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Evegren, Franz

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LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

Assessing fire safety of fiber reinforced polymer composite ship structures

FRANZ EVEGREN
DIVISION OF FIRE SAFETY ENGINEERING | FACULTY OF ENGINEERING | LUND UNIVERSITY

Assessing fire safety of fiber reinforced polymer composite ship structures

Franz Evegren

LUND UNIVERSITY

DOCTORAL DISSERTATION

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Faculty opponent
Björn Karlsson, University of Iceland

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Author(s): FRANZ EVEGREN

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Abstract:

The environmental impact from shipping is driven by the combustion of fossil fuel. It has great potential to be reduced by use of structures in lightweight fibre reinforced polymer composite instead of steel. This has not been possible for ships regulated under SOLAS, since assessment of fire safety of such a fundamental change is complex. The purpose of this thesis has been to provide for the assessment by (1) investigating strategies for identifying hazards and criteria, (2) exploring performance verification methods, and (3) developing the assessment procedure described in MSC/Circ.1002. The regulations have unclear connections and were formed with steel structures in mind. It was therefore concluded that all the regulations' objectives and functional requirements need to be evaluated, not only those of deviated prescriptive requirements. A procedure was developed, illustrated in a flowchart, to identify hazards and criteria based on regulations and prescribed tests. Regarding performance verification, when testing structural fire integrity of fiber reinforced polymer composite bulkheads it was found necessary to apply the design load, not 7 kN/m as prescribed, and that the surface temperature does not appraise performance. A new multiple-core sandwich design showed potential to effectively achieve structural fire integrity without using insulation. Further, a large-scale test method for façades was investigated and found suitable to evaluate fire protection of external surfaces. A heat transfer model for enclosures with lumped heat capacity was also developed to compare the effects of heat transfer through steel and insulated boundaries. To characterize the fire risk in different, or all, areas, a framework was proposed with different levels, allowing to adapt the assessment to uncertainties. Further research is needed to investigate performance and verification of current and future fiber reinforced polymer composite materials. For application of lightweight composite materials to release, examples are needed, to build experience for all stakeholders and to open new ways for ship design.

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Franz Evegren

LUND
UNIVERSITY

Supervisor
Adjunct Professor Haukur Ingason (Lund University/RISE)

Co-supervisors
Senior Lecturer Håkan Frantzich (Lund University), Doctor Kerstin Eriksson (RISE), Doctor Philippe Noury (DNV)

Faculty opponent
Professor Emeritus Björn Karlsson, University of Iceland, Iceland

Examining committee
Professor Bijan Adl-Zarrabi, Chalmers University of Technology, Sweden
Doctor Joelle Gutierrez, Naval Group Directrice de domaines techniques, France
Associate Professor Lars Schiøtt Sørensen, DTU, Denmark

Sponsoring organization
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Cover image by Franz Evegren of the most frequent non-common words used in the thesis randomly put together in a word cloud using WordCloud.com.

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To my patient family

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Executive summary

Shipping is a sustainable mode of transport but there is great potential for improvement. The main environmental impact from shipping stems from the use of fossil fuel, which can be reduced by replacing steel with lightweight structures of fiber reinforced polymer (FRP) composite. Using combustible materials for structures has not been possible for ships regulated under SOLAS, i.e. large commercial ships (over 500 gt) on international voyages, since assessment of fire safety of such a fundamental change is complex. The purpose of this thesis has been to provide for such assessment by:

(1) investigating strategies for identifying fire hazards and performance criteria connected to the use of FRP composite,

(2) exploring verification methods for the performance of FRP composite and safety measures using fire testing and modelling, and

(3) developing how the fire safety of ships with FRP composite can be assessed based on the procedure of the International Maritime Organization described in MSC/Circ.1002.

Strategies for identifying hazards and criteria were investigated by studying the regulatory framework, previous assessments and related research. The regulations are based on use of steel structures and have largely been formulated as a reaction to previous incidents. This has led to unclear connections between prescriptive requirements, functional requirements and regulation objectives. It was therefore concluded that all objectives and functional requirements in SOLAS need to be evaluated when considering FRP composite structures, not only those of deviated prescriptive requirements. A procedure was also developed, illustrated in a flowchart, to identify fire hazards and performance criteria based on the most relevant affected regulations and prescribed verification tests.

Regarding performance verification, three areas were investigated where hazards were identified in relation to the regulations:

- Fire spread on external surfaces had previously not been relevant to regulate or evaluate, but external FRP composite surfaces called for investigating verification through a large-scale test method for façades called SP FIRE 105. A passive fire protective coating and active sprinkler systems were evaluated, and the method was found to be a suitable basis for evaluation.

- Another identified hazard was that the more insulating FRP composite structures could cause quicker fire growth. Investigating this for many spaces called for quick approximate answers, which led to the development of a new simple model to estimate temperatures in pre-flashover enclosure fires during transient heat release rates. The model was based on well-

known fire physics and heat transfer through boundaries with lumped heat capacity. Predictions by the new model were compared with experimental measurements and with simulations using Fire Dynamics Simulator, which provided a promising validation.

- A key hazard using FRP composite structures is their structural fire integrity. Critical aspects of design and verification were investigated based on a test series with FRP composite bulkheads of varied designs. It showed that the critical aspect during combined thermo-mechanical testing is the loading, even if the structure is designed for the applied loading. Therefore, structures should always be tested during application of the design load in loaded fire resistance tests, not with 7 kN/m as prescribed. Furthermore, neither the temperature at the exposed surface nor at the unexposed surface of the FRP composite is useful to appraise structural fire integrity performance. The traditional structures in the test series all had thermal insulation applied as protection, which adds both weight and volume. A new multiple-core sandwich design, with two cores and three laminates, was also tested. Despite having no insulation, it significantly surpassed the structural fire integrity performance of a corresponding insulated FRP composite structure. The multiple-core sandwich design thus proved great potential if sufficient reaction to fire performance is achieved.

With knowledge in the introduced hazards and effects of safety measures, fire risk characterization can be done in different ways. A framework was proposed for risk characterization at one of four levels of (increasing) sophistication, depending on the scope of the alternative design and arrangements:

A. Qualitative assessment

B. Consequence assessment

C. Reliability assessment

D. Probabilistic risk assessment

Dividing the assessment in different areas allows adapting the sophistication of the risk characterizations to the uncertainties. The risk characterization in each area must be suitable to describe the introduced novelty in terms of fire safety without being overly complicated or time consuming. Hence, the consequence assessment outlined in MSC/Circ.1002 may not be suitable.

Further research is needed to investigate performance and verification of current and future FRP composite materials. For application of lightweight composite materials to release, examples are needed, to build experience for all stakeholders and to open new ways for ship design.

Populärvetenskaplig sammanfattning

Fartyg är ett relativt miljövänligt transportslag men potentialen för förbättring är stor. Den huvudsakliga miljöpåverkan kommer från användning av fossila bränslen, vilken skulle kunna reduceras genom att bygga lättare fartyg. En avsevärd skillnad skulle erhållas genom att ersätta stål med lika stark fiberarmerad plastkomposit, men det tillåts inte av regelverket för fartyg på internationella resor. SOLAS-konventionen kräver att bärande strukturer utformas av obrännbart material och det anses generellt svårt att bedöma påverkan på brandskyddet vid en sådan avvikelse. Syftet med denna avhandling har därför varit att bistå sådana bedömningar genom att (1) undersöka strategier för att identifiera faror och kriterier, (2) utforska verifieringsmetoder för prestanda, och (3) utveckla bedömningsproceduren som beskrivs i MSC/Circ.1002.

Som utgångspunkt för bedömningen instruerar MSC/Circ.1002 att avsteg från regler ska dokumenteras. Detta ger dock inte en tillräcklig grund för bedömningen, då kopplingen mellan reglerna och med deras syften och funktionskrav är otydlig. Vidare är många regler utformade med ett outtalat antagande om att stålstrukturer används. Därför är det nödvändigt att utvärdera alla reglernas syften och funktionskrav vid en bedömning av hur ett byte från stål- till komposit-konstruktioner påverkar brandskyddet. En förenklad procedur togs även fram, i form av ett flödesschema, för att tydliggöra vad konstruktioner förväntas prestera i olika avseenden. För att underlätta processen och strukturera bedömningen kan den delas upp i dessa avseenden, eller utifrån reglerna i SOLAS.

När det kommer till verifiering av brandegenskaperna för fiberarmerad plast-komposit utvärderades bland annat en storskalig metod för fasader. Den visade sig vara användbar för att bedöma brandskyddet hos kompositmaterial skyddat med sprinkler eller brandskyddsfärg. Testerna visade att brandtillväxt på en oskyddad komposit kan vara snabb men att både sprinkler och brandskyddsfärg kan ge ett rimligt skydd. Gällande strukturell bärförmåga vid brand utvärderades hur skott ska designas och testas, och det konstaterades att lasten är det som påverkar prestationen mest. Det är därför viktigt att brand-testa den starkaste konstruktion i ett koncept med den dimensionerande lasten, och inte med 7 kN/m som det föreskrivs. Vidare noterades att den uppmätta temperaturen på den exponerade, eller oexponerade, ytan inte ger en bra indikation för strukturell bärförmåga vid brand. Detta bör därför även fortsatt utvärderas genom belastat brandtest.

Ett annat område som undersöktes i detalj var inneslutning av brand, och i synnerhet hur effekterna av ökad isolering kan beräknas. Värmeisolering av komposit-strukturer är ett relevant sätt att skydda interna strukturer. Det medför dock även högre temperaturer i de rumsvolymer som skapas av de isolerade konstruktions-delarna. En modell utvecklades därför för att uppskatta effekterna på temperatur-utvecklingen i ett brandrum beroende på dess värmeisolering. Modellen gäller för olika isolerade strukturer som ur ett uppvärmningsperspektiv kan betraktas ha koncentrerad massa. Modellen kan hantera varierande brandeffekt, som används som indata. I jämförelse med fullskaliga experiment och simuleringar med modellen Fire Dynamics Simulator gav den skapade modellen tillförlitliga resultat, särskilt med hänsyn till dess enkelhet och kortare beräkningstider.

Med kunskap om brandegenskaper och effekterna av skyddsåtgärder kan brandrisken karakteriseras på olika sätt. Ett ramverk föreslogs för hur brandrisken kan karakteriseras på fyra olika nivåer, med ökande komplexitet och detaljeringsgrad:

A. Kvalitativ bedömning

B. Konsekvensanalys

C. Tillförlitlighetsanalys

D. Probabilistisk riskbedömning

Att dela in karakteriseringen i olika områden gör det möjligt att kombinera olika metoder och anpassa valet av nivå till de osäkerheter som finns. Det viktiga är att bedömningen kan beskriva effekten av förändringen av brandskyddet. Den konsekvensbedömning som beskrivs i MSC/Circ.1002 kan alltså vara otillräckligt sofistikerad. Med lämplig karakterisering och ökad kunskap om brandriskerna tros likvärdigt brandskydd kunna garanteras för fartyg med strukturer av fiberarmerad plastkomposit i en nära förestående framtid.

Acknowledgement

The completion of this thesis has been a long and enriching journey, made possible by the guidance, support and encouragement of many individuals. I am deeply grateful to those who have contributed to my academic journey, offering their wisdom, patience, and unwavering belief in my abilities. This work is a reflection of not only my efforts but also the collective support of supervisors, family, friends and colleagues who have stood by me during this significant chapter of my life.

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List of Papers

Paper I

Evegren, F. & Hertzberg, T. (2015). Fire safety regulations and performance of fibre-reinforced polymer composite ships structures. *Journal of Engineering for the Maritime Environment*, 1(231), 46-56. doi: 10.1177/1475090215620449

Paper II

Evegren, F., Rahm, M., Arvidson, M., & Hertzberg, T. (2014). Fire Testing of external combustible ship surfaces. *Fire Safety Science-Proceedings of the Eleventh International Symposium*, 905-918. doi: 10.3801/IAFSS.FSS.11-905

Paper III

Evegren, F. & Wickström, U. (2015). New approach to estimate temperatures in pre-flashover fires: Lumped heat case. *Fire Safety Journal*, 72(2015), 77-86. doi: 10.1016/j.firesaf.2015.02.008

Paper IV

Rahm, M., Evegren, F. (2016). *Structural fire integrity testing of lightweight structures*. Proceedings of the 35th International Conference on Ocean, Offshore and Arctic Engineering (OMAE), Busan, South Korea. doi: 10.1115/OMAE2016-54418

Paper V

Rahm, M., Evegren, F. (2017). *Progress in the Analysis and Design of Marine Structures - The 6th International Conference on Marine Structures (MARSTRUCT 2017)*. Proceedings of the 6th International Conference on Marine Structures (Marstruct 2017), 869-876, Lisbon, Portugal. doi: 10.1201/ 9781315157368-98

Paper VI

Evegren, F. (2017). Fire risk assessment of alternative ship design. *Ships and Offshore Structures*; 6(12), 837-842. doi: 10.1080/17445302.2016.1275474

Author’s contribution to the papers

All papers have been accepted to international scientific journals or conferences after full peer-review. The contributions by the author to the six scientific papers can be described accordingly, by the level of responsibility and work effort in the research and development:

minor The author has taken minor responsibility and performed a small proportion of the work (less than 1/3 of the responsibility and amount of work).

medium The author has taken medium responsibility and performed approximately half of the work (between 1/3 and 2/3 of the responsibility and amount of work).

major The author has taken major responsibility and performed a large proportion of the work (more than 2/3 of the responsibility and amount of work).

The development of each paper can be divided in the five consecutive steps listed in Table 1, which also summarizes the contributions by the author. The contributions by the author have been dominating in the development of most of the appended papers.

Table 1. Contribution by the author in different steps of the appended papers

Step	***Degree of responsibility and work effort***					
	Paper I	Paper II	Paper III	Paper IV	Paper V	Paper VI
1. Planning and preparation	major	medium	medium	medium	medium	major
2. Execution	major	minor	major	minor	minor	major
3. Analysis	major	major	major	medium	minor	major
4. Preparation of paper	major	major	major	medium	medium	major
5. Presentation at conference	n/a	major	n/a	minor	minor	n/a

Paper I was planned and prepared by the author with support from the supervisors, including concretization and formulation of objectives, as well as planning of the literature to be studied. The execution of the literature study and most of the analysis of the collected data were conducted by the author. Preparation of the paper, including the composing, submission administration and revisions, were primarily done by the author, with support from the co-author.

Paper II involved the author to a large degree when it came to identifying the addressed hazard, formulating the scope of the test series and the design of the test procedures. The execution of the test series was led by one of the experienced co-authors and was supported to a small degree, while the main analyses of the test results was led by the author. Preparation of the paper was led by the author, who composed most of it and led the revision with input from the co-authors. The author also prepared a presentation, gave an oral delivery and defended the paper at a scientific conference, where the paper was rewarded.

Paper III involved both the author and the co-author to a large degree in the planning and preparation of the paper, as well as in the formulation of ideas and theory behind the model to be developed. The author did most of the execution of the study, setting up the model, running and fixing it, with support from the co-author. The analysis and comparisons with other models and experiments were led by the author. The experiments were not conducted as part of this paper but were performed in a master thesis project set up and supervised by the author. The preparation of the paper was led by the author, which included most of the writing and revision of the paper, scrutinized and improved by the co-author. A corrigendum was also prepared by the author due to an inverse error identified by the author, which although did not affect the calculations.

Paper IV involved both authors of the paper to a large degree; the planning and preparation of the paper were done in a joint research project where the objectives and design of the test procedure were formulated as well as the practical planning. Since the test series was largely based on a standardized test method, execution was conducted by qualified test engineers. However, the authors analysed the collected data in a structured way in relation to the research objectives and drew conclusions based on comparison of the results. The author composed significant parts of the paper and was involved in preparing all of the parts. Support was also given in preparations for the conference presentation, while the oral delivery and defence were carried out by the co-author.

Paper V involved the author to a lesser degree overall. While being involved in the planning and preparation of the paper, including concretization of the scope, structural design and test planning, the author had minor involvement in execution and analysis. The latter primarily involved comparing the test data of the new structural design with previous test results, which the author was behind. The author was to a large degree involved in preparation of the paper. The work was led by the first author and supported by the co-authors, but the author was involved in composing most parts of the paper. The paper further took inspiration in Paper IV, which was largely composed by the author. Support was given to prepare the presentation for the oral delivery, given by the first author.

Paper VI was planned and prepared mainly by the author, with support from the supervisors. Models and theories were developed by the author over many years, and to some extent also the execution of the literature survey. The analysis and examination of the collected data were mainly done by the author, with advice from the supervisors. They also supported the preparation of the paper, which was fully composed, administered and revised by the author.

Nomenclature

Abbreviations

ADA	Alternative design and arrangements (of fire safety)
Circ.	Circular
CFD	Computational Fluid Dynamics
FDS	Fire Dynamics Simulator (CFD program)
FRD	Fire-Resisting Division
FRM	Fire-Restricting Material, according to FTP Code, Part 10
FRP	Fiber Reinforced Polymer
FTP	Fire Test Procedures (Code)
GS	Global Strength
HazId	Hazard Identification
HDT	Heat deflection/distortion temperature (ASTM D648 and ISO 75-1)
HRR	Heat Release Rate
HSC	High-Speed Craft
IMO	International Maritime Organization
ISO	International Organization for Standardization (no acronym)
LB	Loadbearing
LFS	Low Flame Spread (characteristics), according to FTP Code, Part 5
LOA	Length overall (of a ship)
MSC	Maritime Safety Committee (at IMO)
n-LB	Non-loadbearing
PRA	Probabilistic Risk Assessment
PVC	Polyvinyl Chloride
RO	Research Objective
RCM	Risk Control Measure
SDC	Ship Design and Construction (sub-committee to MSC at IMO)

SFPE	Society of Fire Protection Engineers
SOLAS*	International Convention for the Safety Of Life At Sea
SP	SP Technical Research Institute of Sweden; since 2017 merged in RISE Research Institutes of Sweden
SRtP	Safe Return to Port
Tg	Glass transition temperature (ISO 11357-2)
QRA	Quantitative Risk Assessment

**SOLAS chapter II-2, also abbreviated SOLAS II-2, refers to the second subchapter (Fire protection, fire detection and fire extinction) of chapter II (Construction), also referred to as the "fire safety chapter" in this thesis. SOLAS II-2/9.2.2.3 means SOLAS chapter II-2, regulation 9, paragraph 2.2.3. If not specified, SOLAS chapter II-2 is implied in this thesis, in particular when simply referring to "regulation 17".*

Definitions

Administration is the notion used in SOLAS for Flag States (see below), among other things approving the ship's fire safety.

Alternative design and arrangements (ADA) *of fire safety* means fire safety measures which deviate from prescriptive requirements of SOLAS chapter II-2 but are suitable to satisfy the fire safety objectives and the functional requirements of that chapter.

Fire hazard is a source with potential for harm associated with fire.

Fire risk is the antonym of fire safety and refers to uncertainty of events and consequences associated with fire (accounting for e.g. fire hazards and safety measures).

Flag State is the country where a ship is registered; it is responsible to ensure compliance with international maritime regulations and requires the ship to fly their flag.

FRP composite consists of a polymer matrix reinforced with fibers. This forms laminates which can be used together with core material to make up lightweight sandwich panels and stiffeners, referred to as FRP composite structures or simply FRP composite.

Functional requirements explain, in general terms, what functions the design should provide to meet the objectives.

MSC/Circ.1002 refers to the circular numbered 1002, approved by the Maritime Safety Committee at IMO, which describes "*Guidelines on alternative design and arrangements for fire safety*" and thus a procedure to make a Regulation 17 assessment.

"***Non-combustible** is a material which neither burns nor gives off flammable vapours in sufficient quantity for self-ignition when heated to approximately 750°C, this being determined in accordance with the Fire Test Procedures Code.*" (Chapter II-2, Reg. 3.33 IMO, 1974)

Performance criteria are measurable quantities stated in engineering terms to be used to judge the adequacy of trial designs (IMO, 2002).

Preliminary analysis is described in Circular 1002 (IMO, 2001) as the first step in the Regulation 17 assessment. It is also a coarse method for hazard identification which is often a good starting point to get a picture of the problem at hand.

Prescriptive-based design or prescriptive design means a ship designed with fire safety measures in compliance with the prescriptive regulatory requirements set out in parts B, C, D, E or G of SOLAS II-2.

Regulation 17 refers to SOLAS chapter II-2, regulation 17.

Regulation 17 assessment refers to the assessment required by SOLAS II-2/17 for alternative design and arrangements (ADA) of fire safety.

Risk Control Measure (RCM) and is a means of controlling a single element of risk, usually targeting either probability or consequence (IMO, 2013, 2018).

Risk Control Option (RCO) is a combination of risk control measures (IMO, 2013, 2018).

1 Introduction

In the second half of the 19th century, the shipbuilding industry was going through a revolution; wood in ship structures was replaced by iron and steel. Attempting to pioneer the new materials, shipyard manager Joseph L. Meyer was strongly questioned by the local ship-owners in Papenburg, Germany. They threw iron into the water and said: “*Iron won’t float. And you want to use this for shipbuilding?*” (McGeorge, 2009b). This was one of many arguments made against the new material throughout the world. In an article in The New York Times ("Ships of wood or metal", 1892) it was nevertheless claimed that the new material was superior and safer than wood if properly managed. The article confronted concerns regarding durability and safe construction, but also weight, cost and complexity of repair. Each of these areas indeed had to be overcome and required development of completely new skills and experience, since there were no guidelines or rules for the new technology at the time. In later years, the situation has been very similar, but with the new material fiber reinforced polymer (FRP) composite being introduced to the industry. As illustrated in Figure 1, the arguments are almost identical as over 100 years ago, but the new material does not rot, crack, corrode, or sink - it burns (McGeorge, 2009b).

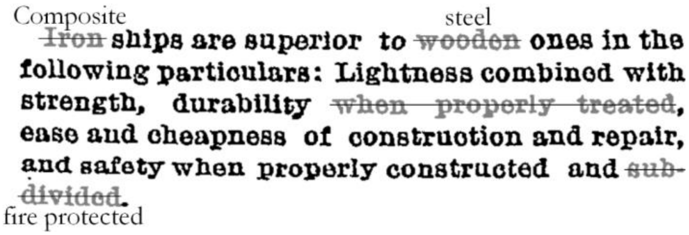

Composite ~~Iron~~ ships are superior to ~~wooden~~ steel ones in the following particulars: Lightness combined with strength, durability ~~when properly treated~~, ease and cheapness of construction and repair, and safety when properly constructed and ~~sub-divided~~ fire protected.

Figure 1. Extract from The New York Times article ("Ships of wood or metal," 1892), adapted to this century, inspired by McGeorge (2009b).

Just as over 100 years ago, shipping today is a vital mode of transport throughout the world, and it is expected to grow significantly in the coming years (UNCTAD, 2024). It solves congestion problems by requiring significantly less infrastructure than land-based modes and it has principal environmental advantages, in particular regarding energy efficiency. However, while land transport has become cleaner by stricter regulations and new technology, there is still great potential in reducing the environmental impact from shipping. The dominating polluter in the lifecycle of ships is by large the combustion of fossil fuels, which is directly impacted by the ship's weight (Hedlund-Åström, 2009, 2011). Reducing weight high up on a vessel can also improve stability and allow reducing the keel several times that weight. The weight savings can otherwise be utilized to carry more cargo or passengers, or facilitate the use of more sustainable power sources. Thus, lightweight design can in different ways increase the pay load/displacement ratio, which benefits the environment at the same time as there are economic incentives for the ship owner (Rubino et al., 2020; Sanchez Heres, 2015).

FRP composite has come into focus as a solution for lightweight design. It consists of a polymer matrix reinforced with for example glass or carbon fibers. This forms strong laminates which can be applied on both sides of a core material to make up lightweight sandwich panels. The use of such structures has increased significantly in the whole transport sector since the 1960s, primarily thanks to outstanding physical, thermal and mechanical properties (Mouritz & Gibson, 2006). In shipping, the materials were first introduced in the 1940s, to replace wood in military boats and small craft, and they are now used widely in maritime applications (see e.g. Graham-Jones & Summerscales, 2015; Smith, 2001; Summerscales et al., 2019). In addition to weighing about a fifth of a corresponding steel structure, FRP composite offers several key advantages in shipbuilding, including low thermal expansion, high specific stiffness and strength, as well as excellent fatigue endurance, corrosion resistance and thermal insulation (Mouritz & Gibson, 2006). Many large naval ships have therefore been constructed with load-bearing FRP composite structures (Mouritz et al., 2001), such as the 73-meter Swedish stealth Visby-class corvettes (Lindblom, 2003), the world's fastest armed ships - the Norwegian Skjold-class corvettes (Harboe-Hansen, 1996), and the deckhouse of the large US multi-purpose Zumwalt-class destroyers (Legault, 2010). However, there are also disadvantages to the materials which must be considered in shipbuilding, such as their anisotropic properties, poor impact damage tolerance and, not least, their fire performance (Mouritz & Gibson, 2006).

Fire performance is arguably the drawback that has been debated most intensely in relation to use of FRP composite ship structures. In military ship applications, fire protection has been solved by allowing safety to be achieved in other ways than according to prescriptive regulations. However, the merchant industry has traditionally been more conservative. For merchant ships on international voyages, the applicable safety regulations are found in the SOLAS (Safety Of Life At Sea) Convention (IMO, 1974), stipulated by the International Maritime Organization (IMO). A fundamental requirement in the Convention is the prohibition of combustible material in structural parts of a ship. The use of load-bearing FRP composite structures for large merchant ships was thereby impeded until 1994, when the International Code of Safety for High-Speed Craft (HSC) was adopted under SOLAS (IMO, 2000). It applies to ships operating above a certain ratio of speed/displacement and allows using combustible materials for structures if they classify as fire restricting (IMO, 2012). The Code is nevertheless also based on a completely different safety philosophy compared to SOLAS, for example requiring HSC to have a much shorter evacuation time and to operate on a fixed limited route with a significantly enhanced safety organization (IMO, 2000). The HSC Code was the result of pressure from the shipbuilding industry, extensively increasing the use of lightweight materials in the 1980s and 1990s to achieve faster transportation.

For displacing merchant vessels, the benefits from using lightweight construction materials were not thoroughly investigated until after the fire safety regulations in SOLAS were reformed in 2002. It introduced a new fire safety chapter II-2 with a performance-based structure and also a new regulation opening up for alternative solutions. Innovative design solutions could now be accepted if they were regarded at least as safe as a design complying with the prescriptive requirements. This opening was explored for the use of load-bearing FRP composite ship structures in a number of research projects - first in LASS (Lightweight Construction Applications at Sea), initiated in 2005, and then in several further projects before the outset of this thesis work, including SAFEDOR (McGeorge et al., 2009), MP08 (Breuillard & Corrignan, 2009) and DE-LIGHT (Noury & McGeorge, 2010). Assessment of fire safety was also determined as the primary key for industrial application of lightweight FRP composite structures for SOLAS vessels (Hertzberg, 2009). Since then, several more projects have followed, addressing fire safety when using FRP composite ship structures, including BESST (Evegren, 2013b; Hugosson, 2011; Rahm, 2012), Eco-Island ferry (Evegren, 2013a), FIRE-RESIST (Monti et al., 2015), COMPASS (Karatzas, 2016), Fibreship (Jogia & Jurado, 2020), RAMSSES (de Bruijn et al., 2021; Verhaeghe & Breuillard, 2021), KOMPIS (Sandinge et al., 2022) and FIBRE4YARDS (Pacheco et al., 2023).

The regulation introduced in 2002 that opened up for alternative design and arrangements of fire safety was SOLAS chapter II-2, regulation 17 (hereafter referred to as ‘regulation 17’). When it was introduced, IMO also published guidelines for how a sufficient degree of fire safety should be demonstrated. They are documented in MSC/Circ.1002 (IMO, 2001) and outline a ‘relative’ fire risk assessment procedure, where the degree of fire safety of the alternative design is compared to that of prescriptive requirements. However, the guidelines are at a high level and leave many gaps for the risk analyst to fill in. Furthermore, the new performance-based fire safety chapter (SOLAS II-2) was established with vague connections between functional and prescriptive requirements. Assessment of fire safety when making such a fundamental change as to replace steel with combustible structures was therefore considered beyond state of the art (Hertzberg, 2009; McGeorge, 2009a).

To demonstrate the alternative fire safety of a ship with FRP composite structures, it is important that hazards and performance criteria can be identified from prescriptive requirements. This is the basis for the comparative assessment.

However, it is complicated when the regulations are unclear and formulated based on traditional steel construction and it therefore requires an insightful strategy. Furthermore, assessment of fire safety of FRP composite structures requires relevant verification of the fire performance of the materials and considered safety measures. It can for example consist in fire testing or modelling, to evaluate FRP composite in relation to the introduced fire hazards. With hazards and performance criteria identified, and the performance of FRP composite and safety measures verified, research in risk assessment can advise how the fire safety can be evaluated and how MSC/Circ.1002 should be applied. This thesis addresses these challenges, as concretized in the subsequent research objectives.

1.1 Research objectives

The purpose of the research work presented in this thesis has been to provide for assessment of fire safety of FRP composite ship structures (based on SOLAS II-2/17) by studying aspects achieving the following research objectives (RO):

RO1: investigate strategies for identifying fire hazards and performance criteria connected to the use of FRP composite;

RO2: explore verification methods for the performance of FRP composite and safety measures using fire testing and modelling; and

RO3: develop how the fire safety of ships with FRP composite can be assessed based on MSC/Circ.1002.

Management of implicit requirements in the regulations, which to a varying degree assume that ships are built in steel, is a reoccurring aspect of this work.

1.2 Publications

The six papers forming the basis of this synthesis are listed on page 13 and appended to this thesis. All papers have been accepted to international scientific journals or conferences after full peer-review. The papers contribute to the purpose and research objectives of this thesis at different levels, as illustrated in Figure 2 and elaborated below. The papers address some specific, but not all, challenges related to assessment of the alternative fire safety of a ship with FRP composite structures.

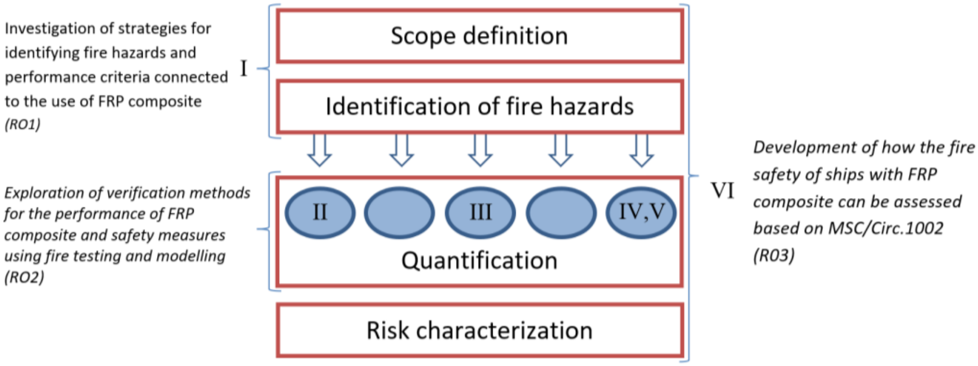


Figure 2. Overview of how the research objectives (RO1-RO3) and papers (I-VI) contribute to assessment of fire safety of FRP composite ship structures; the arrows symbolize identified hazards and the ovals assessment of these.

Paper I mainly addresses the first parts of an assessment of fire safety of FRP composite ship structures. It takes a starting point in the regulatory framework and describes how hazards and performance criteria can be identified. Fire hazards related to use of FRP composite structures are symbolized by arrows in Figure 2 and investigation and assessment of these hazards is symbolized by the ovals. Paper II investigates one particular fire hazard, namely flame spread on external ship surfaces, and evaluates the use of a test method for building façades for performance verification. Paper III was formed based on investigation of another hazard, namely how the use of relatively well-insulated FRP composite divisions could cause an increased fire growth rate. The need for a simple way to estimate temperatures in a fire enclosure depending on the structures' insulation led to the development of a calculation model described in Paper III. Another hazard of FRP composite structures is loss of structural fire integrity at elevated temperatures. Paper IV investigates critical aspects of design and verification in this regard based on a test series with FRP composite bulkheads. Furthermore, the structural fire integrity of a new type of FRP composite structure, a non-insulated multi-cored sandwich panel, was evaluated in Paper V. Paper VI draws knowledge from a number of fire risk assessments for alternative designs as well as risk research to develop and advice how to handle the assessment procedure in MSC/Circ.1002.

Involvement in other research and development project with value for the research objectives has resulted in a number of additional publications. The publications are listed below, in reverse chronological order, preceding a summary of the research involvements.

Dahlbom, S., Andersson, S., De Carvalho, E., Lewandowski, L., Evegren, F. (2024) Fire Risk Model for Fires in Ro-Ro Ship Ro-Ro Spaces. In *Journal of*

Risk Analysis and Crisis Response. 14(3), p. 333-355. ISSN 2210-8491, E-ISSN 2210-8505. https://doi.org/10.54560/jracr.v14i3.503

Jiang, L., Olofsson, A., Ingasson, H., Evegren, F. (2023) Effect of opening geometries on fire development in a ro-ro space. In *Ships and Offshore Structures*. 18(2), p. 272-284. ISSN 1744-5302, E-ISSN 1754-212X https://doi.org/10.1080/17445302.2022.2038467

IMO* (2017). *Interim Guidelines for use of Fibre Reinforced Plastic (FRP) Elements within Ship Structures: Fire Safety Issues*. MSC.1/Circ.1574. London: International Maritime Organization.
**Written by the author of this thesis with input from IMO Member States.*

Evegren, F. & Rahm, M. (2016). Fire protection of FRP composite ship balconies. In *Proceedings of the 11th International Conference on Sandwich Structures* (ICSS-11), Ft. Lauderdale, USA.

Evegren, F., Rahm, M. & Hertzberg, T. (2016). *Fire Tests of FRP Composite Ship Structures*. SP Report 2016:35. Borås: SP Technical Research Institute of Sweden.

Evegren, F. (2015). *Engineering analysis report – Methanol installation on the Stena Germanica*. Reference: 4P05578-rev1. Borås: SP Technical Research Institute of Sweden. [Consortium confidential].

Rahm, M., Evegren, F. (2016). *Preliminary analysis report of car carrier with FRP decks*. 5P01644-01. Borås: SP Technical Research Institute of Sweden. [Consortium confidential].

Evegren, F. & Leandersson, A. (2014). *Preliminary analysis report for fire risk assessment according to SOLAS II-2/17: Methanol installation on the Stena Germanica*. Reference: 3P08246. Borås: SP Technical Research Institute of Sweden. [Consortium confidential].

Evegren, F. (2013). *Engineering analysis report - Eco-Island ferry*. SP Report 2015:05. Borås: SP Technical Research Institute of Sweden.

Evegren, F. (2013). *Engineering analysis report - Norwegian Future*. SP Report 2015:03. Borås: SP Technical Research Institute of Sweden.

Evegren, F. & Rahm, M. (2012). *Preliminary analysis report - Eco-Island ferry*. SP Report 2015:04. Borås: SP Technical Research Institute of Sweden.

Evegren, F. (2012). *Paving the way for lightweight constructions on cruise ships through the LASS-C project*. Paper presented at the Second International Conference on Light Weight Marine Structures (LIWEM), Gothenburg, Sweden.

Piku Amen, M. & Evegren, F. (2012). *Preliminary study of the Øko-Ø-færge project*. SP Report 2012:03. Borås: SP Technical Research Institute of Sweden.

Rahm, M. & Evegren, F. (2012). *Preliminary analysis report - Stena Scanrail*. Reference: PX21670. Borås: SP Technical Research Institute of Sweden. [Consortium confidential].

Evegren, F., Hertzberg, T. & Rahm, M. (2011). *LASS-C; Lightweight construction of a cruise vessel*. SP Report 2011:12. Borås: SP Technical Research Institute of Sweden.

Evegren, F. (2011). *Preliminary analysis report - for composite superstructure on the Norwegian Gem.* Borås: SP Technical Research Institute of Sweden. [published as part of SP Report 2015:03].

The latest engagement in research and development projects in this field was as project manager/coordinator of the EU project LASH FIRE 2019-2023. It had the objective to provide a technical basis for the revision of international IMO regulations for ro-ro ships, based on cost-benefit assessment of fire safety measures. This "*innovation action*" was funded by the European Horizon 2020 programme and involved a 25-partner consortium. Previous engagements include work package leader for "*Technical Assessment*" in the EU project RAMSSES (2017-2021), focusing on testing and demonstration of lightweight material solutions for ships. The EMSA projects FIRESAFE (led by RISE) and FIRESAFE II (2016-2018) evaluated the cost-effectiveness of measures to improve the fire safety of ro-ro ships, but at a smaller scale and in a more theoretical way than LASH FIRE. Contributions in the projects were mainly in moderation of HazId workshops, development of the risk quantification model and project management. In the projects BESST (2009-2013), Eco-Island ferry (2012-2013) and LASS-C (2010-2011), a number of engineering analyses for FRP composite ship structures were conducted based on SOLAS chapter II-2, regulation 17. Contributions have also been made in several military research projects (e.g. FiST and Convince) and commercial projects on fire safety assessment of lightweight structures at sea, as well as in projects addressing for example adaptation of fire protection systems to new power sources, such as batteries, methanol and hydrogen.

1.3 Delimitations

The research work was delimited to consider the *fire performance* of *FRP composite structures* and *assessment* of *fire safety* of *ships* with such structures. Other effects on safety from using lightweight structures, e.g. effects on stability, were not considered. Furthermore, the study was delimited to consider how fire safety can be evaluated through *risk assessment, based on MSC/Circ.1002*. Other methods to manage fire risk, such as accident investigation or socio-technical analyses (see section *3.4.1*), were not considered, nor other parts of risk management, such as risk treatment, monitoring or communication. The thesis addresses areas where knowledge is needed to perform such a risk assessment for a ship in its *operational phase*. Effects on fire safety during construction, retrofit, or dismantling were not considered. Effects on the fire performance of FRP composite from for example poor manufacturing, installation or maintenance were not considered. Effects from ageing, wear and tear of the materials or systems were neither considered (see e.g. Sandinge, 2021).

The results of the research work are based on conclusions from studies of *displacing passenger ships*. The results may be applicable to other ship types, such as cargo ships, high speed craft, and military vessels, but this has not been considered. The type of passenger ships addressed in the research are those *regulated by SOLAS*, i.e. merchant ships over 500 gross tonnage making international voyages. In the same way as the *safety of life* is the main purpose of SOLAS, it has also been the focus in this work. Environmental issues are left out of the scope, as well as for example risks to property, business operation, reputation, and occupational health. Such endpoints are in some ways implicitly considered, but only secondarily to the objective to evaluate life safety. Protection of property is for example considered by managing the potential for fire growth and structural fire integrity, but only since the regulations associate these aspects with protecting lives. Collapse is considered since it affects the safety of passengers and fire-fighting crew working in and around a fire enclosure. Issues with progressive collapses are, however, not addressed by the research of this thesis.

With regard to fire performance of FRP composite, there are many variations and combinations of materials and there is an ongoing search for new materials with improved fire properties. For characterization of fire performance of FRP composite structures, reference has been made to *materials typical in shipbuilding*, elaborated in chapter *2 Background*. These are all sensitive to thermal loading and flame spread.

1.4 Thesis outline

Following this introductory Chapter 1, a foundational background is provided in Chapter 2. It introduces the regulatory framework for ship fire safety and alternative design and concretizes specific challenges related to FRP composite. Challenges are also pointed out regarding how alternative fire safety should be evaluated by a risk assessment according to MSC/Circ.1002. A theoretical background to risk assessment is then provided in Chapter 3. The methods applied in the appended papers to address the identified challenges are described in Chapter 4. Thereafter the research contributions to assessment of fire safety of FRP composite ship structures (purpose) are presented in Chapter 5. It is divided in three sections, in approximate union with the three research objectives:

1. fire hazard identification for novel ship design, and FRP composite ship structures in particular;
2. verification of fire performance of FRP composite ship structures and safety measures; and
3. developed frameworks for fire risk assessment.

In Chapter 6 is discussed how the research objectives have been achieved and the suitability of the methods applied in the papers. Finally, conclusions of the accomplished research and proposals for future work are given in Chapter 7 and Chapter 8, respectively. References are given in Chapter 9 and the scientific papers which this synthesis is based upon follow as appendices.

2 Background

Fire incidents have lately been increasing, and they often cause large damages. During 2022 and 2023 there were over 200 reported fire incidents annually, making it the top fourth cause of incidents (Allianz, 2024). While insurance companies report that fires still represent a relatively small proportion of their handled cases (2.7%), they represent 27% of their claim costs (Kafka, 2024). In 2002-2012 fire was in fact the main cause of total loss of passenger ships (Eliopoulou, 2016), as illustrated in Figure 3. For cargo ships, this figure is smaller, and later statistics for all types of vessels show that fire has been the cause of 14% of the total losses in the past decade (Allianz, 2024).

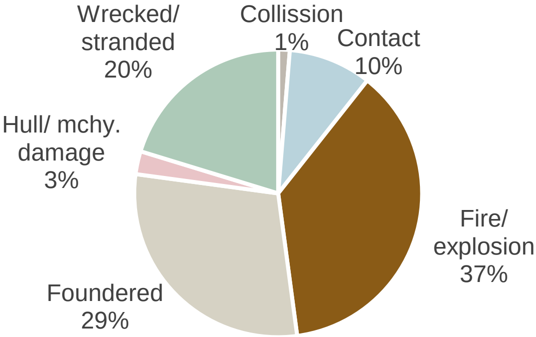


Figure 3. Causes of total loss of passenger ships in 2000-2012, according to Eliopoulou (2016).

Isolation at sea and the extraordinary conditions on a ship make maritime fire safety an important, complex and greatly regulated issue. A fundamental provision in the SOLAS Convention is the use of non-combustible structures, which is challenged when using FRP composite. This is described in further detail in *section 2.3*, preceded by an introduction of FRP composite structures in *section 2.1* and the regulatory framework in *section 2.2*. Alternative materials and safety arrangements are allowed if a degree of safety not less than that provided by prescriptive requirements is achieved. It should be demonstrated by a risk assessment, as further described in *section 2.4*. It requires a good understanding of the prescriptive requirements, to identify areas of impaired fire safety (see RO1), and knowledge in the fire performance of the materials and relevant safety measures (see RO2).

Verification of some specific aspects of fire performance was addressed in this thesis, concretized in *section 2.5*. In addition to the background provided in *section 2.4* on the required assessment procedure in MSC/Circ.1002, chapter *3. Background to risk assessment* provides a theoretical background to risk-based assessment of fire safety (see RO3).

2.1 FRP composite structures replacing steel

FRP composite is interesting for ship structures mainly for its lightness in comparison with steel. Life cycle assessments have shown that the environmental impact can be significantly reduced and that the increased investment can pay back in short time of operation (Hedlund-Åström, 2009). A typical 7 mm steel plate for shipbuilding weighs about 55 kg/m^2 and can from a strength perspective be replaced by an FRP composite sandwich composition weighing about 1/5 of that weight (Hertzberg, 2009). The key is the separation of the strong and stiff laminates by a relatively thick core, which functions similar to the web of a stiffener in an I-beam and carries local transverse loads as shear stresses (Carlsson & Kardomateas, 2011). Altogether, this makes the sandwich panel able to carry considerable in-plane and bending loads (Carlsson & Kardomateas, 2011; Smith & Chalmers, 1987). Furthermore, with FRP composite a hull can be formed in one continuous structure, without conventional joints, which creates a robust structure. FRP composite can further deform elastically under high strain, which reduces stress concentrations and fatigue problems when joints are necessary, for example between a steel hull and an FRP composite deckhouse or superstructure (Lantz, 2011; Smith & Chalmers, 1987).

There are many types of FRP composite structures since they are made up by a combination of different material components, typically a *polymer matrix (resin)*, *reinforcing fibers* and potentially a *core material*. Resin and fibers form a laminate, also referred to as a single skin panel. For load-bearing shipbuilding applications, they are often bonded to a lightweight core to make up a sandwich panel, illustrated in Figure 4.

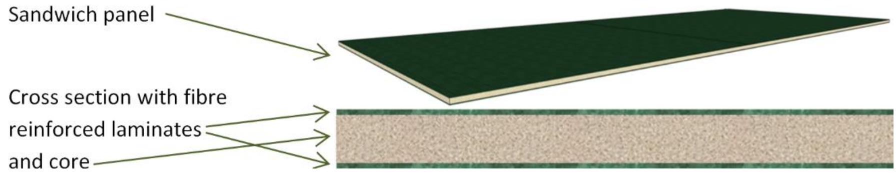


Figure 4. Illustrations of an FRP composite sandwich panel composition, from Evegren (2010a).

The resin is commonly of thermoset type (typically polyester, vinyl ester, epoxy, phenolic, or furan), although there is increasing use of thermoplastic materials, such as polyethylene or polypropylene (Mouritz & Gibson, 2006). The fibres may be manufactured from for example glass, carbon, aramide, basalt or natural fibres such as flax. Typical sandwich core materials are endgrain balsa wood, honeycomb or structural foam, such as PVC (polyvinyl chloride), polyurethane, PET (polyethylene terephthalate), or phenolic (Umair, 2006). For a further practical introduction to composite materials, see e.g. Royle et al. (2019).

Application of FRP composite materials has increased in different parts of the maritime industry (Caramatescu & Mocanu, 2019). This does not include structures on ships regulated under SOLAS; this has been investigated in many research projects (see chapter *1. Introduction*) but the materials' fire properties have been a hold back. The fire performance of FRP composite structures depends on the used material components and their combined behaviors at elevated temperatures. The variety in fire performance is hence large and there is also a constant development of new materials. While fire performance of FRP composite is elaborated on in section *2.5 Fire performance of FRP composite ship structures*, the structure is based on **combustible** materials, which is a fundamental aspect in the maritime fire safety regulations. There are non-combustible composites, such as ceramic and metal matrix composites (Royle et al., 2019), but those are much too expensive for ship structures and outside the scope of this thesis.

2.2 SOLAS' fire safety chapter II-2

To identify introduced fire hazards connected to the use of FRP composite (RO1), an understanding is required of the applicable regulatory framework, introduced below. It is crucial, not least to be able to identify and manage implicit requirements, i.e. where the regulations *assume* steel structures.

2.2.1 Formation of the SOLAS Convention

The International Maritime Organization (IMO) is a specialized agency of the United Nations which primarily regulates safety and the environment through international conventions. It is foremost an organization working for inter-governmental congregation and regulation development amongst the world's coastal countries. Safety matters are handled in the Maritime Safety Committee (MSC), after preparation in one of seven sub-committees.

One of the most important IMO conventions for ships engaged on international voyages is SOLAS, with the main purpose to provide for the "*Safety Of Life At Sea*". The first version of SOLAS was introduced as a result of the Titanic disaster in

1912. At the adoption in 1929, it became the first international maritime safety convention. It has since then been revised in 1948, 1960, and ultimately in the SOLAS 1974 version (IMO, 1974). The latter is with its updates and amendments still the convention in use. It consists of twelve chapters, covering issues such as construction, life-saving appliances, safety of navigation, carriage of cargoes, and other areas of maritime safety. Fire safety has always been of great concern on merchant ships and is managed in SOLAS chapter II-2: *Construction – Fire protection, fire detection and fire extinction*, in this thesis also referred to as the 'fire safety chapter'. As illustrated in Figure 5, SOLAS is an overarching convention which refers to a large number of Codes and IMO circulars, and sometimes to standards, to ensure the safety in different areas.

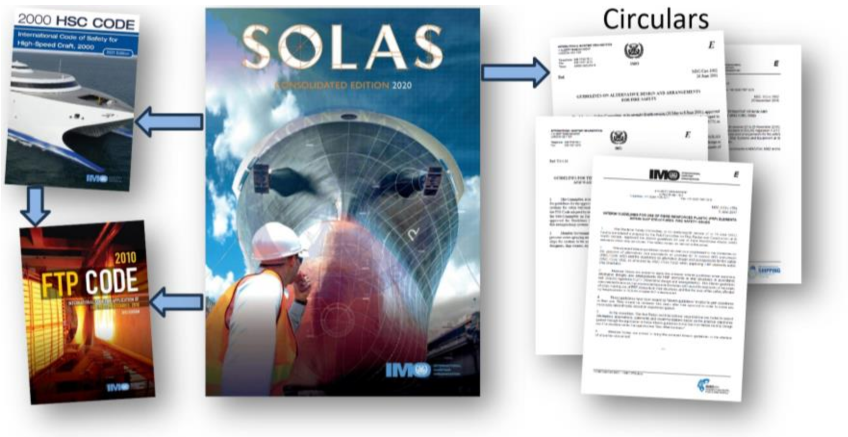


Figure 5. Illustration of how the SOLAS Convention referes to different codes and circulars.

In the same spirit as SOLAS was originated, many of the amendments to SOLAS have been responses to publicized incidents. The catastrophe on the Scandinavian Star for example led to many new fire safety requirements to both new and existing ships, including automatic sprinkler and smoke detection systems in accommodation areas as well as low location lighting to assist evacuation (IMO, 1992a, 1992b; SOU, 1996). Instead of pro-active rule-making, decisions forming the regulations have been reactive, addressing safety deficiencies as a response to a specific incident (Papanikolaou, 2009). This approach has led to complex, and sometimes inconsistent, prescriptive regulations which have made it difficult to introduce new technology solutions (Papanikolaou, 2009).

2.2.2 History of SOLAS chapter II-2

Today's fire safety chapter in SOLAS (chapter II-2: Construction – Fire protection, fire detection and fire extinction) is much influenced by its former prescriptive nature. The purpose of the chapter was then "*to require the fullest practicable degree of fire protection, fire detection and fire extinction in ships*" (IMO, 1974). To address this ambitious purpose, regulations were motivated by *"eight basic principles"* (IMO, 1974). They were formulated as a result of several fires on passenger ships in the early sixties (SOU, 1996) and stated to achieve (punctuation before number, as customary in SOLAS):

.1 division of ships in vertical and horizontal fire zones by thermal and structural boundaries;
.2 separation of accommodation spaces from the remainder of the ship by thermal and structural boundaries;
.3 restricted use of combustible materials;
.4 detection of any fire in the zone of origin;
.5 containment and extinction of any fire in the space of origin;
.6 protection of means of escape and access for fire fighting;
.7 ready availability of fire-extinguishing appliances; and
.8 minimization of possibility of ignition of flammable cargo vapor.

At the sixty-first session of the MSC, in the beginning of the nineties, there was a proposal for a comprehensive review of the fire safety chapter (Sweden, 1992). According to Sweden (2014), the reasoning behind this was partly that the old chapter had become difficult to overview; another major reason came from the evolution of fire safety science, which was rapidly developing and where a more detailed understanding of the processes in a fire had been gained. Consequently, many building regulations around the world were changed, and they also allowed for buildings to be designed in more advantageous ways if not compromising fire safety. An anticipated advantage was thus that a change from prescriptive to performance-based maritime fire safety regulations would allow for technological development and novel design. Therefore, the committee agreed at MSC 61 that the fire safety chapter should be reviewed based on a modern fire safety philosophy (Sweden, 2014).

2.2.3 Overview of SOLAS chapter II-2

After many years of work, in 2002, the fire safety chapter was the first to get a performance-based structure at IMO. The requirements of the previous 63 regulations had been reorganized under 20 new regulations (now 23) covering distinguished areas of fire safety. One of the first regulations sets out the objectives for the whole chapter, referred to as fire safety objectives (reg. 2.1.1):

.1 prevent the occurrence of fire and explosion;
.2 reduce the risk to life caused by fire;
.3 reduce the risk of damage caused by fire to the ship, its cargo and the environment;

.4 *contain, control and suppress fire and explosion in the compartment of origin; and*

.5 *provide adequate and readily accessible means of escape for passengers and crew.*

In order to achieve the fire safety objectives, a number of functional requirements are stated to be embodied in the regulations. These functional requirements (reg. 2.2.1) are the same as the former eight basic principles formulated in the sixties, listed above. An important regulation is also regulation 3, providing definitions.

Prescriptive requirements in the fire safety chapter of SOLAS are given in the following regulations 4-23. Each regulation begins with a purpose statement, with its own objective and functional requirements. Thereafter follow the detailed (prescriptive) requirements, which hence settle how to accomplish the purpose statement. This structure is illustrated in Figure 6, where prescriptive regulations are marked red. For example, Regulation 5 in SOLAS chapter II-2 has a purpose statement, specified in SOLAS II-2/5.1, where the regulation objective is "*to limit the fire growth potential in every space of the ship*". Thereafter follow three functional requirements in SOLAS II-2/5.1.1-3, which shall be met in order to achieve the objective:

.1 *means of control for the air supply to the space shall be provided;*

.2 *means of control for flammable liquids in the space shall be provided; and*

.3 *the use of combustible materials shall be restricted.*

The following prescriptive requirements in regulation 5 detail how the ventilation system shall be capable of being closed from a safe place, how surface materials shall fulfil calorific and *fire-spread requirements*, and how furniture in stairways should be limited. Each regulation in SOLAS chapter II-2 has the same structure, with a regulation objective, functional requirements, and prescriptive requirements.

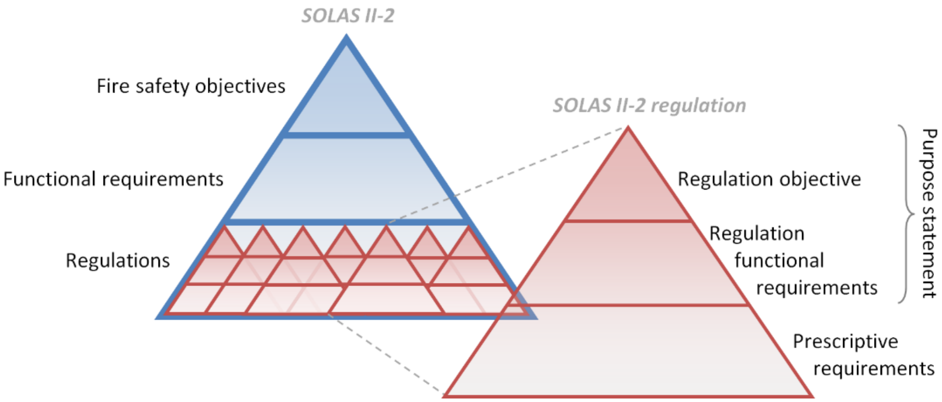


Figure 6. Structure of SOLAS chapter II-2 on fire safety.

Test methods for performance verification of materials are described in the separate Fire Test Procedures (FTP) Code (IMO, 2012), referenced from different SOLAS regulations (see Figure 5). For example, regulation 5.3.2.4 requires surfaces to have "*low flame-spread characteristics*" in accordance with Part 5 of the FTP Code (IMO, 2012). The tests in the FTP Code with relevance for FRP composite structures are primarily:

- Part 1: Non-combustibility test
- Part 2: Smoke and toxicity test
- Part 3: Test for "A", "B" and "F" class divisions
- Part 5: Test for surface flammability
- Part 10: Test for fire-restricting materials for high-speed craft
- Part 11: Test for fire-resisting divisions of high-speed craft

These test methods are also summarized in Appendix D of the IMO guidelines MSC.1/1574 (IMO, 2017), along with remarks on limitations and necessary considerations when testing FRP composite materials.

2.3 Structures in FRP composite – a major deviation

Further to an understanding of the regulatory framework, identification of fire hazards and performance criteria (see RO1) requires a more detailed understanding of the deviated prescriptive regulations and referenced tests. A fundamental provision in SOLAS chapter II-2 is the use of non-combustible structures. Regulation 9 (*Containment of fire*) requires to use divisions of "A" class standard for main vertical and horizontal zones as well as, where necessary, for internal bulkheads (IMO, 1974). "A" class divisions shall be constructed of "*steel or other equivalent material*", which is also required in regulation 11 (*Structural integrity*) for the construction of the hull, superstructures, structural bulkheads, decks, and deckhouses (IMO, 1974). The requirement to use *steel or other equivalent material* hence applies to practically all load-bearing structures on ships, which could all be relevant to construct in FRP composite. The term is defined in regulation 3.43:

> "***Steel or other equivalent material*** *means any* ***non-combustible material*** *which, by itself or due to insulation provided, has structural and integrity properties equivalent to steel at the end of the applicable exposure to the standard fire test (e.g., aluminium alloy with appropriate insulation).*" (IMO, 1974)

The term "*non-combustible material*" is defined according to regulation 3.33:

> "*Non-combustible material* is a material which neither burns nor gives off flammable vapors in sufficient quantity for self-ignition when heated to approximately 750°C,

this being determined in accordance with the Fire Test Procedures Code" (IMO, 2012; cf. ISO 1182, 2002).

Materials with organic content will not pass the non-combustibility test unless present in a very small proportion (IMO, 2017). A polymer-based FRP composite will thus not pass the non-combustibility test, regardless of potential flame-retardants or other additives.

Structural and integrity properties are tested in furnace tests according to Part 3 of the FTP Code (IMO, 2012). It exposes the construction sample to a well-defined temperature increase (ISO 834-1, 1999) while evaluating insulation and flame spread integrity to the unexposed side. The average temperature *rise* at the unexposed side must remain below 140 degrees for a specified time, e.g. 30 minutes for A-30 and B-30 divisions, and 0 minutes (no requirement) for A-0 and B-0 divisions. Furthermore, "A" class divisions must withstand 60 minutes of fire integrity and "B" class divisions 30 minutes of fire integrity. This restricts the allowable size of cracks and emerging flames in the furnace tests. Structural load-bearing capacity is not tested according to Part 3 (IMO, 2012).

The above applies for displacing SOLAS ships. For high-speed craft, the HSC Code (IMO, 2000) requires *fire-resisting divisions* (FRD), which shall be constructed of *fire-restricting materials* (regulation 7.2.1.1, IMO, 2000). They must have properties complying with Part 10 of the FTP Code (IMO, 2012), referring to the "*room corner*" test procedure in ISO 9705 (2016), which means they *can be combustible*. Structural integrity of FRD is verified by the same one-hour standard fire test as "A" and "B" class divisions, with the only addition of an applied static load, as described in Part 11 of the FTP Code (IMO, 2012). The insulation and integrity criteria are the same, but for fire-resisting divisions the integrity requirement applies as long as the insulation requirement, e.g. 60 minutes for an FRD60 division.

If replacing an "A" class structure by an FRP composite structure achieving FRD60, or "B" class by FRD30, they would achieve "*structural and integrity properties equivalent to steel at the end of the applicable exposure to the standard fire test*", as required for *steel and other equivalent material*. This was the starting point for a large number of furnace tests with FRP composite FRD as part of the LASS project (Hertzberg, 2009). Several solutions to FRD60 and FRD30 bulkheads and decks were type approved, as well as penetration solutions such as doors, windows, and cables. However, the additional *requirement for non-combustibility* of steel of other equivalent material *is not time limited*, and polymer-based composite materials can hence never be considered equivalent to steel according to prescriptive requirements. On the contrary, elevated temperatures will deteriorate the materials and compromise the load-bearing capacity of structures, as further elaborated in section *2.5 Fire performance of FRP composite ship structures*.

To summarize, introducing combustible structures requires a deep understanding of both the fire safety regulations and verification test requirements. The connection between prescriptive and functional requirements is unclear, and regulations and tests are based on a general assumption of steel structures. This makes identification of hazards and performance criteria intricate, which argued for investigating and clarifying this matter in Paper I (see RO1).

2.4 Alternative fire safety design with FRP composite

When the new structure of the fire safety chapter was introduced in 2002, it included a completely new regulation called *Alternative design and arrangements*, regulation 17. It allows deviating from prescriptive requirements if at least the same degree of fire safety is provided by alternative means (SOLAS II-2/17.3.4.2), often referred to as an "*equivalence principle*" (Vassalos, 2009). It is thus not an exemption but an alternative way to fulfil the fire safety requirements of SOLAS. To provide a basis for how the fire safety of ships with FRP composite should be assessed (see RO3), the required procedure is outlined below.

2.4.1 Procedure for alternative fire safety design

When laying claim to regulation 17, fire safety should be demonstrated by an analysis, hereafter referred to as a 'Regulation 17 assessment'. The principles for the assessment are summarized in the regulation while guidelines are detailed in MSC/Circ.1002 (IMO, 2001), as amended by MSC.1/Circ.1552 (IMO, 2016). These guidelines rely on performance-based methods of fire safety engineering to verify the level of fire safety. The general procedure is similar to that described in ISO 23932-1 (2018) but less elaborated and different in some aspects. The procedure in MSC/Circ.1002 (IMO, 2001) is illustrated in Figure 7 and can be described as a two-step deterministic risk assessment (Evegren, 2010a):

.1 the preliminary analysis in qualitative terms; and

.2 the quantitative analysis.

In the first part, the basis for the alternative design and arrangements and the scope of the analysis are defined. The regulations affecting the proposed alternative design and arrangements should also be clearly documented along with their functional requirements. However, in contrary to e.g. ISO 23932-1, performance criteria are not determined until later in the process. A large focus of the first part is given to identification of fire hazards and to, from these, develop design fire scenarios. Trial alternative designs are also proposed, accounting for the identified hazards. The components of the preliminary analysis in qualitative terms are documented in a preliminary analysis report. It needs approval from the Administration (see p. 17) and establishes the base for the next step of the assessment, the quantitative analysis.

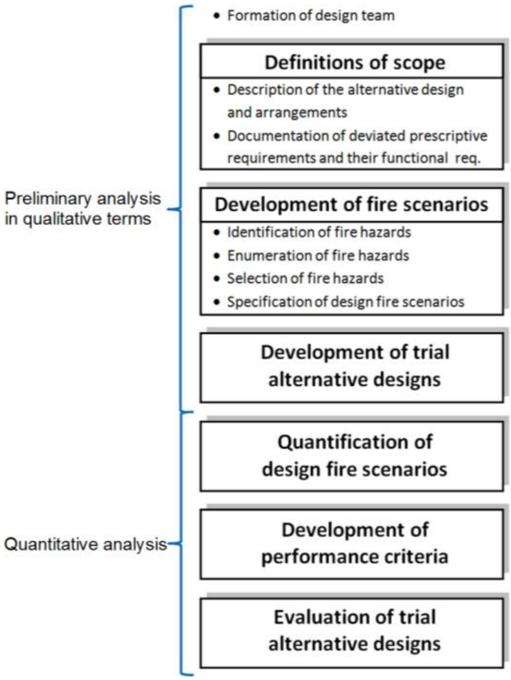


Figure 7. Procedure of a Regulation 17 assessment in accordance with MSC/Circ.1002.

In the quantitative analysis, the design fire scenarios are quantified in fire safety engineering terms, such as heat release rate, flame height, or radiant heat flux (IMO, 2001). The introduced hazards should thus be quantified regarding their effects on these scenarios, as described in different guidelines for fire safety engineering (ISO 16732, 2012; ISO 16733, 2006; SFPE, 2022). Performance criteria should then be developed as quantitative expressions of the fire safety objectives and functional requirements of the SOLAS regulations (6.3.1 in IMO, 2001). This is either done by reference to relevant prescriptive requirements or by comparison to the performance of an acceptable prescriptive design (6.3.3 IMO, 2001). Thereafter each trial alternative design is evaluated by the design fire scenarios to demonstrate that it meets the criteria.

Comparing levels of fire safety in this way involves uncertainties which should be accounted for by safety margins introduced at the outset of the design process (IMO, 2001). The final documentation of the Regulation 17 assessment should thereby with reasonable confidence demonstrate that at least the same degree of fire safety is provided by the alternative design and arrangements as by compliance with prescriptive requirements (IMO, 2001).

2.4.2 Other guidelines for alternative design

Similar openings as regulation 17, for alternative *fire safety* solutions and performance-based design, have been introduced to regulatory directives in other fields internationally, not least for buildings. For this purpose, the international Society of Fire Protection Engineers (SFPE) has taken an active role in developing engineering guides to analyse and design fire safety (e.g. Rosenbaum, 2007). Many standardization organizations and national regulatory authorities have also developed guidelines for how fire risks should be assessed to provide for safe design (BSI, 2019; ISO 16732, 2012; SFPE, 2022; SIS 24836, 2024; Standard Norge, 2014). When regulation 17 was introduced to SOLAS, the IMO guidelines in MSC/Circ.1002 (IMO, 2001) for how fire safety should be assessed were developed based on the current practice for buildings.

About a decade after the ratification of regulation 17, IMO adopted generic guidelines for the approval of alternatives and equivalents, MSC.1/Circ.1455 (IMO, 2013). Openings for alternative design had at the time been provided in various IMO instruments, covering for example machinery and electrical installations in SOLAS II-1/55, life-saving appliances in SOLAS III/38, and design and construction of oil tankers in MARPOL I/19.5 (IMO, 1973). The guidelines in MSC.1/Circ.1455 were not meant to replace the guidelines relating to these openings (IMO, 2001, 2003, 2019b), but they were intended to provide generic support and harmonization.

2.4.3 Applying regulation 17 for FRP composite structures

Assessment of fire safety had been determined as the primary key for industrial application of lightweight FRP composite structures for SOLAS vessels (Hertzberg, 2009). However, the performance-based regulation 17 had been developed with the intention to allow for more cost-efficient and attractive design of fire safety, such as high atriums and long shopping promenades. Nevertheless, while some Flag States opposed, IMO endorsed the application of regulation 17 to assess and approve also FRP composite structures, as the Maritime Safety Committee decided to develop guidelines for this purpose in 2010 (IMO, 2010; United Kingdom, 2010).

A change from steel to FRP composite structures is fundamental and can have complex effects. More developed methods to rationally compare the safety of an FRP composite design to a steel design have therefore been inquired (McGeorge & Höyning, 2002). Furthermore, the guidelines for assessment of fire safety in MSC/Circ.1002 have been accused to lack crucial parts (ABS, 2010), to be contradictive and vague (Evegren, 2010a); they are at a high level and leave many gaps for the risk analyst to fill in. The guidelines instead refer to selected technical resources, such as SFPE handbooks and ISO standards, and several classification societies have hence developed extended guides (e.g. ABS, 2010; Germanischer Lloyd, 2009). The guidelines have also been criticised to in practise only allow for extensions of prescriptive regulations and not to provide opening for true alternatives, going beyond the regulations (Maccari, 2011; McGeorge & Höyning, 2002).

Much was learnt from research where MSC/Circ.1002 was applied for FRP composite superstructures in the coming years (e.g. Evegren, 2010b; Gutierrez et al., 2008; McGeorge et al., 2009). However, the specific need to develop further guidelines for evaluation of FRP composite structures when using regulation 17 was still underlined by both the United Kingdom and Sweden in the IMO Fire Protection sub-committee in 2011 (Sweden, 2011b; United Kingdom, 2011). Even considering MSC.1/Circ.1455 (IMO, 2013), several ambiguities remained and a framework was missing for how to handle different levels of alternative designs in a better way in the assessments. Thus, supplementary advice was needed to provide for harmonized and robust assessment of innovative fire safety solutions, which was the motivation for Paper VI. The starting point for such advice is risk science, the foundations of which are given in Chapter 3.

2.5 Fire performance of FRP composite ship structures

Assessment of alternative fire safety design with FRP composite structures also argues for the importance of methods to investigate and verify their fire performance (RO2). The fire performance depends on the properties of the used material components: the polymer resin, the reinforcing fibers and the core. It also depends on how the materials have been combined. For a practical introduction to the fire performance of FRP composite, the reader is referred to Royle et al (2019), who present the basics of FRP composite materials, combinations, key characteristics defining fire performance, as well as test standards in different sectors. More detailed fire properties of typical FRP composite materials are well summarized in the book *Fire properties of Polymer Composite Materials* (Mouritz & Gibson, 2006). Below follows a brief introduction to fire performance of FRP composite components, followed by sections elaborating on different important aspects when using sandwich structures on ships. This lays the foundation for further exploring verification methods for the performance of FRP composite and safety measures (RO2).

2.5.1 Fire properties of FRP composite components

Regarding polymers, testing for example reveals that heat weakens their stiffness, commonly characterized by the heat deflection (or distortion) temperature (HDT) and the glass transition temperature (Tg). HDT is the temperature at which a sample of the resin bends a certain distance under a load, as defined by ASTM D648 (2018) and ISO 75-1 (2020). Marin grades of common room temperature cured resin systems have an HDT of 70-100°C (Sweden, 2011a), but systems may be produced with significantly improved properties (e.g. Mark, 1999). The Tg of a polymer is not the same as the HDT, but it is often in a similar range. The Tg is the temperature region where the polymer transforms from a hard, glassy state into a soft rubbery state, as defined by ISO 11357-2 (2020). Common resins have a Tg of 70-120°C, but it largely depends on the temperature during post curing (Mouritz & Gibson, 2006; Sweden, 2011a). Hence, reaching these temperatures softens the resin and decreases the strength of a laminate in a fire (Mouritz & Gibson, 2006). This was for example demonstrated by Gutierrez et al. (2008) for standard laminates, and has been investigated in further detail e.g. by Bai and Keller (2011a) and Sun et al. (2015). It should be noted, however, that mass loss typically does not occur until about 300-350°C, when pyrolysis of the material starts (Babrauskas, 2003; Karatzas, 2016; Lyon et al., 2005; Mouritz & Gibson, 2006). Polyester for example starts to pyrolyze at about 350°C, has a piloted ignition temperature of about 400°C and an autoignition temperature of 450-500°C (Hertzberg, 2012, Braun & Levin, 1985). This means that ignition and contribution to a fire may be a secondary issue for load-bearing structures (see Figure 8).

Reinforcing fibers of common marine grades do not contribute significantly to a fire: glass fibers remain chemically inert, while carbon fibers only oxidize at the surface directly exposed to fire/high heat flux (Mouritz & Gibson, 2006). Mechanical properties of the fibers although degrade significantly from around 400-500°C (Hertzberg, 2003, 2005; Mouritz & Gibson, 2006; Sweden, 2011a). Standard core materials for marine applications will lose stiffness at their softening temperature, which for PVC occurs around 90-120°C and for polymethacrylimide around 180-200°C (Gutierrez et al., 2008; Sweden, 2011a). End-grain balsa wood does not have a softening temperature or shrink as a polymer but instead chars, which starts around 220°C (Gutierrez et al., 2008; Sweden, 2011a). This benefits the load-bearing capacity of a sandwich structure during fire, since charring prevents full decomposition of the core and detachment from the exposed face skin (Mouritz & Gibson, 2006).

The fire properties of FRP composite will have an important impact on the fire risk when replacing steel. Some key affected aspects are:

- surface spread of flame;
- heat conductivity of fire enclosure; and
- structural fire integrity.

These aspects of fire performance when using sandwich structures on ships are further elaborated below.

2.5.2 Surface spread of flame

Flame spread on an FRP composite sandwich panel depends on the resin, but also on the core material (Mouritz & Gardiner, 2002). In particular the heat release rate of the material influences the flame spread rate of sandwich structures, which at the initial stage is primarily affected by the resin, and later also by the quality of the core (Marquis et al., 2012). For example composites with resins of bismaleimide, polyimide or high-temperature thermoplastic have shown good fire spread resistance, in addition to phenolic laminates as reported in numerous studies (Mouritz & Gibson, 2006). Core material based on for example PVC can be considered to increase flame spread, while for example phenolic foam core does not; on the other hand its load-bearing capacity is significantly deteriorated by heat (Grenier et al., 1998; Mouritz & Gardiner, 2002).

To assess flame spread on composite material surfaces, arguably the most common test standard is ASTM E162 (2022). It uses a vertical radiant heating panel exposing the composite panel facing downwards at 45°. However, since the most critical mode of flame spread occurs upwards, the test method has been accused of being unrealistic (Mouritz & Gibson, 2006). In the maritime regime, reference is instead made to Part 5 of the FTP Code (IMO, 2012), which prescribes horizontal flame spread evaluation based on ISO 5658-2 (2007). A 0.8 m sample of the material is exposed to a radiating panel at a 15° angle, to evaluate the effect of reduced radiation on horizontal flaming combustion along the specimen.

Standard marine grade FRP composite surfaces show rather poor reaction-to-fire properties and spread fire quickly (Gutierrez, 2005; Mouritz & Gibson, 2006). Hazard identifications for FRP composite structures thereby recognized that external FRP composite surfaces pose a fire hazard (Evegren, 2012). This was later also supported by the COMPASS project, where it was assessed that a strong but realistic external fire could result in structural collapse (Karatzas, 2016). Improvement of the flame-spread characteristics of external surfaces is hence needed, which can be achieved either by passive or active means. Passive fire protection reduces the fire or its effects without intervention, activation or movement; for example by impeding ignition, fire propagation or heat/smoke generation, as well as by compartmentalization (NFPA 3, 2023; Tewarson & Khan, 1991). Active fire protection on the other hand requires intervention, motion or automatic activation to reduce the fire or its effects, such as fire extinguishers or suppression and detection systems, but also smoke ventilators and manual efforts by the fire and rescue services (NFPA 3, 2023; Tewarson & Khan, 1991).

Fire spread on external FRP composite surfaces can for example be mitigated passively by a protective intumescent coating, or actively by a sprinkler system (Gutierrez et al., 2008). Gutierrez (2005) recommended brominated vinylester laminates for ships, since they showed better fire performance than standard vinylester-based composites. However, this was only verified in small-scale cone-calorimeter tests. Arvidson et al. (2008) evaluated fire spread on external FRP composite surfaces in full-scale tests, where fire emerged from a small opening (about 0.9x0.9 m), representing a cabin window. The surface of the standard FRP composite, a glass fiber reinforced polyester/PVC-cored sandwich structure, ignited within a few minutes, which aligns with much ignitability data (Mouritz & Gibson, 2006). The tests also showed that the external surface was quickly extinguished upon activation of a drencher system, mounted about 2 m above the opening (Arvidson et al., 2008).

It was still unknown how a large fire source, e.g. from a balcony opening, would affect external fire spread, and how effective passive and active measures would be in a large area. These questions relating to external surface spread of flame altogether founded the basis for Paper II.

2.5.3 Heat conductivity of fire enclosure

Application of thermal insulation will solve surface flame spread issues and delay decomposition of the underlying core. It is therefore a common way to achieve structural fire integrity of FRP composite structures (Hertzberg, 2009). In addition, the sandwich composite structure is an excellent thermal insulator on its own, and in combination this will make up a much more thermally insulating construction than steel divisions (Hertzberg, 2009). This will reduce problems with heat transfer in case of a fire but it also means that more heat will be kept within the fire enclosure and thus raise the gas temperature (Hertzberg, 2009; United Kingdom, 2010). Depending on the conditions for the enclosure, the temperatures inside the enclosure may in fact be much higher in case of a fire (Hertzberg, 2009; United Kingdom, 2010). This was identified as a potential hazard in the LASS-C and BESST projects, since it could in turn potentially generate quicker fire growth and increased heat exposure to structures (Evegren, 2010b; United Kingdom, 2010). It was a concern that this increase could even diminish the reduced heat transfer through the more insulating structures.

Upon investigating the effects on fire development from using thermally insulated FRP composite structures for a large cruise vessel application (Evegren, 2013b), the need for quick approximate answers was realized. Therefore, instead of using time-consuming numerical fire-simulation tools, such as FDS (McGrattan et al., 2024), simple methods for pre-flashover fire temperature approximations were investigated. It was noted, however, that the correlations in use do not account for the heating history. This is necessary to estimate the temperature evolution, depending on both the heat release rate history and on the boundary materials. At the same time, it was realized that all the input variables needed to solve a physical enclosure heat transfer model were available. This motivated the development of such a calculation model to estimate temperatures in pre-flashover fires from a varying heat release rate in Paper III.

2.5.4 Structural fire integrity

Since the 1980s, much research has gone into modelling the properties of composites during fire (e.g. Chippendale et al., 2014; Gibson et al., 1995; Henderson et al., 1985; Looyeh & Bettess, 1998; Lua et al., 2006). When it comes to modelling of polymer composite structural members and components at elevated temperatures, Davies et al. reviewed the state of the art in 2006, complemented by a critical review by Mouritz et al. of the research progress in modelling of the structural response of FRP composites exposed to fire (2009). Lua et al. (2006) for example developed a temperature and mass dependent thermal model for fire response prediction of marine composites, and in studies by Feih et al. the compressive strength of FRP composite structures was quantified (Feih et al., 2007), also with thermal protection (Feih et al., 2008; Feih et al., 2009). However, as concluded by Bai et al. (2010) in their review of the experimental and modeling work on FRP composite behavior in fire, all the models for properties and responses need further experimental validation. Particularly for long exposure times and with focus on characterization of the failure mechanisms of FRP composites in compression during thermal loading (Bai et al., 2010). Since then, several research groups have worked on the development of fire-structural models to characterize the structural properties of composites during and following fire (e.g. Dai et al., 2022; Pacheco-Blazquez et al., 2022; Tranchard et al., 2017).

As introduced in section 2.3, SOLAS and the HSC Code require structural fire integrity to be tested in accordance with Part 3 and Part 11 of the FTP Code (IMO, 2012), respectively. The exposure and performance criteria are the same for “A” class structures and FRD, except from the added static load in Part 11, founded on the alleviation from the non-combustibility requirement. When the introduction of FRP composite structures for displacing ships was initially discussed at IMO, it was suggested to establish a new set of performance criteria when carrying out tests for structural fire integrity (United Kingdom, 2010). The intention was to avoid heating structures beyond their load-bearing capability in case of fire. Instead of applying an insulation requirement for the unexposed side, which is virtually unaffected with FRP composite when load-bearing capability fails, it was suggested to use a thermal criterion for the *exposed* side (United Kingdom, 2010, 2011). Reference was made to a critical temperature philosophy in MSC/Circ.732 (IMO, 1996), which suggests that no sandwich laminate should be exposed above the resin’s Tg.

While it has been well-established that the load-bearing capacity of a sandwich structure partly depends on the HDT and Tg (Gutierrez et al., 2008; Jihan et al., 2007; Luo et al., 2012; Mouritz & Gardiner, 2002; Mouritz & Gibson, 2006; Ramroth, 2006), the thermo-mechanical behavior is more complex than softening of the resin. When heat reaches an FRP composite sandwich structure, the exposed laminate will first be affected. As it degrades, stresses will be redistributed to the other laminate, which accentuates the importance of the core’s thermal insulation capacity and mechanical resistance to heat (Gutierrez et al., 2008). When the core decomposes, it will detach from the exposed laminate, which deteriorates the key to the prominent load-bearing capacity of the sandwich structure (Mouritz & Gibson, 2006). Decomposition of the core will also cause an air-gap towards the exposed laminate, which causes it to heat up and burn more rapidly (Mouritz & Gibson, 2006). Furthermore, Asaro et al. (2009) mean that the load-bearing capacity of FRP composite sandwich panel degradation is both temperature-dependent and time-dependent. Bai and Keller (2011b) came to the same conclusion, explained by that the glass transition is a progressive kinetic process, where the thermal loading history is relevant.

The load-bearing capacity of FRP composite sandwich structures can hence not simply be linked to the surface temperature of the exposed laminate. This was also demonstrated by Summers et al. (2012) and by Sweden in their input to the IMO discussions (Sweden, 2011a). Based on numerous tests it was shown that no global loss of the structural integrity could be found based on the exposed laminate reaching the Tg or HDT (Sweden, 2011a). FRP composite sandwich structures work as units, where all parts contribute to the structural capacity (Sweden, 2011b). It has, however, been suggested that load-bearing capacity may have stronger association with debonding of the exposed laminate from the core (Hertzberg, 2009; Ramroth, 2006; Sweden, 2011a). The bond depends on both the resin and on the core, as elaborated above, and suggests that the temperature at the exposed laminate/core interface could be a key feature. The temperature for debonding is higher than the HDT and Tg, and significantly lower than the laminate pyrolysis temperature, as illustrated in Figure 8.

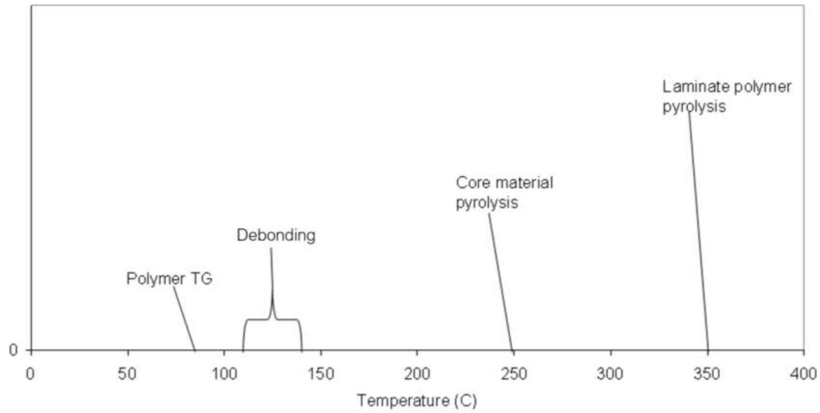


Figure 8. Typical critical temperatures for an FRP composite sandwich structure (adapted from Hertzberg, 2012).

In regard to structural integrity testing of FRP composite it has also been stressed that further consideration needs to be taken to the magnitude of the loading in the standard fire test (Sweden, 2011a). This dependence of load-bearing capability on the applied load in fire tests was supported by Summers et al. (2012) and it has also earlier been suggested that the static loading in Part 11 of the FTP Code does not adequately represent typical design values (Ramroth, 2006). If this is the case, Part 11 tests are not valid for performance verification of FRP composite structures used for higher loads. The above-described needs to further test and investigate the thermo-mechanical effects on the load-bearing capability of FRP composite sandwich bulkheads founded the basis for Paper IV.

2.5.5 Alternative to thermal insulation

Use of thermal insulation is a common way to protect FRP composite structures from an interior fire, and thus delay many of the fire hazards of the materials. However, using thermal insulation on all internal surfaces will add both weight and volume. The addition of insulation at one side of an FRP composite structure could weigh as much as the structure itself and builds about 100 mm into the volume of the space (Arvidson et al., 2008; Hertzberg, 2009). It further requires another stiff surface if the typically soft thermal insulation is not functional in the relevant space. Furthermore, for external surfaces, insulation is generally not an option. Alternatives to using thermal insulation have therefore been investigated.

In the LASS-C project, the reliability of the fire spread protection provided by lightweight ship structures was investigated in combination with active systems, simulated by a developed tool called FISPAT (Hedin & Strandén, 2011; Lundsten & Hedin, 2010). More commonly, passive solutions have been investigated, in particular to make the resin more flame retardant or to use intumescent coatings (Kandola et al., 2002; Krishnan et al., 2021; Laskoski et al., 2018; Mouritz et al., 2006). Another alternative envisaged in the EU project BESST was to improve the structural fire integrity by a new sandwich structure design with multiple cores (Evegren, 2013b; Rahm, 2012).

Based on that the key to the load-bearing capacity of a sandwich structure is dependent on the attachment of the exposed laminate to the core, a structure was designed with multiple cores. The simplest structure envisioned was a structure with three laminates and two cores, where only two laminates and one core were dimensioned to carry the design load. The remaining (exposed) laminate and core would hence function as sacrificial thermal protection. Compared to using insulation, this solution would be lighter, thinner and have a more functional surface, also usable for external applications. It would also contribute to structural redundancy when not exposed to fire. However, this idea of a multiple-core FRP composite sandwich structure had never been evaluated regarding structural fire integrity, which formed the scope for Paper V.

3 Background to risk assessment

As noted in the previous chapter, the SOLAS regulations have weaknesses and the guidelines for a regulation 17 assessment can be insufficient. In particular for the fundamental change to use combustible structures. This combination requires looking beyond the (deterministic) risk assessment procedure in MSC/Circ.1002 (IMO, 2001). As a basis for advice on how to develop the risk assessment procedure, this chapter gives a background to the risk concept and to how assessments thereof can be used to evaluate fire safety (see RO3).

As an introduction, SOLAS II-2 regulation 17 requires an equivalent "*degree of safety*" for alternative designs of fire safety. While MSC/Circ.1002 (IMO, 2001) provides guidelines for a risk assessment, there is no clear notion on how *safety* should be defined. There are many definitions of safety. For example, safety can be seen as the absence of incidents (Leveson, 2004) or as a state of low and acceptable risk (Harms-Ringdahl, 2001). In line with the latter, risk is often seen as the antonym of safety, i.e. that lower risk implies improved safety, which Aven (2009, 2014) concludes as scientifically accurate. This also correlates with the definitions in the glossary provided by the Society for Risk Analysis, defining *safe* as "*without unacceptable risk*" (Aven et al., 2018).

A means to assess fire safety is hence *fire risk assessment*. It utilizes the concept of risk as the antonym of safety to estimate and evaluate probabilities and consequences of events, caused by an activity or change. When it comes to assessment of risk in this way, certain concepts should be recognized which form the foundation of a risk-based design approach. Below, the risk concept is introduced, followed by short elaborations on uncertainty, which is a focus in assessments of risk. Definitions of risk are then described, before introducing the foundations of risk assessment and a review of how fire risk assessments have been used in the maritime field.

3.1 Perspectives on the risk concept

Traditional perspectives on risk and risk perception are briefly described below, followed by a summary of a currently common general perspective on risk.

3.1.1 Traditional perspectives on risk

As application of risk management in society has increased over the past half century, the risk concept has been given much attention in research (Power, 2004; Slovic, 2001). A particularly interesting and fundamental debate has addressed what risk is and what should be considered acceptable risk (Aven, 2009; Fischhoff et al., 1978; Hansson, 2010; Renn, 1998). The debate originates from perspectives in ontology (e.g. Solberg & Njå, 2012; Ylönen & Aven, 2023), the philosophical study of existence (e.g. Jacquette, 2002), and has included the extreme views that risk is fully objective or subjective. Hansson (2010) notes that the dominant view has historically been the objectivist view, i.e. that there is an objective or real risk that can be completely characterized in terms of epistemic facts about the physical world (see e.g. Campbell, 2005; Cohen, 2003). The subjectivist view has instead been that risk is a social construction (Otway & Thomas, 1982) and that risks must be characterizable without any component of facts about the physical world (Hansson, 2010); sometimes to the extreme to say that risk and risk perception are the same (Jasanoff, 1999), which has although been criticized (Rosa, 1998).

3.1.2 Risk perception

Risk perception can be described as people's intuitive judgement about risk; it depends on their experience and knowledge and is thus subjective and differentiated in society (Aven, 2009; Slovic, 1987). Experimental psychologists identified that the most essential factor influencing risk perception is *dread risk*, defined by perceived lack of control, catastrophic potential and inequitable distribution (Slovic, 1987). The aspects are closely related to the feeling of fear, as elaborated by e.g. Loewenstein et al. (2001). Factors influencing people's judgments of risk are further discussed by Ryan (2007), who chooses to summarize the most important factor as *prominence*. It is defined by the size of an event, its proximity and its suddenness. These descriptions relate to *fear* and *dread risk*, and they are also features that attract our attention. This is important since risk perception can be influenced, for example by norms and imperatives, but also by meaningless and fictional statements (Hansson, 2010). As such, risk perception is heavily influenced by media (Slovic, 1987) and can be affected for gain, e.g. through stigmatism by those adversely affected by a risk (Garrick, 1998), by politicians claiming to minimize blown up risks (Breyer, 1993), or by terrorists aiming to instill exaggerated fear (Ryan, 2007). Such effects on risk perception belong neither to the objectivist nor the subjectivist view of risk (Hansson, 2010) but they will, along with potential benefits, affect the acceptability of risk in a population (Aven, 2009; Fischhoff et al., 1978; Starr, 1969).

3.1.3 Current common perspective on risk

Disregarding all risk perception as unjustified stigma, based on an objectivist view, has been found undemocratic and ignorant of the real costs that fear imposes on people (Loewenstein et al., 2001; Roeser, 2006). This has resulted in a perspective on risk where the objectivist and the subjectivist views have to a large extent merged, with a focus on intersubjective safety (Möller et al., 2006). Emphasis has lately rather been on identifying the different factual and valuational components of risk, to properly understand their effects (Hansson, 2010). It has also been accepted that both risk acceptance and risk characterization are based on both objective and subjective components, i.e. both facts *and* values (Aven & Renn, 2009; Hansson, 2010; Renn, 1998). Risk characterization is for example based on subjective knowledge, assumptions, models and estimations (Aven & Ylönen, 2018). The main ideas of a currently common general perspective on risk can based on Aven & Ylönen (2018) be summarized as:

- focus is on uncertainty rather than on probability;
- elucidation of knowledge uncertainty and the strength of knowledge;
- risk assessment attempts to characterize what we know and do not know about relevant risk aspects;
- realization that surprises (black swans) can occur; and
- risk analysis informs decisions makers, who may also consider other aspects.

These aspects are further addressed in the subsequent sections of this chapter.

3.2 Uncertainty

Uncertainty is a fundamental part of risk and always present in decision-making. Known and unknown uncertainties for different risks and decision options contribute, but also the uncertainties introduced in the analysis and presentation of the risk (Hansson, 2004). It is therefore important to analyze these uncertainties and, as far as practicable, estimate their potential effects.

There are several general approaches to classify uncertainties (e.g. Apostolakis, 2004; Helton & Burmaster, 1996; Kammen & Hassenzahl, 1999; Pate-Cornell, 1996; Rowe, 1994). Common is to divide uncertainties into two classes:

- U_A – aleatory uncertainty (randomness/variation in populations); and
- U_E – epistemic uncertainty (due to lack of knowledge).

3.2.1 Aleatory/randomness uncertainty

Aleatory or stochastic uncertainty refers to random errors in a population and is not possible to reduce. It derives from *natural variation* and can be described by the rolling an honest dice; because of natural variation the probability of getting any number is 1/6. It has however been questioned if aleatory uncertainty actually exists, or at least in a meaningful way in risk assessment, or if it is rather a type of knowledge uncertainty (Faber, 2005). The general conclusion has been that a pragmatic division in the two categories is still useful when uncertainties are modelled and analyzed for complex systems (Apostolakis, 2004; Kiureghian & Ditlevsen, 2009). However, Aven and Thekdi (2022) argue that reference to aleatory uncertainty should be avoided when speaking about frequentist probabilities.

3.2.2 Epistemic/knowledge uncertainty

Epistemic uncertainty appears due to *lack of knowledge* concerning a system, causing systematic errors or lack of data. It may for example be unknown if a dice is honest, and thus the knowledge uncertainty could be reduced by rolling the dice many times (Kammen & Hassenzahl, 1999). Epistemic uncertainties appear in *all stages of a risk assessment*. In the hazard identification phase uncertainties can be linked with the used procedure, how detailed it is performed, and the competence of the expert group examining the system. In particular when introducing novel solutions, such as FRP composite, lack of knowledge and experience is a drawback which can for example result in missing or wrong scenarios (Aven, 2017; Spiegelhalter & Riesch, 2011). This will cultivate errors and can greatly affect the risk description. When determining consequences of events, uncertainties depend on the models used and the experience in the expert group, which can be significant sources of uncertainty. Even if it is one of many sources of error, the knowledge uncertainty entering if estimating probabilities of events may be perceived as the dominating one. For new designs, as FRP composite, data will likely be insufficient and not fully relevant, and data may not consider for example updates in legislation (Gutierrez et al., 2008). The statistical base can then be supplemented, and is often replaced, by expert judgments (Möller et al., 2006). With these enter subjective values, risk perception and simplifications, which can include large uncertainties (Cox, 2012; Flage et al., 2014; Skjong & Wentworth, 2001).

3.2.3 Uncertainty assessment

It is important to transparently describe identified uncertainties, including delimitations and assumptions, when assessing risks. In order to determine the influence of uncertainties and which uncertainties should possibly be dealt with, a separate analysis of uncertainties is often performed. Increasing knowledge on influential uncertainties will make them less significant and it also helps structuring the problem. Even if a detailed uncertainty analysis is not carried out, every risk assessment should include some description of how uncertainties can affect the result.

3.3 On the definition of risk

Many people use the term risk equally to ‘likelihood’ and some consider activities to be ‘risky’ if the foreseen consequences of a potential incident are substantial, e.g. traveling in an airplane. Below follow elaborations of qualitative definitions of risk, as well as more technical definitions to estimate risk.

3.3.1 Qualitative definitions of risk

In industry applications, risk is a widely used term with different meanings in different contexts. The Committee of Sponsoring Organizations of the Treadway Commission for example provides guidelines for enterprise risk management and defines risk as “*the possibility that events will occur and affect the achievement of strategy and business objectives*” (COSO, 2020). It hence focuses on possible events affecting objectives. The International Organization for Standardization (ISO) provides a definition in their generic principles and guidelines on risk management for any type of risk, organization, or level of enterprise in ISO 31000 (2018). Here risk is defined as the “*effect of uncertainty on objectives*” (ISO 31000, 2018, p. 1). This emphasizes uncertainty more than the events, and like the COSO definition it focuses on the achievement of objectives. The UK Cabinet Office simply refers to risk as “*uncertainty of outcome […] of actions and events*” (Cabinet Office, 2002) and IMO provides a more traditional definition of risk as “*the combination of the frequency and the severity of the consequence*” (IMO, 2018). The Norwegian offshore industry, which has been a precursor in maritime risk management, had a similar definition until it was changed in 2015; the Norwegian Ocean Industry Authority now has a new definition of risk as the “*consequences of an activity with the associated uncertainty*” (Havtil, 2024), the impact of which has been studied (Haavik et al., 2023; Røyksund & Engen, 2020). The industry thus moved away from a traditional definition of risk as a combination of probability and consequence and put a much stronger *focus on consequences and uncertainty*.

The definition of risk has been widely discussed in the academic field relating to risk management (e.g. Kaplan, 1997). The Society for Risk Analysis summarized different opinions on key elements of risk analysis, where the risk definition was one of the discussed issues (Aven et al., 2015). They present several qualitative definitions of risk and note that they all express *uncertainty* of events and their *consequences*. Hence, the outcome must not be certain, $U \neq 0$, and from that follows that the consequence options must be at least two; with one certain outcome there is no risk. Furthermore, *uncertainty* and *consequences* appear to be two minimal characteristics of risk. When it comes to the concept of risk, it could hence be argued that the simplest and most fundamental definition would be that **'risk is uncertainty of (neg.) consequences'** (cf. Cabinet Office, 2002), or $R=(C,U)$, (see e.g. Ylönen & Aven, 2023). This is also the core of an early definition by Kaplan and Garrick (1981), who suggested that risk is "*both uncertainty and some kind of loss or damage that might be received*". An elaboration of this definition is that proposed by Aven and Renn (2009):

> *"Risk refers to uncertainty about and severity of the events and consequences (or outcomes) of an activity with respect to something that humans value."*

This definition clarifies a number of important aspects about risk. Firstly, consequences (and uncertainties) will always be related to some activity, action or event. These (uncertain) consequences will naturally be measured by their severity and more importantly need to have some significance for the risk to exist ($C \neq 0$). Instead of objectives, Aven and Renn chose to refer to "*something that humans value*". This is hence a core reference value, describing the desired or undesired outcome of events. Without such a reference, it is not possible to determine deviations, which is a principle found already in the Bible.

> *"And where there is no law there is no transgression."* (Romans 4:15)

3.3.2 Technical description of risk

For quantification of risk there are also various definitions used, many of which are summarized in the Society for Risk Analysis Foundations (Aven et al., 2015). One of the earliest and most common quantitative definitions of risk is a combination of probability (P) and consequence (C), generally used to form an expected outcome (Lowrance, 1976). A further developed definition of risk was something that Kaplan and Garrick (1981) called a "*triplet*" (S_i, P_i, C_i), where:

- S_i is a scenario identification or description – "*what can go wrong?*";
- P_i is the probability of that scenario – "*how likely is it?*"; and
- C_i is the consequence or the measure of damage from that scenario – "*if it happens, what are the consequences?*"

A triplet describes one scenario, and adding up all identified scenarios accumulates the total risk. It is hence not only the sum of all risk contributions in one figure, but *the whole set of triplets* (Kaplan & Garrick, 1981). This characterization of risk is well-known and commonly accepted for handling risks quantitatively for technical applications; it is both comprehensive and logical, fully embracing the traditional definition of risk (Callan, 1998). The definition has although been debated in the research community (see e.g. summary in Johansen, 2010), for example due to the *lack of focus on uncertainty*. According to Aven (2014), pure probability-based definitions neither justify safety being the antonym of risk; for that, uncertainty must be acknowledged as a main feature. This is also in line with common nomenclature and how the words are used. The discussions have given rise to another description of risk, $R=(A',C',Q,K)$, where (Aven & Thekdi, 2022):

A'	is a set of specific events (see S_i above);
C'	is a characterization of identified consequences (see C_i above);
Q	is a way to describe the uncertainties regarding these consequences; and
K	is the knowledge supporting the former estimations.

It should be noted that C' refers to the *specified consequences* in the risk assessment, i.e. a delimitation. The uncertainty measure Q of these consequences is typically represented by interval probability *(P)* and strength of knowledge judgements *(SoK)*, i.e. $Q=(P,SoK)$. The epistemic uncertainty depends on the strength of knowledge and it is therefore important to quantify the knowledge that supports the risk characterization in a risk assessment (Bani-Mustafa et al., 2020).

There are many definitions of risk, and the suitability of a quantitative definition depends on the particular conditions of the risk under consideration. In this context it is important to remember that "*whoever controls the definition of risk (i.e. determines the rules of the risk game) controls the rational solution to the problem at hand*" (Slovic, 2001).

3.4 Risk management and risk assessment

The risk concept is often utilized with the intention to make good decisions with regard to safety, health, environment, economy, etc. Risk management is a collective name for systematically accounting for, analyzing and minimizing risks within a project or organization, or as ISO defines it: "*coordinated activities to direct and control an organization with regard to risk*" (ISO 31000, 2018). The goal of risk management is further elaborated below, along with approaches for managing risk. One of the first steps of risk management, also according to MSC/Circ.1002, is to identify *hazards*, which is a term defined subsequently. Thereafter characteristics of different methods for risk assessment are discussed. Risk assessment is an approach of the risk management process to establish a basis for decision making and implementation of safety measures.

3.4.1 Approach for risk management

Risk management has significance in much of what we do (Kaplan & Garrick, 1981), even if it is not always conscious.

> *"[…] we are not able in life to avoid risk but only to choose between risks."* (Kaplan & Garrick, 1981, p. 11)

Naturally we prefer less 'risky' options, but the question is often to what cost or potential benefit? For example, to what limit should society be willing to pay for avoiding a fatality? Life is for most considered priceless and it is inevitably controversial to put a price on it. However, to compare different risks associated with an activity, it can be sensible to make use of this very valuable constituent in risk management (see e.g. Nord, 1999). Thereby the allocation of resources can be optimized to save as many lives as possible, which may be one of the objectives. Sound risk management weighs the many different aspects of a decision and develops risk control options in order to suggest the most appropriate course of action. The goals are to take greater control over the identified risks and to minimize the number of unforeseen and uncontrollable events (Kolluru et al., 1996).

Risk management principles are used daily in most companies, agencies and organizations, even if the extent to which they are documented may vary. The basis is some form of *evaluation to achieve safety*. In the simplest form it can consist in compliance with standards and regulations, perhaps complemented by a safety audit or inspection. A more elaborated approach to ensure compliance, used in the automotive and other manufacturing sectors, is functional safety assessment (Kochanthara et al., 2021; Simon Dean, 1999), used to evaluate the effectiveness of safety functions. Harms-Ringdahl (2004) looks into accident investigations, safety management systems and risk analysis as approaches to achieve safety. Callan (1998) mentions integrated safety assessment and performance assessment as alternatives to probabilistic risk assessment, while Hollnagel suggests to focus on modelling "*systemic accidents*" as results of complex interactions rather than on threads of causes and effects (Hollnagel, 2004). In these lines, he presented the functional resonance analysis method (FRAM), which considers the socio-technical system as a whole. In a similar spirit, Leveson (2004) presented an accident prevention model called STAMP (System-Theoretic Accident Model and Processes), further elaborated in (Leveson, 2015). It is suitable for operator-centered systems, as it covers issues influenced by social and organizational structures. For a change to structures in FRP composite, however, it is reasonable for the risk management approach to focus on functional failures and chains of failure events rather than on the dynamics of a socio-technical system.

Several of the aforementioned approaches can be referred to as risk assessments, and the methodology described in MSC/Circ.1002 (IMO, 2001) has been identified as a type of risk assessment (Evegren, 2010a). *Risk assessment* was therefore selected as the main focus to evaluate the safety of FRP composite ship structures in this thesis. A structure for the risk management process based on risk assessment was standardized by the International Electrotechnical Commission already in 1995 (IEC 300-3-9, 1995), illustrated in Figure 9. It elaborates a simple structure of the risk management process, comprising risk assessment and risk reduction/control. The standard was later merged with an ISO standard in IEC/ISO 31010 (2019), and concepts for the risk management process have thereafter been moved to ISO 31000 (2018). The scope definition has now been lifted out from the risk analysis, similar to MSC/Circ.1002 (IMO, 2001), and the term "*Risk reduction/control*" has been replaced by "*Risk treatment*", excluding *monitoring* which is handled separately.

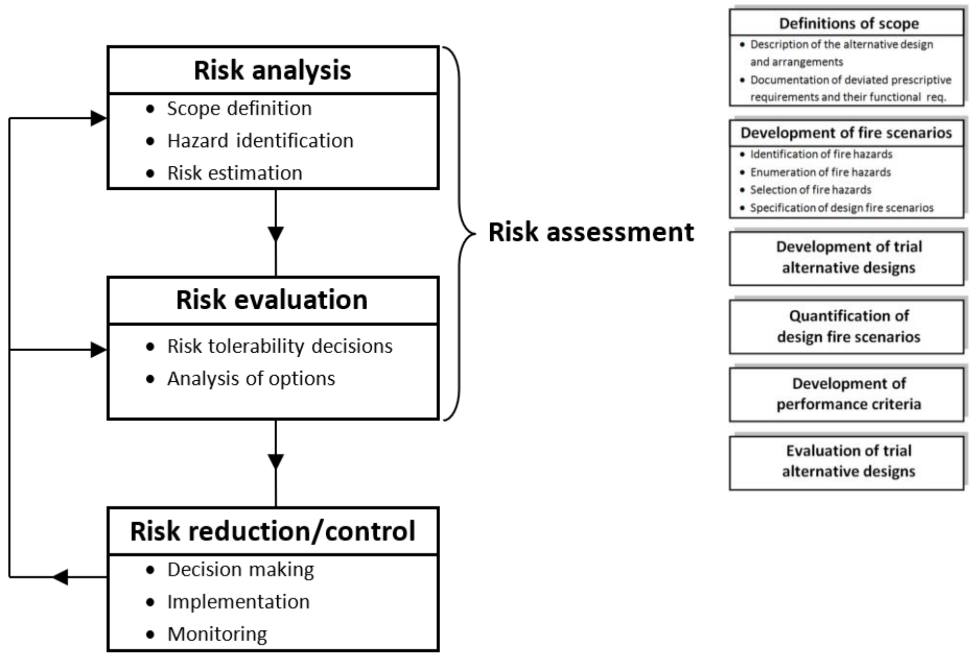


Figure 9. Simple description of the risk management process (adapted from IEC 300-3-9, 1995), where the risk assessment can be compared with the process in MSC/Circ.1002 (IMO, 2001), see Figure 7.

In IEC 300-3-9 (1995), and still in ISO 31000 (2018), the risk assessment consists of two parts: *risk analysis and risk evaluation*. While MSC/Circ.1002 was based on the guidelines for fire safety engineering at the time (ISO 13387, 1999; Rosenbaum, 1999), the procedure also follows that of a risk assessment (see IEC 300-3-9, 1995 in Figure 9). After definitions of the scope, the *hazards* are identified and then the risk is *estimated*, in MSC/Circ.1002 by a scenario analysis. Acceptance *criteria* are then decided, before evaluating the alternatives. For a new or alternative solution, such as FRP composite structures, the goals of a risk assessment are to estimate the specific risks and benefits before the basic phenomena are fully understood, and to rank risk control options (Pate-Cornell, 1996). As discussed above, the risk assessment must also acknowledge and evaluate relevant *uncertainties* affecting the decision-making, and establish whether the *knowledge base* provides sufficient support (Bridges, 2000), e.g. by a strength of knowledge assessment (Bani-Mustafa et al., 2020). Different methods for risk assessment are described below, proceeding descriptions of the term 'hazard'.

3.4.2 Risk analysis and the term hazard

The risk analysis is the first step of the risk management process and creates a base for evaluation of the risk and selection of risk control options. It includes definitions of the scope, i.e. context establishment, system description and choice of endpoints. It also embraces a systematic identification of hazards and a technical estimation of the risk in some form of risk metric, as described in section *3.3.2 Technical description of risk*. The latter is often based on calculation of probabilities and consequences. However, it is important to note that such a risk estimation is not the whole characterization of risk, (*A',C',Q,K*), which should also consider the knowledge base and uncertainties from a wider perspective (Aven & Thekdi, 2022).

The term 'hazard' has been defined variously in different fields over the years, but the definitions have been quite similar:

- *an inherent physical or chemical characteristic that has the* ***potential*** *for causing* ***harm*** *to people, the environment or property* (Guidelines for Hazard Evaluation Procedures, Grossel, 1993);
- *a risk* ***source*** *where the* ***potential*** *consequences relate to* ***harm*** (SRA Glossary, Aven et al., 2018);
- *a* ***potential*** *to* ***threaten*** *human life, health, property or the environment* (FSA guidelines, IMO, 2018);
- ***source*** *of* ***potential harm*** (Risk management vocabulary, ISO 31073, 2022);
- ***potential*** *for* ***harm*** *associated with fire* (Fire safety vocabulary, ISO, 2023);
- *condition or physical situation with a* ***potential*** *for* ***harm****, such as harm to life, limb or property* (Guide to fire risk assessment, SFPE, 2022);
- *'****possible source*** *of* ***danger****' that can initiate or cause undesirable consequences if uncontrolled* (Guide to Performance-Based Fire Protection, Rosenbaum, 2007).

Considering the list above, it may be noted that the definition in the Guidelines for Hazard Evaluation Procedures was developed some 30 years ago with a main focus on the chemical process industry. The Society for Risk Analysis Glossary provides a definition with similarities, but they widen the concept by elaborating that "*hazards could, for example, be associated with energy (e.g., explosion, fire), material (toxic or eco-toxic), biota (pathogens) and information (panic communication)*" (Aven et al., 2018). The IMO definition is similar to that developed for the chemical process industry and can be considered covered by the current ISO definition, which is more generic. There are also several guidelines focused on fire safety and fire risk assessment which define hazard in similar ways. In summary, a hazard seems to refer to some kind of source with potential for harm, see ISO definition, or as defined for this thesis, a *source with potential for harm associated with fire*, where 'harm' could be replaced by 'negative consequences'. How it can materialize, depending on potential safety measures, will define the risk.

3.4.3 Methods for risk assessment

Identification of possible causes of hazardous events and estimation of the risk requires working systematically, using different methods, in the risk analysis. The choice of method/s will depend on the *objectives* or requirements on the study and on the system complexity. It can for example also be affected by when in a project the analysis is carried out, previous knowledge, and available resources (Magnusson et al., 1999). Many times the method has a focus, e.g. accident or consequence oriented, and some are focused on a certain industry for which it has been developed.

Methods for risk analysis have traditionally been categorized on a *qualitative-quantitative* scale based on their inclusion of quantitative measures, or on a *deterministic-probabilistic* scale based on how the likelihood of outcomes is considered (e.g. Bedford & Cooke, 2001; Han & Weng, 2011; Jonkman et al., 2003; Khan & Abbasi, 1998; Olsson, 1999; Tamara, 2016). Probabilistic methods include probability estimations for different events, while deterministic methods are only based on an analysis of expected or worst-case consequences. Quantitative methods use numeric metrics to estimate the risk, while qualitative methods characterize the risk in a descriptive way, simply without numeric measures. All methods will naturally have significant descriptive elements and it has therefore been questioned whether a categorization into qualitative and quantitative 'methods' should be used (Åsberg et al., 2011). It nevertheless provides an overview of the methods for risk assessment, considering some interesting aspects of their characteristics. An illustration of such an overview, categorizing some common methods for risk assessment, was presented by Evegren (2010a) and is shown in Figure 10. Exactly where the methods are placed on the scales can be discussed; it is a matter of judgement, but the figure gives some indication of differences. Further methods for risk assessment are presented for example in IEC/ISO 31010 (2019).

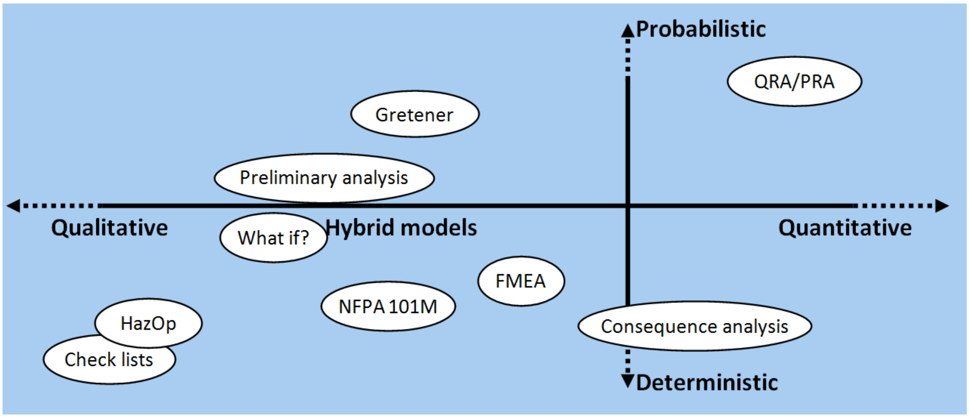


Figure 10. Illustration of how some common methods for risk assessment differ on a two-dimensional scale (from Evegren, 2010a).

Qualitative methods are often used in the hazard identification, but for example also in system delimitation, risk modelling, and in descriptive evaluations of results. Such approaches can be sufficient for the risk assessment as a whole if its objective is simply to identify hazards to support a zero-risk policy, or if it aims to compare risks qualitatively (Pate-Cornell, 1996). Hybrid methods are generally more detailed in their structure than qualitative methods and they often rate probabilities or consequences in some way (Nilsson, 2003), such as so called index methods (e.g. Karlsson, 2002).

Deterministic methods analyze the outcomes from possible events to determine a worst-case scenario. It would, however, be very expensive to base a design on the very improbable worst imaginable event, or black swan if you will (see e.g. Clarke, 2005; Taleb, 2007). More common is therefore an approach where some consideration to likelihood is included. Such a 'plausible worst-case' method is for example used when designing the strength of structures (Pate-Cornell, 1996), using probability-based design values for loadbearing capacity. However, the measure of probability when determining the dimensioning scenario is often unknown when applying a 'plausible worst-case' approach; it makes the "*residual risk*", from not considered scenarios, unknown. Probabilistic methods combine quantifications of several potential consequences and probabilities. The two probabilistic methods noted in Figure 10 are quantitative risk assessment (QRA) and probabilistic risk assessment (PRA). QRAs have for long been used in the chemical process industry and attempt to quantify risks to human life in and around a facility (AIChE, 2010). PRA has a long history from the nuclear industry and is similar to a QRA, but generally concentrates more on underlying events to estimate the likelihood of scenarios (Apostolakis, 2004; Nilsson, 2003).

An advantage of using a simple method, in addition to lower cost and engineering rigor, is that the results may be more *comprehensible*. It however implies more simplifications and coarse handling of uncertainties, which in the end may require a more *conservative* and costly solution. The ambition using a probabilistic method is to make uncertainties more transparent, complementing the risk measure by for example sensitivity analysis, Montecarlo simulations or Bayesian analysis, see e.g. Spiegelhalter and Riesch (2011).

3.5 Fire risk assessment for ships

Risk-based approaches have a long history in many fields. In the maritime industry it started when probabilistic methods were introduced to evaluate ships' damage stability in the early 1960s (Papanikolaou, 2009). In the 1990s it was recognized at IMO that many prescriptive regulations were unable to handle innovative ship design and since then there has been a major development towards goal-based standards (IMO, 2019a). As noted above, the regulations in the fire safety chapter of SOLAS (IMO, 1974) were the first to get a performance-based structure, which came into force in 2002, along with regulation 17. Fire risk assessments had been used for long in the offshore industry (since 1986 in Norway) and for naval ships (e.g. Grzeszkiewicz et al., 1984), but regulation 17 introduced application also for merchant vessels.

In parallel with the regulatory development towards goal-based standards, the risk concept has been extensively elaborated in maritime research. In the EU project SAFEDOR (Design, Operation and Regulation for Safety), holistic safety was proposed as a design objective by basing the approval process on risk assessment (Breinholt et al., 2012; Eliopoulou et al., 2009). The project included determination of *holistic risk evaluation criteria* (individual, societal and environmental) for different ship types, which were proposed to IMO (Skjong et al., 2007). In the SAFEDOR project it was also noted that the approach presented in MSC/Circ.1002 is based on quantifications of a few representative scenarios and therefore does not reveal the total fire risk (Guarin et al., 2007). A probabilistic framework for fire risk was therefore proposed, which led to further development in an EU project called Fireproof (Vassalos et al., 2010). In this project, a probabilistic risk assessment concept based on fire safety engineering for buildings (e.g. SFPE, 2022) was developed. It consisted in a fire ignition model (Themelis et al., 2010) for different categories of spaces onboard, based on a fire incident database (Ventikos et al., 2010). Fire scenarios (Grandison, Wang, et al., 2011) and associated probabilities (Lohrmann et al., 2011) and consequences (Grandison, Burton, et al., 2011; Grandison, Galea, et al., 2011; Henriques, Dias, & Lopes, 2011) were automatically generated by different models to make up a ship specific *fire risk index* (Henriques, Dias, Lopes, et al., 2011). The calculated total fire risk of a ship, in a single risk index figure, was then compared to an explicit risk criterion derived from statistics (Themelis & Spyrou, 2012). This can be questioned due to the *vast uncertainties* involved, lack of detailed data, and the simple risk measure, which gives a sparse characterization of the risk.

The significant number of fire incidents on ro-ro ships made the European Maritime Safety Agency issue two research studies called FIRESAFE and FIRESAFE II. While focusing on different aspects of fire safety, they had the same objective to propose *cost-effective regulatory amendments improving the fire safety of ro-ro passenger ships*. Both studies followed the IMO Formal Safety Assessment methodology, developed to support IMO rule-making when evaluating implementation of new safety measures (IMO, 2002, 2018). It consists in a systematic cost-benefit assessment process, using risk assessment to quantify benefit as risk reduction, illustrated in Figure 11.

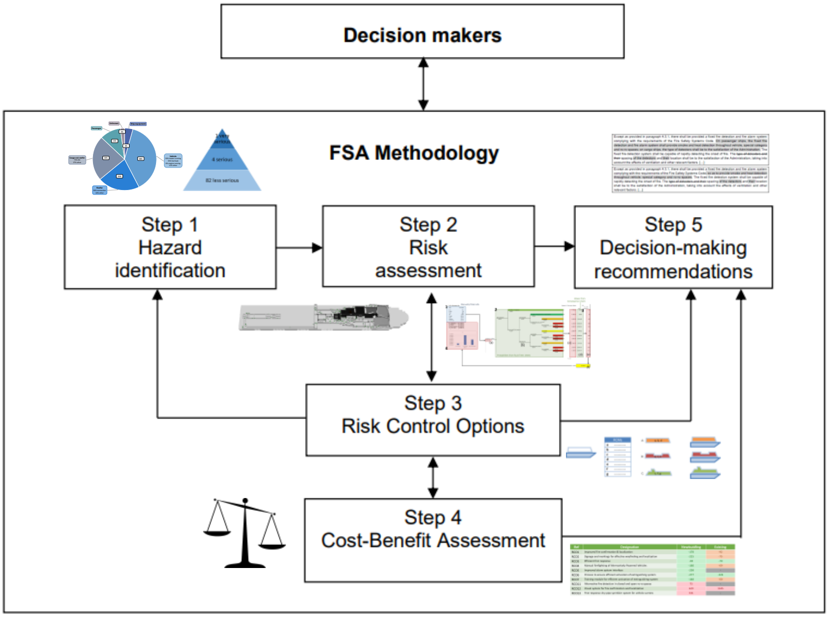


Figure 11. Flow chart of the IMO Formal Safety Assessment procedure, incorporating risk assessment in the cost-benefit assessment (adapted from IMO, 2018).

The FIRESAFE study formed a fire risk model for fires in ro-ro spaces based on a bow-tie principle (Wikman et al., 2016). Instead of a fault tree, the left side of the model consisted of a risk contribution tree based on fire incident statistics. The right side of the model was based on a typical event tree, following a fire chain of events, from ignition to evacuation, where each event was characterized by a fault tree. The risk model was further elaborated in FIRESAFE II (Leroux, Evegren, Mindykowski, Bram, et al., 2018; Leroux, Evegren, Mindykowski, Gustin, et al., 2018) and then also used as basis for further development in the EU project LASH FIRE (Carvalho, Lewandowski, Andersson, Pramanik, Bram, et al., 2023). Each study relied a large number of experts and extensive uncertainty and sensitivity analyses, based on Montecarlo simulations, to evaluate the many assumptions and numerous risk models (Carvalho, Lewandowski, Andersson, Pramanik, & Dahlbom, 2023; Evegren et al., 2017; Leroux, Evegren, Gustin, et al., 2018). Many cost-effective risk control options were found (IMO, 2024b), some of which were implemented, as set out in Annex 7 of MSC 108/WP.4 (IMO, 2024a).

4 Method

Science is about acquiring knowledge in a systematic and methodic way. The produced knowledge should be valid to the problem investigated and it should be reliable and independent of who produced it; it should be possible to control the knowledge and it should be possible to repeat the research with the same results (Robson, 2016; Säfsten & Gustavsson, 2023). Choosing an established research approach is hence vital for the quality of the research (Yin, 2018).

In this thesis, a distinction was made between three different levels of applied research approaches, elaborated subsequently:

> **Type of study:** Exploratory, descriptive, or explanatory, depending on the research motives and the knowledge to be generated.
>
> **Research method:** Established scientific approach to investigate the subject of interest (Ejvegård, 2009).
>
> **Data collection technique:** Procedure to collect information, e.g. to compare, describe, predict, explain, or formulate hypothesis about the subject (Ejvegård, 2009).

The type of study should depend on the research motive and is often categorized as *exploratory*, *descriptive*, or *explanatory* (Robson, 2016; Rosengren & Arvidson, 2002; Yin, 2018). Exploratory studies often answer open research questions and aim to observe and understand the topic and problems generally (Robson, 2016). Descriptive studies aim to describe specific phenomena or characteristics, often answering the questions '*what*', '*which*', '*who*', '*where*' and '*how*', without exploring causation (Goldkuhl, 2011; Rienecker, 2016). If the study aims to investigate causal relationships it is explanatory, generally aiming to answer the question '*why*' (Montgomery, 2020; Robson, 2016). These categorizations were used to discuss the study types used for this thesis. It may be noted that the types of study represent increasing knowledge levels and can be combined in a research study, for example to first explore state-of-the-art before answering '*how*' and '*why*' (Rienecker, 2016).

When it comes to research methods, some authors in research methodology only differentiate between two fundamental types, *observation* and *experiment*, where the difference is explained by whether or not the system is intervened (Andersson, 2012; Hansson, 2007). However, most authors suggest a wider categorization of research methods (e.g. Dahmström, 2011; Ejvegård, 2009; Holme & Solvang, 1997; Robson, 2016; Säfsten & Gustavsson, 2023; Yin, 2018). Yin (2018) for example suggests that there are five essential methods: experiment, survey, archival analysis, history, and case study, and Ejvegård (2009) presents a categorization including nine methods: description, case study, classification, quantification, hypothesis testing, theory formation, model development, comparison, and prediction. While the methods presented by Yin (2018) typically describe the overall type of study, the methods presented by Ejvegård (2009) describe what is done at a more detailed level. The categorizations of research methods proposed by different authors are formulated based on research in their particular fields and can be more or less transferable. Säfsten and Gustavsson (2023) focus on engineering and, without claiming to provide a complete categorization, they present a list with six common research methods *experiment*, *modelling and simulation*, *design research*, *survey*, *case study*, as well as *action and interactive research*. These categories were used as starting point to discuss research methods in this thesis.

The data collection technique is by some authors considered to be part of the research method (Holme & Solvang, 1997), while others distinguish between them (e.g. Ejvegård, 2009; Robson, 2016; Säfsten & Gustavsson, 2023). Exemplified as data collection techniques are *measurement*, *scaling*, *observation*, *interview*, *survey*, *workshop*, *statistics collection* and *document/literature study* (Ejvegård, 2009; Robson, 2016; Säfsten & Gustavsson, 2023). Just as a study can have several motives and seldom produces only one category of knowledge, several research methods and data collection techniques are often used in combination in studies (Säfsten & Gustavsson, 2023). The distinguishment is yet useful to discuss the methods and techniques used in research, and so for the work presented in this thesis.

The motive of this thesis has been to provide for assessment of fire safety of FRP composite ship structures, by investigating strategies for identifying hazards and criteria (RO1), by exploring verification methods (RO2), and by developing how the assessment is carried out (RO3). Hence, the main focus of the thesis has been descriptive/exploratory (see RO1 and RO2). Explanatory parts have although also been important, founded on several experimental investigations. RO3 is the research objective with the most intervening orientation, addressed by advice related to MSC/Circ.1002. There are thus multiple motives to the research work presented in this thesis and a combination of study types has been used. The research methods used for each appended paper and how the studies were carried out are described below, with starting point in the research objectives. Discussions on the suitability of the applied methods are elaborated in chapter *6. Discussion*.

4.1 Paper I

Paper I primarily consists of what can be referred to as a *descriptive* type of study, addressing RO1 and partially also RO3. The primary research method used was *description* (see e.g. Ejvegård, 2009), based on data collection from a brief *survey* of specific literature covering the regulatory framework, Regulation 17 assessments and related research. According to Ejvegård (2009), a description study consists in both observational and empirical research. It is often considered to be of simple nature but it can be rather difficult to achieve good and relevant descriptions of complicated systems; descriptions need to be structured and elucidating and terms need to be clarified (Ejvegård, 2009; Goldkuhl, 2011).

As basis for Paper I the SOLAS fire safety regulations were screened and described, also visually (see Figure 6), complemented by a review of regulation 17 assessments and maritime fire test methods. This literature survey was carried out to attain a full and clarified picture of the regulatory framework and structure, which is seldom fully understood. Relevant regulations and test methods were then studied in further detail to identify deviations and fire hazards when using FRP composite structures. They were systematically documented in Chapter 3 and Appendix D of MSC.1/Circ.1574 (IMO, 2017).

Identification of hazards is a fundamental step of a risk assessment and should in a relative risk assessment focus on the differences. In this case, the fire safety provided by FRP composite structures should be compared with that provided by compliance with prescriptive regulations (existing knowledge). In Paper I, such a comparison was done for the regulations affecting the growth stage of a fire, while other stages are addressed in other papers of this thesis. Paper I investigates and *describes* how requirements and performance criteria in the regulations (see RO1) can be related to FRP composite. For each regulation it was discussed how fire safety can be affected both explicitly and implicitly, i.e. advance from existing knowledge by a new design approach. Explicit effects were generally related to reaction to fire properties determined from standardized and experimental fire tests. Implicit effects were discussed with background in that existing regulations are formulated based on certain assumptions regarding ship design, for example that steel structures are used. By systematically investigating the fire performance implied by the regulations, a procedure was demonstrated for how performance criteria can be derived. Furthermore, it was exemplified how the fire performance of FRP composite structures can be characterized in relation to the prescribed safety.

In conclusion, the paper describes a procedure for identifying fire hazards and performance criteria in relation to SOLAS regulations and standard fire tests.

4.2 Paper II

Paper II was primarily an *exploratory* type of study primarily addressing RO2 and partially also RO1. The research method used was *experiment*, and data was mainly collected by measurements, complemented by *observations*. The paper investigates fire growth on external ship surfaces and how fire performance can be evaluated through a test method for building façades (see RO2).

The exteriors of a ship are generally made in non-combustible steel or aluminum and there is hence no method to evaluate fire growth on ship sides. Such fire properties are although evaluated for building façades by different standardized methods. SP FIRE 105 (SP Fire Technology, 1985) is a well-established façade test method, especially in the Nordics, and was used as basis for the experiments. In difference from most façade test methods, this method does not provide a corner configuration but a flat surface, which was considered more relevant for a ship side. Furthermore, the fire source was judged possible to represent the potential fire exposure from a large opening, such as a balcony door. The test method SP FIRE 105 was modified by using a (slightly higher) specimen without openings for windows, to focus on the potential for fire growth on the actual surface. Furthermore, to make better evaluations, instrumentations were expanded to calculate radiation and assess temperatures along the center of the specimen. This was done to provide a better basis for comparison of fire growth with passive and active protection and with a non-combustible surface. The measurements could also be used to compare the heat exposure in the tests with other relevant tests and performance criteria for ship applications. To complement the quantitative measurements, data was also collected by visual *observations* of the fires and of the resulting damage after the tests.

An experimental study is by definition carried out to investigate cause-effect correlations by manipulations of a system (Andersson, 2012; Montgomery, 2020). In this case the system involved a fire source and an FRP composite panel, whilst manipulations were made by adding different passive and active safety measures. In addition to explaining cause-effect relationships, the tests were conducted to explore the test method as such for FRP and potential safety measures. To allow comparison, it was important that the experiments were under close control and that the setup was designed to eliminate disturbing factors (Chalmers, 1999). The experiments were therefore performed indoors, with calibrated equipment and in a realistic scale, which reduces uncertainties when making comparisons (Andersson, 2012). Considering validity, a real application would likely have included windows, edges and other obstructions, the eternal combination of which could be difficult to represent in a test. Furthermore, in a real application, the large uninterrupted exposed surface in the test may not be found, which could make it overly conservative. However, the size was judged reasonably conservative by a team of shipyard representatives and researchers in the BESST project to assess fire spread and safety measures on a ship side. The test panel hence represents a part of a ship, while it does not represent an entire ship construction or weather conditions. Furthermore, since there had previously been no tests evaluating fire growth on external ship surfaces in this large scale, it was considered highly relevant. Thereby, the study was partly of *exploratory* character, which can also be a purpose of experiments (Montgomery, 2020).

In conclusion, the paper explores how a façade test method can be adapted and used to verify FRP composite ship structures regarding external fire growth.

4.3 Paper III

Paper III is a combination of an *exploratory/explanatory* study, using *modelling and simulation* as research method to address RO2. The data collection technique used was *measurement*, or rather *quantification* of data which were compared with measurements. The paper explores a model, developed to estimate effects on the temperature development in a fire enclosure from increased thermal insulation in boundaries (see RO2b). This was a potential hazard identified from the use of FRP composite, as explained in section *2.5.3. Heat conductivity of fire enclosure*. The research method *modelling* is generally used with the intention to improve, optimize or explain a part of reality and provide a simplified image of reality (Ejvegård, 2009; Säfsten & Gustavsson, 2023). However, the presented image is more specific to describe certain aspects of interest; to develop a useful model is hence much about finding the right balance between approximation and representation (Ejvegård, 2009; Säfsten & Gustavsson, 2023). The more variables involved and the larger the model, the larger the possibility to reflect reality, which inherently is complex (Ejvegård, 2009). The required level of detail of a model depends on the objective, i.e. what it needs to describe to be useful (Ejvegård, 2009).

In this case, model development was used to elucidate how temperatures in pre-flashover fires are affected by increased insulation in boundaries. Such models exist in for example FDS (McGrattan et al., 2024), but for quick calculations reference is often made to the MQH relationship (McCaffrey, Quintiere & Harkleroad, 1981) even if it is not applicable for highly conductive structures (e.g. steel) or varying heat release rates. By combining expressions for heat balance in the fire enclosure and for heat transfer through boundaries, a model was derived based on fire physics and depending only on the heat release rate (HRR). Since the core of the boundary was the only part assumed to store heat, temperatures could simply be derived for any part of the boundary as well as for the hot gases in the enclosure, here referred to as the fire temperature. Furthermore, by calculating (updating) gas and boundary temperatures from the previous time step, the model could properly account for a varying heat release rate. However, the model was thus limited to consider boundaries with lumped heat capacity. It is hence not applicable for e.g. insulated FRP composite or concrete structures, but it can be used to compare highly-conductive and well-insulated structures, such as non-insulated and insulated steel structures.

The constituents of the model were expressed in electric analogy. This allowed presenting an image for how and how much different variables affect temperature development in a space. Showing in this way how variables contribute to a certain mechanism or outcome is of *explanatory* nature, which can often also be a purpose of model development (Ejvegård, 2009). Model development is often combined with quantification of some sort, to allow clear and compressed presentation as well as comparative analysis (Ejvegård, 2009). In this case, output data were used to validate the developed model with experimental quantitative measurements. The model was validated against four test scenarios with different fire sources and boundary set-ups. Even with promising results, this implies limitations with regards to validity and reliability. Quantitative output data were also compared with results from FDS (McGrattan et al., 2024), which is currently one of the most used simulation tools in fire safety engineering.

In conclusion, the paper develops and validates a physical enclosure heat transfer model to estimate effects of structures' insulation qualities in case of fire.

4.4 Paper IV

Paper IV is an *explanatory* type of study addressing RO2. It investigates structural fire integrity of load-bearing FRP composite sandwich panel bulkheads based on loaded fire resistance tests (see RO2). Hence, it was based on *experiment* as research method and used *measurement* as data collection technique. As noted above for Paper II, an experimental study is by definition carried out to investigate cause-effect correlations by manipulations of a system (Andersson, 2012; Montgomery, 2020). In this test series, manipulations were made by systematically changing the design of the sandwich panels to achieve different bulkhead design load capacities, which were applied in the tests based on a safety factor against buckling.

This type of experiment can be referred to as "*systematic parameter variation*", where several essential variables are kept constant while others are varied (Säfsten & Gustavsson, 2023). This is an engineering-based research method with a long history (Berner, 1999) and particularly useful to understand and improve the performance of construction solutions by systematic testing (Berner, 2012). In the current test series, only one parameter was changed in each test, with reference to the first test where a typical bulkhead panel was used. Keeping all other conditions constant increases the control of the tests and helps to determine cause-effect relationships (Chalmers, 1999). Uncertainties and disturbing factors were also reduced by performing the experiments in full-scale and based on a standardized method with large experience and calibrated equipment (Andersson, 2012).

Load-bearing bulkheads on SOLAS ships are generally made in steel and structural fire integrity is tested without load, in accordance with Part 3 of the FTP Code (IMO, 2012). The load-bearing capacity is instead indirectly defined by prescribed dimensions for steel divisions. The critical condition for a steel structure to achieve the structural fire integrity requirements is to avoid heat transfer rather than to avoid collapse. However, for an insulated FRP composite panel the situation is different. Such a structure tends to collapse before the unexposed side is significantly heated, and long before it is ignited if it is thermally insulated. Bulkheads in combustible (but fire restricting) material are allowed on ships built according to the HSC Code but must then pass the structural fire integrity test with an added load. Similarly, Paper IV was based on the loaded fire resistance test method developed for HSC, described in Part 11 of the FTP Code (IMO, 2012), to account for heat deterioration of the bulkhead. However, the load applied according to this test method is generally small in comparison to the real loading of an FRP composite bulkhead. To investigate whether application of a realistic load would shorten the time to failure, it was decided to instead apply the bulkhead design load in the tests. This was calculated from the critical load of each bulkhead and a safety factor against buckling. Except from altering the safety factor and using stiffeners to strengthen the bulkhead, tests were performed with bulkheads with reduced core thickness and with increased thickness of the laminates.

The heat exposure of the laminate followed the standard time-temperature curve (cf. ISO 834-1, 1999) and measurements were made according to the FTP Code (IMO, 2012). Furthermore, temperature measurements were taken at the corresponding positions as in the test standard but at several depths, at interfaces of the structure: at the insulation/exposed laminate interface, at the exposed laminate/core interface and at the unexposed laminate surface. This was done to evaluate correlations between laminate and interface temperatures with loss of load-bearing capacity. Hence the explanatory categorization of the study.

In conclusion, the paper explores structural fire integrity design, performance and verification of FRP composite structures through loaded furnace tests.

4.5 Paper V

Paper V is an *exploratory* type of study addressing RO2 by investigating verification of an alternative structural fire integrity measure for FRP composite structures. This is explored through *experiment* as research method and data collection by *measurements*. Experiments are used to investigate how technical systems behave and perform during different circumstances (Montgomery, 2020), here in case of a fully developed fire. The test set-up was very similar to that in Paper IV and is therefore not elaborated at length in this section. Fire resistance tests were carried out based on Part 11 of the FTP Code (IMO, 2012), except that the actual design load was applied instead of the prescribed 7 kN/m. Furthermore, samples were not manipulated by systematic parameter variation, as in Paper IV, but a new solution to provide structural fire integrity was compared to a state-of-the-art thermally insulated structure. The new solution consisted in a multiple core bulkhead structure with two balsa cores and three laminates; a ‘double sandwich structure’. Hence, the exposed laminate and one core intended to serve as sacrificial fire "*insulation*" while the remaining structure was dimensioned to carry the applied design load.

The new multiple core structure was compared to a sandwich structure protected with non-combustible insulation. Comparison can according to Ejvegård (2009) be considered as a research method on its own. The *comparison* was based on the criteria provided in the FTP Code. They include requirements regarding temperature rise and ignition at the unexposed side, size of cracks and openings, as well as axial contraction and horizontal deflection. Comparison based on these criteria provided objectivity and relevance, which are important factors in a comparative study, regarding structural fire integrity (Ejvegård, 2009). As for Papers II and IV, performing the tests in large scale and in a controlled test environment reduced uncertainties and disturbing factors (Andersson, 2012). This is important to be able to separate the phenomena of interest and to allow reliable measurements (Hansson, 2007; Säfsten & Gustavsson, 2023).

In conclusion, the paper explores the performance and verification of two FRP composite structures with fundamentally different safety features through fire resistance tests.

4.6 Paper VI

Paper VI consists of what can be referred to as a *descriptive* type of study, since it answers the question how and aims to generate guiding knowledge (Goldkuhl, 2011). The research methods *description* and *case study* were applied to address primarily RO3 and partially also RO1. A *literature survey* of relevant publications and reports was used as data collection technique. The paper describes complications and gives suggestions for the fire hazard identification (see RO1) and other steps of the risk assessment procedure (see RO3) described in the IMO guidelines in MSC/Circ.1002. As noted above, description as a research method consists in observational and empirical research forming a structured and elucidating image of a system or, in this case, a process (Ejvegård, 2009). A major challenge when applying description as a method is to provide a structure and context to the presentation, as well as to highlight the essential (Ejvegård, 2009). Here the research method applied was influenced by the case study method by surveying fire risk assessments carried out for alternative ship designs in accordance with SOLAS II-2/17. These were 16 risk assessments where RISE (previously SP) had been involved to varying degrees, in e.g. project management and coordination, fire safety evaluation, fire test management, or fire expertise. Most of the studied risk assessments involved FRP composite structures but other scopes were also included, to survey how the assessments were performed in relation to MSC/Circ.1002 and MSC.1/Circ.1455 (IMO, 2013). Furthermore, the descriptive study was based on a preceding *survey* of relevant literature in risk management, summarized in chapter *3. Background to risk assessment*.

It is not uncommon that the case study method is combined with other research methods in this way (Ejvegård, 2009). Case study is a research method where a specific sample is studied and selected to represent the real world (Yin, 2018). It is particularly suitable to answer the question *why* (explanatory), but it can also be applied with a descriptive purpose, answering the question *how* (Yin, 2018). Here, the method was applied to study the application of an assessment procedure. It is somewhat different from the conventional purpose of a case study, which is generally to understand the studied cases.

The assessments in the case study were studied step by step in parallel with the procedure provided in MSC/Circ.1002. Application of the different steps of the procedure was discussed and exemplified. Focus was on the assessment procedure's function and applicability as a risk-based approach. In the sense that the case study method can be explorative, it allows focusing on specific and less explored phenomena or situations (Säfsten & Gustavsson, 2023). In the paper, particular focus was given to areas considered problematic. Regarding identification of hazards, a simple model was developed to describe how unclear connections in regulations cause complications. Furthermore, particular focus was given to fire risk characterization, which was done differently in the studied risk assessments, much depending on their scopes. Together with risk research, this worked as basis for advising how to perform Regulation 17 assessments.

In conclusion, the paper investigates the risk-based assessment procedure in MSC/Circ.1002 to give advice regarding function and applicability.

4.7 Summary of applied research approaches

The types of studies, the research objectives (RO) addressed, as well as the applied research methods and data collection techniques in the papers of this thesis are summarized in Table 2. A brief note is also given on how they have been applied.

Table 2. Summary of applied research approaches applied in the six appended papers

Paper	***Type of study***	***RO***	***Research method***	***Data collection technique***	***Application***
I	Descriptive	RO1 (RO3)	Description	Survey	Regulations and tests, to identify fire hazards and performance criteria vs FRP composite performance
II	Exploratory	RO2 (RO1)	Experiment	Measurement and observation	Large-scale façade test, to verify FRP composite fire growth and safety measures
III	Exploratory/ explanatory	RO2	Modelling and simulation	Measurement/ quantification (experiment)	Physical heat transfer model development, to assess effects of structures' insulation on temperatures in fire enclosures
IV	Explanatory	RO2	Experiment	Measurement	Structural fire integrity tests, to evaluate design, performance and verification
V	Exploratory	RO2	Experiment	Measurement	Structural fire integrity tests, to evaluate peformance and a fundamentally different design as a safety measure
VI	Descriptive	RO3 (RO1)	Description and case study	Survey	Risk management literature and application of IMO assessment procedure in MSC/Circ.1002, to give advice regarding function and applicability

The summary shows that the six papers attempt to systematically address the research objectives by different research approaches and applications. In Paper I, focus is on literature study, followed by large efforts on experiments and data collection in Papers II-V, done to answer specific questions (see section *2.5. Fire performance of FRP composite ship structures*). After the focus on experiments and data collection, Paper VI addresses risk management and how to apply the IMO methodology when assessing innovative fire safety design. This is important when a new type of combustible construction solution is introduced.

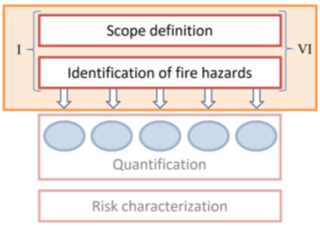
5 Contributions to fire safety assessment

The purpose of this research work has been to provide for assessment of fire safety of FRP composite ship structures (based on SOLAS II-2/17). The aspects studied in the papers of this thesis primarily address:

- Fire hazard identification (RO 1)
- Verification of surface spread of flame (RO 2)
- Modelling of the enclosure heat balance, to assess containment (RO 2)
- Design and evaluation of structural fire integrity (RO 2)
- A more developed framework for fire risk assessment (RO3)

When considering combustible structures, a widened perspective is required in the identification of fire hazards, as further described in section 5.1. Three affected fire hazard areas are further investigated in section 5.2: flame spread, containment and structural fire integrity, addressing performance of FRP composite with and without safety measures and in relation to regulations. This is explored at varying levels of detail and by different verification methods. Finally, to characterize the fire risk there are many approaches. In section 5.3, concrete advice is given for the fire risk assessment procedure, particularly a framework for characterizing fire risk at different levels of sophistication. In this chapter, small inserts of Figure 2 are used to highlight, in orange, the addressed part of the risk assessment.

5.1 Fire hazard identification for novel ship design



The performance-based regulation 17 was developed to open up for innovation, but it was criticized to only allow for extensions of prescriptive regulations (Maccari, 2011; McGeorge & Höyning, 2002). To take on FRP composite structures, unclarities in the early adopted performance-based regulations therefore needed to be handled, along with the fact that the regulations are based on an assumed use of steel structures. As elaborated below, this complicates the identification of hazards, which although is a challenge that needs to be addressed with any innovation going beyond existing regulations.

5.1.1 Challenge to identify hazards based on incomplete regulations

One of the first and most fundamental steps in a risk assessment for alternative design is to identify hazards. It is meant to determine the areas of impaired safety which must be regained in an alternative way. Paper VI explains that MSC/Circ.1002 includes a section on "*Identification of fire hazards*" that instructs to identify what could give rise to fire, burn, and affect fire development in different stages. This is typically done systematically in a multidisciplinary brainstorming session referred to as a hazard identification (HazId) workshop. However, Paper VI claims that the tabulation of effects on fire safety in different stages of fire development rather becomes a way to incorporate hazards into fire scenarios (5.2.1.1 in IMO, 2001). Fire hazards are in practice primarily identified earlier in the assessment, *from deviated prescriptive requirement(s)*. It is instructed that the regulations affecting the proposed alternative design and arrangements, along with their functional requirements, should be clearly understood and documented (5.1.2 in IMO, 2001). This becomes a crucial identification of potential fire hazards and forms the basis for the whole analysis and approval.

A problem is that the fire safety regulations in SOLAS have limitations which make the described process insufficient when evaluating fire safety of novel designs. The current fire safety regulations are based on many assumptions of how ships are used and built, and they leave many *gaps*. In building design, this has been a challenge when replacing concrete with load-bearing wood structures, which compromise fundamental assumptions of the regulations. It has caused major work within ISO, in particular to provide for appropriate identification of fire hazards and definition of performance criteria (Nilsson, 2015). In ship design, such a challenge was for example demonstrated by the fire on the Star Princess (MAIB, 2006). The ship incorporated balcony structures with combustible materials, which the regulations did not foresee or regulate (Breuillard & Corrignan, 2009). As per resolution MSC.216(82), SOLAS now requires use of non-combustible materials or a fixed water-spraying fire-extinguishing system for ship balconies. Using combustible materials on balconies, increasing the number of passengers, and increasing the use of combustible materials in external areas (see IMO, 2008b) are a few examples where the development has gone *beyond prescriptive requirements*. Many more exist, and the problem is at the very core of prescriptively formulated legislation. The reason is often that the regulations have been based on *reactive* decisions, addressing safety deficiencies in incidents, instead of pro-active rule making, setting safety goals and functional requirements. This has led to complex and inconsistent fire safety regulations which make it *difficult to assess* alternative design (Maccari, 2011; McGeorge & Höyning, 2002).

Paper VI took basis in several studies of the fire safety chapter of SOLAS, as part of Regulation 17 assessments (e.g. Evegren, 2013a; Evegren, 2013b, 2015; Rahm & Evegren, 2012). They particularly showed that the regulations have *limitations in the connections between functional and prescriptive requirements*. Many of the unclear connections likely stem from the former purely prescriptive regulations and insufficient validation cross-check between the requirements when they were restructured to become performance based; this was for example concretized by keeping the former basic principles as functional requirements of the whole chapter and having functional requirements which were not formulated for a performance-based code. Such unclarities later led to the release of Generic Guidelines for Developing IMO Goal-Based Standards (IMO, 2019a). As described in Paper I and Paper VI, *three types of unclear connections* can be defined for the fire safety chapter, illustrated in Figure 12:

1. prescriptive requirements without clear connection to any functional requirement;
2. functional requirements without relevant prescriptive requirements;
3. prescriptive requirements affecting functional requirements in other regulations.

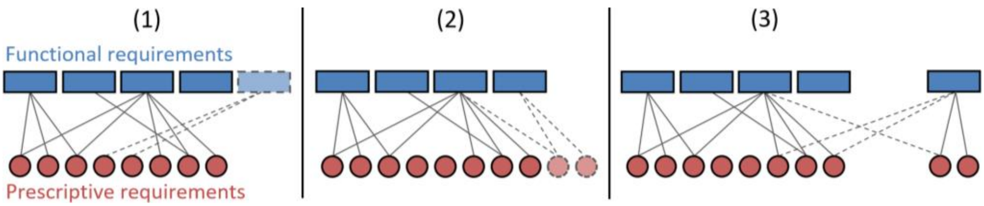


Figure 12. Different types of unclear connections (dashed) between functional and prescriptive requirements in the fire safety regulations of SOLAS.

The first type (1) of unclear connection can stem from traditional reaction-based rule making; new requirements are introduced as results of major incidents, without full consideration to functional requirements. If an alternative design deviates from such a requirement, it can be difficult to determine all effects on safety as well as suitable performance criteria, since there is *no associated functional requirement* (dashed in Figure 12).

The second type (2) highlights to consider that fire safety regulations to some extents are based on assumptions regarding ship design and arrangements (IMO, 2008b). For FRP composite structures, account must be taken to that many requirements are based on an assumption of using non-combustible steel structures.

All safety requirements are therefore not apparent in the regulations (dashed in type 2 in Figure 12) and fire safety can be affected in ways which are *not covered by the specified prescriptive requirements*. This leaves many implicit fire hazards to identify in a Regulation 17 assessment of FRP composite structure, as further investigated for the growth stage of a fire in Paper I.

The third type (3) of unclear connection particularly stems from the general assumption in prescriptive codes that *other regulations are achieved*. This is important when considering FRP composite structures, again since the regulations are in many ways steel based. With the assumption that a requirement of non-combustible structures in one regulation is complied with, similar requirements have been omitted in other regulations. Hence, if deviating from such a requirement, there may be effects on the achievement of functional requirements in other regulations, even if there are no deviations against their prescriptive requirements. Such effects can be difficult to identify and are also found in building regulations, e.g. regarding regulations for acoustics and fire safety.

Further gaps may exist in the performance-based SOLAS chapter. However, by pointing out these three types of unclear connections, Papers I and VI increased the understanding of what *must be made apparent* and considered when identifying fire hazards of novel designs, as further investigated below. The types of unclear connections between functional and prescriptive requirements described could likely also be applied to regulations in other domains, thus contributing to an increased understanding.

5.1.2 Identification of fire hazards of FRP composite structures

The weaknesses in the SOLAS fire safety chapter cause challenges in the identification of introduced fire hazards of alternative designs. It requires to not only identify hazards from deviated prescriptive requirements but to take a more general approach. The regulations should still be the basis for comparison, but also implicit requirements and the general safety level must be considered. Especially for a design with FRP composite structures, with limited field history.

In previous work (Evegren, 2010a), an approach was presented to clarify effects on the implicit level of fire safety represented in prescriptive requirements when introducing FRP composite structures. It was based on a method described in Lundin (2001), with a similar intention to *determine verification needs* in performance-based design, but applied to Swedish building regulations. The approach in Evegren (2010a) was meant to complement the identification of deviations from prescriptive requirements. It consisted in investigating challenges to the fire safety by determining effects on:

A. the fire safety objectives and functional requirements of the fire safety chapter;
B. the objective and functional requirements of each regulation;
C. the structure of the fire safety regulations;
D. the fire safety properties; and
E. the potential for fire development.

As only briefly noted in Paper I, this approach in Evegren (2010a) was for research purposes applied in fire risk assessments considering different FRP composite structures. In particular a 15-deck panamax cruise vessel with the five upper decks designed in FRP composite (Evegren, 2013b) and an island ferry in FRP composite carrying 200 passengers and six cars (Evegren, 2013a). It showed, however, that only the investigation (B) of the regulations' objectives and functional requirements added significant information. Hence the suggestion in Paper VI to always add an *investigation to clarify effects on all the regulations' purpose statements*.

The above conclusion was based on that most fire hazards were identifiable from the regulations' objectives and functional requirements, in addition to deviations from prescriptive requirements, while the other investigations shed limited light on hazards. The investigation (A) of the fire safety objectives for the whole chapter did not add much new information since they are general and to a large degree covered by the regulations. The functional requirements for the whole chapter are more well-defined, but since they are embodied (repeated) in the regulations they did not add any information. The investigations of the fire safety structure (C) and properties (D) identified some new hazards, but once they had been noted they were easily associated to the regulations' functional requirements. The potential for fire development (E) is naturally considered in the regulation for fire growth potential, e.g. by managing the allowed amount of combustible materials and their flame-spread characteristics. Thus, investigating prescriptive requirements as well as the regulations' objectives and functional requirements from a general perspective, with an *ambition to identify missing requirements* (see Figure 12), was considered sufficient to identify hazards of alternative designs. It also follows from Figure 12 that such investigations *can* account for the identified types of missing connections. It can still be relevant to perform all the investigations listed above, e.g. as a detailed study of certain hazards. For the studied cases, the hazards identified from those investigations were although estimated to have small and very uncertain effects on safety.

In conclusion, to identify deviations from prescriptive requirements will not form a sufficient basis for a fire risk assessment involving FRP composite structures. The regulations are based on an assumption of non-combustible structures and connections between prescriptive and functional requirements are not clear. This requires identifying fire hazards from a wider perspective. As stated in Paper VI, additional investigation of *all* the regulations' objectives and functional requirements is necessary to identify introduced hazards. This is exemplified and elaborated in Paper I for the regulations affecting the growth stage of a fire.

5.1.3 Potential fire hazards of FRP composite structures

Investigations of potential fire hazards according to the different approaches described above became the basis for IMO guidelines in MSC.1/Circ.1574 (IMO, 2017), intended to support Administrations when evaluating the fire safety of FRP composite structures. The guidelines were composed representing the Swedish Flag State, with input from a correspondence group on "*Development of Guidelines for Use of Fibre Reinforced Plastic (FRP) Within Ship Structures*", established by the IMO subcommittee for Ship Design and Construction. As elaborated below, the guidelines were heavily contributed by the papers of this thesis, in particular by background work not documented in the papers. Since the publication, Flag States (e.g. DMA, 2017) generally require to follow the guidelines when considering FRP composite ship structures, in addition to MSC/Circ.1002 (IMO, 2001), as amended by MSC.1/Circ.1552 (IMO, 2016).

The guidelines in MSC.1/Circ.1574 (IMO, 2017) are divided in three main chapters and five appendices, as listed below:

Chapter 1: General
Chapter 2: Assessing fire safety of FRP composite structures
Chapter 3: Important factors to consider with regards to chapter II-2 regulations

Appendix A: Issues other than fire safety
Appendix B: FRP Composite Materials and Compositions used in Shipbuilding
Appendix C: Recommendations regarding the assessment
Appendix D: Fire Testing of FRP Composite
Appendix E: Examples of Assessment Procedure

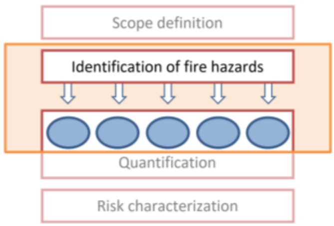
Chapter 1 is of general character and primarily defines terms, the scope and limitations of the guidelines. While the guidelines were initially written with larger ship structures in mind, it was at a final stage decided by IMO to limit their scope to FRP elements, i.e. structures which may be removed without compromising the structural safety of the entire ship. The chapter also points out that there may be other issues than fire safety to consider when using FRP composite materials, listed in Appendix A.

Chapter 2 addresses aspects to consider when it comes to the fire risk assessment of FRP composite structures, and it refers to several appendices. Appendix B describes the typical FRP composite materials and compositions used in shipbuilding as well as their fire behavior, which documents background work for Papers I-V. The chapter further refers to Appendix D, which summarizes relevant IMO test methods along with remarks on limitations and necessary considerations when testing FRP composite materials. This summarizes foundational work for Paper I, and was also a basis for the experimental Papers II, IV and V. In Chapter 2, reference is further made to Appendix C, which for example provides input on how to treat uncertainties and how the assessment can be conducted at different levels of sophistication. While no references were allowed in the guidelines, this appendix was heavily based on Paper I and Paper VI. The chapter finally refers to Appendix E, which exemplifies how a Regulation 17 assessment involving FRP composite structures can be conducted.

Chapter 3 is the main part of the guidelines and moreover documents foundational work for Paper I. It provides a *review of the regulations* in SOLAS chapter II-2 and points out *potential deviations and fire hazards* for FRP composite structures. As suggested in the previous section, it takes a starting point in the regulations´ prescriptive requirements, functional requirements and objectives. The review was also based on fire hazard identifications in many fire risk assessments for FRP composite structures (e.g. Breuillard & Corrignan, 2009; Evegren, 2013a, 2013b; Gutierrez et al., 2008; Hugosson, 2011; McGeorge, 2009a; Noury, 2009; Noury & McGeorge 2010; Noury et al., 2015; Rahm, 2012). As follows from the previous section, some of the identified hazards had clear connections to the prescriptive or functional requirements of one or several regulations. Other hazards lacked such a connection but affected achievement of the regulation objectives.

From the review of fire risk assessments and regulations, it was concluded by the correspondence group that the fire hazards introduced by use of FRP composite ship structures primarily concern the following *areas* (IMO, 2017), symbolized by the arrows in the inserted figure:

- probability of ignition (reg. 4);
- fire growth potential (reg. 5);
- potential to generate smoke and toxic products (reg. 6);
- containment of fire (reg. 9);
- fire fighting (reg. 10); and
- structural integrity (reg. 11).



It should be noted, however, that ignitability is generally not an issue for FRP composite. This was explained elsewhere in MSC.1/Circ.1574, and elaborated in Paper I and by Karatzas (2016) based on Cone Calorimeter (ISO 5660-1, 2002) tests. However, it was still added to the list of fire hazard areas in MSC.1/Circ.1574 (IMO, 2017) as a last-minute change when the circular was finalized. To show once and for all that ignition by a small flame is not an issue, a test series with different typical FRP composite materials was conducted according to ISO 11925-2 (2020), which only resulted in discoloring and no ignition (Sandinge, 2024).

The above-described clarifications of the regulatory structure, implicit requirements, affected areas, and how to cover them are important contributions from the research in this thesis. They prepared the foundation for continued knowledge development and gave direction to further relevant areas of research.

5.2 Fire performance verification of FRP composite

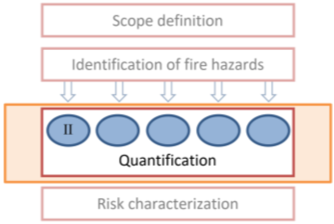
Paper I shows a procedure for how to manage regulations, deviations and introduced hazards in a structured way, ensuring that explicit and implicit functional requirements are achieved. This was exemplified for reaction to fire properties and includes relating the performance of FRP composite to criteria in fire tests. Papers II, III, IV and V go more into depth and explore how new and existing verification methods can be used to assess the *fire performance* of FRP composite and safety measures.

Similar to how identification of hazards was suggested to be founded on the regulations, Paper VI proposes a procedure where introduced fire hazards of FRP composite structures are assessed in smaller areas, for example divided on the affected regulations (see *5.3.2 Integration of fire hazards in the assessment*). The same division forms the structure of this section and is symbolized by the ovals in the inserted figures. The regulations, i.e. areas of potentially affected fire safety, which mainly have been addressed by the papers of this thesis are *fire growth potential*, *containment of fire* and *structural integrity*, as expanded upon below.

5.2.1 Fire growth potential

Paper I shows, based on a review of regulations, how the fire growth potential can be broken down into two areas: amount of combustible materials and their *flame-spread characteristics* (this is the term used in SOLAS, while the FTP Code and the papers sometimes use the term flammability). With a starting point in these areas, Paper I systematically investigates requirements, hazards and performance criteria connected to FRP composite structures in interior spaces and externally. It is concluded that both areas can be affected negatively by use of FRP composite structures. Safety measures can although be added, both passive and active. Thermal insulation on interior FRP composite surfaces, modification of the FRP composite (or application of a coating) to achieve low flame-spread characteristics, or addition of an extinguishing system were identified as relevant safety measures (Evegren, 2013b). The *flame-spread characteristics* of FRP composite surfaces with and without these measures were investigated in Papers I and II with focus on external surfaces, as further detailed below.

5.2.1.1 *Flame spread on large unprotected FRP composite*



As elaborated above and in Paper I, ignitability is generally not an issue, but FRP composite could become involved if exposed to a fire. This makes the flame spread important to evaluate if the surfaces are not thermally protected, which is not an option in external areas.

Various experimental and standardized tests may be used to quantify the flame-spread characteristics of FRP composite. Small-scale test results are numerous in literature (see e.g. Gibson & Hume, 1995) but for *large applications* it is important with verification in large scale to properly understand fire behavior. For external applications, Arvidson et al. (2008) showed in experimental tests how a fire emerging through a window caused vertical fire spread on an exterior FRP composite surface. As a reference, the fire growth rate was correlated with a "*t-squared fire*", $\dot{Q} = \alpha \cdot t^2$; it gave an α-value of about 0.016 kW/s^2, which is close to a "*medium*" fire growth rate (Schifiliti et al., 2016), as illustrated in Figure 13.

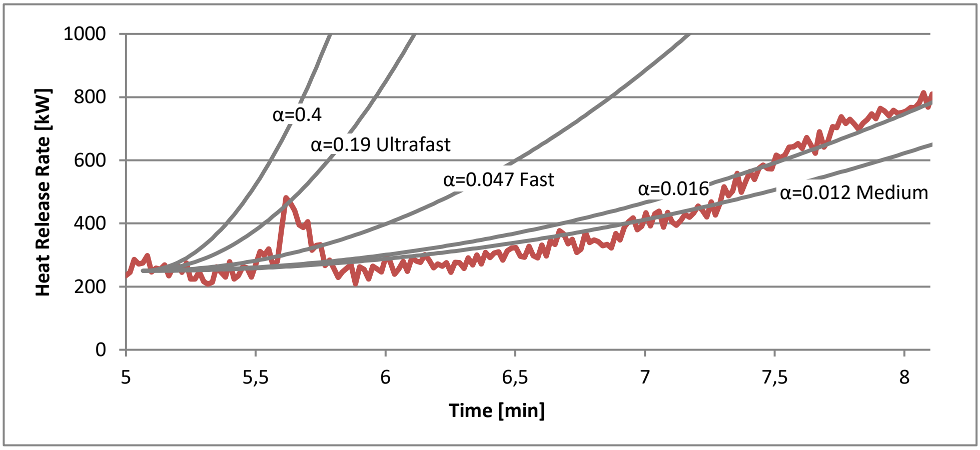


Figure 13. Heat release rate from fire growth on a vertical unprotected FRP composite surface (red) when exposed to a fully developed fire through a window, from when the surface ignited (Arvidson et al., 2008), in comparison with other fire growth rates (Schifiliti et al., 2016).

Paper II explored whether it was possible to evaluate fire growth for larger external surfaces based on a large-scale standardized test method for building façade systems, SP FIRE 105 (SP Fire Technology, 1985). As part of the EU project BESST, tests were performed with 4.0x6.5 m (WxH) FRP composite panels of glass fiber reinforced polyester face laminates on a cross-linked PVC foam core. The fire source in the test was intended to represent a large cabin fire emerging through a balcony opening. It could for example be compared to the cabin fire test scenario set up by Evegren and Rahm (2016) according to MSC/Circ.1268 (IMO, 2008a), to evaluate whether a certified balcony sprinkler would control a balcony structure in FRP composite material. The fire source in SP FIRE 105 could then qualitatively, based on the size of flames, be said to well cover a large cabin fire. It generated *rapid fire growth* with an α value of between 0.19 kW/s^2 (denominated "*Ultrafast*") and 0.4 kW/s^2. The heat release rate from when the FRP composite surface ignited until a fixed fire-extinguishing system was activated (after about 4.5 min) is depicted as "*Drencher*" in Figure 14.

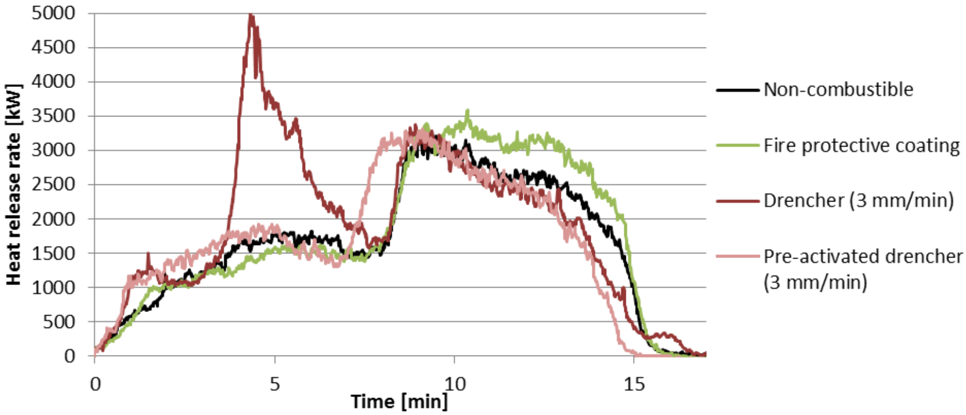


Figure 14. Heat release rates from fire exposed FRP composite panel with active or passive protection as well as from a non-combustible surface (i.e. the fire source).

Based on Paper II and previous research, Paper I concluded that quick flame spread can be caused on unprotected FRP composite surfaces when ignited but that the fire growth rate naturally stands in relation to the fire exposure. The relation is unlikely linear, but with reference to the above tests, an about 10 times higher fire exposure gave an about 20 times higher α value. In case an internal fire spreads to exteriors, the *size of the opening* can thus make a significant difference. It was also concluded in Paper I that fire spread was primarily in the *vertical direction*, even if wind could cause lateral and further increased external fire growth. The fire spread results in Paper II are not easily applicable to an internal fire in an enclosure with unprotected FRP composite surfaces, considering the large fire source, unlimited oxygen, lack of a smoke layer, etc. When enclosure fire dynamics start affecting the fire, significant further complexities are involved which are not present in an open fire, as further discussed below.

Regarding using the full-scale test method SP FIRE 105 to verify external fire spread and protection, Paper II suggested several improvements and how performance criteria could be defined. Furthermore, to evaluate if test results could be transferrable from a *smaller scale*, comparison was made with the standard IMO test evaluating the flame-spread characteristics of interior surfaces, described in Part 5 of the FTP Code (IMO, 2012). Using this small-scale test method to verify the flame spread on large external surfaces would be much more economical. While Part 5 has a lateral alignment and thus omits exposure to convective heat, which could be critical for vertical fire spread, it provides about corresponding incident *radiation levels* as the façade test. Furthermore, Paper II shows how a passive protection system passing the Part 5 test provided good results also in the façade test (see below). This indicates that a system passing Part 5 could potentially prevent external fire spread also in larger scale. Hence, systems passing Part 5 could be a good starting point for selecting an external surface material.

5.2.1.2 Flame spread with passive protection

For evaluation of fire spread on external surfaces, Paper II explored how a passive safety measure would perform in the large scale façade test method SP FIRE 105 (SP Fire Technology, 1985). As illustrated in Figure 14, in comparison with a non-combustible surface the tested *fire-protective coating limited fire spread* by delaying ignition and then by restricting the energy contribution from the panels. The heat release rate was only ever about 10% higher than in the test with a non-combustible panel and the fire self-extinguished when the fire source quenched. The tested system appeared promising regarding the possibility to find passive protection systems for external surfaces. In a real application, consideration must also be taken to ageing and wear of the coating. The performance also depends on the final design and application on a real ship, where it is essential to follow all the requirements for mounting the system.

For interior spaces, it is required to attain "*low flame-spread characteristics*" based on the test described in Part 5 of the FTP Code (IMO, 2012). This can be achieved in different ways with FRP composite structures, as continuously investigated (Sandinge, Ukaj, et al., 2022; Sjögren et al., 2022). Paper I notes that the regulations include an alleviation: if flame-spread characteristics are sufficient, it is not required to evaluate the materials' potential to generate smoke and toxic gases according to Part 2 of the FTP Code (IMO, 2012, Annex 2, §2.2). Restricted flame spread is namely important both to limit fire growth and to limit generation of *smoke and toxic gases*. This is briefly summarized in Paper I, based on the simplistic view that production of toxic products is proportional to the fire growth. The gas that generally presents the greatest health hazard to humans during fire is *carbon monoxide* (Hirschler, 1987). In line with the above view, production of carbon monoxide from fire in FRP composite has been found to correlate linearly with the heat release rate (Mouritz et al., 2006). Production of the main toxic gas, carbon monoxide, can thus be minimized by limiting flame spread. The Part 2 alleviation hence appears applicable for FRP composite. However, it should be noted that materials can produce high yields of carbon monoxide and irritant smoke also in smouldering and non-flaming fires (Purser, 2000). Thereby, many materials which have been treated to impede ignition and flame spread produce smoke and toxic gas in relatively high levels (Purser, 2000; Purser et al., 2010). Such treatments could make it challenging to pass a test according Part 2 of the FTP Code (IMO, 2012). It has even been argued that flame retardants increase smoke toxicity more than they reduce the fire growth rate (McKenna et al., 2018). It could therefore be recommendable to always also test the smoke and toxicity generation of exposed FRP composite surfaces according to Part 2, even if flammability properties are sufficient.

As further pointed out in Paper I, while the Part 5 test applies to surfaces in interior spaces, it must be kept in mind that it does not represent all the conditions of an enclosure fire. Formation of a smoke layer, other modes of heating, ventilation conditions, etc., affect fire growth, especially in the later stages. The conditions of an *enclosure fire* are better represented in the "*room corner test*" (ISO 9705, 2016), which IMO uses to define higher-performing materials referred to as "*fire-restricting materials*", see Part 10 of the FTP Code (IMO, 2012). This is required for surfaces on high-speed craft (IMO, 2000). A thin layer (13-20 mm) of thermal insulation (e.g. mineral wool or glass/phenolic foam) on an FRP composite surface has for example proven sufficient to meet the fire-restricting material requirement (Gutierrez, 2005). The EUCLID project, addressing naval composite ship fire safety, suggested to protect all interior FRP composite surfaces with such protection (Gutierrez et al., 2005). As concluded in Paper I, this will give a high degree of protection against flame spread. Solutions to achieve fire-restricting material quality *without thermal insulation*, such as laminate modifications and surface linings, continue to be investigated, currently for example in the ongoing Norwegian project *Cost-FRM* (The Research Council of Norway, 2024).

The 'next step' in the maritime test regime would be to cover the surfaces with sufficient thermal insulation to achieve structural fire integrity, which would protect the structures from fire involvement even longer (Arvidson et al., 2008). It implies that the fire growth stage will *not be governed by the surface materials* but by furniture, furnishings, luggage, etc. A further factor that significantly affects the fire growth stage is the *ventilation conditions*. For example, a fire in a small enclosure with limited ventilation will unlikely be significantly affected even by unprotected FRP composite surfaces before it becomes ventilation controlled. However, if the space is large or if there is an opening, the surfaces' flame-spread characteristics will surely affect the fire growth. These factors should be considered in the Regulation 17 assessment, together with the additional amount of combustible material introduced, even if they are underneath a protective layer. It could for example be relevant to evaluate potential effects from using FRP composite structures on fire evacuation, as demonstrated in the master thesis by Panagiotopoulos (2014).

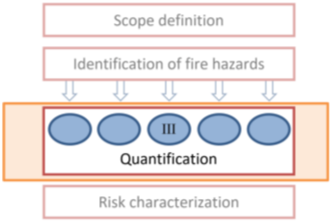
5.2.1.3 Flame spread with active protection

Arvidson et al. (2008) showed that a fire which spread through a window and established in a 2.4 m panel was immediately suppressed by an open deluge (drencher) system. Paper II shows that this result is achievable also in larger scale, based on tests carried according to the façade test method SP FIRE 105 (SP Fire Technology, 1985). With fire established in the 4.0x6.5 m^2 (WxH) FRP composite panel, pyrolysis reactions were *quenched almost immediately* with a properly designed drencher system, as illustrated in Figure 14. Paper II evaluates different discharge rates based on evaluations of heat release rate, temperatures and fire damage. It also concludes that the potential for quick fire spread and structural deterioration makes *pre-activation preferable*. To quickly control an external fire is also important since a prolonged fire will store heat in the material, which makes it difficult to suppress and increases the probability of re-ignition. Combustion of FRP composite occurs due to thermal breakdown of organic molecules in the material and when pyrolysis temperatures have been reached deep within the structure, its insulating quality requires continued *cooling to prevent re-ignition*. This conclusion is supported by the experiments described in Paper V and Paper VI, as well as in Arvidson et al. (2008) and Hertzberg (2009). Paper II showed that pre-activation could prevent ignition completely; however, the short pre-ignition time in case of fire exposure and the potential scenario in case of system failure must also be considered. Furthermore, the tests represented idealized conditions and took no consideration to wind or to ageing and wear of the external sprinkler system, which could all affect functionality.

In addition to evaluating if a sprinkler system could be a suitable safety measure for external surfaces, using the experimental set-up in SP FIRE 105 (SP Fire Technology, 1985) as a method to verify active measures was discussed in Paper II. Criteria for *when to activate* the system in the test were exemplified and *performance criteria* were suggested. The small-scale method in Part 5 of the FTP Code (IMO, 2012) was judged not possible to use for verification of active systems for various FRP composite materials. Arguments for this are for example the small sample, the above addressed missing convective heat, sprinkler application difficulties, and the poor representation of the potential distance between nozzles and the fire source in reality.

For interior spaces, the full-scale cabin-corridor test by Arvidson et al. (2008) showed that the effectiveness of nozzles tested according to IMO Resolution A.800(19), as amended (IMO, 1995), was not affected by the use of thermally insulated FRP composite structures. With FRP composite surfaces covered, containment will hence be improved, with likely positive effects on extinguishment, also with traditional water-based systems.

5.2.2 Containment of fire



FRP composite structures require thermal protection to stay loadbearing in case of fire, which creates a much more insulating division than steel. Fire containment will thus be greatly surpassed as long as collapse does not occur. This will significantly improve the conditions outside the fire enclosure. However, as noted in chapter *2. Background*, the reduced heat transfer also led to questions regarding how significantly this could worsen the conditions *inside* the fire enclosure (Evegren, 2013a, 2013b; Hertzberg, 2009; Panagiotopoulos, 2014; United Kingdom, 2010). This was investigated in research work supporting this thesis, as further elaborated below.

5.2.2.1 Experimental evaluation of fire conditions with increased insulation

When a fire is fully developed the heat release rate is determined by the ventilation conditions. However, a hazard identified in several investigations of FRP composite ship structures was that the well-insulated FRP composite boundaries could affect *fire growth* and the potential for flashover (Evegren, 2013a, 2013b; Panagiotopoulos, 2014). This was addressed in Back (2013); the overall scope of the study was formulated by the author and support was given in test set-up, evaluation of test data, and scrutiny of the report. The hypothesis was that thermal insulation behind enclosure surfaces is *insignificant* during the fire growth stage and the ambition was to test this hypothesis. The largest difference in insulating capacity will appear if replacing an A-0 division (unprotected steel) with an FRP composite FRD60 structure. The part of the FRD60 structure impacting heat transfer the most would be the protective thermal insulation on the FRP composite structure. Tests were performed where this was represented by simply adding insulation to steel divisions.

The experiments were performed in full scale in a 20 ft steel container, illustrated in Figure 15. Two fire sources were used to represent two characteristically different types of fuel; wood that needs to thermally decompose to produce a combustible gas and a heptane pool that easily evaporates a combustible gas when heated.

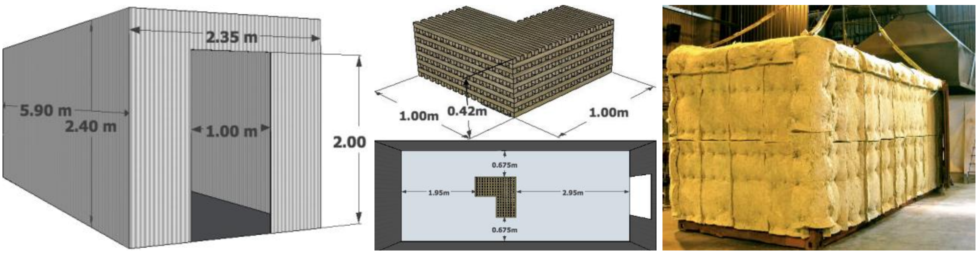


Figure 15. Dimensions of the test arrangements and photo of the insulated enclosure, reproduced with permission from Back (2013).

The experiments showed that insulation fitted on outside surfaces of a steel container did have *effects on the fire development*, depending on the fuel (Back, 2013). With heptane, the fire growth rate doubled and the peak heat release rate increased by 25%, as shown in Figure 16. The temperature of the gases in the hot upper layer, in this thesis referred to as the fire temperature, increased by 200 degrees. With a wood crib fire source, the fire growth rate and the peak heat release rate were only slightly increased, but the 125 degrees higher fire temperature was enough to generate flaming through the opening. The relatively larger effects on the fire growth rate with heptane depend, as mentioned above, on that it relatively easily evaporates into flammable gas when heated. Wood must go through a more complicated process of mass and heat transfer to thermally decompose before flammable gases are produced. Heat is thereby buffered, which makes it less sensitive to re-radiation and causes a magnitude's difference in the fuels' heat release parameter, i.e. amount of energy generated per unit amount of energy absorbed (Tewarson, 2002). Furthermore, as noted for the free burning fires in Figure 16, the magnitude of the heptane fire source was greater to begin with, which also generated increased heating in the space and of the fuel. Together with a higher sensitivity to increased temperatures, this generated larger and particularly earlier effects observed when using heptane than when using wood as fuel.

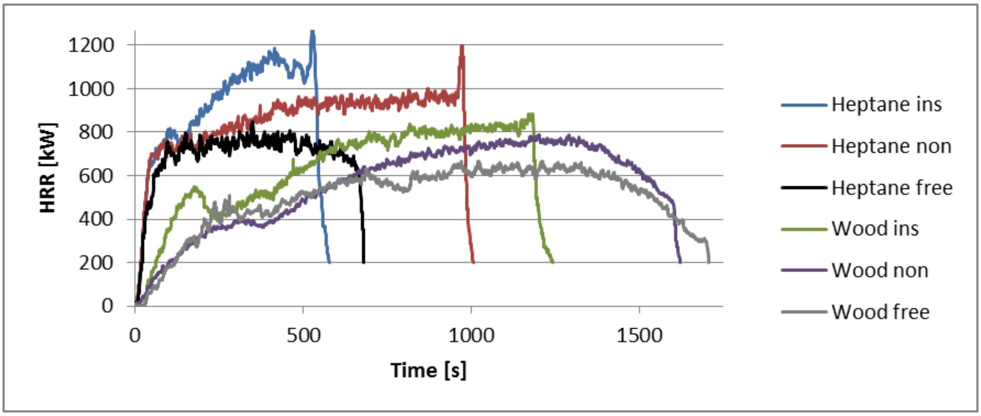


Figure 16. Heat release rate histories from fires in insulated (ins) and non-insulated (non) container and from the corresponding free burning fires (free), adapted from Back (2013).

The heat transfer for a correspondingly insulated FRP composite "*container*" would not be the same as for the steel container. The steel structure attains lumped heat capacity and the FRP composite sandwich structure would in itself add heat transfer resistance. However, the tests in the insulated container show that a well-insulated structure *can* generate effects on fire growth and a more likely flashover. These effects were therefore addressed in the fire risk assessment for the Norwegian Future, with an FRP composite superstructure (Evegren, 2013b). It was nevertheless concluded in Paper I that there are few spaces where such effects are relevant; only spaces without insulation in a conventional steel design and primarily where flammable liquids may be present. There are also several conditions which could make the *effects secondary*, such as a sprinkler system, the size of the space, ventilation conditions, or the location of the fire. Furthermore, the alternative to have a non-insulated steel structure, prone to spread fire, was considered worse than increased fire growth inside a well-insulated structure. The concluded potential negative effects from well-insulated structures have hence thereafter not been considered.

5.2.2.2 Simplified heat-transfer dependent fire-temperature estimation

When quantifying effects of increased heat in a well-insulated space, a need was identified to make simple estimations of the fire temperature depending on the heat transfer through boundaries. From a fire containment perspective, the fire temperature, i.e. the temperature of the gases in the hot upper layer, is important. It influences the time until a boundary fails or fire spreads to the unexposed side, e.g. due to exceeding the temperature rise requirement in Part 3 and Part 11 of the FTP Code (IMO, 2012). It is relevant to estimate the fire temperature both in the pre-flashover and post-flashover stage, but in Paper III it was decided to focus on the pre-flashover stage.

Commonly used simple methods for pre-flashover fire temperature approximations are based on the correlation developed by McCaffrey, Quintiere and Harkleroad (1981), the so called "*MQH*" relationship, based on the founders initials (Walton & Thomas, 2002). It builds on a simplified energy balance and regression correlation with data from numerous test fires. However, contrary to what has often been stated (McCaffrey et al., 1981; Walton & Thomas, 2002), the MQH relationship is not very suitable for *transient fire growths* since the fire temperature is solved from the heat release rate at a particular time step; hence, it takes no account of the fire growth history (e.g. slow or constant). Furthermore, it is inappropriate when the surrounding boundaries are *thin and highly conductive* (Peatross & Beyler, 1994).

Paper III describes how a new simple model was developed from well-known fire *physics* to estimate temperatures in pre-flashover fires from a transient heat release. It combines expressions for heat transfer through boundaries with expressions for heat balance in the fire enclosure (see e.g. Karlsson & Quintiere, 2000), as illustrated in Figure 17.

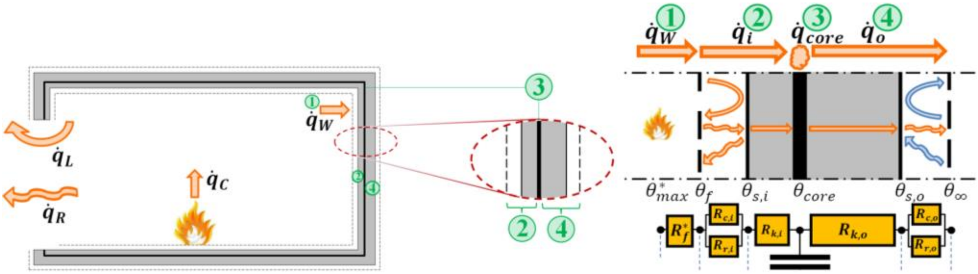


Figure 17. The developed model combines expressions for heat balance in the fire enclosure with expressions for heat transfer through boundaries in an electric analogy to calculate temperatures at different positions.

The model was developed for a case when the enclosure boundaries can be assumed to have *lumped heat capacity*, such as thin conductive boundaries or well-insulated boundaries. The model was derived in *electric analogy*, with the intention to make it easily understood: the core can be identified as a capacitor and the boundary conditions at each side of the core as heat resistances, as illustrated in Figure 17. The main derived expression, Eq. 1, can be used to calculate temperatures at different positions of an enclosure boundary and solves the temperature of the smoke layer, referred to as the fire temperature. Using electric analogy, Eq. 1 can be derived *directly* from Figure 17 (corresponding to Eq. 16 in Paper III).

$$\theta^{i+1}_{core} = \theta^{i}_{core} + \frac{\Delta t}{c\rho d}\left[\frac{1}{R^*_f+\left(\frac{1}{R_{r,i}}+\frac{1}{R_{c,i}}\right)^{-1}+R_{k,i}}\left(\theta^*_{max}-\theta^i_{core}\right) - \frac{1}{R_{k,o}+\left(\frac{1}{R_{r,o}}+\frac{1}{R_{c,o}}\right)^{-1}}\theta^i_{core}\right]$$

(Eq. 1)

Predictions by the new model were compared with averaged temperature measurements in the full-scale container experiments described above, as well as with predictions by the MQH relationship and FDS simulations (see Paper VI for heat transfer settings). Constants in the model were taken from well-known literature, such as Eurocodes (CEN, 2002, 2005), and the heat release rates from the experiments were used as input. As illustrated in Figure 18 for the insulated compartment with the heptane fire source, the fire temperature prediction by the model matched very well with the experimental data (5% average deviation between 50-550 s). So did the FDS predictions, while the original MQH relationship gave unrealistic results for the problems studied (peaking at 1 100°C for the case below, but excluded above 700°C).

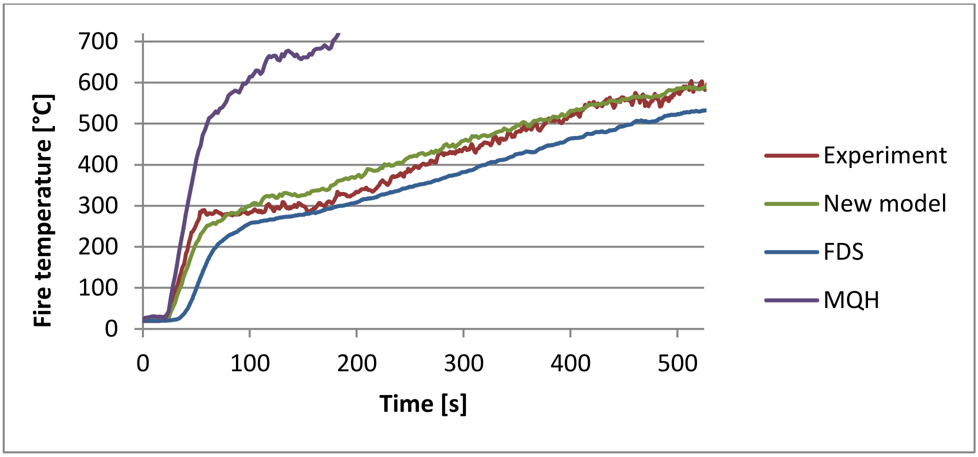


Figure 18. Fire temperature, i.e. the temperature of the gases in the hot upper layer, measured in experiments inside an insulated container, compared with estimations by different models using the measured HRR as input ("*Heptane ins*" in Figure 16).

In contrast to the MQH relationship, the new model can properly account for transient HRR, is applicable for conductive as well as insulated structures, and is based on fundamental fire physics. Its benefits compared with CFD modelling are its readiness and simplicity, as well as the *negligible computation time* needed. Furthermore, unlike FDS or two-zone models, the developed Excel application of the model is not a 'black-box' but gives a good understanding of how different *boundary conditions* affect heat transfer. However, its simplicity obviously comes with shortcomings. It is currently only available for structures with lumped heat capacity, it was only validated against four single-room experiments and it does not consider factors such as multiple rooms/vents, smoke movement, or allow as many model outputs as FDS. Nevertheless, the new model could be used for many fire-related problems and e.g. replace two-zone model simulations where the structures can be assumed to have lumped heat capacity. This was for example illustrated in Beshir et al. (2021). The model was also developed for a wider application, covering semi-infinite structures (Byström & Wickström, 2015; Byström et al., 2016), which however increased complexity significantly. The simplicity and speed of computation by the developed model makes usage particularly beneficial for preliminary evaluations, when evaluating multiple fire scenarios or when performing sensitivity assessments. The model also opens up for using input distributions to better describe effects of uncertainties on the result, e.g. in combination with Monte Carlo simulations.

The model was developed to support risk-based estimations of fire safety for well-insulated ship structures by estimating the temperature at the unexposed side of the structure from its properties and the HRR. This is illustrated in Figure 19, which shows the unexposed wall temperature estimated by the new model and FDS, compared with experimental measurements. It also confirms the previous statement, namely that the risk of fire spread by heat conduction will be *drastically reduced* with a well-insulated structure, such as insulated FRP composite. This applies regardless of the fire growth in the enclosure, as long as structural collapse does not occur.

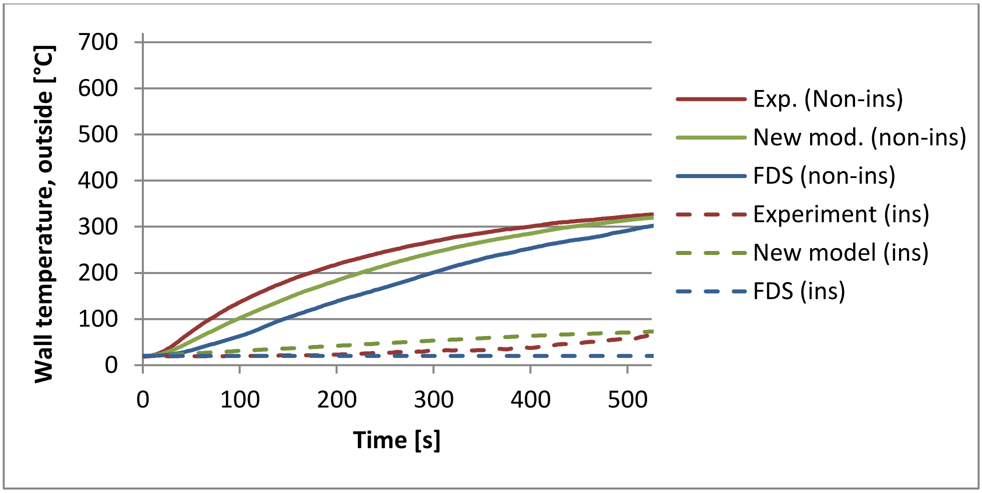
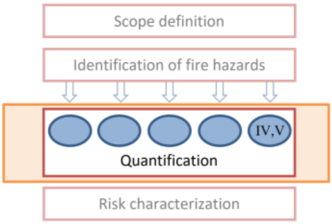


Figure 19. Temperature of unexposed side of insulated (ins) and non-insulated (non-ins) container wall, measured in experiments and compared with estimations by different models using the HRR measured in experiments as input.

5.2.3 Structural integrity



It has been concluded above that fire containment and integrity will generally be improved as long as collapse does not occur. However, structural fire integrity and the *potential for collapse* of FRP composite during fire has been identified to be critical. Collapse can make available otherwise protected combustible materials and it affects the safety of evacuating passengers and fire-fighting crew onboard. The latter was concluded in a bachelor thesis supervised by the author; the overall scope of the study was formulated and support was given to set-up the literature review and interviews as well as in scrutiny of the report (Falkman, 2013). In addition to giving recommendations for fire fighting in FRP composite structures, negative impacts were identified in catastrophic scenarios, when collapse might occur; underlined was also the need for crew education and training in new routines addressing awareness of collapse (Falkman, 2013).

As a follow-up to Paper I and Paper II, which focused on reaction to fire properties, Paper IV and Paper V focused on the structural fire integrity of FRP composite structures. Paper IV addresses how structures should be tested and designed and Paper V evaluates a new type of structure designed without thermal insulation. These aspects are further addressed below, preceded by a brief review of current test procedures.

5.2.3.1 Current large and intermediate-scale verification test procedures

This section provides a brief review of current large and intermediate-scale maritime verification test procedures addressing structural fire integrity, due to the currently ongoing discussions on the subject at IMO (Germany/CESA, 2023; IACS, 2023; IMO, 2024c) in relation to the Paper IV results.

Structures on HSC are verified with an applied static load according to Part 11 of the FTP Code (IMO, 2012), as described in section *2.3 Structures in FRP composite – a major deviation*. Structural integrity tests are expensive and, while it is easy to determine that a collapsing FRP composite structure fails, the phenomena leading to failure have not been clear. This has made it difficult to form a test series without having to test every dimension of structures on a ship. In 2013, the UK Maritime and Coastguard Agency published MGN 407 (MCA, 2013), a procedure for testing *thermal insulation* for use with composite ship constructions. It sought to reduce the number of fire tests for a given FRP composite design concept and extrapolate its applicable range of fire performance. This is based on indicative-sized furnace tests (>1x1 m) generating the same temperature exposure as in Part 3 and Part 11 but without loading (MCA, 2013). Sufficient fire protection is instead evaluated purely based on *heat transfer*. Sandwich structures need to demonstrate that the absolute temperature at the exposed surface is below the HDT (ISO 75-1, 2020) of the laminate resin at the end of the test (MCA, 2013). This criterion has in analogy been suggested for *loaded* Part 11 tests with *load-bearing* FRP composite structures (Jogia & Jurado, 2020). MGN 407 claims that the most onerous construction of a design concept, which needs to be tested with the thermal insulation, is the one with:

- the least dense core;
- the thickest core; and
- the thinnest laminate.

5.2.3.2 Thermo-structural failure phenomena and verification guidance

Paper IV was based on a full-scale furnace test series with *applied loading*, based on Part 11 of the FTP Code (IMO, 2012). The tests were carried out to examine whether the structural fire integrity of a common sandwich structure is sensitive to the *design load*, the *design principle* and the *safety factor against buckling*. Independence of the applied load would mean that the performance is solely a matter of heat transfer, as inferred by MGN 407, which would significantly simplify fire resistance testing.

The tested samples were selected with starting point in a typical FRP composite sandwich panel (test 1), designed for a critical buckling load of 31 kN/m. With a conventional safety factor against buckling of 2.5 (DNV, 2013) it gives a design load of 12.4 kN/m, which was applied in the furnace test. Tests were further performed with adjusted safety factor and thickness of laminates and core, to indicate sensitivities in design. These variations are marked green in Table 3, where the different panels and results are summarized. All the structures had the same thermal insulation at the exposed side, certified to achieve FRD60 (Hertzberg, 2009). The temperature was also studied at different positions, to investigate how critical the heating may be for structural integrity.

Table 3. FRP composite bulkheads of varied design (green) and results from loaded fire resistance tests

	Test 1	**Test 2**	**Test 3**	**Test 4**	**Test 5, stiffened**
t_{core} [mm]	50	50	37	50	50
Core quality	H80	H80	H80	H80	H80
$t_{laminate}$ [mm]	1.3	1.3	1.3	3.9	1.3
$P_{critical}$ [kN/m]	31	31	17.4	98	78
P_{design} [kN/m]	12.4	12.4	7	39.2	31
P_{test} [kN/m]	12.4	20.7	7	39.2	31
Safety factor against buckling	2.5	1.5	2.5	2.5	2.5
Time to failure [min]	56	53	58.5	51	55
Temperature on laminate surface at failure [°C]	260	206	255	161	223
Temperature between exposed laminate and core at failure [°C]	148	149	154	87	136

It is well established, and follows logic, that the time until structural failure of a specific sandwich panel in fire resistance testing is shortened if the loading is increased (Mouritz & Gibson, 2006). This was later also confirmed for maritime FRP composite structures by Karatzas, based on a large number of small and large-scale fire tests (Karatzas, 2016). What the test series in Paper IV showed is that this dependency also applies for structures *designed* for the applied loading (see results marked red in Table 3). Testing can thereby be simplified by not having to test all dimensions of a structural concept. To achieve conservative evaluation, a structural concept should be evaluated by testing the panel designed for the highest applicable load level; it should be *tested with its design load*, not with 7 kN/m as prescribed by part 11 of the FTP Code (IMO, 2012). For non-stiffened designs, and a safety factor of 2.5, this gave a narrow variation until failure of 55-58.5 minutes. The conclusion to evaluate structural fire integrity using the design load has since the publication of Paper IV been a general recommendation for FRP composite structures (e.g. Jogia & Jurado, 2020). The tests further indicated that structural resistance for high loads is better achieved by use of stiffeners than by thick laminates.

MGN 407 has a sole focus on *thermal loading* to evaluate sufficient thermal protection, "*assuming that the structure has been sufficiently protected to ensure no collapse*" (MCA, 2013). Important to note then, based on Paper IV, is that the MGN 407 instruction for the "*most onerous case*" to test in a design concept becomes backwards when considering *thermo-mechanical loading*. It is obvious that the exposed surface temperature will be higher if the structure blocks more heat at the surface. A thicker core, less dense core or thinner laminate implies a more insulating construction or that the highly insulating core is closer to the surface. However, two of these factors contribute to a weaker structure. As shown by Paper IV, in *loaded* fire tests, the *strongest* construction in a design concept should be tested for a conservative result. This means that the following criteria apply for a design concept, to test the most onerous construction regarding…

…*thermal* loading of surface:

- the least dense core;
- the thickest core; and
- the thinnest laminate.

[MGN 407 (MCA, 2013)]

…*thermo-mechanical* loading of structure:

- ► the most dense core;
- ► the thickest core; and
- ► the thickest laminate.

[Paper IV]

Hence, the guidance in MGN 407 for "*the most onerous case*" is correct to evaluate *thermal insulation* for concepts of composite structures. However, the guidance is not applicable for structural fire integrity testing of load-bearing structures. In particular, the principles of the most onerous case in MGN 407 **cannot** be applied to extrapolate thermo-mechanical capacity based on testing according to Part 11 (IMO, 2012).

Another conclusion of Paper IV was that the temperature at the interface of the heat-exposed laminate and the core *is* critical for thin-laminate, unstiffened sandwich structures. It is referred to as debonding and illustrated on a scale with other key temperatures in Figure 20. This conclusion was shared by Karatzas (2016), who showed a clear power law relation between the load-bearing capacity as a function of the interface temperature. This can significantly assist in the design of fire resistant FRP composite solutions, by dimensioning for when the interface reaches e.g. 140°C (or a temperature where the bonding between core and laminate is lost). For the sandwich structure with thick laminates, however, the temperature at failure was significantly lower. This underlines the design principle to achieve increased structural resistance by stiffeners rather than by thick laminates, but it also questions the relevance of the interface temperature when using thick laminates. Regardless of design principle, a conservative evaluation will be achieved as long as the panel tested is the one designed for the highest applicable load level.

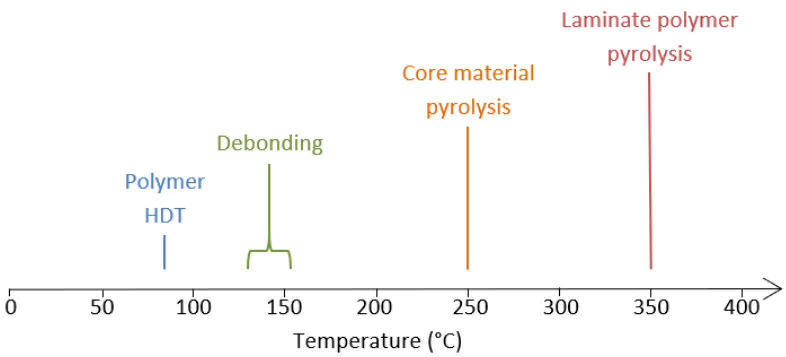


Figure 20. Key temperatures for the thin-laminate FRP composite sandwich structures (polyester FRP and Divinycell H80 core) tested in Paper IV (based on Hertzberg, 2012).

The test results presented in Paper IV naturally showed that failure occurs long before the average temperature rise at the *unexposed* side exceeds 140 degrees, which is the criterion when testing structures according to the FTP Code (IMO, 2012). In the tests, this temperature only increased between 2-11 degrees, as illustrated in Figure 21, along with criteria and other key temperatures. While the tested structures were not insulated at the unexposed side, it can be reiterated that FRP composite structures are inherently insulating; there would hence be little effect on the temperature at the exposed side if insulation was added at the unexposed side (Sweden, 2011a). This conclusion, however, goes against the more recent recommendation from the FibreShip project guidance note to always apply insulation also at the unexposed side, for conservative reasons (Verhaeghe & Breuillard, 2021).

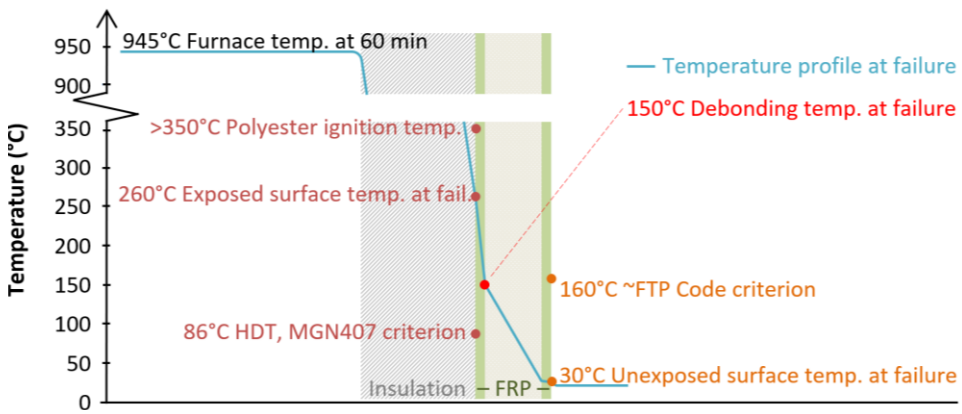


Figure 21. Temperature profile at failure (turquoise) and critical temperatures of typical FRP composite sandwich structure (not to scale), along with proposed criteria according to FTP Code and MGN407.

It may also be noted that the temperature at the *exposed* surface upon failure in all tests presented in Paper IV was significantly lower (~100 K) than the polymer pyrolysis temperature (>350°C) and significantly higher (~100-150 K) than the HDT (86°C). This was valid regardless of design principle. As illustrated in Figure 21, this enforces that the critical condition for structural integrity of FRP composite when exposed to fire is not laminate ignition or combustion, despite the major deviation associated with combustibility. It further implies that requiring the exposed surface to be below the HDT, as suggested by MGN 407, is extremely conservative in thermo-mechanical testing. While the conservative HDT-based criterion may be argued relevant to make up for the lack of loading and the intermediate-scale, it is not valid for testing according to Part 11 (IMO, 2012), as proposed by Jogia & Jurado (2020); it is also irrelevant since the test already includes structural deformation criteria. Hence, a temperature criterion at the exposed surface or laminate-core interface is not needed.

5.2.3.3 Investigation of structural design without thermal insulation

The load-bearing capacity of an FRP composite sandwich structure when exposed to fire varies with the composition of the core and laminates as well as how well it is thermally protected. For external surfaces, insulation is not an option, while in the COMPASS project it was assessed that an external fire could result in structural collapse (Karatzas, 2016). Load-bearing capacity can also be improved by structurally redundant design, e.g. by adding supporting stiffeners or pillars, or by using panels with over-capacity. This was the focus in Paper V, where a lightweight sandwich structure constructed with multiple cores was evaluated. The tested design had two cores and three laminates but no thermal insulation. This means that the exposed laminate and core served as 'sacrificial thermal protection' in case of fire.

Paper V extended the structural fire integrity test series in Paper IV, based on Part 11 in the FTP Code (IMO, 2012), with the above described multiple-core sandwich structure. Comparison with a conventional structure designed for the same load but with insulation showed that the multiple-core sandwich structure can achieve notably *better load-carrying capacity* (90 min compared to 56 min). A similar panel but with four glass fiber reinforced furan laminates and three balsa cores was later developed and tested well in the EU project FIRE-RESIST (Rahm & Blomqvist, 2015). It was developed to achieve FRD60 but lasted for 77 minutes in the loaded Part 11 (IMO, 2012) test (Rahm & Blomqvist, 2015).

The triple skin multiple-core sandwich panel evaluated in Paper V, with two cores and three laminates, weighed about 23 kg/m^2 (with cores and laminates as above). It significantly surpassed the structural fire integrity performance of a double-insulated FRD60 FRP composite structure, weighing ~27 kg/m^2: 12 kg/m^2 for the FRP composite and 7.5 kg/m^2 per side of thermal insulation (Hertzberg, 2009). Both structures can replace a 7 mm A-0 steel structure which weighs ~55 kg/m^2, or an A-60 structure weighing ~70 kg/m^2. Multiple-core sandwich structures hence have great potential for maritime structures; they are lighter, thinner, weather resistant and provide added stiffness and load-carrying capacity when not exposed to fire. They could thus for many reasons be an attractive solution, but they also leave FRP composite surfaces *exposed* to fire, requiring sufficient reaction to fire performance.

5.2.3.4 Long-lasting structural fire integrity implicitly required

As elaborated in Paper VI and section *5.1 Fire hazard identification for novel ship design*, it is important to identify and assess implicit effects on fire safety. One such effect concerns how the structural fire integrity is affected in case of a long-lasting fire. This was not directly investigated in the research work of this thesis. However, its direct connection to structural fire integrity makes it relevant to be pointed out, as done in the simplified flowchart for scoping a Regulation 17 assessment (see section 5.3.1). The subject is therefore briefly elaborated on below.

As noted in the background, section *2.3*, equivalent structural *and* integrity properties to steel can be achieved by FRP composite "*at the end of the applicable exposure to the standard fire test*" (reg. 3.43). This has lately been referred to as "*local equivalence*" (Jogia & Jurado, 2020), even if it rather sets a *limit in time*. Deviation from the infinite non-combustibility requirement by use of FRP composite structures means that they will eventually deteriorate. Even if not directly prescribed, this is an important difference in load-bearing capacity between steel and FRP composite structures that can materialize in case of a *long-lasting fire*. The time span between a steel structure's insulation failure and load-bearing failure is an *implicit benefit* (Karatzas, 2016) which is not clear in the regulations, nor accounted for in the test for structural fire integrity. Its impact on fire safety when using FRP composite is not clear either, since the consequences of loss of load-bearing capacity can span from insignificant to causing a progressive collapse (Karatzas, 2016). This impact must hence be assessed on a global scale for the particular ship design considered with FRP composite structures.

The IMO guidelines in MSC.1/Circ.1574 conservatively manages this unclear risk by only allowing FRP composite elements which may be removed without compromising the safety of the ship (IMO, 2017). Hence, the guidelines "*do not fully address the risks of progressive structural collapse or global loss of structural integrity due to fire associated with a fully FRP composite ship or FRP composite structures contributing to global strength.*" This does, however, not release the full potential of FRP composite structures.

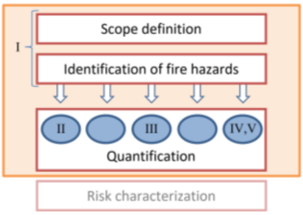
A simple approach to manage long-lasting global structural fire integrity for large FRP composite structures was suggested by the author in 2018, in the preliminary fire risk assessment for an 85 m offshore patrol vessel in the EU project RAMSSES. It consisted in requiring *increased* structural fire integrity for structures critical for the global strength of the ship; for three hours in line with Safe Return to Port requirements (IMO, 1974), or for a time considered necessary to reach sufficient *structural robustness* for the ship. The three-hour requirement was applied in the continued work with the fire risk assessment (Verhaeghe & Breuillard, 2021). It was also picked up by the FibreShip project, proposing in their project guidance notes three hours of structural fire integrity for structures participating to the longitudinal strength of the ship and to its floatability (Jogia & Jurado, 2020).

A more sophisticated way to manage long-lasting global structural fire integrity of FRP composite structures was also initiated in the FibreShip project, and elaborated in the Fibre4Yards project. It consisted in a simulation-based methodology (Pacheco et al., 2023), coupling fire simulations with a thermo-mechanical tool specialized to FRP composite structures (Pacheco-Blazquez et al., 2022); it was applied to assess structural fire integrity globally for a containership (Pacheco-Blazquez et al., 2023). As expected, it was shown that FRP composite outperforms steel structures with regard to fire containment and during escape, but that a long-lasting fire could be worse for global structural fire integrity (Pacheco-Blazquez et al., 2023).

5.3 Developed frameworks for the fire risk assessment

In section *5.1* were clarified the challenge and importance of identifying implicit hazards and requirements, and in section *5.2* were explored verification methods and fire performance of FRP composite. To move forward from the knowledge created in these areas, Paper I describes a procedure which can be visualized in a summarizing flow chart. It is described below and lays out the foundation for a Regulation 17 assessment involving FRP composite structures. Paper VI further developed parts of the assessment procedure described in MSC/Circ.1002 (IMO, 2001). In particular regarding how to manage fire hazards and treat uncertainties when characterizing the fire risk, as described subsequently.

5.3.1 Simplified flowchart for scoping the assessment



Effects on the growth stage of a fire from using of FRP composite ship structures were elaborated in Paper I. Here follows a very concise summary of effects on all the hazard areas identified in MSC.1/Circ.1574 (IMO, 2017), based on the knowledge created in Papers I-V:

> **Ignitability:** As elaborated in Paper I, and confirmed by Karatzas (2016) and Sandinge (2024), ignition of FRP composite as a first fuel by a small ignition source is generally not an issue. This can easily be verified by an ignitability test, such as ISO 11925 (ISO 11925-2, 2020).

Fire growth potential: As discussed in Paper I, fire growth potential can be divided in amount of combustible material and their flame-spread characteristics, further investigated in Paper II. Effects on flame spread depend on the area of application and on how the surfaces are protected. With thermal insulation, flame spread is unaffected. Non-insulated FRP composite surfaces of common marine grades are prone to quick flame spread. This can be mitigated by an active system or a surface coating achieving low flame-spread characteristics (Part 5), which would interiorly fulfil prescriptive requirements (IMO, 2012). Achieving "*fire-restricting material*" quality according to Part 10 of the FTP Code (IMO, 2012) would further improve the flame-spread properties of the surfaces.

Potential to generate smoke and toxic products: Paper I notes that this is primarily affected by the heat release rate, which correlates with the fire growth potential (Mouritz & Gibson, 2006). However, non-flaming fires, which could be a result of flame retardants, can generate a disproportionate amount of toxic species. This makes it recommendable to test exposed surfaces according to Part 2 of the FTP Code (IMO, 2012), even if flammability properties are sufficient.

Containment: It is generally improved, as long as structural integrity is not compromised, even accounting for potential increased fire growth due to contained heat. A model for such investigations was contributed by Paper III.

Fire fighting: Safe and effective fire fighting requires new equipment and training, investigated by e.g. Carlsén and Winkler (2000) as well as Andersson and Krasniqi (2001). Falkman (2013) concluded that fire fighting will not be negatively affected as long as collapse does not occur.

Structural integrity: Load-bearing capacity during fire is *critical* and requirements can be achieved in different ways for the duration of the prescribed test, investigated in Paper IV and Paper V. However, if using FRP composite to achieve global strength, effects from a long-lasting fire must also be considered.

To assist in the Regulation 17 assessments for eight demonstration cases in the EU project RAMSSES, a flowchart was developed by the author in 2018. Based on the above summary, it focuses on the two areas primarily affected by a change to FRP composite, namely fire growth potential (called reaction to fire) and structural fire integrity (resistance to fire). The flow chart was a *visualization* of the procedure elaborated in Paper I for the growth stage of a fire (reaction to fire), expanded to also cover resistance to fire. The purpose of the flowchart (and Paper I) was to clarify the performance of FRP composite structures in relation to maritime test requirements. The purpose was also to point out hazards that need to be further considered in a Regulation 17 assessment of alternative design and arrangements (below simplistically referred to as ADA) involving FRP composite structures. The flowchart is depicted in Figure 22 and has previously only been partially published (de Bruijn et al., 2021).

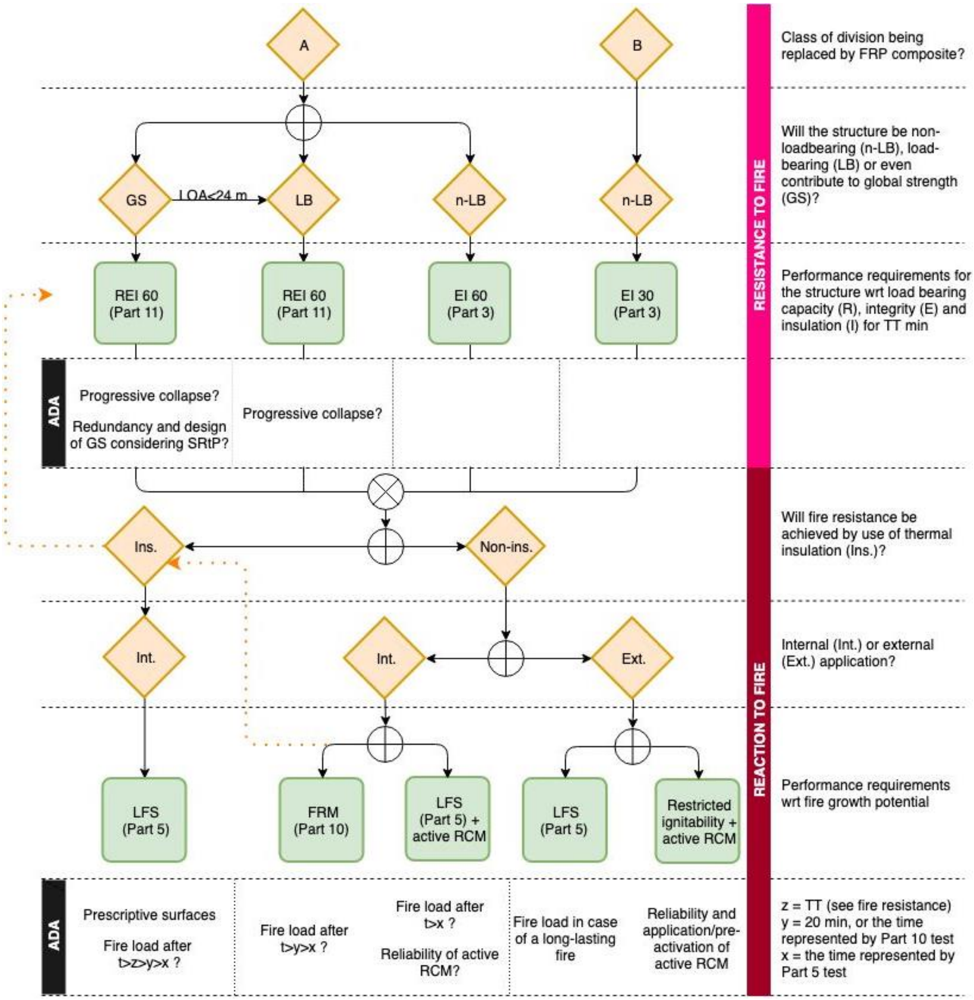
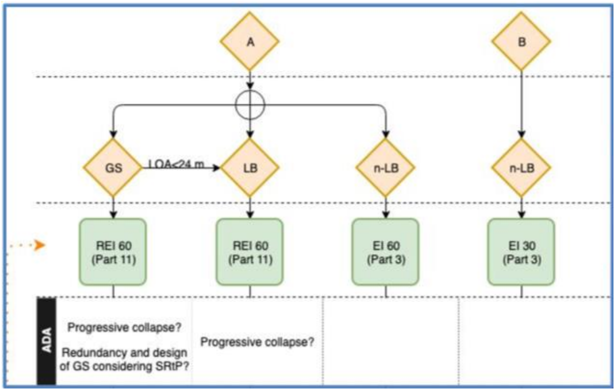
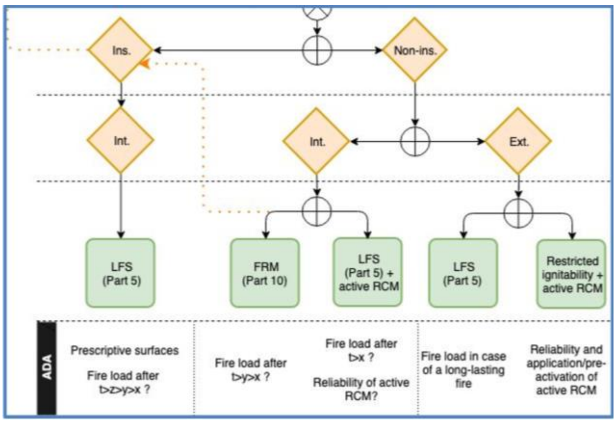


Figure 22. Flowchart illustrating the assessment scope definition when replacing "A" or "B" class divisions with FRP composite structures (partially published in de Bruijn et al., 2021).

To clarify what is actually required, it was proposed by the author in 2018 to transfer to an REI-TT notation, as for buildings, where "*R*" specifies if the structure is load-bearing, "*E*" signifies integrity and "*I*" thermal insulation capacity, all for a specified time "*TT*" (EN 13501-2, 2023). This proposal was supported by the project partners (de Bruijn et al., 2021; Krause et al., 2020) and was also picked up by the ongoing sister project FibreShip (Jogia & Jurado, 2020). For example, the current notation A-15 requires 15 minutes of insulation, 60 minutes of fire spread integrity *as well* *as non-combustibility*, and the notation FRD60 requires 60 minutes of insulation, 60 minutes of fire spread integrity *and* 60 minutes of structural fire integrity, *as well as surfaces of fire-restricting material quality*. Separating requirements regarding reaction to fire and fire resistance makes it more clear what is required and hence what might be deviated.



Starting out at the top of Figure 22, making use of FRP composite in ship structures implies replacing "A" or "B" class divisions with combustible ones. As a first step, the category and load-bearing capacity of the replaced division need to be identified, which will determine what test is suitable to show sufficient structural fire integrity. If it is a non-loadbearing (n-LB) "A" class division, it only needs to be evaluated regarding fire integrity and insulation for one hour (EI 60), according to Part 3 (IMO, 2012). A load-bearing (LB) structure should also be evaluated regarding load-bearing capacity (REI 60), according to Part 11 (IMO, 2012) but, as shown in Paper II, while applying the design load. Effects on structural integrity beyond the test need to be considered in the ADA. Small ships with a length overall (LOA) of less than 24 m are generally not considered to pertain to global strength in class society rules, based on the International Load Line Convention, as amended (IMO, 1966). Load-bearing capacity and potential progressive collapse still need to be considered. However, for longer ships, structural redundancy and the design of global strength (GS) need to be assessed (elaborated in section 5.2.3.4) as well as Safe Return to Port (SRtP) requirements (IMO, 1974).

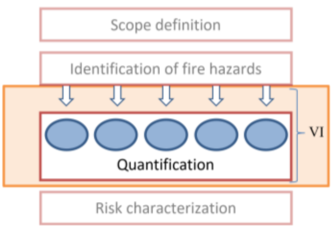


Whether thermal insulation is used to achieve structural fire integrity determines how to proceed with the reaction to fire property fire growth. If thermal insulation is used, which is naturally only relevant for interior surfaces, the exposed surfaces will comply with prescriptive requirements. It will still need to be considered in the ADA how increased use of combustible materials may potentially affect fire growth when the structures ignite after a time $t>z$, where $z=TT$ in the fire resistance test. If insulation is not used to achieve structural fire integrity, it would be recommendable for surfaces in interior spaces to achieve fire-restricting material (FRM) quality (see *5.2.1.2 Flame spread with passive* protection), as required for fire-resisting divisions on high-speed craft (IMO, 2000). According to Part 10 of the FTP Code (IMO, 2012), such materials have limited contribution to a 100-kW fire for ten minutes, and then to a 300-kW fire for another ten minutes. Hence, fire spread on such surfaces would be limited for a time y, where y=20 minutes or a time represented by the Part 10 test. SOLAS, however, only requires surfaces to have low flame-spread characteristics (LFS), which gives a lower flame-spread protection than with FRM, i.e. for a time $x<y$. Considering what is required for combustible structures on high-speed craft and the importance of a swift fire-fighting response with FRP composite surfaces, FRM may be considered necessary. If only LFS is achievable, it could for example be combined with an active risk control measure (RCM), such as increased sprinkler system reliability. Regardless, it also needs to be considered in the ADA how the increased fire load made available after the time t may affect safety.

For external surfaces, without thermal insulation, it could be relevant to require verification in large scale, as investigated in Paper II. LFS characteristics according to Part 5 of the FTP Code may also be considered sufficient, as indicated possible in Paper II. This was later also proposed in the guidance note from the FibreShip project (Jogia & Jurado, 2020). However, a long-lasting fire exposing the surfaces would still involve the materials, the consequences of which may need to be considered in the ADA. If fire growth on external surfaces is instead managed by an active system, its activation and reliability must be considered. A possibility could also be to use fire resistant glass according to Part 3 of the FTP Code (IMO, 2012) to avoid fire spread to external surfaces (see e.g. O'Connor, 2016; Manzello et al., 2007).

The flowchart was found very useful at the onset of the Regulation 17 assessments in the RAMSSES project. It gives a useful overview and helps describe how different design concepts affect the assessment scope and it assists to identify suitable tests and define performance requirements for the materials.

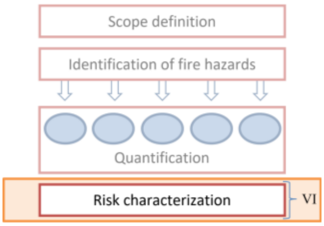
5.3.2 Integration of fire hazards in the assessment



Above are investigated many fire hazards potentially introduced when using FRP composite structures, regarding their performance in relation to regulations and referenced tests. To work effectively and scientifically with the fire hazards in a Regulation 17 assessment, Paper VI gives many advice. Firstly, when it comes to selecting fire hazards to form fire scenarios, MSC/Circ.1002 instructs to select a range of incidents which covers the largest and most probable fire hazards (IMO, 2001). This is useful if applying an approach where functional requirements are directly evaluated. As noted in 6.3.3 (IMO, 2001), a design with novel or unique features makes it relevant to compare it with a commonly used (prescriptive) acceptable design. The priority must then instead be to include the *introduced* fire hazards and, unless justified, to consider *all* introduced fire hazards, as elaborated in Paper VI.

Paper VI also gives advice for how the assessment can be structured, by use of new nomenclature, and suggests improvements in the process and how various hazards can be addressed. An experience from several projects (Evegren, 2013a, 2013b, 2015; Rahm, 2011, 2012) was for example that the assessment becomes simpler if some of the hazards can be managed individually. Limited fire hazards can thereby be excluded from the 'main' evaluation. It can also be relevant to divide the assessment and evaluate safety in several *limited areas*, depending on the hazards introduced. Paper VI notes that such delimited areas of safety are often possible to define in line with the *regulations* or functional requirements. If the alternative solution performs sufficiently in one area, it is not necessary to include those hazards in a holistic risk figure, which can significantly reduce the engineering rigor. To quantify the safety of the whole affected part of a ship in *one risk figure* may nevertheless be necessary if hazards are interconnected, or to balance pros and cons. Except from providing a good structure, dividing a risk assessment in smaller areas allows for adapted characterization and evaluation of the different risks, as further elaborated below.

5.3.3 Framework for assessing risk in Regulation 17 assessments



Regardless of whether hazards are assessed individually, in small groups or holistically, it is imperative that the assessment is of *sufficient sophistication* to describe the introduced novelty in terms of fire safety. Optimization may require a quite advanced assessment whilst a simple and well-protected alternative solution should not require a complicated or time-consuming assessment. For example, proposing use of FRP composite for limited interior structures which are universally thermally insulated may not require a lengthy or detailed assessment, as described in Appendix E of MSC.1/Circ.1574 (IMO, 2017). This is further elaborated in Paper VI, where it was also noted that the approach outlined in MSC/Circ.1002 is deterministic; a typical consequence assessment of design fire scenarios. Such an assessment may thus be overly advanced or not sophisticated enough to adequately assess the changes in fire safety. A framework was therefore developed for assessing fire risk in Regulation 17 assessments at different useful levels.

5.3.3.1 Categorization of risk assessment sophistication

As concluded in chapter *3. Background to risk assessment*, risk assessment is about elucidating the uncertainty and knowledge about different undesired consequences. Rather than to accurately estimate the 'objective' risk by advanced methods, the aim of a risk assessment is to better *understand* the risk (Apostolakis, 2004; Aven & Thekdi, 2022). It can even be argued that the risk *insights* that come from a risk assessment are more important than the final risk figure (Apostolakis, 2004; Callan, 1998). Attempting to describe risk in a better way is hence not solely about using more advanced methods to better estimate probability figures, but rather about creating an improved understanding and *reducing knowledge uncertainty* (Möller et al., 2006). Different ways of expressing knowledge uncertainty have been explored to better communicate the full understanding of risk. Spiegelhalter and Riesch (2011) were precursors to the strength of knowledge concept (e.g. Aven, 2013) in their proposal of five levels of expressing uncertainty, where levels 4-5 express the *confidence* in the reductionist analysis carried out at levels 1-3. They also suggest how such uncertainties can be assessed based on qualitative scales (EFSA Scientific Committee, 2007; Guyatt et al., 2008). Pate-Cornell (1996) also suggested different levels in the treatment of uncertainty and presented six different levels in which risk analysis can be carried out. The most sophisticated level describes how knowledge uncertainty can be presented as a distribution across a set of risk curves, similar to how Kaplan and Garrick suggested to describe "*confidence*" in 1981 (Kaplan & Garrick).

5.3.3.2 Proposed levels to assess risk

As previously visualized in Figure 10, there are many methods to characterize risk, and they have often been categorized based on their inclusion of quantitative or probabilistic measures. The above authors instead categorize a method's sophistication based on how well it evaluates uncertainties of outcomes. With inspiration from these categorizations, the foundations of risk and the experience of applying varying methods, Paper VI suggests a framework with four levels to assess risk in Regulation 17 assessments, illustrated in Figure 23.

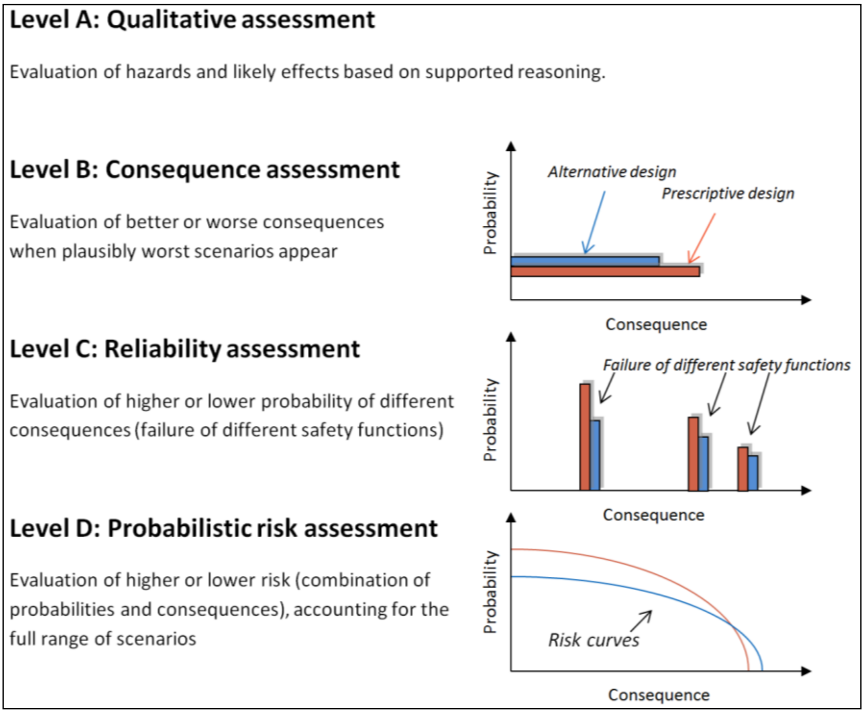


Figure 23. Suggested levels in Paper VI to describe and evaluate safety in Regulation 17 assessments.

While founded on both literature and experience, the suggested categorization in Figure 23 may from a risk perspective appear mere common sense. After the *qualitative level* (A), risk is either evaluated with focus on the *consequences* (B) or with focus on *probabilities* (C). It is not until level D that both consequences and probabilities are properly assessed in combination, often referred to as *risk*.

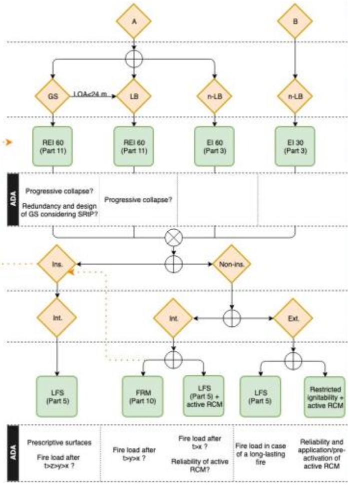
As described in Paper VI, an assessment at level A (*qualitative assessment*) is based on developing relevant fire scenarios, i.e. focusing on identifying a set of specific events, S_i in the classic risk triplet (Kaplan & Garrick, 1981). Conclusions regarding consequences and probabilities of scenarios are drawn from for example logic reasoning, statistics, proven solutions and simple calculations (e.g. SIS 24836, 2024). Moving to level B (*consequence assessment*), a measure of the consequences is added to the risk characterization. The approach presented in MSC/Circ.1002 is at level B and, as illustrated in Figure 23, it includes estimation of expected consequences when plausible worst-case scenarios appear. As Callan (1998) states, such an approach implies some elements of probability in the selection of scenarios to be analyzed, but focus is on the two other parts of the classic risk triplet: “*what can go wrong*” and “*what are the consequences*”. The suggested *reliability assessment* at level C is in a way opposite of the consequence assessment at level B. Instead of evaluating the consequences when certain scenarios appear, the probability is evaluated of specific consequences. The selection of consequences should stem from the identified hazards and can advantageously be taken from the functional requirements challenged in the regulations. At level D (*probabilistic risk assessment*) estimations are made of both consequences and probabilities, to describe the full distribution of potential outcomes, e.g. as a typical QRA/PRA. The resulting probability density function can be presented as some kind of risk curve, such as an F-N curve describing the frequency of exceedance of different outcome levels per time unit (generally the frequency, F, of exceeding a number, N, of fatalities per year). It is hence not until this level that a measure of what is often referred to as the total 'fire risk' can be revealed.

In common for all levels of assessment is that simplifications are made in order to model complicated systems. Even the most detailed risk assessment contains limitations, and uncertainties are involved throughout the whole process. From the scope definition and hazard identification, through the selection and investigation of scenarios, and finally in the evaluation of safety by selected criteria. The difference between the four levels of assessment is how well these uncertainties are investigated and documented. Such assessment of uncertainties should also be complemented by an assessment of the strength of the knowledge, which founds the basis for e.g. determination of scenarios, consequences and probabilities (Bani-Mustafa et al., 2020); compare with the risk definition $R=(A',C',Q,K)$. With regard to uncertainties in the last step, risk evaluation, it should particularly be pointed out that using *absolute acceptance criteria* at level D can become very uncertain in a Regulation 17 assessment. Such criteria (see e.g. McGeorge et al., 2009; Skjong et al., 2007; Themelis & Spyrou, 2012; Vanem & Skjong, 2004) generally stem from statistics and are associated with *fundamentally different uncertainties* than the uncertainties included in the risk calculated from e.g. fire scenarios. As further discussed in Paper VI, it is therefore suggested to perform relative Regulation 17 assessments, also at the more sophisticated levels.

5.3.3.3 Application of the risk assessment framework

According to MSC/Circ.1002, performance criteria should be determined during the quantification of fire scenarios, but it is common that criteria are established earlier in the risk assessment process. For example, both ISO 23932-1 (2018) and MSC.1/Circ.1455 (IMO, 2013) instruct to identify criteria already at the onset of the assessment. It is done in association with selecting the appropriate method for the assessment, since the method, metrics and criteria are connected. Together with a testing and analysis strategy, they set out a plan for the risk assessment (IMO, 2013). For Regulation 17 assessments where the above adaptable risk assessment framework is applied, such a risk assessment plan is recommended to be developed in association with the scope definition and hazard identification, for example supported by use of the flowchart in Figure 22.

If using the flowchart in Figure 22, the performance assessment will take a starting point in standardized tests. Each test can be considered as a level B consequence assessment, representing a plausible worst-case scenario. The related hazards not considered by the test, noted in the ADA field, can be addressed by an independent assessment or by assessing them together with other hazards, at a suitable level. For example regarding structural fire integrity, effects on safety might materialize after 60 minutes on a ship with REI60 FRP composite structures. The ship might however be on a fixed 90-minute route, meaning it will be a maximum of 45 minutes from shore. This could potentially make the increased risk of collapse acceptable by logic reasoning (level A). Or the ship might operate transatlantic, and how a safe assembly station will be ensured for a reasonable time in case of a long-lasting fire must be further analyzed. It might also be the case that interior FRP composite structures have limited protection and eventually could increase the potential for fire growth in a space. A redundant sprinkler system would mitigate this risk, and an assessment at level C could argue for a total reduced probability of fire growth in the space. A risk characterization at level D could give a complementing understanding of low-probability and high-consequence events, for example the risk if a drencher system for external surfaces does not work. An assessment at level D could also be necessary if many hazards are interconnected, or it could be used to balance between pros and cons in different areas. These are just a few examples of how fire hazards can be separated to assess the risk at different levels in Regulation 17 assessments.



6 Discussion

The methods used in the appended papers are discussed below, preceding a discussion on how the research objectives have been achieved. Thereafter follows a more general discussion on the relevance of the research purpose.

6.1 Critical evaluation of used methods

The methods used in the appended papers are described in chapter *4. Method* and their usefulness is critically evaluated below. Paper IV and Paper V were based on the same test method and are discussed together. Paper I and Paper VI also shared a large part of their foundation and applied similar research methods and are therefore also discussed together, at the end of this section.

6.1.1 Paper II

Paper II presents a fire test series evaluating fire spread on an FRP composite surface protected with active and passive measures. The tests were based on a standardized test method for building façades and were to represent the conditions of an interior fire spreading to the exteriors of a ship. Standardized test methods have been developed to evaluate certain characteristics under certain conditions and have in many cases been simplified to a smaller scale. However, small-scale tests require validation to real-scale tests in order to determine how well larger conditions are represented. Performing experiments in a real scale, as was the case, thus reduces uncertainties and correlates best with real-world application (Andersson, 2012). In judgements of research quality, this is often referred to as validity, relating to the accuracy of the study (Robson, 2016). In this case the real scale of the test was for example considered to better capture the combined heat exposure of convection and radiation to the surface. However, there are several other aspects to consider with regard to validity. For example, windy conditions are common at sea, which can significantly affect the potential for fire growth, also in the lateral direction. This was not included in the test method applied (SP Fire Technology, 1985) and was not considered in order to keep the scope of the study manageable. Furthermore, the panel used in the tests was quite large, 4.0x6.5 m, whilst open surfaces on e.g. a cruise ship can be rather limited, at least over openings which could provide such a fire source (Evegren, 2013b). This can make the test results overly conservative with regard to the extent of fire growth. However, as noted in the method description, the size was judged reasonably conservative by a team of shipyard representatives and researchers to assess fire spread and safety measures on a ship side.

Considering the fire source, validity can be questioned since reference is made to a test method used for buildings, i.e. is it accurate for ship applications? This was indirectly addressed in the paper by comparison with the small-scale maritime test method used to evaluate flame-spread for interior surfaces (ISO 5658-2, 2007) and the maritime method representing a room (cabin) fire (ISO 9705, 2016). As noted above, however, standardized test methods evaluate certain characteristics under certain conditions and may not imply a realistic exposure. The fire exposure from an interior fire to the exteriors mainly stands in relation to the size of the opening, regardless of being on land or at sea. A fire spreading through a cabin window had already been tested (Arvidson et al., 2008) but was not considered to be valid for the potentially large openings on a cruise ship. The fire source in SP FIRE 105 (SP Fire Technology, 1985) was considered able to represent a larger opening, e.g. from a cabin balcony opening or a large broken window. The fire source was also compared with the fire source in the cabin fire test scenario in MSC/Circ.1268 (IMO, 2008a), developed to evaluate the effectiveness of a balcony sprinkler, which SP FIRE 105 visually well covered.

Another parameter used to evaluate the quality of research is reliability, i.e. its reproducibility (Robson, 2016). This was ensured by using a standardized method as basis for the tests at an accredited test lab, with calibrated instruments and equipment to document the conditions of the procedure and the sample. The heptane fire source further provided a similar heat release rate in all tests, disregarding the time before reaching 100 kW, which strengthened the reliability of the test procedure. Reliability is also closely connected to repeatability. Repeating the same tests would have strengthened reliability, but this was not done in the test series. Single tests, i.e. one test per setting, are common when performing full-scale destructive tests due to limitations in resources. Three tests were although performed with delayed activation of different extinguishing systems, which indicated similar fire growth potential of the unprotected material. To be able to make a recommendation for a particular safety system it could although be relevant to carry out repeated tests.

6.1.2 Paper III

In Paper III, a model was developed to make simple estimations of temperatures in pre-flashover fire enclosures depending on the heat release rate and the insulation capacity of boundary structures. This was relevant since highly-conductive steel structures were investigated to be replaced by well-insulated FRP composite. The model applicability for FRP composite structures can although be questioned, since they do not fulfil the model assumption of lumped heat capacity. The model can nevertheless compare the effects of a highly-conductive steel structure with those of a well-insulated one by assigning insulation at the exposed side. Such a representation is generally valid in the early stages of a fire. The objective with the model was in particular to estimate the temperature of the hot gases in the pre-flashover stage, to indicate effects on the fire development. It would have been most interesting with a model including feedback to the fire source, to update the HRR, but this was considered beyond the scope of a simple model. It could further have been interesting to compare the model results using the HRR from a free burning fire source instead of that measured in the enclosure. This is likely the most relevant application of the model and could have been a way to estimate the expected reliability of the model, although depending on invalid input data.

The comparison of the model results with experimental measurements indicated a high validity of the model, as illustrated in Figure 18; the calculated average deviation from the experiments was 5%. In addition to the HRR, as noted above, it although depends on the validity of the input data. When making the comparison, input data were taken from Eurocodes (CEN, 2002, 2005), to make a neutral impact on the model result by mimicking likely use. This was done even if more valid data was available in-house, which made the validation, in a sense, less valid. To evaluate reliability, a sensitivity analysis could have been carried out to see if any single variable affected the results significantly, and to assess the uncertainty of that variable. This was although not done, as focus in the paper was rather on the development and validation of the model assuming normal, and not on evaluation of the input variables.

The validation was based on a comparison with four test scenarios with different fire sources and boundary set-ups. Despite the accurate results in comparison with experiments, the validity of the model can be questioned since it was only validated against four scenarios. Furthermore, the validation was only made against one standard-sized room, which is not sufficient to ensure valid results for other cases. The model has for example not been validated for large volumes, slow heat-release rates or low oxygen concentrations. A wider validity has been shown by e.g. Beshir et al. (2021), but further limitations of the model are yet to be defined. In this regard, it should be noted that the model includes very few assumptions besides the well-established expressions for heat balance in a fire enclosure and for heat transfer through a boundary. Therefore, the model can be claimed to have the same limitations as the expressions which formed it. The most controversial of the assumptions behind the model is that the heat flux (by convection and radiation) was considered uniform to all the enclosure boundaries, including the floor. More conventional is to assume that the heat exchange takes place in the upper hot gas layer, since this is where the heat flux by convection transpires. However, the model calculations made it comprehensible that radiation is the dominant mode of heat flux in the majority of a fire's development. Thus, it is more justified to make an assumption applicable to radiation than one applicable to convection, which although is common praxis in two-zone models.

The need of the model can be questioned due to its resemblance with two-zone models, which are available with simple interfaces and provide quick results. However, in addition to being faster than such models, the developed model is completely transparent and based on fire physics. It is thus possible to be in full control of the calculations and comprehend the effects of variables on the result. Furthermore, the new model can be set up to perform numerous instant calculations in combination with e.g. Monte-Carlo simulations to provide a temperature probability distribution, which is not possible in a two-zone model interface.

6.1.3 Paper IV and Paper V

Regarding post-flashover fires, Paper IV and Paper V evaluated the structural fire integrity of FRP composite structures based on loaded fire-resistance tests according to Part 11 of the FTP Code (IMO, 2012). In Paper IV, a test series was set up for a systematic parameter variation of the panel design, and in Paper V a new type of fire-resistance solution was explored. For these studies to be reliable, it was important to carry out the tests in a controlled test environment without disturbing factors. This was ensured by conducting the tests according to a standardized method, developed to reduce aleatory effects on the test result, and by carrying out the tests in an accredited laboratory. It is a guarantee for the quality of the test, e.g. how it is conducted, that measuring equipment is calibrated, the quality of sensors, and that observations and documentation are done the same every time, strengthening the reliability of the results. To ensure objectivity and relevance for the comparisons made, the criteria according to Part 11 of the FTP Code (IMO, 2012) were used to evaluate the structural fire integrity. Measurements were made regarding temperature rise and ignition at the unexposed side, the size of cracks and openings, as well as regarding axial contraction and horizontal deflection. Regarding the temperature, there can be local variations, or malfunction of a thermocouple, which the test method already considers by averaging the temperature in five positions, ensuring the reliability of the results.

An aspect of furnace testing according to Part 11 of the FTP Code (IMO, 2012) is that the oxygen concentration inside the furnace is generally very low, perhaps around 4%. This could be considered as a non-conservative aspect of the standardized test, since combustion of the material could transpire to a higher degree in a real case. However, for insulated structures, as those tested in Paper IV, the combustion is not affected by the oxygen concentration in the test since the ignition temperature is not reached before failure in load-bearing capacity. This is illustrated in Figure 20 and Figure 21. For a non-insulated structure, such as the multiple-core sandwich structure evaluated in Paper V, the situation is different since the combustible surface is exposed. Hence, in a real scenario where the structure is exposed to a large fire, it could be claimed to combust to a larger degree than in the furnace test. However, it should also be noted that the furnace test is supposed to represent a fully developed enclosure fire. Something that defines such a fire is that it is ventilation controlled and that combustion takes place outside the space due to insufficient oxygen inside the enclosure. Combustion will still occur inside the enclosure, to an extent dictated by the ventilation conditions. In addition, materials will be exposed to the heat in the space causing heat deterioration and pyrolysis, as in the furnace. So is it possible that combustion could occur to a larger degree in a real scenario with non-insulated structures? Yes, if the ventilation conditions allow more combustion inside the space than can be provided by the remaining combustible materials in the space. The evaluation of non-combustible structures in the furnace test could although still be argued valid. The furnace test will namely expose structures to the same standardized heat, causing deterioration and pyrolysis. Combustion of the gases takes place in the gas phase inside the furnace, together with the combustion gas supplied to heat the furnace according to the standard time-temperature curve (cf. ISO 834-1, 1999).

As for Paper II, performing the tests with samples in a size close to that intended for real-world application reduces the uncertainties of cause-effect relationships and also strengthens validity (Andersson, 2012). Even if the standardized test in Part 11 of the FTP Code (IMO, 2012) has ideally been developed with consideration to the plausible worst-case conditions on a ship in case of fire, the validity could be questioned. As any test, the fire scenario represented by the temperature in the furnace gives no knowledge about the performance of the structure in a scenario with increased temperature, exposure time or loading. Likewise it is difficult to draw any far-reaching conclusion regarding the safety margin in case of a real exposure to a less severe fire scenario. It is particularly difficult to draw any conclusions regarding this safety margin when the critical parameters are different: for steel it is heat transfer to the unexposed side and for FRP composite it is loadbearing capacity. For steel structures, loadbearing capacity is not even tested, but guaranteed by design, according to Part 3 of the FTP Code (IMO, 2012); only applied insulation, penetrations, etc. are tested. What can at least be said for sure is that the safety margin will generally be increased for FRP composite structures if applying the design load instead of the prescribed 7 kN/m in structural fire integrity tests.

In addition to the testing procedure, set-up and equipment, an important factor for the experimental reliability is the production of samples, which will always have some natural variation. As noted in MSC.1/Circ1574 (IMO, 2017), for FRP composite these can come from anisotropy and inhomogeneity of the material and will affect the test results depending on the positioning. As the FRP composite material is deteriorated, e.g. from different plies of resin-impregnated fiber cloths delaminating, there can also be local and global effects on the result (IMO, 2017). This may explain some of the variations in the test results, which are however difficult to draw any conclusion about since only single tests were conducted for each setting.

6.1.4 Paper I and Paper VI

The research method used in Paper I and Paper VI was primarily "*description*". In Paper I the objective was to provide a procedure for identifying fire hazards and performance criteria, and in Paper VI to develop advice for the Regulation 17 assessment procedure. To achieve this, structured and elucidating descriptions were key. In Paper I it was first found necessary to provide a description of the regulatory framework. This was difficult, as increasing comprehension of the framework also revealed further complexities, unclarities and missing links. Important unclarities were attempted to be described visually, such as the connection between different objectives as well as functional and prescriptive requirements (Figure 6), and missing connections between regulations (Figure 12).

Both Paper I and Paper VI were based on literature studies resulting in descriptions documented elsewhere. The work for Paper I included a review of all the regulations in SOLAS chapter II-2 to identify potential deviations and fire hazards when using FRP composite. It was systematically documented in Chapter 3 of MSC.1/Circ.1574 (IMO, 2017). While the intention was to consider all types of applications of FRP composite, the review was conducted with typical solutions in mind. These were primarily thermally insulated internal structures and exterior surfaces protected with sprinkler. Non-insulated internal structures were also foreseen, even if such solutions had not been found, and passively protected external surfaces were considered. Nevertheless, the foreseen solutions at the time likely implied some limitations to the review, which should hence not be considered applicable to all (future) solutions. Another literature study conducted for Paper I reviewed the relevant IMO test procedures and gave advice regarding limitations and necessary considerations for FRP composite structures. It was summarized in Appendix D of MSC.1/Circ.1574 (IMO, 2017). The advice were based on many years of experience in testing such materials, and may not be considered a scientific result based on a structured review of the procedures. Furthermore, as for the review of potential deviations, the conclusions implied a limitation to the materials tested. Nevertheless, important experiences were judged noteworthy for others and worked as a basis for the experiments in Papers II, IV and V. The experimental experiences for example also led to the development of a new test rig for the Cone Calorimeter (Sandinge, Blomqvist, et al., 2022). For Paper VI, another literature survey was conducted to provide a theoretical foundation for evaluating MSC/Circ.1002 as a risk-based approach. The aspects of risk with relevance for the papers of the thesis are documented in chapter *3. Background to risk assessment*. It was noted that the views on risk and risk management have changed much over the 25 years since MSC/Circ.1002 (IMO, 2001) was developed. It gave further clarity to evaluate the assessment procedure and showed that some aspects in MSC/Circ.1002 are not fully up to date. Paper VI therefore widened the scope to also consider the later developed and more general guidelines for alternative maritime solutions, MSC.1/Circ.1455 (IMO, 2013).

While being denoted "*description study*" in chapter 4.7, particularly Paper VI, but also Paper I, could be said to be based on a form of "*case study*". The papers were namely founded on a study of 16 Regulation 17 assessments, primarily involving FRP composite structures. Half of these were led by the author and most of them involved the author to some extent. While this experience is quite unique, the objectivity could be questioned of a case study with such large personal involvement. An objective mindset was pursued throughout the analyses, but it is impossible to claim that it was attained. An alternative could have been to only study assessments without any personal involvement, but this would have led to a very limited basis. Very few external publications from Regulations 17 assessments were found, even from those performed in research projects. These were nevertheless seen as an important generalizing contribution to the studied cases. Regarding the type of study applied, it should be noted that Paper VI was rather performed with inspiration from the case study method, while it differed in some key respects. In particular, the study was not performed to attain an objective description of the studied cases, i.e. the assessments themselves, but rather to study how the assessment procedure in MSC/Circ.1002 had been applied. This was done to evaluate the guidelines' function and applicability, and to gain an understanding for potential development areas. The possibility to use and combine multiple methods and sources of information in this way is a strength of the case study method according to Yin (2018).

As noted initially, both Paper I and Paper VI were mainly considered to be based on "*description*" as research method, even if this is not a very common research method referred to. From the above discussions, the research method could also have been considered to be "*case study*", "*survey*" or even "*document analysis*" (Bowen, 2009). In particular Paper VI, for which the assessment guidelines (IMO, 2001) were systematically reviewed and evaluated, in line with the definition of a document analysis (Bowen, 2009). However, it is not the notion of a study that is important but that it has been performed in a scientific manner to provide value for research. It has even been questioned if it is suitable to use well-established research methods at all, since it restricts scientific progress by limiting the potential research activities (Feyerabend, 2010). Such a statement implies that the definition of research is wider than the research methods defined to create it. From a general perspective, research could then be defined as a combination of (existing) knowledge to create new knowledge. In Paper I the new combination would be the way the regulations were investigated and connected with performance of FRP composite, and in Paper VI how the assessment procedure was evaluated.

6.2 Achievement of research objectives

The research objectives have been achieved in different ways, which is the nature of objectives; they give indication of what should be achieved but not exactly in what way or to what extent. This has been defined by the research process, which is one of the benefits of open research; to be able to concentrate on hypotheses formulated by findings along the way. Below is described how the three research objectives were achieved, based on the publications of this thesis.

6.2.1 Research objective 1

Investigate strategies for identifying fire hazards and performance criteria connected to the use of FRP composite

Paper I clarified the structure of the fire safety regulations in SOLAS and investigated how introduced hazards should be identified. As noted in Paper VI, the prescribed "*identification of hazards*" in MSC/Circ.1002 (IMO, 2001) is rather a preparatory step to develop fire scenarios; fire hazards are in practice primarily identified from deviated prescriptive requirements. However, not only deviated prescriptive requirements need to be considered, as required by the assessment procedure. There are also implicit requirements, which for example stem from the regulations' assumption of steel structures and from a mismatch between (deviated) prescriptive requirements and functional requirements. It is therefore necessary to seek the intention of the requirements, for which Paper I notes different strategies. Based on application of the different strategies, Paper VI concludes it to be necessary to at least additionally evaluate the achievement of all the regulations' objectives and functional requirements when identifying fire hazards of alternative designs.

It is also suggested by Paper I, and elaborated in Paper VI, that identified hazards should preferably be managed in delimited affected areas, e.g. those covered by each regulation. This will structure the assessment and simplify determination of performance criteria. Paper I exemplified a procedure for this for reaction to fire properties, referring to performance criteria in requirements and related tests. It was concluded that ignitability is generally not an issue for FRP composite, and that smoke generation and toxicity is to a large extent considered by assessing the *fire growth potential*. It can be divided in (1) amount of combustible materials, which is not well restricted, and (2) their flame-spread characteristics. The latter can be achieved in different ways for interior and external surfaces and should be the focus when it comes to reaction to fire properties.

The suggested procedure in Paper I to identify fire hazards and relate the performance of FRP composite to relevant tests and criteria was visualized in this thesis as a flowchart.

6.2.2 Research objective 2

Explore verification methods for the performance of FRP composite and safety measures using fire testing and modelling

Standardized tests referenced in the regulations are a good basis for the assessment, but account must be taken to that these have often been developed based on critical characteristics for steel structures. New test methods and models to support the assessment were therefore explored in three areas: fire growth potential (flame-spread), containment and structural fire integrity.

Paper II demonstrated how flame spread on external ship surfaces could be evaluated based on a test method for building façades, SP FIRE 105 (SP Fire Technology, 1985). The test method proved suitable to evaluate external fire spread and performance criteria were discussed for both active and passive safety measures. It was shown that flame spread on an unprotected FRP composite panel can be rapid, mainly in the vertical direction, depending on the fire exposure. A well-dimensioned water-based extinguishing system proved effective to control an established fire in FRP composite as well as for preventing fire involvement, if pre-activated. Comparison was made with the heat exposure in smaller-scale methods, which indicated that a passive system passing Part 5 of the FTP Code could potentially prevent external fire spread also in larger scale.

Paper III developed a new model for estimating temperatures in pre-flashover fires in enclosures where boundaries can be assumed to have lumped heat capacity. This was needed to evaluate whether the often much more insulating FRP composite structures (with thermal protection) could worsen the conditions inside the fire enclosure. The model was derived from physical equations for mass balance in the enclosure and heat transfer at the boundaries; it can thus calculate the temperature development in a fire enclosure depending on the thermal insulation of boundaries. The model gave accurate results when compared with a few full-scale experimental scenarios, particularly considering the model's simplicity and computation time.

Paper IV and Paper V explored design and verification of structural fire integrity of FRP composite structures. Prescriptive tests for maritime structures are based on evaluation of heat transfer, which is critical for steel, while loadbearing capacity was confirmed critical for FRP composite. It was also shown that the applied load is dimensioning for the performance in structural fire integrity bulkhead tests; hence the design load should be applied, not 7 kN/m as prescribed. This insight can simplify the testing of insulated FRP composite structures, by testing the strongest panel in a non-stiffened design concept. It was also noted that structural fire integrity for such structures seems associated with a critical temperature for debonding of the exposed laminate and the core. Heat transfer to the exposed surface was however concluded to not be a good basis for evaluation of structural fire integrity, despite current suggestions in IMO discussions. A temperature criterion is neither needed when there are already relevant structural deformation criteria in Part 11 of the FTP

Code; it would further not be applicable for non-insulated solutions. One such structure, with two cores and three laminates, was evaluated using the design load, as recommended. It had notably improved structural fire integrity (90 min compared to ~60 min) and showed great potential for similar multiple-core sandwich designs, not only where insulation cannot be used.

6.2.3 Research objective 3

Develop how fire safety of ship with FRP composite can be assessed based on MSC/Circ.1002

Paper VI concluded that MSC/Circ.1002 is in some regards inconsistent and vague as a risk assessment guideline. Above was described how the papers contributed to the identification of fire hazards and performance criteria, and how tests and models can be used to verify the fire safety of FRP composite structures. Further contributions to the risk assessment procedure include the developed flowchart, which was extended to cover both reaction to fire and fire resistance properties. It summarizes much of the knowledge created in the papers and, in addition to relating hazards to performance criteria in tests, it helps to point out hazards which are not considered in the tests. These need to be considered in other ways in the assessment.

Paper VI gives further advice for how to manage the fire hazards in the assessment and, as noted above, suggested to proceed with the assessment divided in separate areas. The risk characterization in each area must be suitable to describe the introduced novelty in terms of fire safety without being overly complicated or time consuming. An adaptable risk assessment framework was therefore developed to describe and evaluate the risk in different areas, or for the whole assessment, at one of four levels of sophistication. The risk characterization outlined in MSC/Circ.1002 may hence not be suitable, depending on for example the scope, potential safety measures or optimizations.

6.3 Research purpose – relevance and outlook

As mentioned at the beginning of this chapter, the purpose of the research in this thesis has been to provide for assessment of fire safety of FRP composite ship structures. The relevance of this purpose is supported by that both the industry and authorities want simple procedures for approval. The IMO guidelines in MSC.1/Circ.1574 (IMO, 2017) were developed much based on the research work of this thesis, primarily intended for Administrations but referred equally by the industry. The guidelines give an overview to the potential hazards introduced with FRP composite structures, but they have been criticized for not providing sufficient performance criteria. This is a balance between how much should be specified and the openness to be provided for alternatives. Defining performance criteria for FRP composite structures today may hinder other materials or applications in the future. The guidelines were therefore intentionally left without performance criteria, which fall within the scope of each assessment to determine. In these lines, the framework provided for risk characterization at different levels is adaptable to the studied object, attempting to simplify assessment and approval at the same time as an openness is provided for alternatives.

The foundation for successful guidelines is that they are understood and followed by all stakeholders. Otherwise the risk of failure is evident. A fear among some Administrations and industry stakeholders is that FRP composite structures will be approved with insufficient protection if instructions are not sufficiently specific. What they are indirectly aiming for with such arguments are not only performance criteria but specific solutions which will provide sufficient safety. That is, prescriptive requirements applicable to FRP composite structures. This could significantly simplify the approval process, reduce the uncertainties in design, and hinder solutions with insufficient safety. As a matter of fact, such a development may be necessary to release the shipbuilding industry to FRP composite structures. The prescriptive requirements could for example require 60 minutes of thermal fire protection of interior surfaces, passive or active protection of external surfaces over 10 m^2, and to only allow loadbearing structures on ships within 4 hours from land. However, the formulation of such requirements will make it very difficult to introduce alternatives to those solutions, even if sufficient safety can be demonstrated. A limited opening for novel design today can thus reduce the openness for innovation in the future. It could therefore be a better option to make known how the assessment of fire safety of FRP composite structure should be performed and reviewed.

The purpose to provide for a fire safety assessment of FRP composite structures was targeted by studying different aspects, as defined by the research objectives discussed above. These describe areas with, at the time, identified knowledge gaps necessary to bridge in order to carry out the assessment and manage the hazards of FRP composite. There is obviously a need for more knowledge in several of these areas but what particularly is required is experience:

- experience of performing Regulations 17 assessments, to better comprehend the procedure and to present effects on safety in a transparent and comprehensible way, and
- experience of reviewing and approving the assessments as part of the iterative risk-based design spiral.

Furthermore, new knowledge and skills are required at the shipyards and amongst the ship crew, to properly install and manage the new structures, new equipment and new routines. Each of these areas requires the development of completely new skills, which will only be overcome with experience, indeed in the same way as it was done about 150 years ago; the shipping industry was then going through a revolution as wood in ship structures was being replaced by iron and steel. Attempting to pioneer the new materials, people said: "*Iron won't float. And you want to use this for shipbuilding?*". The article in The New York Times in 1892 ("Ships of wood or metal", 1892) tried to convince of the material's superiority if properly used and argued against concerns over safety. Today, similar voices are heard regarding FRP composite: "*FRP composite is combustible. And you want to use it for shipbuilding?*" There are limited guidelines, rules and experience of this new technology for large commercial ships. However, hopes are that the increased knowledge by this thesis will provide a step towards improved assessment and safer use of FRP composite structures. This is needed to ensure, and convince, that sufficient safety is achieved, and to start a new revolution towards lightweight ships in acceptably deep waters.

7 Conclusions

The purpose of this thesis has been to provide for assessment of fire safety of FRP composite ship structures, by studying different aspects. It was concluded that:

- SOLAS' fire safety regulations have unclear connections between prescriptive and functional requirements. It is thus necessary to evaluate the achievement of all the regulations' objectives and functional requirements when considering alternative solutions. For FRP composite structures, it must continuously be considered that the regulations were formulated with steel structures in mind, which causes implicit requirements.
- Identified hazards should preferably be managed in delimited areas, for example those covered by each affected regulation, which will structure the assessment and simplify determination of performance criteria. A procedure for this, based on relevant tests, was presented and illustrated in a flowchart, which also helps to point out hazards not addressed by the tests.
- A framework was proposed to characterize and evaluate the risk in different affected areas, or in all areas, at one of four levels of sophistication. The level should be chosen ensuring that effects on fire safety can be described with sufficient safety margin, i.e. adapting the assessment rigor to uncertainties. The level given in MSC/Circ.1002 may hence not be suitable.

The thesis investigated fire performance verification of FRP composite structures and potential safety measures in different areas, with the following conclusions:

- It was shown that the fire protection of external surfaces can be verified through a test method for building façades, SP FIRE 105.
- To compare heat spread through steel and insulated boundaries, a physical model was derived and validated through full-scale tests. While the risk of increased heating in FRP composite fire enclosures was dismissed, the model has further use for applications with lumped heat capacity.
- Structural fire integrity should be tested with the design load, not 7 kN/m as prescribed, since the loading is dimensioning. Further, the temperature at the exposed surface is not a good measure of performance. A new multiple-core sandwich design showed great potential in structural fire integrity, but flame spread on the non-insulated surface must then be managed.

The research in this thesis has actively been implemented to support the shipbuilding industry and authorities. Not least, it formed the basis when the author composed the IMO guidelines in MSC.1/Circ.1574 (IMO, 2017), supporting ship builders and Flag States when assessing and evaluating the fire safety of FRP composite ship structures.

8 Future work

The thesis is based on conclusions from studies addressing displacing passenger ships. Many of the results may with some consideration also be applicable to other ship types, such as cargo ships, high-speed craft and military vessels. A tanker can for example require other safety measures and a different approach to assess safety due to a diverging fire load and great threats posed against the environment. Other necessary considerations are for example operational conditions, value of cargo, current hazards and threats to the ship. Transferring the current research to other ship types would hence require further research.

Regarding fire performance and verification of FRP composite structures, this thesis primarily addressed flame spread, containment and structural fire integrity. Another area of interest relating to fire safety is for example firefighting, which has not been significantly addressed in research. Some examples exist (e.g. Carlsén & Winkler, 2000; Falkman, 2013) and much experience is available from military applications of FRP composite ship structures. Knowledge and best practise could therefore beneficially be transferred and evaluated regarding applicability on commercial ships in future research.

Further relevant future research topics identified throughout the journey of this thesis are elaborated below.

Improved verification and evaluation

While SP FIRE 105 was found highly suitable to evaluate the fire protection of external combustible ship surfaces, some adjustments and clearer performance criteria are needed, which require further research. It is for example necessary to define a strong criterion for when to activate an active system, and it was proposed to change the fire source to a gas burner for increased reliability. Further research should also address a wider validity of the test method, for example by considering lateral fire spread in case of windy conditions, e.g. as in MSC/Circ.1268 (IMO, 2008a). It would require a larger panel, and would make the test more complex, but it would be a relevant aspect to consider (see e.g. Song et al., 2024). It would also be relevant for future research to investigate the possibility of using a smaller scale method for more cost-effective evaluation of fire protection of external ship surfaces.

The tests conducted in Paper IV included five different sandwich panels, most of which were designed based on the same principle. The applicability of the conclusions for other designs, e.g. stiffened solutions, thick laminate sandwich panels etc. needs to be further investigated. In particular, it was noted that investigations should be carried out to explain the early collapse of the thick-laminate bulkhead. Further research is also needed to better explain the failure sequence of the bulkhead sandwich structures with relatively thin laminates. It was for example noted that the temperature increase accelerated at the interface between the core and exposed laminate shortly before deformation and failure of the bulkhead. Such knowledge is important to provide for improvement of the loadbearing capacity, and to allow for more cost-effective approximation and product development.

Developed modelling

As noted above, further testing is needed to support fire-performance verification of FRP composite structures. It is also needed to enable less time consuming and costly investigations by modelling, for example of the abovementioned façade fire test (see e.g. Anderson et al., 2017; Carlsson & Karlsson, 2001; Nilsson et al., 2018). The enclosure heat transfer model developed in this thesis is considered to have great potential but has yet to be further explored and validated in future research. It was validated against four test scenarios with two different fire sources and two boundary set-ups in one room geometry. Beshir et al. (2021) also applied the model with good results. However, for the model to find increased use, it needs validation with a further variety of boundary conditions. As noted in the discussion, it would also be interesting to validate the model based on expected use, i.e. using a free-burning HRR curve. The validation in this thesis was done using the actual HRR in relevant tests, which is more valid but unlikely available in a real case. Future research should also carry out a sensitivity analysis of the input parameters, to give further guidance regarding how sensitive parameters should be set. The simple and quick model can further be utilized in future research for high-number simulations, e.g. to provide a temperature probability distribution.

New FRP composite designs

Something believed to increase the commercial interest in applying FRP composite structures is a relieved need for thermal insulation. It would significantly reduce the weight and the required volume of structures as well as the complexity of applications. In this regard, the tested multiple-core structure showed great potential, and several aspects would be interesting to investigate further. A panel with four laminates and three cores was for example later developed and tested (Rahm & Blomqvist, 2015), but the variety of possible structures is endless and calls for thermo-mechanical optimization. The multiple-core design concept, or a combination with insulation, could also be an option to achieve significantly improved structural fire integrity; it could be a means to achieve long-lasting global strength, e.g. during a safe return to port or for main vertical zones. Structural fire integrity in case of a long-lasting fire is something that certainly needs to be further investigated to allow for large applications of FRP composite structures on ships in far-reaching operation in the future.

New ways of ship design

This thesis has aimed to contribute to opening up for a new technology, in form of FRP composite ship structures, which could have many incentives. Primarily, it would reduce the use of fossil fuel but it could also enable use of other new technology, such as air-assisted propulsion, foiling, or battery propulsion, as such technologies become more interesting for a lighter ship. It could also allow for reduced manning, thanks to reduced maintenance, and provide for a new freedom in ship design. To gain the most economical and environmental benefits of FRP composite materials, ship design likely needs to be further reformed. It needs to not only involve material equivalency to steel, but the particularities of the new material must be considered. For example the anisotropic characteristics, insulation properties and corrosion resistance, but also the construction technique, joining of the materials, etc. On one hand, all these new unfamiliar material characteristics impose practical problems to be solved, but on the other hand, they provide completely new ways of ship design and ship building. For example, the Swedish Visby class corvette is built entirely in FRP composite; instead of installing internal bulkheads in a framework of load-bearing structures, all internal bulkheads contribute to the global strength. This reduces the need for longitudinal stiffeners and makes the ship even lighter. Another advantage of FRP composite structures is the possibility to form complicated three-dimensional shapes and to create structures without conventional joints (see e.g. Geuskens et al., 2019). Hence, the particularities of FRP composite make it possible to reconsider basic ideas in ship design. This was partly investigated in the Fibreship project (Jogia & Jurado, 2020) but is an area in need of further research as FRP composite structures become introduced in ship building.

Limited experience requires research

Even if FRP composite structures perform well in current and developed tests and are assessed safe, unknown risks can still appear in a real application. There is for example limited long-term experience regarding the reliability of the structures and of potential safety systems. This includes mechanical behavior, such as ultimate limit strength, fatigue and other degrading mechanisms related to ageing, including fire performance. While this was for example addressed by Sandinge (2021), it is an area in need of further research. Structures will eventually also need to be repaired, which means that their post-repair fire performance will need to be guaranteed.

Examples of application are needed for many reasons, as discussed in section *6.3*, and the limited field history should argue for caution. It could be wise to initially build experience by demonstrating relatively simple and safe designs, such as universally thermally protected interior structures and superstructures. Thereafter it could be relevant with more complex and substantial designs in FRP composite. The former could be cabin modules or deck houses in FRP composite, which should not require lengthy or detailed assessments, as illustrated in Appendix E of MSC.1/Circ.1574 (IMO, 2017). Multiple decks on a cruise vessel or a full ship in FRP composite will on the other hand come with a large need for verification and interaction with the Administration to find an acceptably safe solution.

Introducing new technology and, likely, unknown risks also introduces an ethical perspective. The character of the risk will change compared to a conventional vessel, which can affect the acceptance of the risks amongst passengers and the crew. An area for future research could for example be to study human behavior and if people would react differently in case of fire on a ship with FRP composite structures. The decision to introduce FRP composite structures is likely commercial and made by the ship owner, while risk is carried by those onboard. The shift in the character of the risk and the effect on risk perception and acceptance could hence also be an area for future research. It can in this sense be repeated that it could be wise to start with allowing relatively simple and safe designs, to avoid building a stigma against FRP composite structures in case of a fire.

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