all reviewed reports are presented:

5.2.1 Structural collapse process of an FRP composite panel

Structural mechanics theory teaches that a sandwich construction will lose almost all its load-bearing capacity and collapse if one of the laminates separates from the core (Gdoutos & Daniel). In an FRP composite construction exposed to fire, this occurs when the fire exposed laminate reaches about 120°C - 200°C, depending on what polymer matrix is used to bond the fibers. Tests indicate that this is also true in actuality if the sandwich panel is heavily loaded.

It seems that an FRP composite panel that is loaded to or near its design load will most likely behave in the expected way. However, constructions that have stiffeners seem to be slightly more redundant, as the load may be transferred to the stiffeners if the main sandwich panel loses its load bearing capacity.

If the sandwich panel is less heavily loaded, or the weight is distributed to the surrounding structure as a panel loses its load bearing capacity, the sandwich panel may have a tendency to first bulge or sag increasingly over time before a collapse occurs.

5.2.2 Time to structural collapse

The SP in-house tests of FRP composite sandwich panels, weighted to their design loads, indicate that it is possible to insulate the construction so that it can withstand 60 minutes of standardized furnace temperatures according to IMO Resolution A.754.

Furthermore, it was found from the other tests that the sandwich panels may be able to bear lesser loads for 60-140 minutes. These times are discussed in Chapter 6.3.2.

5.2.3 Gland installations and integrity

This could be a weak spot of an FRP composite construction, much as it often is also in the prescriptive design. Initial reports from tests being performed at SP indicates that gland installations can be protected from fire while ensuring the integrity of the construction.

5.2.4 Additional properties

In addition to the possibility of structural collapse, it was found that the FRP composite possesses the following properties that are relevant to a fire safety assessment:

- High thermal inertia, which leads to better containment of fire and higher temperatures inside an enclosure.
- Combustibility, which indicates that production of pyrolysis gases, is possible. The pyrolysis gases may in turn add to the fire load and increase the amount of toxic smoke.
- Tendency to reignite locally after extinguishment of a severe fire that has heated the structure sufficiently for pyrolysis to take place.

6 Analysis

This chapter aims to solve the issues with fighting a fire in the novel FRP composite design. It also discusses implications towards firefighter's personal risk and firefighting efforts effectiveness.

6.1 Fire scenario comparison of prescriptive and novel design

The novel design changes some parameters that affect how a fire might behave on board. In this subchapter those differences are analyzed, primarily from a firefighting perspective.

In respect to fire behavior, the novel design changes the following parameters:

- Increased thermal inertia.
- Possibility of structural collapse.
- Combustibility of structural material.
- Production of pyrolysis gases from combusted structural material, adding to the fire load.
- Production of toxic gases from combusted structural material.

Analyzing the parameters from a fire dynamics point of view, the following differences are implied by the novel design when compared to the prescriptive design:

- Probable similar fire development up until the point in time that the inner ceiling fails. The inner ceiling separates the enclosure from the load bearing structure via a void space.
- Fires in larger inboard spaces, such as restaurants or theatres, will also likely behave in a similar fashion up until the point in time that the inner ceiling fails.
- If, or when, the inner ceiling fails, the temperatures in the hot smoke layer and ceiling jet are likely to get higher with the novel design due to the increased thermal inertia. Although inner ceilings may fail after some 10-20 minutes of exposure to severe fire, it was able to withstand a fully developed fire that led to an almost completely burnt out cabin in the fire incident on board the Star Princess.
- In case either no inner ceiling is installed which may be the case in machinery spaces et cetera, or if the fire starts in the actual void space, fire development may be more rapid. The improved thermal barrier in the novel design may result in higher temperatures and the difference may be significant, especially if the divisions are of A-0 class in the prescriptive design which has great conductive capabilities.
- When or if the inner ceiling fails, temperatures are likely to get higher with the novel design compared to a steel prescriptive design. The improved thermal barrier in the novel design may result in higher temperatures and the difference may be significant, especially if the divisions are of A-0 class in the prescriptive design which has great conductive capabilities.
- Outboard fire spread is possible with the novel design. It is at this point unclear what preventive protection will be installed, but external drencher systems or outer layers that are either incombustible or have low flame spread characteristics, are solutions that are being considered at the moment.
- Fire spread over load-bearing boundaries is likely to occur following a collapse in the novel design, rather than by conduction as in the prescriptive steel design.

- Fire spread through installation passages seems possible both in the novel and the prescriptive design. Especially when the ship has seen some years of service and may have undergone upgrades, maintenance, repairs et cetera.
- The greatly thermal resistance of the novel design will make it much more difficult or even quite impossible to locate the fire seat by detecting hotspots in the adjacent space.

Summarizing the impressions in a timeline of sorts, we can analyze at what point in time the differences start occurring: It is likely that the fire will behave quite similarly up until the point in time that the inner ceiling fails. Tests and incident reports suggest this may or may not occur during a complete fire development in a cabin. If, or when, the inner ceiling has been breached by the fire, the subsequent ceiling jet in the void space above may be somewhat more intense, leading to a quicker fire spread in the void space.

In the prescriptive design there are many onboard compartments that only are separated by A-0 or B-0 class. This is essentially just a steel plate without insulation. If there is a fire on either side of such a boundary, the risk for fire spread via conduction is large. The FRP composite in combination with added insulation will contain a fire much better than the prescriptive steel design in these spaces.

In a severe fire scenario, temperatures are likely to get higher with the novel construction to some extent. This may imply more severe conditions for BA-teams to work in because of the increased heat.

After 60 minutes time of unhindered fully developed fire, the FRP composite's ability to bear loads is compromised. Collapses should be considered an imminent threat, with subsequent fire spread to the adjacent compartment. In a real world fire scenario this time to collapse is likely to be higher due to several factors, such as presence of inner ceilings and more modest fire developments compared to the tests.

If the fire has been severe enough, an FRP composite will be more difficult to fully extinguish as it will tend to reignite at local places for quite some time after the main fire has been put out.

6.2 Fire severity required for a deviant fire behavior

Based on the arguments in the following two subchapters 6.2.1 and 6.2.2, it can generally be said that in the case of an inboard fire incident, the outbreak must be very severe indeed for the fire to behave differently in a more negative manner with the novel design. All minor incidents, moderate fires and most or all plausible worst case fire scenarios seem to benefit from the novel design due to its ability of better fire containment. In the case of a catastrophic scenario where active and passive protection fails and the fire is not combated for some reason, the novel design will after at some 60 minutes of severe fire be likely to fail structurally, starting with the most fire-exposed area. The time of 60 minutes may on the somewhat conservative side due to the nature of the tests, but the fact remains that if a severe fire is not fought it is probable to cause collapses.

Analyzing what may happen in the case of an outboard fire is difficult due to uncertainties as to what protection is to be installed. Quite likely a high level of safety will be agreed upon with drenchers/sprinklers and some sort of outer layer. If an area that is furnished with combustible material is constructed of either unprotected FRP composite or FRP composite with an outer laminate that only possesses low flame spread characteristics, and this area either does not have sprinklers installed or they malfunction, a more intense fire is possible with the novel material compared to the prescriptive steel design. If the outer layer is incombustible and the sprinkler fails, fire development should be about the same as with the prescriptive design.

6.2.1 Inboard fires

In order for a fire to become sufficiently severe to induce a deviant behavior on board a ship with the novel design, one or more safety systems must first malfunction. As long as the sprinkler system is operational for instance the fire will not be able to pose any serious threats to the load carrying structure, though it may grow rather strong locally if the fire seat is obstructed. Thus, the first requirement for a fire to grow sufficiently is that the sprinkler system is out of order. In addition to this, if the fire seat is in a confinement such as a cabin, the door closers must also cease to function in order for allowing the fire air supply.

6.2.1.1 Cabin fires

When it comes to cabin fires, tests and reports indicate that in the case of cabin enclosure fires, it seems that it is not until after the fire's HRR has already peaked and has started to dwindle, that the confinement's inner ceiling and walls get severely compromised. Naturally, it will also be hot in the void space above and around the cabin, but on a lower scale than if the walls and ceiling had not been there at all. Inspecting the results from the SP cabin fire test (Appendix C.1) it seems that the weak spot in these types of fires are the floor, as it received quite a bit of damage with an estimated 10% mass loss, while upper deck and bulkhead were quite undamaged. However, even though the cabin was allowed to get completely burnt out with oxygen supply limited only by the openings to the cabin, the intense fire was probably still not enough to cause any collapses in the load carrying structure (the test was performed unloaded).

The SP cabin test indicated that the fire spread to the adjacent cabin after around 40 minutes from ignition (although smoke penetration started much earlier). Not long thereafter, the first cabin was almost completely burnt out. It is difficult to say for sure what would happen with the load-bearing structure if a fire for instance start in one cabin and is left untouched for long enough to spread to the two adjacent cabins on either side. Considering the 60 minutes span which is the result from constant flames onto the same place at one FRP panel, it seems that subjecting different parts of the FRP deck at intervals as the fire skips through cabins, will cause a collapse if the process is not stopped.

6.2.1.2 Enclosures without inner ceiling

There may be onboard spaces where no inner ceiling is present. These may include machinery spaces et cetera where access to installations is a higher priority than décor appearances. These spaces may also contain highly flammable materials, such as motor or hydraulic oils et cetera. Should a severe fire break out in a space like this, the time until collapse of 60 minutes is to be considered valid, especially if the space has a high supply of combustible materials and access to air.

6.2.1.3 Larger inboard spaces such as restaurants, theatres et cetera

When it comes to larger spaces with the potential for a high power output fire, there is also reason for extra caution. A severe fire here may be able to affect a larger area of the FRP composite above and is also more likely to be able to transfer a lot of heat to a part of the above deck for a longer period of time. Although these type of spaces normally have inner ceilings which should help prolong the time to collapse, there is reason for extra caution when handling fires in these spaces. The reason for this being that if a collapse does occur, the consequences are likely to be higher than in a cabin area. Since the fire may affect a larger area of the deck above, a collapse is likely to be larger than that which may occur when a smaller compartment fails. In addition to this; the larger the part of the load bearing structure that is subjected to fire, the smaller the chance is that the surrounding (still unaffected) parts of the structure is able to bear also the affected structure's load. Thus, the risk of a collapse taking place is also increased.

6.2.2 Outboard fires

The case of the fire onboard Star Princess has indeed shown that the risk of outboard fire spread must not be ignored. The presence of combustible materials on the outside of the hull or on deck is a potential fire hazard. In the prescriptive design the outboard side of the hull is not really susceptible to flame spread since it is made out of steel. However, most large cruise vessels built today have balconies that have proven to be a hazard. Tests (Hertzberg, Axelsson, & Arvidson, 2008) have shown that an unprotected FRP sandwich is susceptible to quick flame spread along its surface. The same tests also showed that a drencher system is very effective for eliminating this threat, even if there is a severe cabin fire with a broken window present. What type of protection the hull will be equipped with is still uncertain as it is a work in progress but as of now outer layers that are either incombustible or has low flame spread characteristics, drenchers, or a combination of both are considered.

Most modern cruise ships such as the Norwegian Gem have one or several sun decks. To accommodate the passengers' needs for amusement and relaxation they are often quite packed with facilities constructed in combustible materials, such as waterslides, poolside sun chairs, bars and restaurants et cetera, as can be seen in figure 8. This makes for a potentially large fire if conditions are unfavorable.

Figure 8. Sun deck on the Norwegian Gem (SP internal pictures).

What are the implications of introducing the novel construction to such an area? Again, the final decision has not been made what measures will be taken to reduce fire risk in these areas. Much like with the outboard side of the hull, designers consider different outer layers and/or sprinkler solutions. Given these premises it is not really possible to say what will happen in case of an established fire, but one can easily see how an unprotected FRP panel would increase the severity of the fire. However, the layout of the area being outdoors and mostly open, speaks in favor of the likelihood of a rather swift and effective firefighting effort.

When there is a fire on the outboard side of a ship, spread may be either assisted or hindered by the weather. Onboard the Star Princess a strong wind hastened flame spread, until the captain altered the ship's course to minimize winds on the port side where the fire had broken out. This is an advisable approach, as well as attacking the fire from the upwind side if possible.

6.3 Structural failures

From a firefighting perspective, structural failure is a very important aspect. How long is the novel structure likely to withstand a severe fire? The nature of how collapses occur is also relevant information. These issues are attended to in this chapter.

6.3.1 Collapse process of a steel construction

History shows that passenger ships built in steel is normally not susceptible to serious collapses as a result of a fire. Incidents such as the fires on board the Scandinavian Star (Almersjö, o.a., 1993) and many others have shown that even if fires rage for several days on steel passenger ships, the structure may become quite deformed but is unlikely to collapse.

6.3.2 Collapse process of an FRP composite panel

The particular FRP composite sandwich panels that are to be utilized when constructing a cruise ship in the novel design in the wake of the BESST project, is best represented by the in-house tests conducted at SP Borås. The tests show that it is possible to reach the requested goal of 60 minutes resistance to temperatures that represent a fully developed fire, as specified by paragraph 8.3.1 in IMO Resolution A.754. This is achieved through insulation that is capable of keeping the temperatures in the laminate under the threshold value, keeping the bonding intact for the duration of the test. When the (quite heavily loaded) SP tested sandwich panels failed, they did so in a rather sudden fashion. Only minor, if any, bulging or sagging was visible prior to collapse.

It should be noted that the time of 60 minutes may be a somewhat conservative figure in actuality due to the following reasons:

- Most likely an additional thermal barrier exists between the fire seat and the load bearing structure. The inner ceiling and walls separate most interior spaces on board from the FRP composite via void spaces that is used for wiring, ventilation, plumbing et cetera. These inner ceilings and walls are likely to withstand the initial flashover phase and the first ten or so minutes of fully developed fire. This reduces the thermal load received by the load bearing construction.
- Probable limitations in supply of fuel or air in an actual fire scenario will lead to lower or less sustained temperatures.

The above reasoning is based on the results from a full scale (un-weighted) cabin test at SP (Appendix C.1), as well as the incident reports from HMS Ladbury (Appendix D.2) and Star Princess (Appendix D.1).

This report is thus based on the reference time of 60 minutes until collapse occurs in lab tests. Of course, what this means in actuality is different from case to case, but it is an important reference.

In the prescriptive design the fire protection of the load-bearing structure ranges from class A-0 to A-60, depending on the compartments located on either side. Without going into too much detail, all A-class structures must withstand one hour of the standardized fire test without passage of flame and smoke. Furthermore, an A-xx class division must also achieve a temperature requirement; after xx minutes the temperature on the unexposed side may not rise more than 140°C on average and 180°C as a local maximum (IMO, 2009). What this means in practice is that an A-0 class division is just a steel plate. An A-xx division would be a steel plate with sufficient insulation *on one side* of the plate to fulfill the previously stated requirement for xx minutes. This means that although the A-0 division for instance will be able to withstand a very serious fire without collapsing, it would instantly start transporting heat away from the hot compartment. The temperature on the unexposed side will quickly rise to match that of the exposed side's and would pose a very serious threat for fire spread.

The base design of the Norwegian Future is that all divisions and load bearing structures of FRP composite are to be constructed of FRD-60 class. This is the High Speed Craft (HSC) code counterpart of A-60 class (IMO, 2000), which is practical since the HSC code has been in use long enough for industry to develop technical solutions that fulfill its requirements. High Speed Crafts are usually constructed in lightweight designs such as aluminum or FRP composite. The definitions of the A-class divisions and the FRD divisions in the HSC Code are presented in Appendix E. However, a disclaimer should be added; there is the possibility that some specific parts of the FRP composite design that are deemed low risk and perhaps not load bearing, are constructed with a lesser protection from fire (e.g. FRD-30). Such areas could perhaps be balconies or the uppermost overhead deck that does not bear heavy loads.

6.3.3 Collapse propagation through the overall structure

The introduction of the novel design puts higher demands on the firefighting commanders on board. In addition to requiring a swift and efficient response, it also requires greater understanding of when and where it is necessary to adopt a defensive strategy or withdraw. When it comes to evaluating the risk of structural collapses, all onboard fires will be different and the dangers they imply will vary from case to case. For instance a weakened bulkhead in the bottom FRP composite deck may compromise all decks above as they may fall down. A fire that only affects horizontal decks in a significant fashion, should be less likely to cause major collapses and should only affect the adjacent decks in a closer vicinity to the fire seat. Thus, protecting the load-bearing bulkheads and hulls from heavy fire exposure may in some cases be more crucial than protecting decks if one is limited in firefighting resources.

However, this is an area that needs more research – perhaps it could be done by computer simulations, where one looks at how the load is distributed when different load-bearing components are removed or weakened? The results from such research could aid fire commanders on board. In the end, they will be the ones who will need to make decisions on a case-to-case basis, regarding the safety of the firefighting crew. Having the tools and experience to make the most informed decision possible should be a priority.

6.4 Added toxicity, smoke production and fire load

The novel design introduces a potential problem in that it is combustible and will thus produce toxic gases and smoke through pyrolysis when exposed to sufficiently high temperatures. It will thus also add to the fire load. In the following two subchapters, those issues are debated from two scenarios: before and after collapses.

One of the risks identified in a preliminary study (SP, 2012), was that the introduction of combustible material in the load-bearing construction may cause a greater production of toxic gases in the case of fire. This is naturally true, but how much practical impact does this have in actuality? Large scale tests in which a standard cabin was burnt out showed that the gases produced by furnishings and interiors were very toxic. For instance, the amount of CO produced by one cabin in 15 minutes was estimated to be sufficient to make an area of 2100m^2 on board inescapable due to incapacitation. The HCl production peaked after 5 minutes and was measured to almost 20.000 ppm which is over 60 times the 300ppm limit for incapacitation when inhaled (average production throughout the test was 6600 ppm) (Hertzberg, Axelsson, & Arvidson, 2008).

When the temperature rises, the FRP composite laminates will start to pyrolyze in the region of 250-300°C for both polyesters and phenol resins (Troitzsch, 2004) (Hertzberg, 2009). However, it is not until the materials reach temperatures of 350-400°C and ~520°C, respectively, that they produce a sufficient amount of gases to be ignited by pilot flame (flash ignition) (Hilado, 1998). How long it would take for the FRP laminate to reach 250°C and above is difficult to say for sure, as it will vary from case to case depending of the intensity of the fire and amount of insulation. In the large scale cabin test, the temperature registered by the two thermocouples *in the center of the ceiling FRP composite's core* registered 90°C and 120°C after 60 minutes. They peaked at 127°C and 142°C after 85 minutes (total test length was 115 minutes) (Hertzberg, Axelsson, & Arvidson, 2008). The FRP core temperature graph is presented in Appendix C.1. Although the temperature on the exposed side of the core and in the laminate would have been higher than in the core, the structure was quite undamaged and had thus not undergone much, if any, pyrolysis. However, the floor of the cabin received quite a bit of damage to the exposed laminate and its core. It was estimated to have lost around 10% of its core mass during the fire (Appendix C.1) (SP, 2012).

6.4.1 Pre-collapse toxicity, smoke production and fire load

Since the FRP composite sandwich construction's stiffness and load-bearing capability is largely dependent on intact laminate bonding, it should be unlikely that any pyrolysis takes place before the structure fails in most cases. The delamination of an FRP composite panel occurs at around 120°C-200C°, while the pyrolysis will start to occur somewhere in the region of 250°C-300°C. However, the loss of load bearing capacity is localized to the area that is fire exposed and it may be so that even though a part of the structure has lost its load bearing capability, the surrounding structure is able to bear that load. Thus, there is certainly a possibility that some pyrolysis of the sandwich construction can occur before it collapses.

How large is this addition of toxic gases from the novel design? Let us take a look at the large scale cabin test performed at SP and compare the amount of HCl produced by the cabin's interior to that of the novel construction material. In this case the core material was made of balsa wood, but let us makes the assumption it was 100 kg/m^3 PVC foam. It is assessed that around 10% of the floor was consumed in the fire (SP, 2012). Neither walls (bulkheads) nor ceiling (upper deck) received serious damage. The cabin's floor area was 12,9m^2. A 100 kg/m^3 PVC core with a thickness of 50mm for such an area would weigh 64,5kg. Thus ~6,5kg PVC would have been consumed in this event, should the core have been made of PVC. To put this figure into perspective, 47kg PVC was also consumed inside the cabin when the standard issue interior and luggage was burned.

What about the sandwich construction's contribution to fire load and production of pyrolysis gases? PVC has a heat of combustion of 14,9 MJ/kg (Hertzberg, Axelsson, & Arvidson, 2008). This means that the 6,5kg PVC which the novel design contributed with in the cabin fire test equals a fire load of 96,1MJ. This roughly equates to an addition of 3,1% when compared to the cabin's total calculated fire load of 3080 MJ. Thus, the addition of general toxic fire gases from combustion (which thus also makes out practical added fire load) from the sandwich in this particular case is in the region of 3%. Added production of HCl was in the region of 14%, based on the arguments in the previous clause.

It can be concluded that as long as the fire stays in the region of a *plausible worst case scenario,* the additional gases produced by the novel construction are quite marginal when put into context of the amount that is produced by the fire itself – both in respect to toxicity (14% HCl addition and 3% CO_x addition) and fire load (3% pyrolysis gas addition).

6.4.2 Near-or-post-collapse toxicity, smoke production and fire load

After 60 (See Chapter 6.3.2 for more detailed information regarding this time) of severe fire, structural collapses may occur. A fire which is still intense after this long has some implications for just how severe the fire is. That firefighting efforts still are futile at this point means some rather unexpected event must have taken place and the fire has been allowed to spread, otherwise the fire should have been controlled already. At this stage when collapses start occurring, the novel design seems likely to start adding to the fire load in a more than insignificant fashion. A collapse may damage the insulation and expose the sandwich panel to the fire, quickening the pace of combustion. However, such a collapse would also lead to imminent fire spread to the adjacent compartment which will add new fuel (furnishings et cetera) to the fire if it is not fought by crew. This added fuel seems likely to pose a larger threat than the sandwich panel itself. Not only because of sheer mass (comparing mass of the combustible material in a furnished cabin ,for instance, to that of a sandwich panel it is in the region of 3:1 (Hertzberg, Axelsson, & Arvidson, 2008)), but also because the exposed area of the fuel in the cabin is many times larger than that of the panel. The cabin fuel leads to a more rapid and intense fire development since HRR is correlated to fuel surface area as long as there is a sufficient supply of air (Karlsson & Quintiere, 2000). However, if the collapsed sandwich core is made of PVC and not wood, a significant amount of HCl may be added to the smoke at this point.

It seems that the most critical problem caused by a structural collapse is not that the construction material is added to the fire. Rather, the bigger problem lies in the actual spreading of the fire to the adjacent space. This adds fuel that is not only more substantial in weight, but also has a much larger surface area exposed to the fire, allowing a more rapid contribution of pyrolysis gases to fuel the fire. It should also be kept in mind at this point that fire spread is also a concern in the prescriptive design, although it is not likely to be caused by a structural collapse in this case.

6.4.3 Recommendations for fire gas toxicity minimization

Based on the arguments in chapter 6.4.1 and 6.4.2, it could be argued that if one wishes to increase safety on board by minimizing HCl production in the case of a fire, it is recommended one primarily starts with minimizing the amount of PVC in furnishings and interior surfaces (carpentry and flood laminates for instance are major contributors of PVC). When considering both passenger and crew safety it should be most important to improve conditions in the earlier stages of a fire, rather than at the latter stages when evacuation has already taken place. The FRP composite construction only starts contributing to production of toxic gases in a more than marginal manner in the late stages of a plausible worst case scenario and in disastrous scenarios. At this point the fire has been combated for a long time and any crew coming into contact with smoke should long since have been using BAs.

If one has already minimized PVC in the interiors, the next step would be building with wood core instead of PVC core to also eliminate the contributions from the novel design, but before all interior surfaces have been overseen the composite's core is of secondary significance.

6.4.4 FRP composite fire aftermath: decontamination

One other concern regarding the toxicity of a FRP composite that has carbon fiber in it, is how the fibers may oxidize and fractionate when subjected to high temperatures. This may cause the carbon fibers to obtain physical properties that allow them to get transported deep into the lungs, where they may cause health related problems (Mouritz & Gibson, 2006) (Hertzberg, 2003). After combustion they are likely to get deposited on surfaces that the smoke comes into contact with. During main firefighting efforts, crew of course uses breathing apparatuses. However, it is also important to make sure adequate protection is being used in the clearing work after a fire. The deposited particles are easily disturbed to once again become airborne even though the smoke has already cleared. These particular particles are of course only one part of the spectrum of hazardous particles that are deposited from a fire, and an air-purifying respirator should be worn in any case when cleaning up after a fire.

For these dangerous fiber particles to form in a significant scale, high temperatures normally associated with a fully developed fire of at least 600-700°C are required (Hertzberg, 2003). It is thus unlikely the particles are formed as long as there is insulation present between the fire and the laminate. However, if a fire takes place that leads to a structural collapse this could be an issue. More likely in actuality, this issue needs to be taken into account if a fire takes place where the FRP laminate is unprotected and also exposed to high temperatures. It is probably also required that either additional high energy output fuel is present, or the construction forms some sort of confinement, for the laminate to reach high enough temperatures to produce the dangerous fiber particles (Hertzberg, 2003). Inventorying the spaces on a ship, it is most likely such an event can take place outboard on decks, balconies or similar areas, since interior spaces are insulated.

The following materials are recommended for decontamination (Hertzberg, 2003):

- Sealed clothing such as a chem suit or decontamination suit. Disposable protective suit made of paper is not sufficient.
- Leather gloves
- Respiratory protection with filter. Disposable face mask is not sufficient.
- Sealed protective goggles.
- Protective rubber boots.

6.5 Firefighting strategies, techniques and equipment

This chapter discusses novel firefighting strategies, techniques and equipment.

6.5.1 Boundary cooling or cooling of hot smoke from adjacent space?

Performing the method of boundary cooling on the un-exposed side of a bulkhead or deck that is traditionally performed on steel ships will not be effective in an FRP composite construction. The thermal barrier, that is due to the FRP composite construction's high thermal inertia, is much too great for this method to have an effect. Instead, this method should be replaced with the method of cooling the hot smoke on the exposed side from the adjacent space. Not only does this reduce temperatures significantly which will reduce the risk of a collapse occurring, but also dampens the fire which increases the odds of firefighters being able to put it out. The method of cooling of hot smoke from the outside of a confinement is best used when the fire is fully or partially ventilation controlled (Svensson, 2005).

This method with cooling of hot smoke could be made possible by two types of tools; Cutting Extinguishers (CE), and Fog Nails (FN). However, the need to investigate first and foremost the CEs' ability to function properly in the specific construction that is to be used in the novel design was found. That is, its ability to penetrate both an FRP composite panel with insulation on the backside, as well as the inner ceiling/wall that makes out the cabin modules and other interiors.

6.5.2 Cutting Extinguisher or Fog Nail?

Both Cutting Extinguishers and Fog Nails are effective tools, albeit they both have strengths and weaknesses. However, if used correctly they are often able to put out most of the fire which eases subsequent firefighting efforts in the hot area. Other than for the purpose of cooling of hot smoke, the CE can also be used for cutting holes in the structure for ventilation purposes. Furthermore, the CE has the capability to penetrate a steel construction, something that the FN is unable to do.

The CE (Figure 9) is a tool that shoots out water with an added granulated abrasive under very high pressure (200 - 300+ bar), enabling it to cut through all materials used in constructions today. The abrasive is added to the water stream by the command from a radio transmitter and is used when cutting. When a hole has been established no abrasive is needed. To use the CE the operator simply puts the nozzle against the wall/ceiling/floor, applies pressure and pulls the trigger. The water spray will cut through the wall in a matter of seconds, forming a hole through which water is allowed to flow and cool the adjacent space. In the targeted compartment, the powerful water spray will have fully broken up into a mist after 5-7 meters. The water flow velocity through the hose is around 4,8m/s, indicating that there is an approximate 22s delay in a 100m hose, after abrasive is added to the water (at the pump). Furthermore, the pressure loss in the hose is low (< 0,1 bar/m) which indicates it is possible, although perhaps not optimal in terms of practicality, to use a quite long hose (Carlsén & Winkler, 2000).

The study by Carlsén & Winkler also shows that the CE is fully capable of penetrating an FRP composite construction. However, it is at this point unclear whether the CE has the power to penetrate both the FRP composite construction, insulation and also the inner ceilings/walls of the cabins/compartments. This is something that needs to be tested.

Figure 9. A Cutting Extinguisher's spray pattern (Skärsläckarkonceptets operativa användande, 2010)

The FN (Figure 10) is basically a steel pipe that connects to a fire hose at one end and has a nozzle at the other to disperse the water flow into a mist. The FN comes in different lengths to accommodate for different geometries. It is adapted to operating at the lower pressure of onboard fire pumps and does not need to be powered by a high pressure pump. The FN is either hammered through a wall/ceiling/floor or inserted through a hole predrilled with a battery-powered power-tool, depending on the toughness of the construction. Tests have shown that it is difficult or impossible to hammer a FN through an FRP composite; a drill is thus required for aiding placement (Andersson & Krasniqi, 2001), if adequate holes are not already installed during construction of the ship. Furthermore, a FN is not capable of penetrating a steel construction.

Figure 10. Fog Nail and hammer (Andersson & Krasniqi, 2001)

Comparing the two systems it appears that for this type of application on board large cruise ships, the CE has the main advantage of being able to penetrate all types of constructions (also steel). In addition to this, it is quick and easy to deploy and reposition. Some sources also indicate that CEs seems to have the upper hand when it comes to sheer cooling performance from a single unit (MSB, 2006), especially when taking into account the slightly lesser amount of water used. Unless adequate holes are installed for the purpose of accommodating FNs, will they FN requires more of an effort to deploy in the FRP composite construction, and is not applicable at all in the steel construction. However, FNs are cheap and easy to adapt to current materiel and could be very useful in the FRP construction for maintaining boundary lines or dampening large fires that a CE cannot control without assistance. Furthermore, the FNs have the possibility of more accurate control of where the water mist is deployed as the CE is quite powerful which may cause difficulties if one for instance would like to cool a void space.

The CE is a system that may have some difficulties in adaptation to use on large cruise ships. The apparatus weighs in at a minimum of around 500kgs and this means it would need to be permanently installed at appropriate intervals throughout the ship. If complete coverage is desired will the reach of the hose from one unit need to overlap that of the next unit, indicating that the intervals at which the units needs to be placed are the same as the actual reach of a unit's hose. The standard reach from a unit is normally 60-80 meters, but this can be extended up to about 200 meters by connecting additional hoses (Trewe, 2012).

A problem with installing the Cutting Extinguisher would be how to pass the hose through the ship without disturbing the main vertical zones. Keeping fire zones intact in the case of a fire is very important for a number of reasons. This could probably be solved by either installing fixed high-pressure piping along the length of the ship, where firefighters can connect the CE hose and nozzle, much like the main fire line that supplies the ships' fire posts today but with the exception that the CE hose and nozzle needs to be collected from an assembly station. It could also be solved with fixed connections through all fire zone boundaries, although this would mean firefighters may need to lay out a lot of hoses which slows down the firefighting operation.

One middle-road in choosing equipment is installing both, implying that with the two systems overlapping each other, redundancy is created. The Cutting Extinguisher would be installed as a primary choice for hot smoke cooling with fixed piping along the length of the ship, with CE fire posts at appropriate intervals where the CE hose and nozzle can be connected. This means that one unit installed mid-ship can cover the full length of a ship. This system can then be complemented by giving firefighters access to Fog Nails that can be used in case the CE fails or is rendered inoperative due to the fire. Fog Nails would also be suitable for holding boundary lines in the FRP composite construction. This should be a fairly cost efficient solution that is also redundant, and it is this solution that is recommended by the author of this report.

Furthermore, it may also be suitable to (discreetly) mark areas inside the ship that are appropriate for CEs and/or FNs. This is to ensure efficient results when deploying the equipment and to minimize the risk of some obstruction impeding with the effectiveness of the equipment.

6.5.3 Fog Nail and Cutting Extinguisher strategies and purpose

Warning: implementation of CE or FN must, for effective results, be accompanied with proper training of both fire commanders as well as firefighters that will be handling the equipment. The following subchapter is not to be used for educational purposes. Furthermore, the CE is a dangerous tool that may cause serious injury or death if handled improperly.

In case traditional fire extinguishing with BA-teams is problematic or dangerous e.g. due to high temperatures, one solution is to cool the hot smoke from an adjacent compartment with a water mist. When the mist gets into contact with the hot smoke it is vaporized, expands 1700 times and creates inert steam (at 100 °C) in the process (Särdqvist, 2006). The strategy is best used in a closed compartment that is kept shut so the cooling effect works in synergy with ventilation control. A Cutting Extinguisher does not have the extinguishing power of a regular hose when it come to putting down open flames (not ventilation controlled), especially if the fire is severe. Outboard fires are thus still better fought with standard materiel and neither CEs, nor FNs, are recommended here. Furthermore, aggressive firefighting with BAs is also not the intended use of CEs. The reason for this is its inability to form a protective screen of water that the firefighter may need for his or her safety.

The strategy of cooling of hot smoke could be employed with CEs and FNs in the novel design both through interior compartment boundaries, as well as load-bearing boundaries. In addition to this, CEs (but not FNs) would also be able to penetrate a load-bearing structure that is constructed in steel. In the application case Norwegian Future this would be all decks below the uppermost five. Giving firefighters access to CEs throughout the whole ship should therefore be considered, to grant them the possibility of cooling of hot smoke in all onboard areas. Cooling of hot smoke would be beneficial in respect to both firefighting effectiveness and firefighters' risk exposure, also in a prescriptive design.

A CE may also be useful in some cases when it comes to putting out fires in areas such as void spaces that are difficult to access, and residual fires in the composite behind the insulation.

Hot smoke cooling strategy can also be effective for maintaining a boundary line. If using FNs, it is recommended that several units are deployed simultaneously at appropriate spaces for best effect. However, care must be taken to the amount of water that is injected so that excessive amounts are not used, as this may affect the stability of the ship. One strategy that can reduce the amount of injected water when maintaining a boundary line is switching the nozzle on and off in intervals; for instance 30s on and 60s off.

Furthermore it is important to try and visualize where the water mist will be deployed in the adjacent compartment. Does one wish to cool the void space or the cabin behind it? How thick is the construction? Questions such as these must be considered; the strategy is only effective as long as the water mist gets into direct contact with the hot smoke and the water is vaporized, especially when it comes to working with FNs due to the larger drop size.

(Bengtsson, 2001) (Sirenen, 2007) (Skärsläckarkonceptets operativa användande, 2010) (Carlsén & Winkler, 2000)

6.5.4 Location of fire seat from adjacent space

The thermal resistance of the prescriptive design varies, depending on how much insulation is added to the load carrying steel construction. The amount of insulation may vary between nothing and enough to keep the unexposed side below 140°C - 180°C for as long as up to 60 minutes, depending on what compartments are adjacent (see Appendix C:a for more information). The FRP composite however, has added insulation as well as its built in properties of having high thermal resistance in itself. In the case of a severe fire, it is thus likely the unexposed side of the novel design will remain cool for a much longer time than if it would have been constructed in steel.

The great thermal resistance of the novel design will thus make it more difficult or even quite impossible to locate the fire seat by detecting hotspots in the adjacent space. It is more likely such a technique is successful with the prescriptive steel design.

6.6 Firefighting operations' effectiveness and efficiency

This chapter discusses the firefighting operations' effectiveness and efficiency in the novel design

6.6.1 Effectiveness in the novel FRP composite design

There are several factors that speak for an improved firefighting effectiveness on board a ship of the novel design when comparing to one of the prescriptive design, when novel firefighting strategies and equipment are taken into account for. Removing the need to perform defensive boundary cooling will free firefighting resources that can be rerouted to either assisting in actively combating the fire by assisting BA-teams or adopting a strategy involving cooling of hot smoke from an adjacent compartment. Boundary cooling is a strategy that uses up resources without actually fighting the fire and is primarily in the purpose of hindering fire spread.

Combining these added firefighting resources with the introduction of Cutting Extinguishers (CS) and Fog Nails (FN) will allow the fire to be dampened from outside of the fire seat. This is a great strength, should the fire be too fierce for firefighters to initially be able to control it. In addition to suppressing the fire, deployment of FN or CS in case of a severe fire are also strategies that should significantly increase the time until collapses start occurring.

A parameter that speaks for a decline in firefighting efficiency with the novel construction is that if the fire has been severe for quite some time and has taken root in the FRP composite, it will be more difficult to fully extinguish than in the prescriptive steel design. This implies more resources may be needed for monitoring of fire scorched areas to ensure flames do not reignite. However, this should not interfere too much with the critical stages of taking control of the fire.

Furthermore, the improved thermal resistance of the structure also implies great difficulties of finding the seat of the fire from adjacent compartments due to the lack of sufficient temperature rise on the backside of heat exposed FRP composite.

All in all the ability to focus more resources on actually fighting the fire, combined with the introduction of techniques and strategies to cool hot smoke from an adjacent compartment are believed to improve the effectiveness of firefighting efforts. This is also a conclusion shared by the European military collaborative project EUCLID RTP3.21, that spanned over three years and was coordinated by Det Norske Veritas (McGeorge & Høyning, 2002) (Gutierrez, o.a., 2005).

6.6.2 Effectiveness and efficiency from the organization management's point of view

Given how the rules governing the ships' safety organization are functionally-based (see Appendix B), there is quite a bit of room for differences in how well such an organization is set up and managed. Is the management on board advocating fire drills that barely meet minimum requirements or is a real effort made to create the best performing organization possible at a reasonable cost? Depending on where the ship is flagged and where it sails, inspections may also be more or less zealously performed.

One can draw the conclusion that the performance of the organization is very much dependent on how much effort is put into it. Noteworthy is that the firefighters are not required to have any additional training other than Basic Safety Training, in order to become a member in a firefighting squad. It is thus up to the shipping company to set a high standard of safety management and the onboard organization is responsible to carry it out into effect. The point of this whole setup, according to ISM, is to recognize that no two ships or shipping companies are the same, and that each organization may thus become optimized to the task that is at hand. One fine example of when the firefighting organization onboard has performed admirably was in the case of the large fire onboard Princess Cruises' ship Star Princess. The firefighters were able to put out a large fire that originated on the ships' balconies and quickly spread along the ship's side, also involving cabins. The organization proved that it was trained well enough to be able to deal with this unexpected and unrehearsed scenario in a commendable manner. More information on this case can be found in Appendix D.1.

On the other hand, there are examples such as the Scandinavian Star, where fire safety was obviously not a priority. Not only was the installed fire protection poor, but also did the crew not respond to the fire threat in any effective or efficient manner. As a matter of fact, they barely responded at all. All in all the incident became a tragedy and 158 people lost their lives (Almersjö, o.a., 1993).

6.7 Complexity and robustness of firefighting performance

Introducing additional routines to an existing firefighting organization is bound to increase the complexity of it. From a Human Errors and MTO (Man-Technique-Organization) perspective this in turn implies a greater risk of human errors and thus increased risk of dissatisfactory results of an operation to some extent. In order to minimize these added risks, it is important any novel routines are designed in such a manner that the complexity added to the organization is minimized. This is suitably done by adopting techniques that are as similar as possible to those firefighters and commanders are used to from their training and experience.

The robustness of the firefighting organization on board on the other hand, is likely to increase with the novel design. Since more firefighting resources will be available to combating the fire, rather than being tied down in boundary cooling operations, there should be more redundancy for handling unexpected events.

6.8 Firefighters' personal risks

When assessing risks that firefighting crew are subjected to, one must look at the whole span of fire scenarios that may occur. In this subchapter we shall start by looking into which inboard scenarios brings lower, unaffected or increased personal risk when implementing the novel structural design in combination with novel firefighting strategies and equipment. The scenario identification is followed by a discussion about implications on total personal risk and risk management.

It should be noted at this point that the term *firefighters' personal risk* is hereby defined as the probability of being subjected to a serious injury or death during a set amount of time while enlisted in the core firefighting organization (described in chapter 5.1) on board a ship.

6.8.1 Scenarios with reduced firefighters' personal risk

Introducing the strategy of cooling of hot smoke will imply a lower risk to firefighters in certain scenarios. Those scenarios are first and foremost the quite severe ones, which are difficult to combat in a traditional way with BA-teams. Instead of being forced to enter a hot area with potential risks such as backdraft or flashover that may cause harm to firefighters, the crew can instead use the safer strategy of cooling of hot smoke prior to entering.

In addition to this, less crew should be tied down in defensive boundary cooling operations when fires take place in areas constructed in FRP composite.

6.8.2 Scenarios with unaffected firefighters' personal risk

The majority of fire incidents that take place on board never reach a serious state. Most of the time the fire self-extinguishes, is prevented from growing by passive or active systems, or is put out by someone at an early stage. All these scenarios should be considered unaffected by the novel design when it comes to firefighting risk. The fire's severity is not great enough for the novel strategies to make much of a difference, at least in terms of personal risk. Furthermore, the additional manpower is not likely to make a noticeable reduction when it comes to firefighters' personal risk, since such a small firefighting operation should not benefit much from the added available workforce.

In this report all outboard fires will be considered scenarios with unaffected risk. The reason for this is partly due to the lack of data to base the analysis on, as the risk management process is not complete. Depending on which different solutions for managing outboard fires are chosen, a fire may be more likely, less likely or equally likely to pose a threat to firefighters in the end. For instance, if outboard decks are fitted with sprinklers in the novel design, this could lower the severity of a fire since the areas are often furnished with flammable material, which means a severe fire is possible also in the prescriptive design without sprinklers. Furthermore, outboard fires should generally be less risk-intensive to combat than inboard fires as smoke filled enclosures are not such a concern. On the other hand, there are always uncertainties associated with introducing a novel design and some unknown fire hazard may be overseen. However, the risk engineers' perspective is of course that fire safety shall be equal or better with the novel design.

6.8.3 Scenarios with increased firefighters' personal risk

A fire that has reached a catastrophic state will lead to an increased risk to firefighters, when it takes place in an area that is constructed in FRP composite. Structural collapses, which do not really occur in a steel design, would be a great concern for safety. This topic is something that fire commanders need to address and learn about so that they can minimize the risk of someone getting injured in a collapse.

6.8.4 Firefighters' Personal Risk discussion

Summarizing the different scenarios in table 1 below, it becomes apparent that when adopting a relative risk approach, the question that ultimately needs to be answered is whether the increased personal risk caused by a catastrophic scenario is outweighed or not by the decreased personal risk in the serious scenarios.

Fire scenario	*Risk implication for firefighters*
Small/moderate fires	Unaffected
Serious	Reduced
Catastrophic	Increased

Table 1. Fire scenarios of varying size and their corresponding risk implication

In order to properly calculate a relative risk, two key variables are required. In this case it would be the probability of getting seriously injured while serving on board in a firefighting group for a set amount of time, both with the prescriptive and the novel design. Both these probabilities are missing.

$$RR = \frac{P(serious\ injury|novel\ design)}{P(serious\ injury|prescriptive\ design)}$$

However, the scope of the report is not to give an exact figure, e.g. RR=0.8, but to answer whether RR is lower, equal or higher than 1. Thus a comparison between P(serious injury|prescriptive design) and P(serious injury|novel design) is needed. The former probability should be possible to estimate from statistics and incident reports, although it would likely be associated with large uncertainties given that one of the limitations of this report is that it applies to large modern cruise ships only – thus making the statistical sample small. Furthermore, since no ships of this type have been built with the novel design yet, both statistics and incident reports of injuries are nonexistent.

The analysis proceeds by looking at how many scenarios firefighters' are exposed to that are beneficial in terms of personal risk, in relation to the ones that are detrimental. A common model for describing accidents that originate from similar causes is the Iceberg Model (Akselsson, 2008). It generally describes a crude ratio between incidents, accidents and major accidents or similar definitions. Depending on the application, the definitions and ratios vary. The most commonly cited model is probably the original one from 1931 with the ratio of 1:29:300 for major accidents/accidents/incidents (Heinrich, 1931). This ratio describes an average of different accidents in industries at the time (Rosness, o.a., 2010). Another example of an accident ratio described by the iceberg model is 1:10:30:600 (Akselsson, 2008), see figure 11.

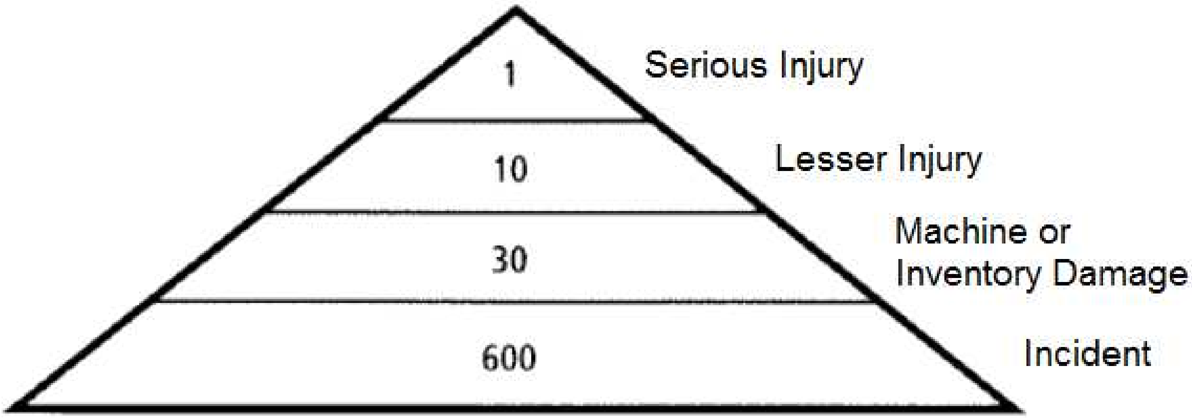


Figure 11. Ice-berg model example (Akselsson, 2008)

Looking once again at the different scenarios that affect firefighters' personal risk; catastrophic (detrimental) and serious (beneficial) while keeping in mind the introduction of hot smoke cooling strategy which is believed to increase firefighting effectiveness and help protect the structure from collapses by lowering temperatures, it seems that the ratio could be estimated to somewhere in the region of 1:5 - 1:10. This would be the ratio between the serious scenarios and ones where collapses occur that may lead to a full or near total loss of the ship, which take place in an area built in FRP composite.

What implications does this have for the RR comparison? Given that the serious scenarios are five to ten times more likely than the catastrophic one; to be able to state that the novel design is *at least as safe* as the prescriptive design in terms of firefighters' risk, the combined safety increase in all the serious scenarios must match or surpass the safety decrease of the one catastrophic scenario. In other terms, each serious scenario must induce a reduction of firefighters' absolute personal risk that corresponds to at least 10% - 20% of the personal risk increase caused by a catastrophic scenario.

So, is the firefighters' personal risk reduced by the smoke cooling strategies in combination with increased manpower enough to outweigh the increased risk implied by the danger of structural collapses? It is difficult to say for sure with this ratio interval of 1:5 - 1:10; it may be so.

However, upon installing Cutting Extinguishers on board, the author of this report recommends that it is done in such a manner that it covers the whole ship. Considering the reach of a unit, it should not be a too large undertaking. The reason for this recommendation is the following. Giving firefighters the option of cooling of hot smoke strategies not only in the uppermost FRP composite decks but also the rest of the ship, of course gives them the same benefits when it comes to reduced personal risk when fighting fires in the steel built areas. It has slightly other implications when it comes to effectiveness as complementary boundary cooling still may be necessary, if the CEs are not effective, but effectiveness is believed to increase also in the steel built areas.

Assuming the areas built in FRP composite make out roughly 1/3rd of all onboard spaces, implies that the number of serious fire scenarios (that of course can occur at any deck, not just on composite decks) that benefit from the access to CEs, are now tripled. At the same time, the added risk of collapses that may occur in the FRP composite design is not really a concern in these areas. This in turn means that the previously mentioned ratio interval of 1:5 - 1:10 is now 1:15 - 1:30. Expressed in other terms, a serious scenario must induce a reduction of firefighters' absolute personal risk that corresponds to at least 3% - 7% of the personal risk increase caused by a catastrophic scenario.

The different scenarios' consequences for the RR comparison are again illustrated in figure 12 below. The figure illustrates how a number of beneficial scenarios with a modest decrease in consequence (thus lowering firefighters' personal risk), may balance the increase caused by a detrimental catastrophic scenario. If it is so, that the beneficial scenarios balances or outweighs the detrimental one, the summarized consequence to firefighters' personal risk remains at, or below zero. This indicates that in a comparison of relative risk prior to, and after the introduction of the novel design, the RR is at the most 1.

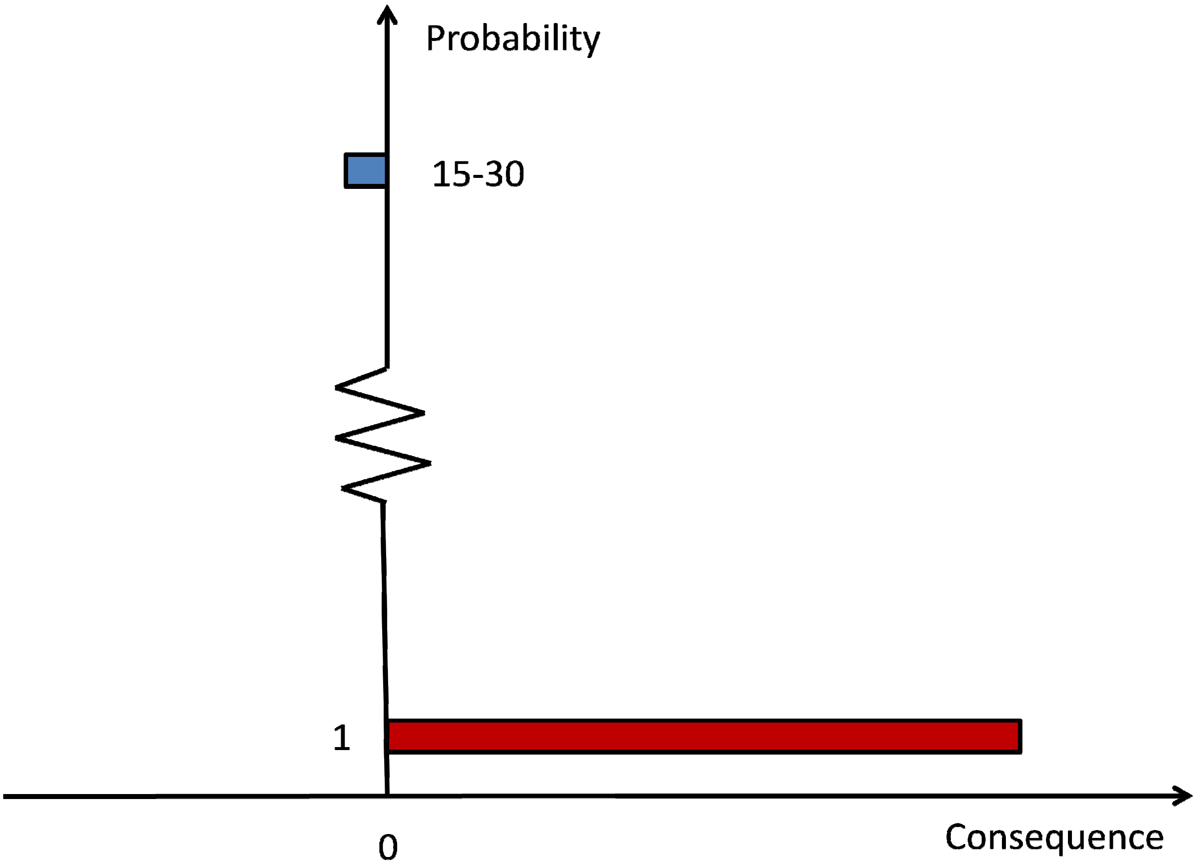


Figure 12. Illustration of how different scenarios may affect RR. If the beneficial scenarios each reduce firefighters' absolute personal risk by an amount that corresponds to at least 1/30th - 1/15th of the personal risk increase caused by one detrimental scenario, the consequence is zero or negative. This would indicate that RR is at the most 1.

With this interval of scenarios and keeping in mind the crew's often somewhat modest experience with aggressive BA-team operations in difficult environments, it appears probable to the author of this report that the benefits from new firefighting strategies and tools would negate or outweigh the increased personal risk to firefighting crew caused by structural collapses. Proper training is of course also an important part of this puzzle.

6.9 Ship construction which accommodates new firefighting techniques

During the process of writing this report some ideas and suggestions arose as to how the ship may be constructed to ease the adaptation of the new firefighting techniques and equipment. These are presented in this chapter:

- Marking of areas that are suitable for deploying a Cutting Extinguisher. This could be done discreetly and would decrease the risk of firefighters accidently cutting apart vital installations such as sprinkler piping etc. It would also increase the chance of effective results.
- Pre-installed discreet holes where Fog Nails can be inserted. This would increase the chance of effective results and also greatly ease deployment as pre-drilling of holes is not needed.
- Pre-installed connections through the main vertical and horizontal zones for extending the Cutting Extinguisher hose throughout the ship, without compromising the fire zone boundaries.

7 Conclusions

In this chapter, the conclusions of the report are presented.

7.1 Recommended firefighting strategies and equipment

The main differences to consider when fighting a fire in an FRP composite superstructure are the following:

- The possibility of structural collapses must be regarded as a great threat to both the safety of the crew, as well as to the effectiveness of the firefighting efforts. In case a fire is difficult to combat by traditional means with BA-teams, it is important to quickly apply hot gas cooling. This will not only lower temperatures and dampen the fire, enabling the BA-teams greater chances of success in subsequent attempts, but will also protect the load bearing structure from high thermal loads, increasing its chance of not collapsing.
- Traditional boundary cooling is ineffective and should be replaced with cooling of hot smoke from an adjacent compartment, with Cutting Extinguisher or Fog Nail. The strategy is effective both for improving firefighters' working conditions by suppressing the fire prior to entering, as well as holding a boundary line since it will greatly reduce the structure's exposure to heat.
- Firefighting commanders must be aware of the fact that the structure is susceptible to collapses and that individual parts of the structure is likely to withstand roughly one hour of exposure to fire. Commanders must, in order to prevent collapses from occurring, always try to stay one step ahead of the fire and plan for what's next.
- That a deck or bulkhead is of ambient temperature on the unexposed side is no indication as to whether or not there is a severe fire in the adjacent compartment. This is due to the FRP composite's high thermal inertia.
- Making use of the ship's advanced fire detection system is a great way to keep track of where exactly the fire started (and is thus likely to be the most intense here), and how it spreads. This information may be vital to firefighting commanders as they may need to deploy CEs and/or FNs while it is difficult or impossible to locate the fire seats from an adjacent compartment. It is thus important that great heed is taken to the order in which the different smoke detectors are triggered and that heat sensors are monitored closely (if applicable).
- After a severe fire in an FRP composite area has been successfully suppressed, it may tend to reignite locally for some time afterwards. Thus, the area needs to be monitored until temperatures in the structure have fallen to a safe level. The cooling process may be quickened by tearing down insulation and cooling the FRP composite directly. Furthermore, the adjacent compartments will also need to be monitored to ensure no creeping fires are propagating slowly through the construction.
- Non-insulated FRP composite materials that have been subjected to severe fire may produce harmful particles that requires extra caution when working in, or decontaminating, a fire-exposed area.
- Large inboard areas such as cinemas or restaurants that at the same time expose a larger part of the load bearing structure to fire, may be a priority to combat. The weakening of an FRP composite structure is localized to the actual site of exposure to fire, due to its poor conductive properties.

The size of a collapse occurring in such an area may thus be larger than in a small area, such as a cabin. The risk of a collapse taking place is also likely higher due to the larger part of the load bearing structure that is affected.

7.2 Firefighting crew risk

With the introduction of the new firefighting strategies and equipment presented in this report combined with adequate training, it is the author's assessment that the firefighting efforts can be performed in a manner that is at least as safe in the novel design as in a prescriptive design.

7.3 Firefighting organization's effectiveness and efficiency

With the introduction of new firefighting strategies and equipment presented in this report combined with adequate training, it is the author's assessment that the firefighting efforts can be undertaken in a more effective and efficient way in the novel design.

7.4 Requirements of firefighting organizations

Introducing novel strategies and equipment to the existing organization requires appropriate training of both firefighting crew and commanders. Firefighting crew and commanders must be aware of the differences associated with fighting a fire in the novel design, compared to the prescriptive one. New equipment and strategies are only effective if used correctly. To successfully extinguish fires on board an FRP composite ship, a swift and efficient response is of great importance due to the risk of structural collapses.

Furthermore, it will be increasingly important that the firefighting efforts in an ongoing operation are consistently reevaluated so that risks associated with structural collapses can be foreseen and minimized. The necessities of staying one step ahead of the fire and plan for different outcomes is increasingly important in the novel design.

The two previously mentioned requirements imply that the firefighting organization needs to go that extra distance when it comes to training and being prepared for all types of scenarios. It will not be sufficient to only meet the minimum requirements of SOLAS, which mostly consists of inspecting the equipment's functionality.

7.5 Collapse process of an FRP composite panel

When a weight loaded FRP composite panel is subjected to fire, it will collapse when the laminate on the fire exposed side delaminates. The particular FRP composite sandwich panels that are to be utilized when constructing a cruise ship in the novel design in the wake of the BESST project, is best represented by the in-house tests conducted at SP Borås. The tests show that through insulation, 60 minutes of resistance to temperatures that represent a fully developed fire, is achieved. When the (quite heavily loaded) SP tested sandwich panels failed, they did so in a rather sudden fashion. Not much, if any, bulging or sagging was noted prior to collapse. Other tests indicate that panels that are less heavily loaded may stand for longer than this, and also permit some bulging or sagging.

It should also be noted that the time of 60 minutes may be a somewhat conservative figure in actuality due to the following reasons:

- Most likely presence of an additional thermal barrier between the fire seat and the load bearing structure. The inner ceiling and walls separate most interior spaces on board from the FRP composite via void spaces that is used for wiring, ventilation, plumbing et cetera. These inner ceilings and walls are likely to withstand the initial flashover phase and the first ten or so minutes of fully developed fire. This reduces the thermal load the load bearing construction receives.
- Probable limited supply of fuel or air in an actual fire scenario may lead to lower or less sustained temperatures.

7.6 Toxicity and smoke production

It was concluded that when the fire stays in the region of a plausible worst case scenario, the additional gases produced by the novel construction are believed to be marginal when put into context of the amount that is produced by the interiors. A test where a cabin with malfunctioning sprinklers was almost completely burnt out, revealed a 14% HCl and 3% CO_x addition to the toxic smoke, compared to a prescriptive design. Pyrolysis of the FRP composite also caused a marginal 3% increase in fire load.

If the fire escalates further and starts reaching a catastrophic state, the FRP composite will start to contribute to the fire in a more than marginal manner. However, it seems that the most critical problem is not that the construction material is added to the fire. Rather, the bigger problem lies in the actual spreading of the fire to the adjacent space. The fire spread adds fuel that is not only more substantial in weight, but also has a much larger surface area exposed to the fire, allowing a more rapid contribution of pyrolysis gases to fuel the fire. It should also be kept in mind at this point that fire spread is also a concern in the prescriptive design, albeit not likely due to a collapse, but via conduction et cetera.

7.7 Installation of the new firefighting equipment

During the process of writing this report some ideas and suggestions arose as to how the ship may be constructed to ease the adaptation of the new firefighting techniques and equipment:

- The Cutting Extinguisher should be installed midship with permanently installed high pressure pipes that runs along the length of the ship, supplying CE fire posts at appropriate intervals. CE hose and nozzle can then be connected to the CE fire posts, much like standard low pressure firefighting hoses and nozzles. If this proves difficult to achieve, fixed connections through all main vertical (fire) zones needs to be installed along with CE hoses in each section so that firefighters quickly can set up the system without disturbing the integrity of the fire zones.
- Marking of areas that are suitable for deploying a Cutting Extinguisher. This could be done discreetly and would decrease the risk of firefighters accidently cutting apart vital installations such as sprinkler piping etc. It would also increase the chance of effective results.
- Pre-installed discreet holes where Fog Nails can be inserted. This would increase the chance of effective results and also greatly ease deployment as pre-drilling of holes is not needed.

8 Additional Discussion

8.1 Further research

A need to investigate the applicability of using Cutting Extinguishers and Fog Nails in the specific novel design was found. The argumentation presented in the report is based on the assumption that using these new equipments is possible. It needs to be ensured that such is the case, if the results from this report are to be considered valid.

The question of how collapses propagate through the construction stands out as an uncertainty. This is a subject that needs research, perhaps in the form of computer modeling where one looks at how the load is distributed when different load-bearing components are removed or weakened? The results from such research could be of aid to firefighting commanders and ship builders.

The writing of this report had the objective of presenting a firefighting organization that can be at least as effective and safe in the novel design, as in the prescriptive one. Firefighters' absolute personal risk has not been investigated in this report but doing so could possibly reveal that even if their personal risk increases to a certain extent when no novel equipment and strategies are introduced together with the novel design, it is still in the ALARP region and may thus be accepted. However, this report advocates the continuing development of fire safety and is based on the concept of equal, or better safety, effectiveness, and efficiency.

9 Acknowledgements

First of all, I would like to express my gratitude to Franz Evegren at SP, for taking such good care of me, both with exceptional academic guidance as well as making me feel welcome in Borås. Thank you!

Stefan Svensson has provided much valuable input and feedback and has been a great asset. Thank you Stefan!

Håkan Warnemyr, big thanks to you for taking the time to receiving us at Revinge and following up on all the subsequent questions!

Furthermore, this report would not have been made possible without the large number of people that helped out with crucial input. All of you contributed with important pieces to the puzzle. You know who you are, and thanks to you all!

Finally, I would like to direct a big thanks to Robert Jönsson at LTH for being so devoted to his students and creating the greatest program conceivable! The Department of Fire Safety Engineering and Systems Safety would not be the same without you.

References

Akselsson, R. (2008). *Människa, Teknik, Organisation och Riskhantering.* Lund: Lund University.

Allison, D., Marchand, A., & Morchat, R. (1991). *Fire Performance of Composite Materials in Ships and Composite Structures - page 129-140 from Marine Structures vol. 4.* Elsevier Applied Science.

Almersjö, O., Ask, E., Brandsjö, K., Brokopp, T., Hedelin, A., Jaldung, H., o.a. (1993). *Branden på passagerarfärjan Scandinavian Star den 7 april 1990.* Stockholm: Socialstyrelsen.

Andersson, M., & Krasniqi, A. (2001). *Utvärdering av brandrisker på HMS Visby.* Lund: Lund University.

Bengtsson, L.-G. (2001). *Inomhusbrand.* Karlstad: Räddningsverket.

Carlsén, T., & Winkler, H. (2000). *Skärsläckaren som röjnings och släckverktyg för fartyg av kolfiberkomposit.* Lund: Lund University.

Charternet.com. (u.d.). *www.stcw.org.* Hämtat från www.stcw.org: www.stcw.org den 24 may 2012

Evegren, F. (2010). *Assessing Fire Safety in Maritime Composite Superstructures - A Risk-Based Approach.* Lund: Department of Fire Safety Engineering and Systems Safety, Lund University.

Evegren, F., Hertzberg, T., & Rahm, M. (2011). *LASS-C; Lightweight construction of a cruise vessel.* Borås: SP Technical Research Institute of Sweden.

Gdoutos, E., & Daniel, I. *Failure Mechanisms of Composite Sandwich Structures.* Evanston, Illinois: Northwestern University.

Gutierrez, J., Parneix, P., Bollero, A., Høyning, B., McGeorge, D., Gibson, G., o.a. (2005). *Fire Performance of Naval Composite Structures.*

Heinrich, H. (1931). *Industrial Accident Prevention.* New York: McGraw-Hill.

Hertzberg, T. (2009). *LASS, Lightweight Construction Applications at Sea.* Borås: SP Technical Research Institute of Sweden.

Hertzberg, T. (2003). *Risker med kolfiberlaminat vid brand.* Borås: SP Technical Research Institute of Sweden.

Hertzberg, T., Axelsson, J., & Arvidson, M. (2008). *Large-scale fire tests in a passenger cabin.* Borås: SP Technichal Research Institute of Sweden.

Hilado, C. J. (1998). *Flammability Handbook for Plastics.* Lancaster, Pennsylvania: Technomic Publishing Company, Inc.

IMO. (1998). *FRP Code, Internationall Code for Application of Fire Test Procedures.* London: International Maritime Organization.

IMO. (2000). *International Code of Safety for High-Speed Craft.* London: International Maritime Organization.

IMO. (2009). *SOLAS Consolidated Edition.* London: International Maritime Organization.

IMO. (2012). *www.imo.org*. Hämtat från www.imo.org: www.imo.org/About/Membership/Pages/MemberStates.aspx den 24 may 2012

IMS. (2002). *ISM Code - International Safety Management Code.* London: IMO.

International Convention on Standards of Training, Certification and Watchkeeping for Seafarers. (1995). *Seafarers' Training, Certification, and Watchkeeping (STCW) Code.* London: IMO.

Karlsson, B., & Quintiere, J. G. (2000). *Enclosure Fire Dynamics.* Boca Raton, FL: CRC Press.

Lattimer, B. Y., Oulette, J., & Sorathia, U. (2004). *Large-Scale Fire Resistance Tests on Sandwich Composites.* Long Beach, CA: SAMPLE 2004.

MAIB. (2006). *Report on the investigation of the fire on board Star Princess.* Southampton: Marine Accident Investigation Branch.

McGeorge, D., & Høyning, B. (2002). *Fire Safety of Naval Vessels made of Composite Materials: Fire Safety Philosophies, Ongoing Research and State-of-the-Art Passive Fire Protection.* NATO Research and Technology Organisation.

Mouritz, A., & Gibson, A. (2006). *Fire Properties of Polymer Composite Materials.* Dordrecht, Netherlands: Springer.

MSB. (2006). *Databank - insats med skärsläckare/Cobra metoden.* MSB.

Potter, P. (2002). *Survivability of Composite Structures for Naval Applications.* Arlington, VA: Office of Naval Research.

Rosness, R., Grøtan, T. O., Guttormsen, G., Herrera, I. A., Steiro, T., Fred, S., o.a. (2010). *Organisational Accidents and Resilient Organisations: Six Perspectives. Revision 2.* Trondheim: SINTEF Technology and Society.

Sirenen. (2007). Skärsläckaren bidrar till breddat metodval. *Sirenen Nr 5* , 28-29.

SP. (2012). Internal Unpublished Test Results. Borås: SP Technical Research Institute of Sweden.

Svensson, S. (2005). *Fire Ventilation.* Huskvarna: Swedish Rescue Services Agency.

Särdqvist, S. (2006). *Vatten och andra släckmedel.* Kalmar: Räddningsverket.

Södra Älvsborgs Räddningstjänsförbund, SP Technical Research Institute of Sweden. (2010). *Skärsläckarkonceptets operativa användande.* MSB.

Trewe, A. (den 02 08 2012). Email conversation with Anders Trewe at ColdCut Systems www.coldcutsystems.com. Borås.

Troitzsch, J. (2004). *Plastics Flammability Handbook 3rd Edition.* Munich: Carl Hanser Verlag.

Warnemyr, H. (den 19 04 2012). (F. Falkman, & F. Evegren, Intervjuare)

Appendix A. Interviews

Interview with Håkan Warnemyr

Håkan Warnemyr is currently teaching firefighting at MSB Revinge College. He is also involved in research and has worked several years on board different large cruise liners as Safety Officer and First Firefighter. Below follows a summary of the impressions from an interview 19/4 2012.

- Access to equipment for lowering temperatures inside a compartment from the outside would be very beneficial in the case of a severe fire. With the novel FRP design, the Fog Nail would be his choice rather than a Cutting Extinguisher with the motivations of its simplicity to use together with current typical firefighting materiel that is already installed.
- If the need of boundary cooling is removed and firefighters only have to monitor adjacent spaces, more resources can be focused on combating the fire.
- The novel design's properties of having risk for local collapses after 60 minutes of fully developed fire, would imply an increased risk for firefighting crew of unknown magnitude.
- Keeping in mind the type of environment firefighters have to work in that is implied by a fire that is still not under control after 60 minutes, it is perhaps doubtful that an "aggressive" firefighting strategy is still being utilized. The severe heat associated with this type of fire could imply rather short firefighting crew stamina in this scenario.
- Consideration to firefighting crew's safety lies much in the attitude of the officer in charge of the firefighting efforts (typically the Chief).
- It is estimated that following a detected fire (by smoke/heat detectors or that someone gives the alarm) staff normally arrives on scene;
    - in 2-3 minutes at the most for first efforts staff w/o breathing apparatus.
    - in 4-5 minutes at the most for a First Firefighter, if such exists, with a breathing apparatus.
    - complete firefighting squad with breathing apparatuses shortly thereafter.
- The ship's ability to use its advanced controls over ventilation on board is of great assistance for managing smoke spread in combination with sealing off main vertical fire zones.
- Given the rather high standard of passive and active fire protection installed in these ships today, it is quite unlikely that a fire would escalate to the point that it has not been suppressed within an hour. Generally speaking staff arrives on scene quickly and is able to put out a fire before it becomes severe if active and passive systems fail.

Appendix B. Current firefighting organization's structure, regulations and routines

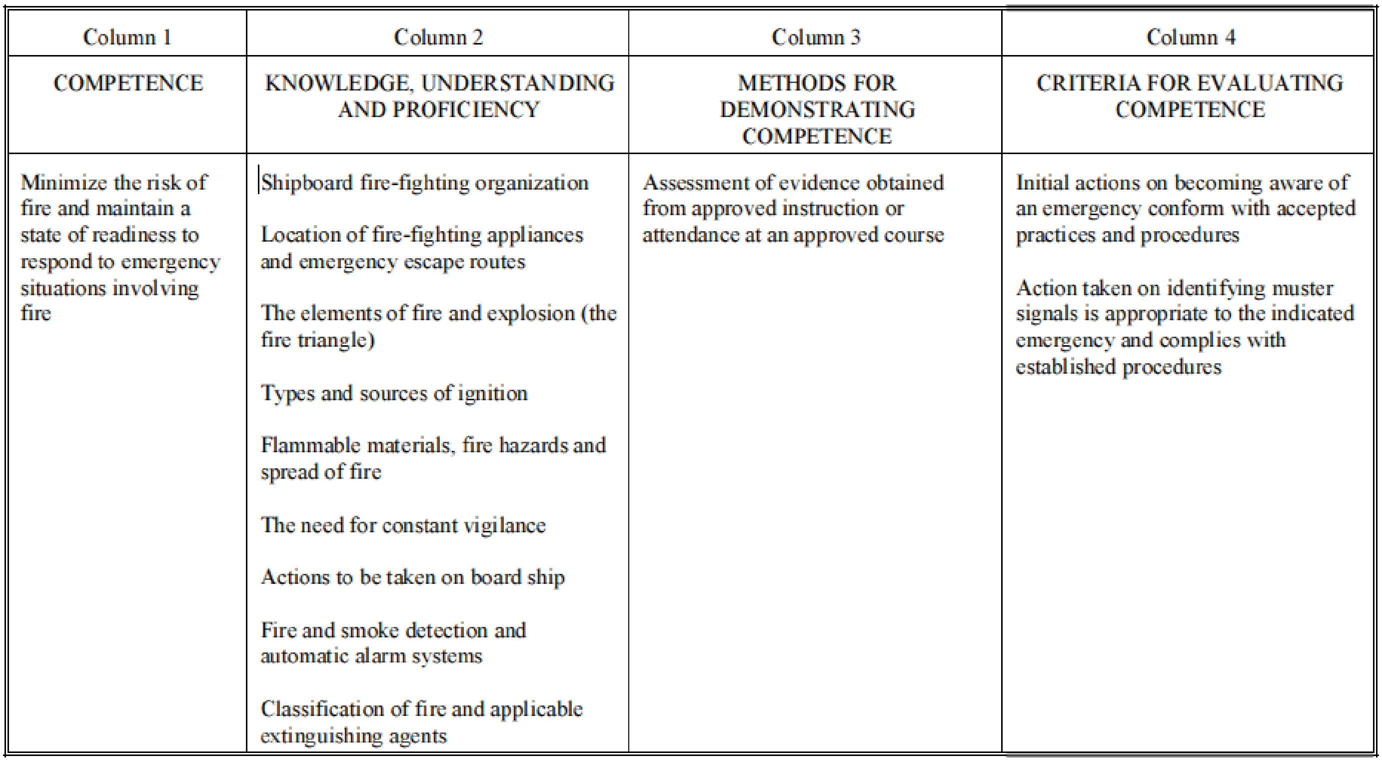
In this chapter current firefighting organization's structure, regulations and routines are inventoried.

App. B.1 Firefighting routines and regulations on cruise ships

The International Maritime Organization (IMO) is an agency of the United Nations which through the SOLAS code governs safety on international voyages. The term *international voyages* is defined in SOLAS Regulation I/2-d as "A voyage from a country to which the present Convention applies to a port outside such a country, or conversely". At the moment, 170 nations are signed to abide by the IMO codes (IMO, 2012). When a ship enters any nation's water, it also has to abide by the rules and laws of the particular nation. Even though a nation may have regulations that differ slightly (some more strict; some less strict) from SOLAS, this will always be the common ground for a lowest agreed-upon level of safety for international voyages to and from any of these countries. The types of ships analyzed in this report are assumed to undertake international voyages as described in Regulation A-I/2-d, and all analysis is thus based upon SOLAS and IMO regulations.

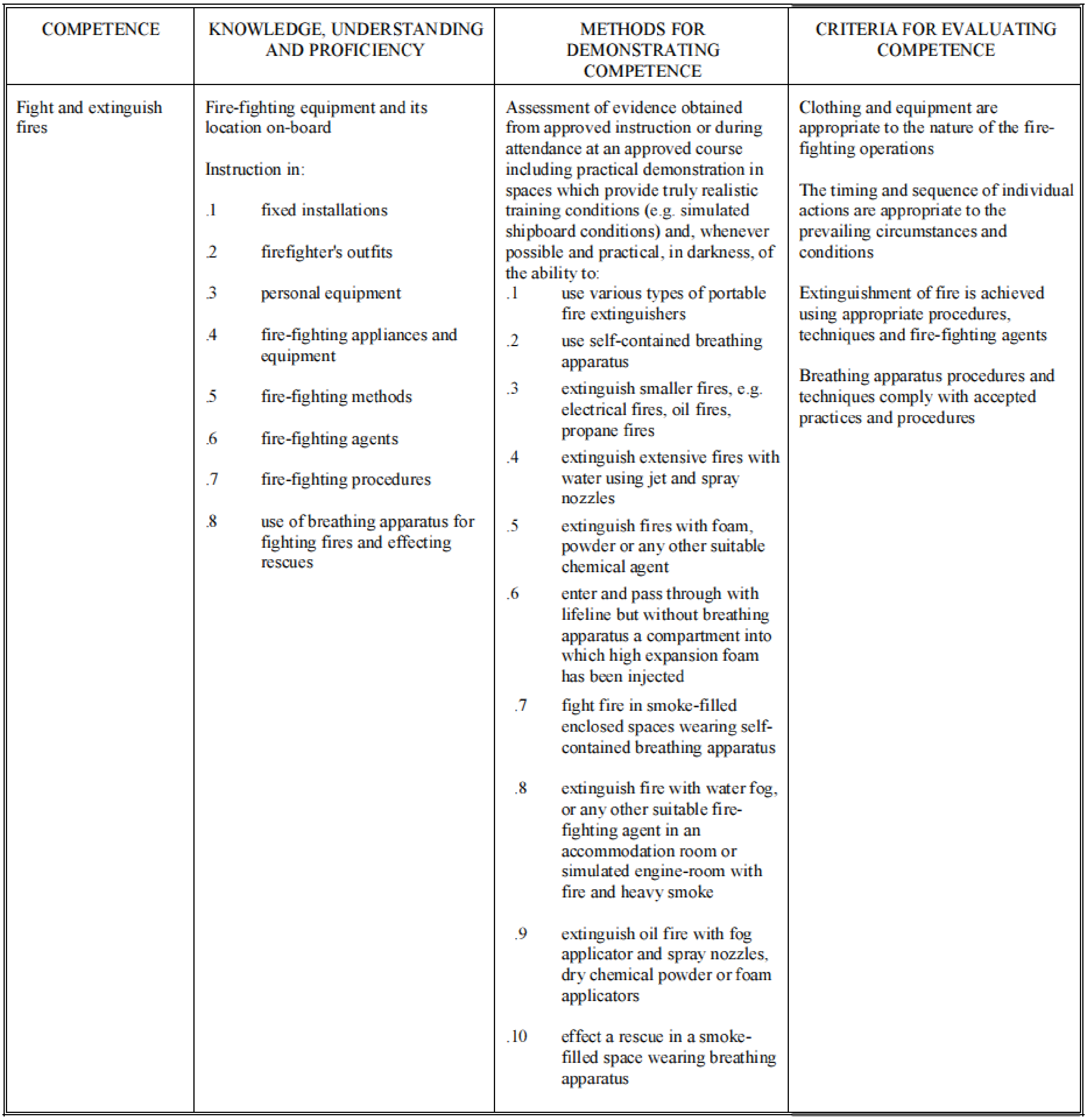
App. B.1.1 Firefighting regulations and enrollment requirements

Seafarers on board ships that abide under IMO regulations are required to heed the STCW code (Seafarers' Training, Certification, and Watchkeeping (STCW) Code, 1995) (www.stcw.org). To be able to enroll on a ship that will undertake international voyages **all seafarers must have the Basic Safety Training**, according to A-VI/1 and A-VI/2 of the STCW-95 code. What this means more specifically in terms of fire safety training, is listed in the table below. The table is an extract from what is required of a Basic Safety Training course according to the STCW code. Further guidance in addition to the table below is also given in Section B-VI/1 in STCW-95.



Column 1	Column 2	Column 3	Column 4
COMPETENCE	KNOWLEDGE, UNDERSTANDING AND PROFICIENCY	METHODS FOR DEMONSTRATING COMPETENCE	CRITERIA FOR EVALUATING COMPETENCE
Minimize the risk of fire and maintain a state of readiness to respond to emergency situations involving fire	Shipboard fire-fighting organization Location of fire-fighting appliances and emergency escape routes The elements of fire and explosion (the fire triangle) Types and sources of ignition Flammable materials, fire hazards and spread of fire The need for constant vigilance Actions to be taken on board ship Fire and smoke detection and automatic alarm systems Classification of fire and applicable extinguishing agents	Assessment of evidence obtained from approved instruction or attendance at an approved course	Initial actions on becoming aware of an emergency conform with accepted practices and procedures Action taken on identifying muster signals is appropriate to the indicated emergency and complies with established procedures

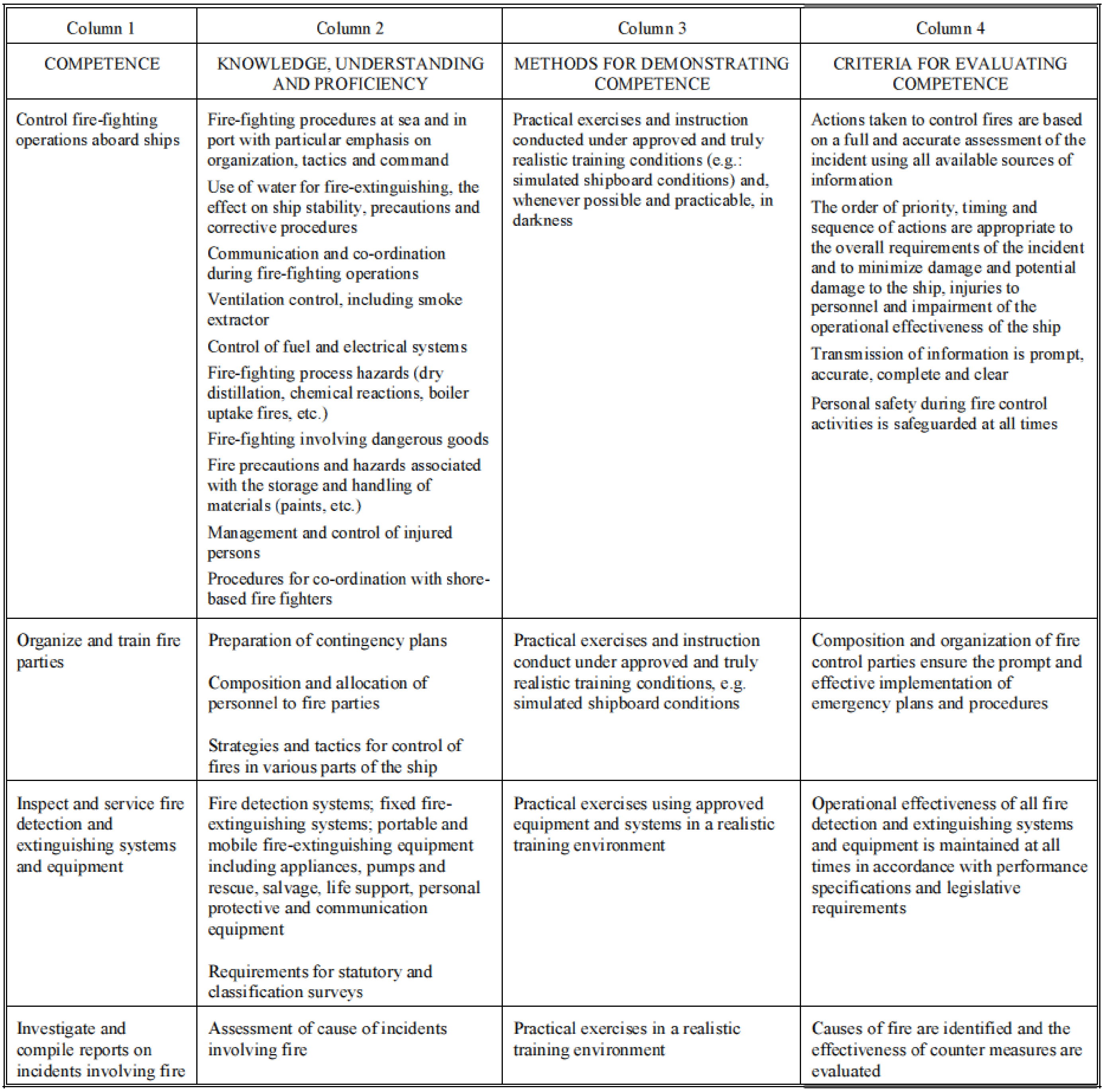
Table 2. Criterias for Basic Safety, part 1 (International Convention on Standards of Training, Certification and Watchkeeping for Seafarers, 1995).



COMPETENCE	KNOWLEDGE, UNDERSTANDING AND PROFICIENCY	METHODS FOR DEMONSTRATING COMPETENCE	CRITERIA FOR EVALUATING COMPETENCE
Fight and extinguish fires	Fire-fighting equipment and its location on-board Instruction in: .1 fixed installations .2 firefighter's outfits .3 personal equipment .4 fire-fighting appliances and equipment .5 fire-fighting methods .6 fire-fighting agents .7 fire-fighting procedures .8 use of breathing apparatus for fighting fires and effecting rescues	Assessment of evidence obtained from approved instruction or during attendance at an approved course including practical demonstration in spaces which provide truly realistic training conditions (e.g. simulated shipboard conditions) and, whenever possible and practical, in darkness, of the ability to: .1 use various types of portable fire extinguishers .2 use self-contained breathing apparatus .3 extinguish smaller fires, e.g. electrical fires, oil fires, propane fires .4 extinguish extensive fires with water using jet and spray nozzles .5 extinguish fires with foam, powder or any other suitable chemical agent .6 enter and pass through with lifeline but without breathing apparatus a compartment into which high expansion foam has been injected .7 fight fire in smoke-filled enclosed spaces wearing self-contained breathing apparatus .8 extinguish fire with water fog, or any other suitable fire-fighting agent in an accommodation room or simulated engine-room with fire and heavy smoke .9 extinguish oil fire with fog applicator and spray nozzles, dry chemical powder or foam applicators .10 effect a rescue in a smoke-filled space wearing breathing apparatus	Clothing and equipment are appropriate to the nature of the fire-fighting operations The timing and sequence of individual actions are appropriate to the prevailing circumstances and conditions Extinguishment of fire is achieved using appropriate procedures, techniques and fire-fighting agents Breathing apparatus procedures and techniques comply with accepted practices and procedures

Table 3. Criterias for Basic Safety, part 2 (International Convention on Standards of Training, Certification and Watchkeeping for Seafarers, 1995).

The next level of required knowledge in terms of fire safety is that which is required by "Seafarers designated to control fire-fighting operations" as found in Section A-VI/3 and Table A-VI/3 of STCW-95. The section and table describes the mandatory minimum training of advanced firefighting. Further guidance in addition to the table below is also given in Section B-VI/3 in STCW-95.



Column 1	Column 2	Column 3	Column 4
COMPETENCE	KNOWLEDGE, UNDERSTANDING AND PROFICIENCY	METHODS FOR DEMONSTRATING COMPETENCE	CRITERIA FOR EVALUATING COMPETENCE
Control fire-fighting operations aboard ships	Fire-fighting procedures at sea and in port with particular emphasis on organization, tactics and command Use of water for fire-extinguishing, the effect on ship stability, precautions and corrective procedures Communication and co-ordination during fire-fighting operations Ventilation control, including smoke extractor Control of fuel and electrical systems Fire-fighting process hazards (dry distillation, chemical reactions, boiler uptake fires, etc.) Fire-fighting involving dangerous goods Fire precautions and hazards associated with the storage and handling of materials (paints, etc.) Management and control of injured persons Procedures for co-ordination with shore-based fire fighters	Practical exercises and instruction conducted under approved and truly realistic training conditions (e.g.: simulated shipboard conditions) and, whenever possible and practicable, in darkness	Actions taken to control fires are based on a full and accurate assessment of the incident using all available sources of information The order of priority, timing and sequence of actions are appropriate to the overall requirements of the incident and to minimize damage and potential damage to the ship, injuries to personnel and impairment of the operational effectiveness of the ship Transmission of information is prompt, accurate, complete and clear Personal safety during fire control activities is safeguarded at all times
Organize and train fire parties	Preparation of contingency plans Composition and allocation of personnel to fire parties Strategies and tactics for control of fires in various parts of the ship	Practical exercises and instruction conduct under approved and truly realistic training conditions, e.g. simulated shipboard conditions	Composition and organization of fire control parties ensure the prompt and effective implementation of emergency plans and procedures
Inspect and service fire detection and extinguishing systems and equipment	Fire detection systems; fixed fire-extinguishing systems; portable and mobile fire-extinguishing equipment including appliances, pumps and rescue, salvage, life support, personal protective and communication equipment Requirements for statutory and classification surveys	Practical exercises using approved equipment and systems in a realistic training environment	Operational effectiveness of all fire detection and extinguishing systems and equipment is maintained at all times in accordance with performance specifications and legislative requirements
Investigate and compile reports on incidents involving fire	Assessment of cause of incidents involving fire	Practical exercises in a realistic training environment	Causes of fire are identified and the effectiveness of counter measures are evaluated

Table 4. Criterias for Advanced Firefighting (International Convention on Standards of Training, Certification and Watchkeeping for Seafarers, 1995)

App. B.1.2 Firefighting training and drilling

Other than the training received during Basic Safety Training courses, no formal training is usually required to become a part of the firefighting squads on board. However, once a seaman has enlisted to the core firefighting organization on board, he or she will start to train with them. As required by Regulation III/30 in SOLAS, fire drills are performed once a week on all passenger ships. However, each crew member is obligated to attend only a minimum of one drill per month. What the fire drills are required to contain is specified in SOLAS Regulation III/19-3.4;

3.4 Fire drills

3.4.1 Fire drills should be planned in such a way that due consideration is given to regular practice in the various emergencies that may occur depending on the type of ships and the cargo.
3.4.2 Each fire drill shall include:

> *.1 reporting to stations and preparing for the duties described in the muster list required by regulation 8;*
> *.2 starting of a fire pump, using at least the two required jets of water to show that the system is in proper working order;*
> *.3 checking of fireman's outfit and other personal rescue equipment;*
> *.4 checking of relevant communication equipment;*
> *.5 checking the operation of watertight doors, fire doors, fire dampers and main inlets and outlets of ventilation systems in the drill area; and*
> *.6 checking the necessary arrangements for subsequent abandoning of the ship.*

As seen in the paragraphs above, the prescriptive rules dictates mostly how fire drills require checking of all relevant equipment. This implies that the quality of firefighting crew's training depends mostly on the organization on board. It is thus up to the firefighting organization with the Captain, Fire Chief, Safety Officer if applicable, and their associates to make sure adequate training is performed.

App. B.2 Firefighting organization

As required by SOLAS Regulation IX/3-1, a ship and its shipping company must comply with the requirements of the International Safety Management (ISM) code. The ISM code provides functional requirements for "an international standard for the safe management and operation of ships and for pollution prevention" (IMS, 2002). Below follow some key excerpts from the IMS Code;

1.4 (…) Every Company should develop, implement and maintain a safety management system which includes the following functional requirements:

> *.2 instructions and procedures to ensure safe operation of ships (…)*
> *.5 procedures to prepare for and respond to emergency situations (…)*

6.3 The Company should establish procedures to ensure that new personnel and personnel transferred to new assignments related to safety and protection of the environment are given proper familiarization with their duties. (…)

6.5 The Company should establish and maintain procedures for identifying any training which may be required in support of the safety management system and ensure that such training is provided for all personnel concerned.

8.1 The Company should establish procedures to identify, describe and respond to potential emergency shipboard situations.

8.2 The Company should establish programs for drills and exercises to prepare for emergency actions.

As it is, the shipping companies are responsible of developing and establishing functioning safety management for its ships. It is thereafter the Captains responsibility to implement it to shipping company's protocols. Exactly how an organization on board a ship is built may thus differ from ship to ship, but generally the ships (of similar size and application) that operate in the same shipping company are similarly organized.

An example of a firefighting organization on a large scale cruise ship is presented in general terms in the figure 12. It was compiled with assistance from Håkan Warnemyr (Warnemyr, 2012) and Gabor Szemler at the fire safety department of Transportstyrelsen.

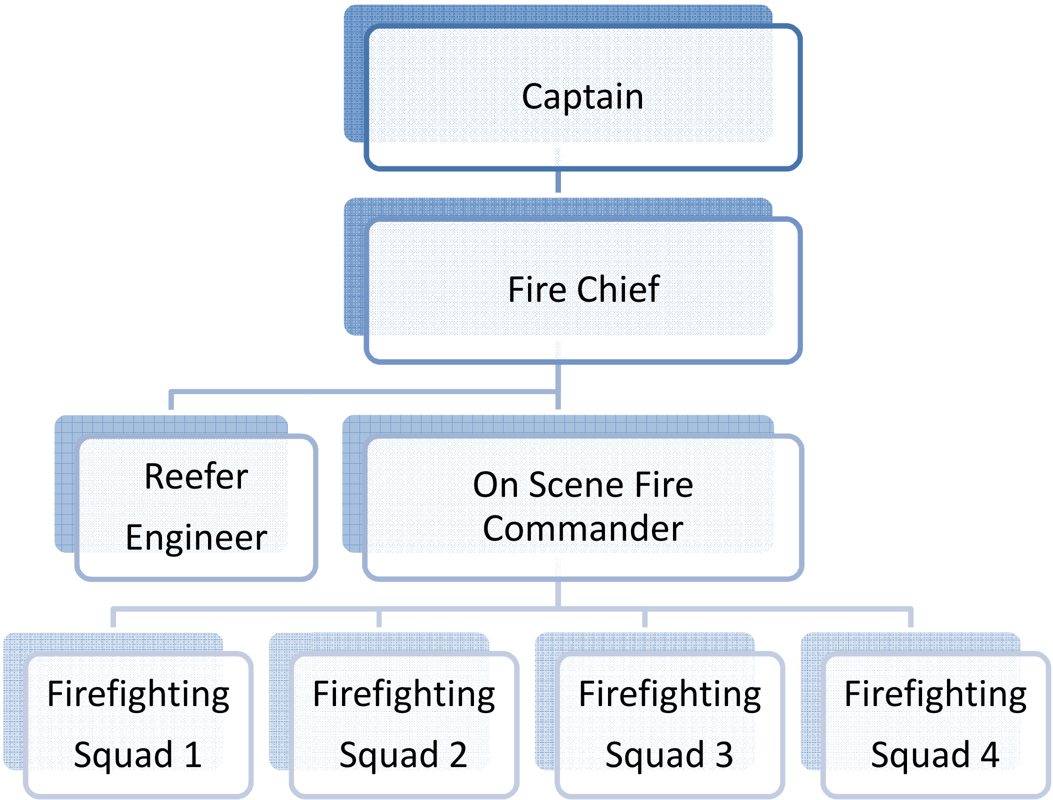


Figure 13. Schematic overview of an onboard firefighting organization

The captain on board is always the commanding officer and ultimately in charge of all onboard operations. The Fire Chief is in charge of firefighting operations and is a position normally appointed to the Chief Engineer. The Reefer Engineer is in charge of managing ventilation systems on board and the On Scene Fire Commander has operative command at the site of fire. Additional crew is also available to assist the Captain, Fire Chief, Reefer Engineer and On Scene Fire Commander. The number of Firefighting Squads, and also the amount in men in each squad, may vary on different ships but generally a squad consists of around ten to 25 men, of which four or six usually are assigned to BA-teams.

In addition to this core firefighting organization, every seaman on board has undergone Basic Safety Training as described in section 2.1.1. In the event of a fire (or any other emergency for that matter), all personnel on board will have a specific task assigned to performed.

Appendix C. Selected FRP composite fire tests

App. C.1 Large scale fire tests in a passenger cabin

A series of tests were performed at SP (Hertzberg, Axelsson, & Arvidson, 2008), with different setups of fire safety systems failing in the case of a cabin fire. It was concluded that for the fire to be able to become severe it was necessary that both sprinklers and door closers failed. One of the test setups was meant to represent a plausible worst case scenario with a fully developed fire in the furnished cabin with 54 additional kilos of luggage. Total fire load in the cabin was 3,1 GJ at 12,9m^2. The door to the cabin was left open and fire was allowed to burn unhindered, reaching a fully developed stage in less than 9 minutes. Most of the fuel had been consumed in the cabin after 45-60 minutes and the test was terminated after 156 minutes.

The composite superstructure was constructed from sandwich panels made of glass fibre reinforced plastic on a core of 50mm thick PVC Divinycell. The panels had stiffeners and were produced at Kockums using infusion technology. The resin used was polyester.

Figure 14. Interior and exterior of the large scale cabin test, before testing commenced. The bottom right image was taken after flashover had occurred in the cabin. Not shown in the interior picture are the luggage and clothes (Hertzberg, Axelsson, & Arvidson, 2008).

Figure 15. Overhead deck's bottom side and cabin floor, after completed test (Hertzberg, Axelsson, & Arvidson, 2008).

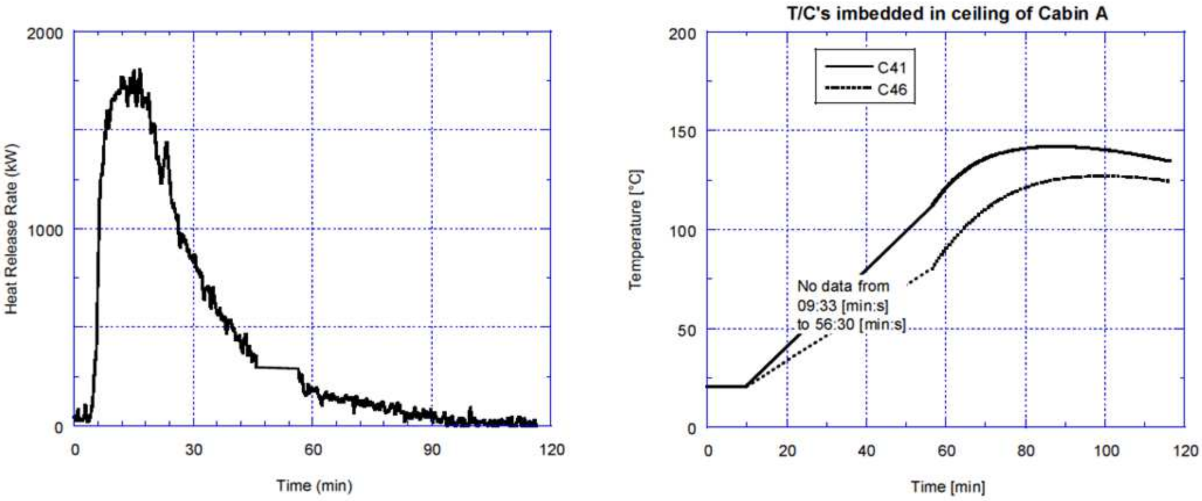


Figure 16. HRR and temperature in the FRP ceiling construction (Hertzberg, Axelsson, & Arvidson, 2008).

It was concluded that the FRP bulkheads and overhead deck in this setup were able to withstand the fire without critical damage. Furthermore, it was observed that the heat exposure the construction received was localized to right above the cabin that was burnt, since the FRP composite combined with the insulation is a poor conductor of heat. However, it was discovered that the bottom deck of the cabin sustained higher temperatures and more heat radiation that expected, resulting in quite a bit of damage to the floor and an estimated 10% mass loss. The floor was not weight loaded and was supported from underneath by a concrete slab and it is thus unclear how much load-bearing capacity was lost. The test concluded that the 20mm insulation that was tested for the floor was not sufficient for the floor construction while bulkheads and top deck passed the test. This amount of floor insulation was subsequently recommended to be increased to 30mm in another project as a result of this test.

Although the heat transfer to the top deck's FRP composite would be more intense as a result of exposure to not only radiation but also convection, it also has a much more secure thermal barrier between it and the fire. In order for the fire to damage the top deck's or the bulkhead's FRP construction, it must first penetrate the cabin's inner ceiling and walls that separates the cabin compartment from the space around it. This surrounding void space houses installations such as wiring, ventilation, plumbing et cetera. After that the heat must penetrate the insulation which in this test was 100mm thick. The reason that the floor insulation is not also simply made in 100mm thickness is due to the technical difficulties in combining good insulation with the ability for the floor to be strong enough to walk on.

Analyzing this test it is clear that because of the relative difficulty of insulating the floor, an implication is that the floor could be a weak spot in the design, in the case of a severe fire in an enclosure.

App. C.2 US. Navy large scale fire test of composite bulkheads and overhead decks

This test report (Lattimer, Oulette, & Sorathia, 2004) tells of a series of six loaded tests; four bulkheads and two overhead decks both with and without insulation. The FRP panels were quite sturdy with a total thickness of 88,9mm. Its laminates were both 6,35mm thick with 10 layers of fibre glass on each side of a balsa wood core of 76,2mm thickness. Insulation was in applicable cases 31,8mm thick. Samples were subjected to a temperature of about 1100 °C. Load applied to bulkheads were 87,5kN/m. Deck loads applied to the uninsulated and insulated subjects were 14,4kN/m^2 and 8,6kN/m^2 respectively. All bulkheads and the insulated deck had some form of stiffening on one side of the panel while the uninsulated overhead deck did not have any stiffeners.

The following figures illustrates in order of appearance the FRP composite panel with insulation, T-joint detail, T-joint stiffened bulkhead test setup, T-joint installed un-stiffened overhead deck test setup, bulkhead stiffened with carbon stiffener test setup, T-joint stiffened overhead deck test setup and finally a carbon stiffener detail.

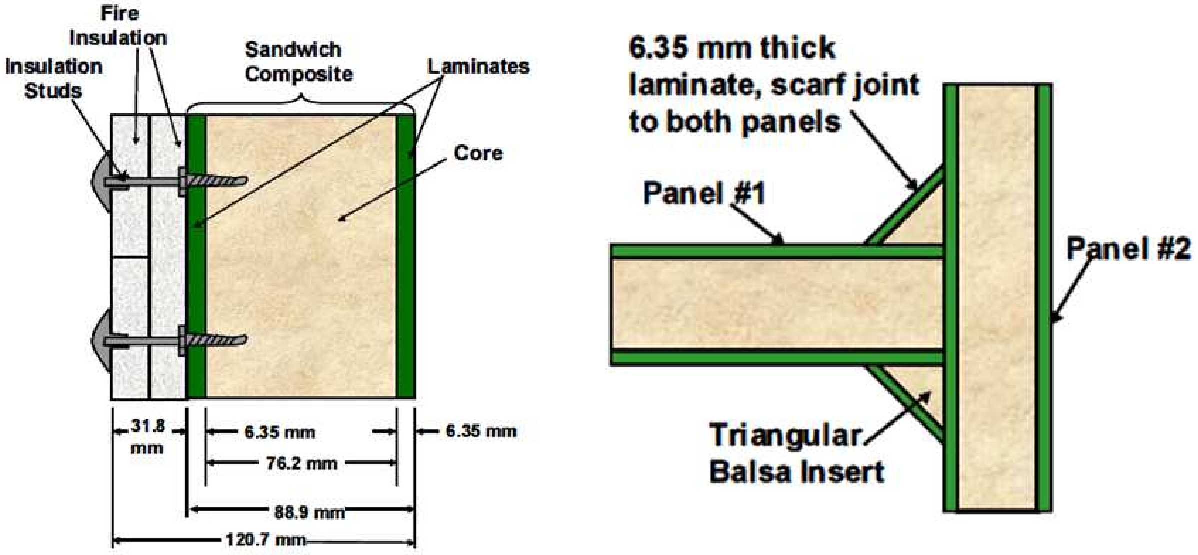


Figure 17. The tested FRP composite's construction, with insulation fastening and a T-joint (Lattimer, Oulette, & Sorathia, 2004).

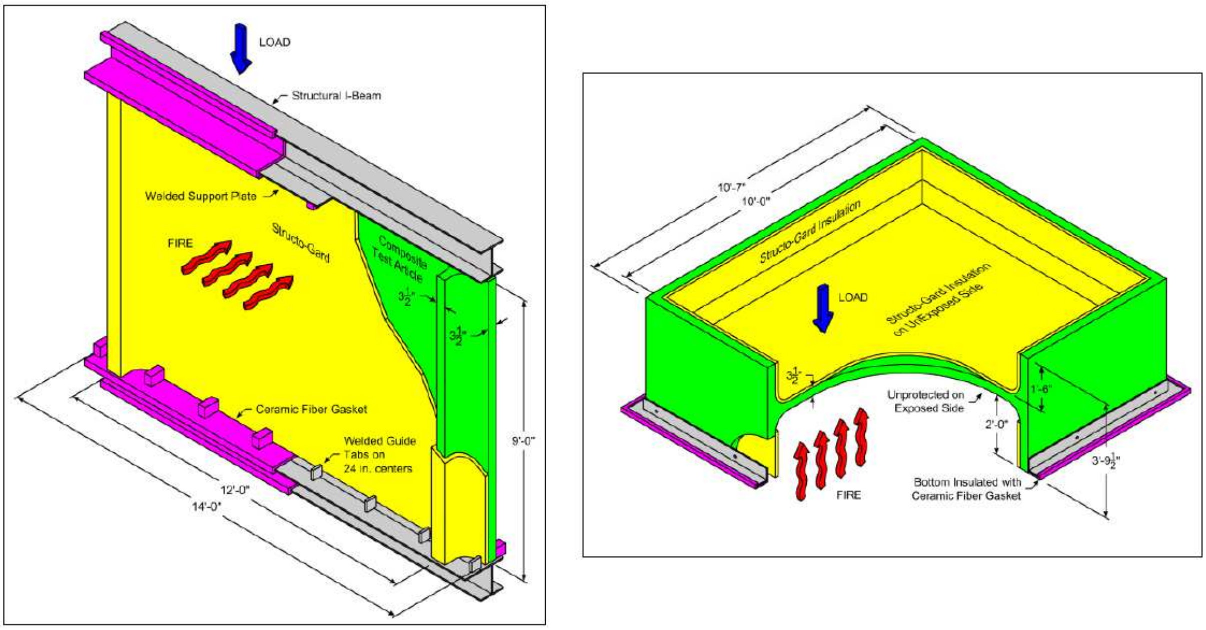


Figure 18. T-joint stiffened bulkhead and un-stiffened deck (Lattimer, Oulette, & Sorathia, 2004).

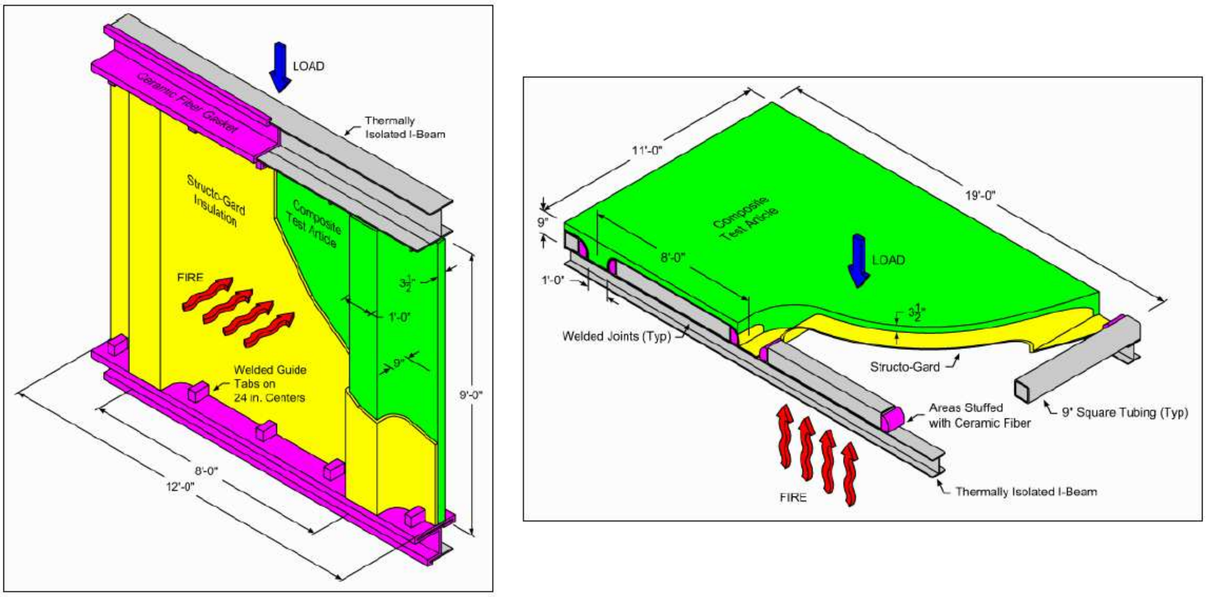


Figure 19. Bulkhead with carbon stiffeners and deck with T-joint stiffeners (Lattimer, Oulette, & Sorathia, 2004).

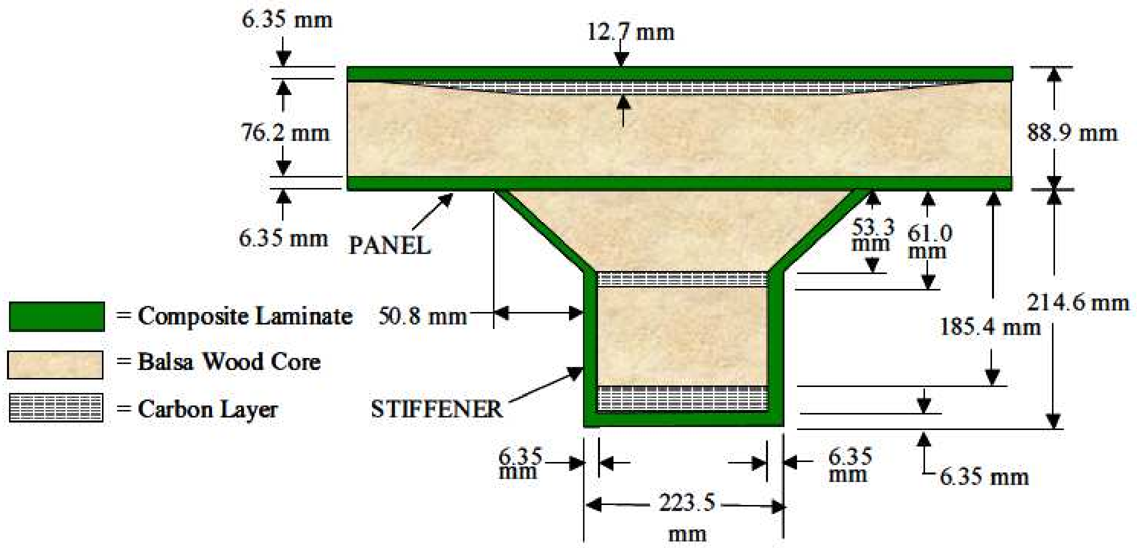


Figure 20. Detail of a carbon stiffener (Lattimer, Oulette, & Sorathia, 2004)

The tests performed in the report are summarized in the following table:

No	Description	Dimensions	Insulated	Load	Test Method / Exposure	Reason for Test
1	Bulkhead with T-Joints, Insulated, T-Joint Side Exposed	4.27 m wide, 2.75 m high, 88.9 mm thick T-joints 3.66 m apart	YES	87.5 kN/m	IMO A.754(18), UL 1709 for 30 min	Fire Resistance and Structural Integrity of design
2	Bulkhead with T-Joints, Uninsulated, T-Joint Side Exposed	4.27 m wide, 2.75 m high, 88.9 mm thick T-joints 3.66 m apart	NO	87.5 kN/m	IMO A.754(18), UL 1709 for 75 min	Fire Resistance and Structural Integrity of Bulkhead Uninsulated
3	Overhead with T-joints Around Perimeter, Uninsulated	Overall : 3.23 m by 2.83 m Exposed : 3.05 m by 2.65 m	NO	14.4 kPa	IMO A.754(18), UL 1709 for 32 min	Fire Resistance and Structural Integrity of Overhead Uninsulated
4	Bulkhead with Stiffeners, Insulated, Stiffener Side Exposed	3.66 m wide, 2.75 m high, 88.9 mm thick Stiffeners 2.44 m apart	YES	87.5 kN/m	IMO A.754(18), UL 1709 for 30 min	Fire Resistance and Structural Integrity of Design
5	Bulkhead with Stiffeners, Uninsulated, Side without Stiffeners Exposed	3.66 m wide, 2.75 m high, 88.9 mm thick Stiffeners 2.44 m apart	NO	87.5 kN/m	IMO A.754(18), UL 1709 for 120 min	Fire Resistance and Structural Integrity of with Fire on Unstiffened Side
6	Overhead with Stiffeners, Insulated, Stiffener Side Exposed	Exposed : 5.49 m by 3.05 m, 88.9 mm thick Stiffeners 2.44 m apart	YES	8.62 kPa	IMO A.754(18), UL 1709 for 120 min	Fire Resistance and Structural Integrity of Design

Table 5. Test setup overview **(Lattimer, Oulette, & Sorathia, 2004)**.

The report concludes some interesting results since all tested panels ware measured for deflection which is something that occurred in all incidences, whether insulated or not since insulation was rather thin. The conclusion of the report was that neither bulkheads nor decks would collapse suddenly and without warning. The panels general behavior when subjected to the fire was such that as the laminate on the exposed side reached its critical temperature for loss of bonding, the panel would start to bulge or sag. This initial deflection caused by the first delamination would occur over a rather short period of time. The deflection would then continue to increase in a linear fashion as the fire proceeds to weaken the core.

The two overhead deck tests were run for 30 and 120 minutes respectively for the uninsulated and the insulated subjects. The insulated deck had stiffeners on its exposed underside. Generally it can be said about these two subjects that they remained intact on the unexposed for the duration of the test with no flame or smoke spread. Both subjects experienced quite a bit of sag: 85mm and 240mm respectively after 30 and 120 minutes, but no collapses. Do note that the difference in size of the panels, different loads and the addition of stiffeners to the insulated panel means that no real correlation can be made between the two in regards to amount of deflection as a function of time. Figure 20 pictures the two overhead deck panels deformation as a function of time.

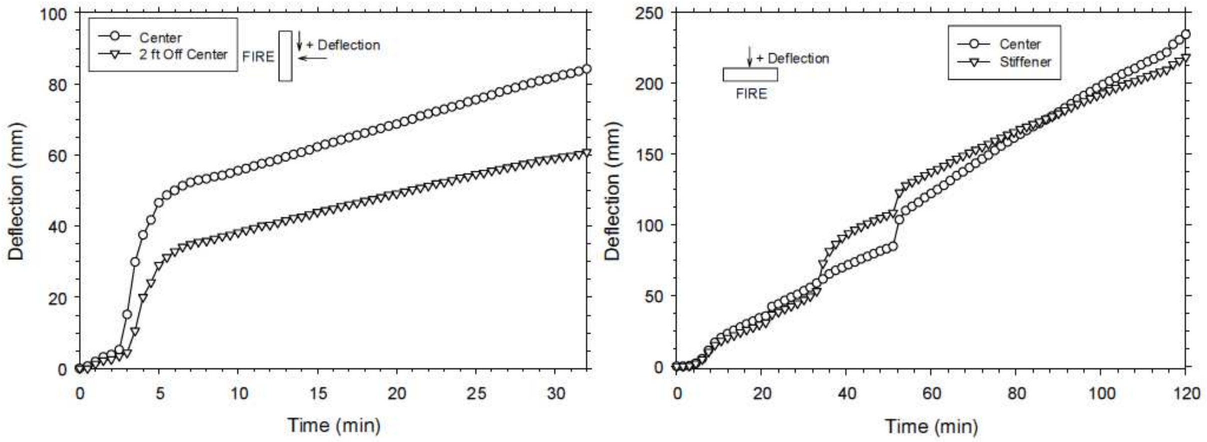


Figure 21. Graphs picturing transversal deflection in centre of tested FRP panels. Left hand graph is from test #2, Right hand graph is from test #6 (Lattimer, Oulette, & Sorathia, 2004).

Examining the graphs one can clearly see the initial deformation spike from delamination and the subsequent linear behaviour in the un-insulated case (left graph). In the insulated case this process is more gradual, because of the fact that there is insulation and a stiffener. The volatility in the region 35<t<55 is caused by the supporting steel structure deflecting due to high temperatures.

The four bulkheads were tested for 30 to 120 minutes depending on test setup. Much like with the overhead decks the FRP panels started to deflect as the exposed side's laminate reached critical temperature. However, as two of these tests were designed to really stress test the construction with long exposure and no insulation some interesting observations could be made. After around 55 minutes temperatures got high enough in these two stress tests to also delaminate the unexposed side of the FRP panel, the structure was still able to carry the load for about 20 and 60 minutes more depending on whether stiffener side was exposed or not. Also, the exposed stiffeners were of T-joint construction whilst the un-exposed ones were of carbon construction.

App. C.3 SP internal tests

In addition to the tests performed at the time of writing of this report, a series of older tests that were performed at SP but not released to the public for different reasons (SP, 2012), were reviewed. Referring to these specific results is thus not possible in this report. However, some results and conclusions of relevance can be described in general terms and they will be presented in this chapter.

Generally speaking it can be said about the FRP composite construction that it does not suddenly collapse when one laminate's bond is lost as a result of fire exposure. Rather, decks and bulkheads will sag or buckle increasingly for some time until collapse occurs.

Another interesting find in the performed tests was that the composite material is rather difficult to extinguish completely once it has caught fire. The construction will tend to relapse into ignition with local flames mostly in intersections, joints et cetera. A reason for this could be the large amount of insulation present. While the insulation is a thermal barrier that lengthens the time until the underlying composite heats up, it is also equally good at keeping heat inside of the construction once the fire source is removed.

There is also a risk of a creeping fire, that may slowly burn through the material because of the difficulties with removing the heat in the structure. This results in a need to monitor the FRP composite for many hours after a fire has been extinguished.

A balsa core bulkhead was tested. It had with a thickness in the span 40-50mm and was stiffened on the exposed side. It was insulated enough to withstand around 35-40 minutes of standardized fire before the underlying exposed laminate reached delamination temperature and was able to bear its load for just over two hours. Horizontal deflection at the centre of the panel was 10cm shortly before structural failure and 3cm halfway through the test.

A balsa core deck with the same construction and insulation as the previously mentioned balsa core bulkhead was tested. The deck failed after around 100 minutes. Deflection at the centre of the panel was again around 10cm at the time of failure but halfway through it was only about 1cm.

A PVC core bulkhead was tested. It had a thickness in the span 25-35mm and was stiffened on the exposed side. It was insulated enough to withstand around 40-45 minutes of standardized fire before the underlying exposed laminate reached delamination temperature and was able to bear its load without failure for 60 minutes when the test was terminated. Horizontal deflection was at this point a little more than 3cm.

A PVC core deck with the same construction and insulation as the previously mentioned PVC core bulkhead was tested. The deck was able to bear its load without failure for 60 minutes when the test was terminated. Deflection was at this point around 5cm.

Appendix D. Incident reports

In this chapter two incidents are summarized that are of relevance and interest for this report, namely the fires on Star Princess and HMS Ladbury.

App. D.1 Star Princess - outboard fire on balconies

This is an interesting case, as it is a recent major fire on board a large cruise ship that involved both outboard and interior spaces. In conclusion several important lessons can be taught from this accident. First of all, the crew made a commendable effort in combating the rapidly spreading large fire. They responding quickly and efficiently, proving that a well functioning firefighting organization can perform admirably. Second, the hi-fog system installed in all interior spaces was a huge factor in tipping the scale in favor of firefighters. In the cabins where the system was fully or partially functional, the fire was unable to take root. However, in a few cabins the system malfunctioned, probably due to broken sprinkler bulbs. One cabin got almost completely burnt out, resulting in a badly buckled and nearly breached inner ceiling and alleyway door. The following figure shows the cabins in which the hi-fog system was functional, respective non-functional.

Figure 22. Damage done to a cabin with a functioning hi-fog system (left), and damage to the cabin with a malfunctioning hi-fog system (right) (MAIB, 2006).

Some further details on this incident are hereby summarized: In March 2006, a fire broke out on a balcony on the port side of cruise ship Star Princess. At the time 2690 passengers and 1123 crew were on board. The fire started on deck 10 and after an estimated 20 minutes of smoldering phase, it quickly spread once established. Within six minutes after fire establishment, deck 11 and 12 and two main vertical fire zones were involved. After 24 more minutes it had spread further, involving a third main vertical fire zone. The fire spread to the cabins after the glass doors separating them from the balconies shattered from the heat. Here, the fire was contained by the cabins' Marioff Hi-Fog fire-smothering system and was hindered from spreading further inboard. Temperatures on the balconies were high, in excess of the 550°C that is required to melt the aluminum structure. A total of 79 cabins were condemned by the fire, and another 218 were damaged by fire, smoke or water. During the fire a total of 168 water mist heads were activated. 8 failed to operate, 7 of which due to glass bulbs being empty. The cabins in which the water mist heads failed to operate were much more severely damaged, compared to the other cabins. They were all but burnt out and their interior walls, ceilings and alleyway doors were buckled and almost breached, as opposed to the relatively slim damage in the other cabins where the Hi-Fog system functioned.

The heavy smoke generated by the fire entered adjacent cabins and alleyways and made evacuation difficult, especially on deck 12. As a result, one passenger died from smoke inhalation and another 13 were treated for smoke inhalation effects.

The fire was declared extinguished about one and a half hour after it had started. Firefighting efforts had then been active for one hour, suppressing the fire with water hoses. The fire was reported being difficult to get to, as balconies were vertically separated between cabins. Firefighters made a commendable effort given the severity of the fire and that the whole scenario was both unexpected and unrehearsed.

The onboard firefighting organization was divided into two main squads; one comprised of 20 personnel from deck and one with 27 personnel from engine crew. The deck fire squad was normally used as lead fire squad in case of fire in accommodation areas while the engine fire squad was used as lead fire squad in case of fire in machinery spaces. Each squad had six appointed members nominated to dress up in firefighting suits with BA's. One of the suits in each squad had a built in thermal imaging camera. Both squads also had one handheld TIC device each, primarily used to locate hot spots while boundary cooling.

(MAIB, 2006)

App. D.2 HMS Ladbury – fire in machinery space

A significant diesel oil fire occurred on board HMS Ladbury in a machinery space. What year the incident occurred is not specified in the report, but is described as recent and the report was published 1991. The fire had the following principal points:

- High temperatures were thought to have been achieved in the compartment.
- The fire was put out after 4 hours.
- The only fire spread that occurred, was some burn-through via a gland (an installation passage), to an adjacent compartment.
- Completely extinguishing the structure was difficult, as reigniting occurred in several instances.
- Repairing the damaged structure afterwards was not difficult.

(Allison, Marchand, & Morchat, 1991)

Appendix E. IMO Codes definitions

App. E.1 “A class” divisions according to SOLAS

The definition in SOLAS 2009 II-2/3-2 states the following:

“A” class divisions are those divisions formed by bulkheads and decks which comply with the following criteria:

- *.1 They are constructed of steel or equivalent material;*
- *.2 They are suitably stiffened;*
- *.3 They are insulated with approved non-combustible materials such that the average temperature of the unexposed side will not rise more that 140°C above the original temperature, nor will the temperature, at any point, including any joint, rise more than 180°C above the temperature, within the time listed below;*
    - *Class “A-60”* *60 min*
    - *Class “A-30”* *45 min*
    - *Class “A-15”* *15 min*
    - *Class “A-0”* *0 min*
- *.4 They are so constructed as to be capable of preventing the passage of smoke and flame to the end of the one-hour standard fire test; and*
- *.5 The Administration required a test of a prototype bulkhead or deck in accordance with the Fire Test Procedures Code to ensure that it meets the above requirements for integrity and temperature rise.*

App. E.2 Fire-Resisting Divisions (FRD) according to HSC Code

The writing of this report ia based upon the assumption that all load-bearing FRP panels are to be constructed and tested according to the IMO High Speed Craft Code which is the current suggestion presented. Specifically the panels are to be tested according to paragraph 7.2.1: Fire-resisting divisions. Since all FRP composite panels and would be required to pass 60 minutes of such a test.

7.2.1 Fire-resisting divisions are those divisions formed by bulkheads and decks which comply with the following:

- *.1 They shall be constructed of non-combustible or fire-restricting materials which by insulation or inherent fire-resisting properties satisfy the requirements of 7.2.1.2 to 7.2.1.6.*
- *.2 They shall be suitably stiffened*
- *.3 They shall be so constructed as to be capable of preventing the passage of smoke and flame up to the end of the appropriate fire protection time*
- *.4 Where required, they shall maintain load-carrying capabilities up to the end of the appropriate fire protection time.*
- *.5 They shall have thermal properties such that the average temperature on the unexposed side will not rise more than 140°C above the original temperature, nor will the temperature at any point, including any joint, rise more than 180°C above the original temperature during the appropriate fire protection time.*

- *.6 A test of a prototype bulkhead or deck in accordance with the Fire Test Procedures Code shall be required to ensure that it meets the above requirements.*