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Abstract

Main authors of the chapter: NMTF

The RAMSSES consortium developed a methodology called Smart Track to Approval (STtA), which is aiming for accelerating the market uptake of advanced innovative materials in the maritime sector by shortening the two main elements of the risk-based design process, which are the risk assessment and testing process. For risk assessment, currently carried out case-by-case, the project aims to introduce "standard risk scenarios" covering a range of similar applications. These can be referred to in the future without the need to carry out extensive quantitative risk assessments. For testing, the database of test results and pre-approved solutions, to be developed in RAMSSES, will avoid the necessity of repetitive tests if a simple qualitative risk analysis shows that relevant results and solutions are already available.

The results of the RAMSSES project can be of value for the evaluation of MSC.1/Circ.1574 Interim guidelines for use of fibre reinforced plastic (FRP) elements within ship structures: fire safety issues.

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Contents

1 Executive summary

Any product design, material or production process in the maritime sector is subject to approval by supervising authorities, mostly based on prescriptive rules and regulations. During recent years, opening clauses were introduced allowing the demonstration of equivalent safety for alternative designs, arrangements and innovative solutions not covered by the prescriptive requirements. This approach requires a case-specific risk assessment, from which specific “risk control measures” are derived.

While this process in principle is well known and increasingly established in industrial practice, the procedure is more or less difficult, costly and time consuming depending on the risks of an application (defined by the probability an accident happens and the consequences of it). However, the market uptake of lightweight composite solutions is still hindered by the fact that this procedure makes it very hard to know before signing a shipbuilding contract whether or not an alternative design will meet all safety requirements or that additional risk control measures are necessary.

To overcome this barrier the RAMSSES consortium developed a methodology called Smart Track to Approval (STTA), which is aiming for accelerating the market uptake of advanced innovative materials in the maritime sector by shortening the two main elements of the risk-based design process, which are the risk assessment and testing process. For risk assessment, currently carried out case-by-case, the project aims to introduce “standard risk scenarios” covering a range of similar applications. These can be referred to in the future without the need to carry out extensive quantitative risk assessments. For testing, the database of test results and pre-approved solutions, to be developed in RAMSSES, will avoid the necessity of repetitive tests if a simple qualitative risk analysis shows that relevant results and solutions are already available.

With every tested application the database will become more valuable to ship designers; when they find solutions for similar applications which have been tested and approved before, time and costs are saved. This time can then be used to assess the safety for new applications.

The Smart Track to Approval (STTA) is not changing any rules and regulations, but rather makes use of the existing instruments and enabling re-using information and solutions from previous projects and safety assessments. An overview of the history of SOLAS fire protection requirements as well as an overview of class rules for composite vessels provide the basis for the STTA.

In January 2020 the RAMSSES consortium presented the concept of the STTA to the Ship Design and Construction Sub Committee. The Sub Committee agreed to invite interested Member States and international organizations to consider the need to review MSC.1/Circ.1574 and to submit any proposals to that effect to SDC8 (2022). A single submission could lead to the start of the evaluation process, possibly followed by the development of amendments in future sessions.

2 Introduction

Main author of the chapter: Arnold de Bruijn (NMTF)

Any product design, material or production process in the maritime sector is subject to approval by supervising authorities, mostly based on prescriptive rules and regulations. During recent years, opening clauses were introduced allowing the demonstration of equivalent safety for alternative designs, arrangements and innovative solutions not covered by the prescriptive requirements. This approach requires a case-specific risk assessment, from which specific “risk control measures” are derived.

While this process in principle is well known and increasingly established in industrial practice, the procedure is more or less difficult, costly and time consuming depending on the risks of an application (defined by the probability an accident happens and the consequences of it). However, the market uptake of lightweight composite solutions is still hindered by the fact that this procedure makes it very hard to know before signing a shipbuilding contract whether or not an alternative design will meet all safety requirements or that additional risk control measures are necessary.

2.1 Technical approach

No project, even the size and duration of RAMSSES, can change existing rules and regulations in the scope of its work. RAMSSES therefore follows a multi-level approach to make sure solutions developed in the demos are acceptable and the “track to approval” can be simplified and shortened in the future: This “Smart track to approval” aims to shorten two main elements of the risk based design process:

- **Risk assessment**. Currently carried out case-by-case, the project aims to introduce “standard risk scenarios” covering a range of similar applications. These can be referred to in the future without the need to carry out extensive quantitative risk assessments.

- **Testing**. As an outcome of a risk assessment, expensive and lengthy physical tests are often required to prove certain functional properties. The database of test results and pre-approved solutions, to be developed in RAMSSES, will avoid the necessity of repetitive tests if a simple qualitative risk analysis shows that relevant results and solutions are already available.

With every tested application the database will become more valuable to ship designers; when they find solutions for similar applications which have been tested and approved before, time and costs are saved. This time can then be used to assess the safety for new applications.

To accelerate the market uptake of lightweight solutions even further, it is necessary the database will continue to exist, new solutions can be included in the future and be available to the maritime sector and the methodology can be put into practice. Therefore the RAMSSES consortium has renamed the database to an innovation platform and transferred the management and maintenance of the database to the E-lass network. E-lass is the European network for lightweight applications at sea, with approx. 600 members.

3 Current regulatory regime

Main author of the chapter: Arnold de Bruijn (NMTF)

The Smart Track to Approval (STTA) is not changing any rules and regulations, but rather makes use of the existing instruments and enabling re-using information and solutions from previous projects and safety assessments. For the application of composite materials, the fire safety is of primary concern. Therefore, the RAMSSES consortium created a short history of fire protection requirements & introduction of composite materials, which is included in Annex A. This has been done in order to have at the same time in one chapter a general, complete and objective perspective of the history of the fire protection requirements at IMO. In that sense, the reader can have an overview of the regulatory context in which the use of composite materials onboard ships takes place.

In Annex B the main certification processes considered by the classification societies and their requirements regarding the design and the hull construction of a hull made of fibre-reinforced plastic within the scope of ship classification or hull certification are evaluated. Different certification schemes are usually used by the classification societies to assess materials and equipment fitted on board ships classed and to assess ships constructions built using composite materials. All these global survey schemes are based on the following steps of assessment:

1. Raw materials
2. Structure design
3. Specimen tests of FRP
4. Manufacturing and testing at works
5. Final test and inspection of the construction.

Both annexes served as a basis for the development of a new methodology for design and approval, a new approach to achieve a “Smart Track to Approval” (STTA) for innovative solutions, including new materials.

4 Smart Track to Approval

Main authors of the chapter: Arnold de Bruijn (NMTF), Stéphane Paboeuf (BV); Franz Evegren (RISE)

The proposed STTA is based on the experience gained during previous research or commercial projects, by sharing knowledge with other industrial sectors, i.e. aeronautics, railway and automotive, by using existing database and by standardizing results. Annex C provides more details of the methodology including guidelines covering the topics of Fire Safety, Mechanical Performance. On request of the Maritime Advisory Group, the consequences for damage stability and comfort (vibration and acoustics) are also briefly evaluated. For each topic there is a subchapter with background information, as well as guidance for both the design and approval phases.

The STTA is composed of two layers: one led by the classifications societies and one led by the shipyards, engineering or design offices, see Figure 7. The STTA will be a first step to prepare an Approval In Principle (AIP), leading to the certification or the classification of a vessel or a part of the vessel. The STTA is developed in the RAMSSES project to propose an alternative to the prescriptive rules concerning the introduction of innovative materials in the shipbuilding industry. Figure 7 resumes the process and gives the main steps of the STTA.

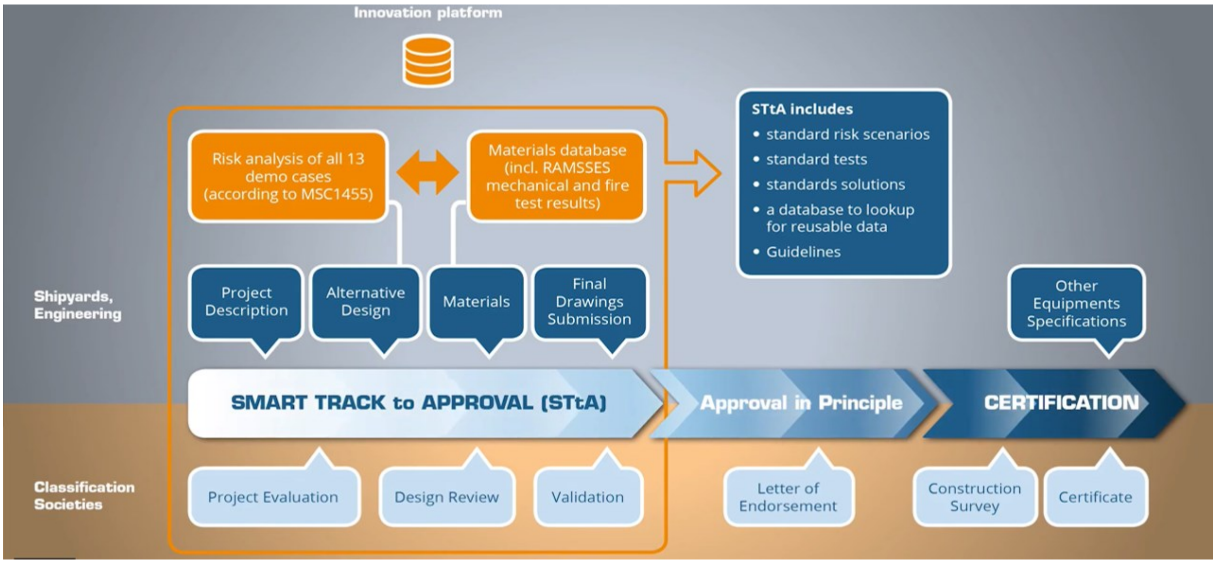


Figure 1: Smart Track to Approval, process overview.

The ambition is that the STTA will mainly be used for alternative design solutions performed in accordance with the circular MSC.1/Circ.1455, see Figure 8. In the context of RAMSSES, several risk analyses are carried out to demonstrate the feasibility of new concepts, to validate different design options, to confirm the performance of innovative materials and to prove equivalent fire safety compared to conventional structures. All risk analyses will be supported by numerical simulations, such as Finite Element Analysis, Computational Fluid Dynamics, evacuation simulations, thermo-mechanics calculations, etc. Model or full scale test for the RAMSSES demonstrator cases, will be used to verify the assumptions in the assessment.

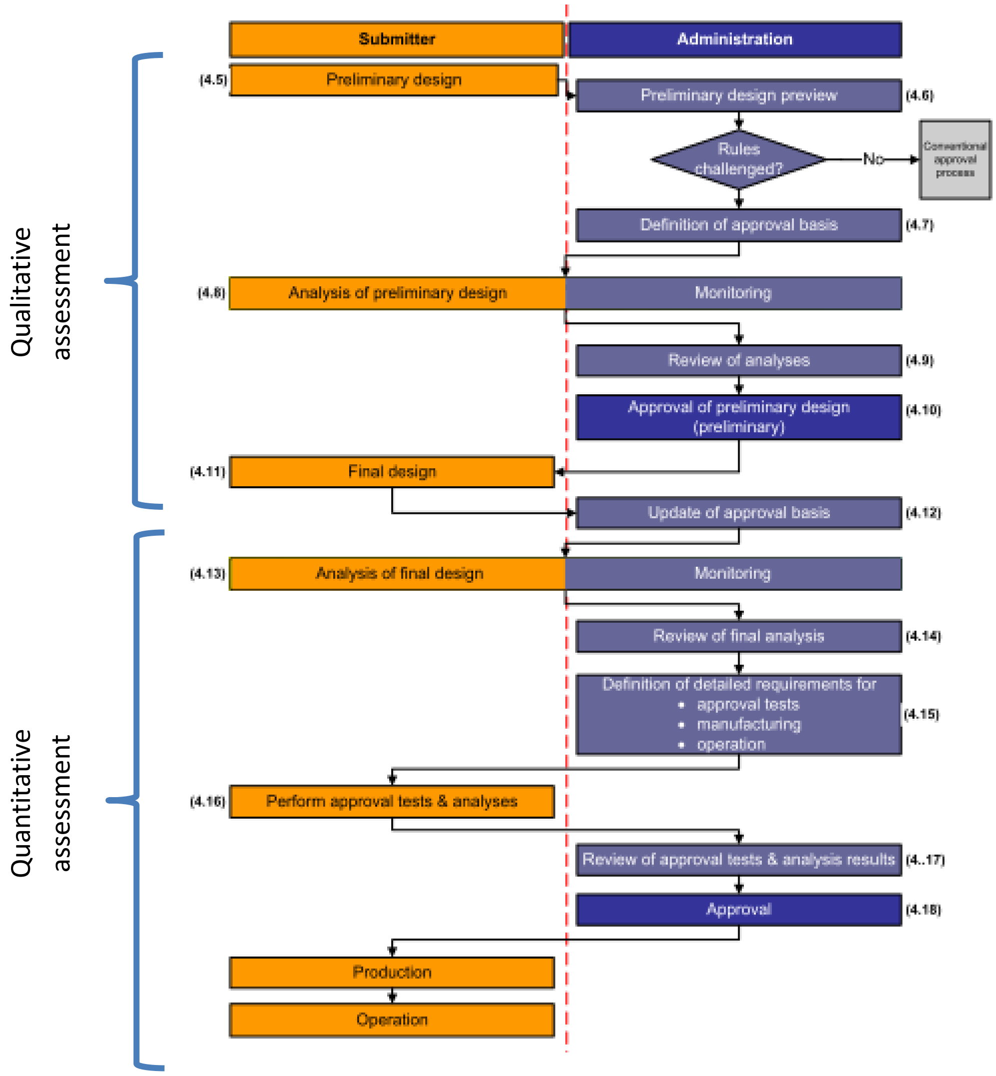


Figure 2: Design and Approval Process [14].

From the results of demonstrator case risk analyses, the STTA will propose standard risk scenarios, standard tests, standard solutions and a database to lookup for reusable data. The quantitative analyses are currently carried out on a case-by-case basis. The objective aims to develop standard risk scenarios covering a range of similar applications. These can be referred to in the future without the need to carry out extensive quantitative analyses or tests. The definition of standard risk scenarios will be based on the demonstrator cases developed in RAMSSES.

The standard risk scenarios will cover the following aspects:

- Fire safety,
- Stability, including damage stability,
- Materials,
- Structural arrangement.

For example, when evaluating fire safety for FRP composite structures, the encountered challenges are often similar. Standard risk scenarios developed in the project cover several applications and include scenarios defining suitable reaction to fire properties for external and internal surfaces as well as required fire resistance for internal and loadbearing bulkheads. As an input to the fire risk assessment, significant testing is often required to prove the functional properties. The second objective of the STTA is therefore the creation of a materials database, named RAMSSES Knowledge Repository, see Figure 9. It is a web browser based platform on invitation access (https://repository.ramsses.eu/) In addition to descriptions of the maritime materials, it will define for example fire safety, mechanical and acoustic properties of materials tested standardized tests. A large number of tests, mechanical and fire tests, will be performed during the 4 years of the RAMSSES project on a multitude of materials, composites and metallic. The database of test results and pre-approved solutions, developed in RAMSSES, should avoid the necessity of repetitive tests if a simple qualitative risk analysis shows that relevant results and solutions are already available. The approach will be documented in a project guideline, which may form the basis for future modified class rules, or possibly amendments to MSC.1/Circ.1574.

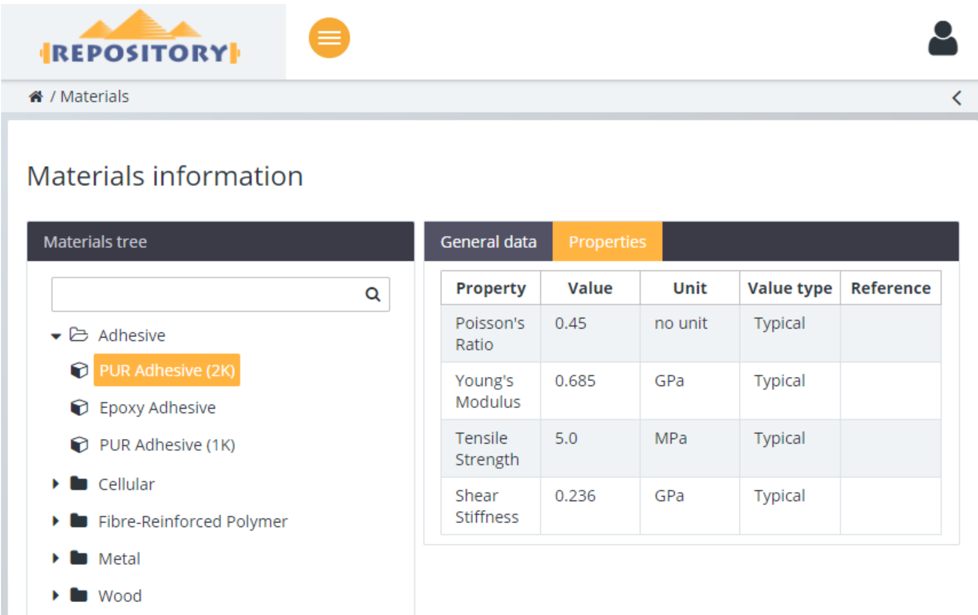


Figure 3: RAMSSES Knowledge Repository platform (https://repository.ramsses.eu).

5 Recommendations to Rule and Policy makers

Main author of the chapter: Arnold de Bruijn (NMTF)

In January 2020, the RAMSSES consortium presented the concept of the STTA to the Ship Design and Construction Sub Committee (SDC7). The presentation was jointly organised with the FIBRESHIP project, another EU project with a more long term approach to FRP vessels. Compared to FIBRESHIP, the RAMSSES project scope is focused on short and medium term results. Since the STTA makes use of existing regulations and enables re-using information and results of safety assessments of previously accepted solutions, it becomes a valuable source for the rule and policy makers as well.

The Sub Committee agreed to invite interested Member States and international organizations to consider the need to review MSC.1/Circ.1574 and to submit any proposals to that effect to SDC8 (17-21 January 2022). A single submission could lead to the start of the evaluation process, possibly followed by the development of amendments in future sessions. In that case the RAMSSES guidelines in Annex C might provide input for developing amendments.

At the moment of writing this report none of the flag states which were contacted by the RAMSSES consortium have collected any experience with MSC.1/Circ.1574, which explains why there are no submissions yet.. The COVID-19 pandemic has led to a drop in newbuilding orders worldwide and running orders were delayed due to travel restrictions, delivery and financial issues. Even without the pandemic the time to complete a single new build project nearly equals the evaluation period of 4 years. Therefore we might need an extension of the evaluation period in order to collect sufficient experience using the guidelines.

The E-lass network will continue to maintain and fill the database, together with new EU projects like FIBRE4YARDS and FIBREGY. Some of the RAMSSES partners have joined those projects as well and will continue working on accelerating the market uptake of lightweight applications and support flag states with safety assessment if required. The database will be mainly used by the maritime sector, but is equally valuable for the rule and policy makers to look into.

6 Annexes

A History of fire protection requirements & introduction of composite materials

A.1 History of SOLAS fire protection requirements

Description by BV

In this paragraph, green text is extracted from the IMO website (http://www.imo.org, [1]), while orange text is quoted from different versions of the SOLAS Convention. This has been done in order to have at the same time in one chapter a general, complete and objective perspective of the history of the fire protection requirements at IMO. In that sense, the reader can have an overview of the regulatory context in which the use of composite materials onboard ships takes place.

A.1.1 1914 and 1929 SOLAS Convention [2][3].

Description by BV

The 1914 SOLAS Convention was developed in response to the sinking of the Titanic in 1912. It presented the first fire protection requirements for international shipping (Chapter IV-Construction Article 19. and Regulations-Construction Article XII. [2], cf. below):

"**Article 19**.

Fireproof Bulkheads.

With a view to retarding the spread of fire, ships shall be fitted with fireproof bulkheads in accordance with the provisions of Article XII. Of the annexed Regulations."

"**Article XII**.

Fireproof Bulkheads.

In parts of a ship above the margin line there shall be fitted fireproof bulkheads which will serve to retard the spread of fire. The mean distance between any two consecutive bulkheads of this description shall not be greater than 40 metres (equivalent to 131 feet). Recesses in these bulkheads shall be fireproof and the openings in these bulkheads shall be fitted with fireproof doors."

These fire requirements have been further developed in the 1929 SOLAS Convention (Annex I. Regulations-Construction Regulation XVI. [3], cf. below):

"**Regulation XVI.**

Fire-resisting Bulkheads.

Ships shall be fitted above the bulkhead deck with fire-resisting bulkheads which shall be continuous from side to side of the ship and arranged to the satisfaction of the Administration.

They shall be constructed of metal or other fire-resisting materials, effective to prevent for one hour, under the conditions for which the bulkheads are to be fitted in the ship, the spread of fire generating a temperature of 1,500°F. (815°C.) at the bulkhead.

Steps and recesses and the means for closing all openings in these bulkheads shall be fire-resisting and flametight."

It is to be noted that for the first time in SOLAS Convention, the definition of the term "Equivalents" was made in Chapter VII. Article 57. [3], without any explicit reference to materials (only particular fitting, appliance or apparatus, or type thereof or any particular arrangement). These "equivalents" could be adopted as long as any Administrations were satisfied by suitable trials showing that these equivalents were at least as effective as that specified in the 1929 SOLAS Convention [3].

A.1.2 The Morro Castle fire [4] and the 1948 SOLAS Convention

Description by BV

The Morro Castle was a passenger ship of the 1930's, built for the New York and Cuba Mail Steamship Company. It did voyages between New York City and Havana, Cuba. On September 8, 1934, a fire was detected in a storage locker. Within the next 30 minutes, the Morro Castle became engulfed in flames. The fire killed 137 passengers and crew members. Aside from the questionable crew practices and deficiencies, the design of the ship and the materials used in its construction highly participated to the fire on-board. For example, the major part of the decor of the ship was made of veneered wooden surfaces and glued panelling that helped the fire to spread quickly. Another example concerns the structure of the ship: there existed a wood-lined, six-inch opening between the wooden ceilings and the steel bulkheads. This provided the fire with a flammable pathway that bypassed the fire doors, enabling it to spread. The devastating fire aboard the Morro Castle was a catalyst for improved shipboard fire safety [4].

After the adoption of the 1929 SOLAS Convention, many lessons were learned about the safety of shipping in general, including fire protection. The investigation of the Morro Castle fire, and the lessons learned from it, played a major part in the development of the non-combustible construction regulation which today form the basis of the fire safety regulations for passenger ships. That led to the adoption of the 1948 SOLAS Convention, updated with the 1960 SOLAS Convention.

The 1948 SOLAS Convention introduced new fire safety concepts, all listed in Chapter II-Construction, Part D-Fire Protection in Accommodation and Service Spaces. Among them, the following ones can be listed: "A" and "B" class bulkheads, incombustible material, combustible material and steel or other equivalent material ([6], cf. below).

"**Regulation 25**

Application and General

(b) The main structure, including deck and deck houses, shall be of **steel** except where the Administration may sanction the use of other suitable material in special cases. It shall be divided into main vertical zones by "A" class bulkheads (as defined later) and further divided by similar bulkheads forming the boundaries protecting spaces which provide vertical access and the boundaries separating the accommodation spaces from the machinery, cargo and service spaces and others.[…]"

"**Regulation 256**

Definitions

(a) "Incombustible Material" means a material which neither burns nor gives off inflammable vapours in sufficient quantity to ignite at a pilot flame when heated to approximately 1382° F. (or 750° C.). Any other material is a "Combustible Material".

[…]

(c) "'A' Class or Fire-resisting Division" are those divisions formed by bulkheads and decks which comply with the following:

(i) They shall be constructed of **steel or other equivalent** materials.

(ii) They shall be suitably stiffened.

(iii) They shall be so constructed as to be capable of preventing the passage of smoke and flame up to the end of the one-hour standard fire test.

(iv) They shall have an insulating value to the satisfaction of the Administration, with regard to the nature of the adjacent spaces. In general, where such bulkheads and decks are required to form fire-resisting divisions between spaces either of which contains adjacent woodwork, wood lining, or other combustible material, they shall be insulated that, if either face is exposed to the standard fire test for one hour, the average temperature on the unexposed face will not increase at any time during the test by more than 250° F. (or 139° C.) above the initial temperature nor shall the temperature at any point rise more than 325° F. (or 180° C.) above the initial temperature. Reduced amounts of insulation or none at all may be provided where in the opinion of the Administration a reduced fire hazard is present.

(d) "'B' Class or Fire-retarding Division" are those divisions formed by bulkheads which are so constructed that they will be capable of preventing the passage of flame up to the end of the first one-half hour of the standard fire test. In addition they shall have an insulating value to the satisfaction of the Administration, having regard to the nature of the adjacent spaces. In general, where such bulkheads are required to form fire-retarding divisions between cabins, they shall be of material which, if neither face is exposed for the first one-half hour period of the standard test, will prevent the temperature on the unexposed side from increasing during the test by more than 250° F. (or 139° C.) above the initial temperature. For panels which are made of incombustible materials it will only be necessary to comply with the above temperature rise limitation during the first 15-minute period of the standard fire test, but the test shall be continued to the end of the one-half hour to test the panel's integrity in the usual manner. Reduced amounts of insulation or none at all may be provided where the opinion of the Administration a reduced fire hazard is present.

[…]

(l) "**Steel or Other Equivalent Material**." – Where the words "steel or other equivalent material" occur, "equivalent material" means any material which, by itself or due to insulation provided, has integrity properties equivalent to steel at the end of the applicable fire exposure (e.g. aluminium with appropriate insulation). "

Even though the writing of the aforementioned definitions has evolved in the following SOLAS Convention versions, it should be noted that in the "B" Class definition, the need for having non-combustible material was not prescriptive in the 1948 SOLAS Convention.

A.1.3 1974 SOLAS Convention

Description by BV

In the 1960's, a series of fires aboard international passenger ships highlighted many problems, which revealed that fire safety requirements of SOLAS Conventions of 1914, 1929, 1948 and 1960 were inadequate for passenger ships. As a consequence, many changes were incorporated into the 1974 SOLAS Convention. It is still in force today, as amended. One of the most noticeable changes is that fire requirements have been separated into two new chapters: chapter II-1 on Construction – Structure, subdivision and stability, machinery and electrical requirements, and chapter II-2 on Construction – Fire protection, fire detection and fire extinction. The 1974 SOLAS Convention required all new passenger ships to be built of non-combustible materials and to have either a fixed fire sprinkler system or fixed fire detection system installed. Requirements for cargo ships were also updated with special regulations for specific types of cargo ships such as tankers.

In 1990, a fire aboard the Scandinavian Star passenger ship left 158 persons dead. The incident raised a number of issues relating to fire protection an evacuation. In December 1992, IMO adopted a comprehensive set of fire safety amendments, applicable to both new and existing passenger ships. Among them, the upgrading of fire safety-bulkheads to non-combustible materials was required.

Also in 1992, the Sub-Committee on Fire Protection agreed to undertake a comprehensive revision of SOLAS chapter II-2 as it was felt that the adoption, over a number of years, of various sets of amendments, made the chapter difficult to use and to implement. In particular, the existing chapter had many vague phrases such as “to the satisfaction of the Administration” or “a means shall be provided”. In addition, the existing chapter had no support structure to accommodate novel designs and features.

The 1996 amendments to SOLAS chapter II-2 – which entered into force in 1998 – included changes to the general introduction, Part B (fire safety measure for passenger ships), Part C (fire safety measures for cargo ships) and Part D (fire safety measures for tankers).

A new International Code for the Application of Fire Test Procedures was also developed and made mandatory on 1 July 1998. The Code is use by Administrations when approving products for installation in ships flying their flag. The FTP Code provides international requirements for laboratory testing, type approval and fire tests procedures.

A.1.4 2000 amendments – Revised chapter II-2

Description by BV and RISE

At FP37 and MSC61 (around 1993) there where proposals for a comprehensive review of chapter II-2, see e.g. MSC61/6/6. The reasoning behind this was partly that the old chapter had become difficult to overview. Another major reason for the review 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, allowing for buildings to be designed in a more advantageous way with regards to fire safety. The idea was to change from detailed prescriptive requirements to performance-based regulations. The main advantage with performance-based regulations is that they allow for novel designs without compromising fire safety. At MSC 61 the committee agreed that the new chapter should be based on modern fire prevention and firefighting technology and philosophy.

To FP39 Sweden submitted a report discussing the pros and cons with prescriptive regulations and performance-based regulations, (FP39/INF.23). The report also proposed how the new chapter could be structured in a way allowing for performance-based design while keeping the old prescriptive regulations. Some significant features were also the introduction of regulation 17 and the purpose statements in each regulation. The objectives of the old chapter were rewritten and divided into Fire safety objectives and Functional requirements as seen in current regulation 2.

In December 2000, IMO adopted a completely revised SOLAS chapter II-2, which entered into force on 1 July 2002. The new structure focuses on the “fire scenario process” rather than on ship type, as the previous SOLAS chapter II-2 was structured. In addition, to make the revised SOLAS chapter II-2 more user-friendly, specific system-related technical requirements have been moved to the new International Fire Safety Systems Code and each regulation has a purpose statement and functional requirements to assist port and flag State. The revised SOLAS chapter II-2 has a new part E that deals exclusively with human element matters such as training, drills and maintenance issues and a new part F that sets out a methodology for approving alternative (or novel) designs and arrangements, opening the way to possible use of composite materials on-board ships.

It was very clear during the development of the new chapter that it should be possible to introduce novel designs and that any requirement in the new chapter could be challenged by an alternative design providing the same level of fire safety. The main concerns (then and now) were although how to prove that an alternative design provides the same level of safety, and indeed which level of safety the prescriptive requirements provide. For a minor alternative design that only affects a single requirement in the regulations this could be relatively simple. When larger changes are proposed, e.g. use of new structural materials, the analysis becomes more complex.

After discussions in correspondence groups lead by Japan (reported to FP40) and the US (reported to FP44 and 45) it was agreed that an assessment of fire safety when laying claim to part F (SOLAS chapter II-2, regulation 17) should be based on guidelines developed in MSC/Circ.1002. These guidelines define "Alternative design and arrangements" for fire safety, as "[…] fire safety measures […], including alternative shipboard structures and systems based on novel or unique design […]". Alternative shipboard structures were mentioned since it was discussed that the use of different materials in the structure could be a possible alternative design. The definition underlines that alteration of fire safety in such a fundamental way as to use alternative materials in structures is in line with regulation 17.

Despite the obvious advantages that the use of composite materials will offer to the shipping industry (weight reduction, corrosion resistance, fatigue performances, etc.), they have also one major inconvenient: their flammability. And, as the fire protection requirements, throughout the evolution of the SOLAS Convention, led to the restriction of combustible materials on-board ships, one can easily understand the reluctance from different actors of the shipping industry to use these new materials. Once the opening for possible use of composite materials in ship structures was introduced, through part F (regulation 17) in the SOLAS fire safety chapter, it therefore took several years of research before the item was brought up at the IMO.

The work program request was triggered by UK in MSC 87 (2010) which had several questions on their position about recent research program designs. The paper MSC 87/24/9 [7] proposed to consider the establishment of a fire test procedure specific to FRP (fibre reinforced plastic) construction for demonstrating the equivalence of composite materials to steel under the provisions of the 1974 SOLAS Convention at FP 55, Sweden and UK presented ways forward through paper FP 55/19 [8] for the consideration of FRP within ship structures. Two options were proposed in [8] Option 1 consisted of the development of guidelines for the application of SOLAS II-2/17 for evaluating FRP structures (i.e. alternative design and arrangements regulation). Option 2 was about considering that FRP should not be regarded as a novel concept, but instead may be regulated for as a material type within the framework of SOLAS and the FTP Code. Sweden, with the paper FP 55/19/1 [9] supported that FRP ship structures shall be based on a fire engineering analysis (SOLAS chapter II-2, regulation 17 and MSC/Circ.1002 [10]Based on [8] and [9] Sweden submitted a paper at FP 56 (document FP 56/[11]), proposing a new set of guidelines regarding the use of FRP for ships. In response to [11]the paper FP 56/12/1 [12] presented the United States' views on the possible use of FRP materials in ship structures within the limits of the SOLAS chapter II-2 fire safety regime. In this document, they reminded that "*By providing a combination of non-combustible fire protection features and an active fire extinguishing system, a multi-layered system of protection was created where failure of one of the elements would not lead to a complete failure of the system.*" They also state that in case of using composites in ship structures, "*an inoperative or damaged sprinkler system could lead to rapid failure of the division and could cause the production of lethal amounts of smoke and toxic gases. This is inarguably a much lower level of safety than is achieved by the current chapter II-2 requirements.*"

Since 2012, wide ranging discussions on the use of FRP materials took place in the IMO Ship Design and Construction sub-committee between the different stakeholders. In particular, strong disagreements appeared on the definition of which part(s) of the ship that should be possible to construct in FRP. They came to an agreement in the new MSC.1/Circ. 1574 "*Interim guidelines for the use of Fibre Reinforced Plastic (FRP) elements within ship structures: Fire safety issues*" [13], by defining the FRP element as a structure which may be removed without compromising the safety of the ship (in the sense of SOLAS Chapter II-2).

A.2 MSC.1/Circ. 1574: A first step towards the use of composite materials in ship structures

In June 2017, the Maritime Safety Committee approved the *Interim guidelines for use of Fibre Reinforced Plastic (FRP) elements within ship structures: Fire safety issues, [13]*

A.2.1 Context

These Interim Guidelines are intended to be applied when approving Alternative Designs and Arrangements for FRP elements in ship structures in accordance with SOLAS regulation II-2/17. The purpose is to ensure that a consistent approach is taken with regards to standards of fire safety of ships making use of FRP elements in their structures and that the level of fire safety afforded by the provisions of SOLAS chapter II-2 is maintained.

In other words, the guidelines should be applied in accordance with SOLAS chapter II-2 Regulation 17, and complementary to other guidelines related to the approbation of alternative design and arrangements:

- MSC.1/Circ.1455, Guidelines for the Approval of Alternative and Equivalents as Provided for in Various IMO Instruments [14] and
- MSC/Circ.1002, Guidelines on Alternative Design and Arrangements for Fire Safety [10] as amended by MSC.1/Circ.1552 [15].

The guidelines were issued as "Interim Guidelines" in order to gain experience in their use. They should be reviewed 4 years after their approval in order to make any necessary amendments based on experience gained. Member Governments and international organizations are invited to submit information, observations, comments and recommendations based on the practical experience gained through the application of the Interim Guidelines and submit relevant safety analyses on FRP elements used within ship structures to IMO.

A.2.2 Table of contents of MSC.1/Circ.1574

The Interim Guidelines are divided into 3 chapters and 5 appendices listed below:

- Chapter 1 *General*
- Chapter 2 Assessing fire safety of FRP composite structures
- Chapter 3 Important factors to consider when evaluating FRP elements with starting point in the regulations of SOLAS II-2
- Annex A Issues other than fire safety
- Annex B FRP composite materials and compositions used in shipbuilding
- Annex C Recommendations regarding the assessment
- Annex D Fire testing of FRP composite
- Annex E Example of assessment procedure

A.2.3 Summary of chapters 1, 2 and 3

Below, chapters 1, 2 and 3 of the interim guidelines in MSC.1/Circ.1574 are summarized, with large parts quoted from the guidelines.

A.2.3.1 Chapter 1 – General

The guidelines raise issues which are pertinent also to non-combustible FRP composite structures, but any element that can comply with the prescriptive requirements is outside the scope of the guidelines. Only combustible FRP elements are concerned.

The guidelines currently 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.

For the purpose of the guidelines, a FRP element is a structure which may be removed without compromising the safety of the ship.

In accordance with SOLAS regulation II-2/17.2.1, the alternative design and arrangements shall meet the fire safety objectives and the functional requirements in SOLAS chapter II-2.

These guidelines have been developed to provide support for Administration to ensure that fire safety evaluation of FRP elements can be made in a consistent way by any Flag State. The guidelines contain important factors that should be addressed in the engineering analysis required by SOLAS regulation II-2/17.

The guidelines are intended to facilitate the safe use of FRP elements in shipbuilding, which may be categorized, for example, as:

- Integrated structures: elements integrated into the ship structure that do not contribute to global strength (e.g. pool, sliding roof, stage, tender platform, etc.); and
- Components: non-structural parts that are connected to the ship structure via mechanical or chemical joining methods (e.g. balcony, funnel, mast, gantry, flooring, etc.).

These categories and/or examples could be refined and/or expanded, based on experience gained from the use of the guidelines.

There is a diversity of FRP composite compositions with different properties and the scope of their intended use may vary widely. Therefore, the guidelines cannot provide all the necessary information for approval. Nonetheless, it is important that all essential questions are raised during the approval process, which may be remedied by these guidelines. They contain known properties, problems and solutions with regard to fire safety but cannot be considered to cover all possible hazards associated with use of FRP composite materials. Furthermore, use of FRP elements may also affect other parts of a ship's safety than those associated with fire (cf. Annex A of MSC.1/Circ.1574).

A.2.3.2 Chapter 2 – Assessing fire safety of FRP composite structures

Within the guidelines, FRP is defined as multi-material compositions of monolithic or sandwich constructions. Monolithic constructions and skin layers of sandwich constructions are based on long-fibre reinforced resins. Reinforcements can be for example fabrics of glass, carbon, aramide or basalt fibres. Resins shall be based on duromer (thermoset) resins. Sandwich core materials are typically based on structural foams or honeycombs. Coatings (gelcoats, topcoats, or paints), casting masses and adhesives are handled under the guidelines as well.

Assessment, review and approval of FRP elements shall be carried out based on SOLAS II-2/17, MSC/Circ.1002 [10] as amended by MSC.1/Circ.1552 [15] and MSC.1/Circ.1455 [14].

Fire hazards relevant for further investigation, categorized according to the regulations in SOLAS II-2, are particularly:

- Probability of ignition;
- Fire growth potential;
- Potential to generate smoke and toxic products;
- Containment of fire;
- Firefighting; and
- Structural integrity.

A.2.3.3 Chapter 3 – Important factors to consider when evaluating FRP elements with starting point in the regulations of SOLAS chapter II-2

The different fire safety regulations in SOLAS II-2 were analysed with the intention to identify important factors that could be necessary to address when using FRP elements in ship structures. The results of this analysis are presented in chapter 3 of the interim guidelines.

A.3 Other codes: HSC and LY3 Codes

Description by BV

A.3.1 General comments

The main approach of the HSC (High Speed Craft) Code proponents and the rules for LY (Large Yacht) commercial yachts to the IMO is based on the principle that the international conventions for conventional vessels have been mainly developed for vessels engaged in long voyages. The possibility of using other different regulatory criteria, with an equivalent degree of safety, should therefore not be ruled out for new types of vessels engaged in voyages of a specific nature.

This approach has helped to develop a fundamental argument: without changing international rules, it is not possible to change the design of HSC-type vessels and commercial yachts, which hinders the commercial operation of these vessels.

A second important basic argument has been used to promote the development of new rules: a large number of new vessel types have been built and have been in service for a long time and although they do not fully satisfy international conventions, they have proved that they could be exploited with a degree of security equivalent to these conventions when they make journeys of specific nature (limitation of the navigation zones, weather conditions, facilities for the embarked passengers, etc.).

These "alternative" texts, presented to IMO by groupings of Flags States (for the HSC Code) or by the Maritime and Coastguard Agency of the UK flag (including the Red Ensign, i.e. many countries), were accepted only on the basis of facts (ship evolution and low accidentology) and equivalence basis linked to technical adjustments and specific operating conditions.

A.3.2 HSC Code

The first repository published in 1994 was based on the DSC (repository of safety rules for Dynamically Supported Craft) adopted by the IMO in 1977. The DSC recognized that the levels of safety could be considerably enhanced by the infrastructure associated with regular service on a specific route.

The idea of accepting non-conventional building materials is justified by the fact that fast vessels must have a low displacement, and that steel-type materials do not necessarily make it possible to achieve this objective.

The HSC Code bases its new safety criteria on risk management and the traditional protection principle in the event of an accident.

To achieve a degree of security equivalent to international conventions, risk management is based on:

- The layout of the premises (no passenger cabin for example);
- The adaptation of passive safety rules;
- Implementation of specific active security systems;
- Operating limits (allowing, among other things, fast outside help); and
- Quality management and the organization of human factors.

In 2000, two different concepts of protection and assistance were introduced in the HSC Code taking into account the availability of relief and the limitation of passengers giving rise to categories A and B of fast ships, treated differently by the new code.

Finally, it is recalled that the code can be used only in its entirety because if one of the parts of the code were not respected, the overall safety of the ship could be questioned.

A.3.3 LY3 Code on large commercial yachts

The first LY1 Code published in 1998 is limited to commercial yachts of less than 12 passengers. This code, based on the main idea that this type of vessel is of limited length with few passengers on board, proposes safety standards deemed equivalent to international conventions, as the standards of these conventions cannot be applied reasonably or practically to commercial yachts in operation.

The LY2 Code is published in 2004 and limits the size of these yachts to 3000 GT (about a maximum length around 100 m) for the application of the code. A category of yacht with a limitation of navigation (maximum 60 miles of the coast with navigation under weather cover) is created, allowing to adapt safety rules on board ships.

The LY3 Code, published in 2012, updates the previous code to take into account the evolution of technologies related to the yacht, in particular concerning radio-communications.

This last example is representative of the approach followed: the safety of a yacht must be approached from a total point of view, and the improvement of some systems (e.g. the radio-communication allowing faster external interventions if needed) can justify and reinforce the idea that it is possible to adjust the security rules of international conventions by maintaining a satisfactory overall level of security.

A.3.4 Conclusion

For HSCs and large yachts, the approach that allowed the IMO to accept texts adapting the safety rules of international conventions on topics such as the use of composite materials, but also other varied subjects such as that the criteria of invasion, the protection of openings against invasion, etc., is based on the same scheme:

- Impossibility of changing the design of this type of vessel by applying existing international conventions;
- Impossibility of taking into reasonable account all the requirements of international conventions in the context of the specific operation of these ships;

- Possibility of changing the safety rules (passive and active) conventions to conventional ships making long journeys on the assumption that:
    - HSCs have specific operating areas (maximum distance from a shelter, navigation with weather coverage, regular lines); and
    - Commercial yachts are limited in number of passengers, in size, and in some cases, limited in distance from a shelter with navigation under weather coverage.

It is important to stress here that the use of composite materials accepted in these two HSC and LY codes, recognized by IMO, is linked on the one hand to an intrinsic approach of the materials and its insulation for the treatment of fire, and on the other hand, to a specific exploitation of these ships, very different from the conventional ships covered by SOLAS.

A.4 References

[1] International Maritime Organization website. History of SOLAS fire protection requirements. Available at: www.imo.org.
[2] 1914 SOLAS Convention. Available at: www.imo.org.
[3] 1929 SOLAS Convention. Available at: www.imo.org.
[4] SS Morro Castle 1930. Wikipedia article. Available at: www.en.wikipedia.org/wiki/SS_Morro_Castel_1930.
[5] Sea Girt Lighthouse – The Morro Castle. Web article. Available at: www.seagirtlighthouse.com/page/the-morro-castle.aspx
[6] 1948 SOLAS Convention. Available at: www.imo.org.
[7] MSC 87/29/9. 9 February 2010. Proposal for identification of new regulations required for use of composite materials in ship building. United Kingdom.
[8] FP 55/19. 23 May 2011. Consideration of fibre reinforced plastic within the regulatory framework. United Kingdom.
[9] FP 55/19/1. 24 May 2011. Proposal for a new set of guidelines regarding fibre reinforced plastic for ship. Sweden.
[10] MSC.1/Circ. 1002, 26 June 2001. Guidelines on Alternative Design and Arrangements for Fire Safety.
[11] FP 56/12. 5 October 2012. Proposal for a new set of guidelines regarding fibre reinforced plastic for ship. Sweden.
[12] FP 56/12/1. 1 November 2012. Development of guidelines for use of fibre reinforced plastic (FRP) within ship structures. United States.
[13] IMO MSC.1/Circ. 1574, 9 June 2017. Interim guidelines for use of fibre reinforced plastic (FRP) elements within ship structures: fire safety issues.
[14] MSC.1/Circ. 1455, 24 June 2013. Guidelines for the Approval of Alternative and Equivalents as Provided for in Various IMO Instruments.
[15] MSC.1/Circ. 1552, 25 November 2016. Amendments to the Guidelines on Alternative Design and Arrangements for Fire Safety.

B Overview of rules for the classification of vessels in composite materials

Description by BV

B.1 General

B.1.1 Introduction

The purpose of this chapter is to evaluate the main certification processes considered by the classification societies and their requirements regarding the design and the hull construction of a hull made of fibre-reinforced plastic within the scope of ship classification or hull certification.

This chapter only focus on the hull structure approach of FRP construction and does not include other technical subjects such as fire specification.

The classification societies considered in the present chapter are Det Norske Veritas and Germanisher Lloyd (DNVGL), American Bureau of Shipping (ABS), Nippon Kaiji Kyokay (ClassNK), Lloyd's Register (LR) and Bureau Veritas (BV).

B.1.2 List of current rules of classification societies considered in this chapter

The main rules of classification societies considered in the present study are:

- DNVGL:

  Rules for classification, Pt 1 General regulations, Ch 3, Documentations and certification requirements, general [1]

  Rules for classification, Pt 2, Materials and welding, Ch3 Non-metallic materials [1]

  Rules for classification high speed and light craft, Pt 3 structures, equipment, Ch 4 hull structure design, fibre composite and sandwich constructions [2]

  Offshore standard DNV-OS-C501 Composite components [3]

- ABS:

  Rules for materials and welding, Pt 2, Ch 6 Materials for hull construction FRP [4]

  Rules for building and classing high-speed craft, Pt 3, Hull construction and equipment [5]

- ClassNK:

  Guidance for the approval and type approval of materials and equipment for marine use – Part 4, Chapter 3- Approval of raw materials for hull of ships of FRP [6]

  Rules for the survey and construction of ships of FRP [7]

- LR:

  Rules for the manufacture, testing and certification of materials – Chapter 14- Plastics materials and other non-metallic materials [8]

  Rules and regulation for the classification of special service craft, Pt 8, Hull construction in composite [9]

- BV:

  NR320 Certification scheme of materials and equipment for the classification of marine units [10]

  NR546 Hull in composite materials [11]

  NR600 Hull structure and arrangement for the classification of cargo ships less than 65 m and non-cargo ships less than 90 m [12]

B.2 General methodology for approval of composite structure

B.2.1 Classification societies rules

Different certification schemes are usually used by the classification societies to assess materials and equipment fitted on board ships classed and to assess ships constructions built using composite materials. All these global survey schemes are based on the following steps of assessment:

6. Raw materials
7. Structure design
8. Specimen tests of FRP
9. Manufacturing and testing at works
10. Final test and inspection of the construction.

These individual steps of assessment are detailed in B.3.

Each step of assessment requires to define the:

- Type testing program and standard to be used or assessment methodology,
- Validation criteria of test results and assessment,
- Body in charge of tests and assessments and responsibilities (manufacturer, independent laboratory or classification society)
- Type of certificates granted to certify the assessment process and body in charge to issue these certificates.

B.3 Individual steps of the global survey scheme:

B.3.1 Raw materials assessment:

B.3.1.1 General:

The first step of the global survey scheme is the assessment of raw materials used for the construction of ships, based on the two following steps according to the classification society rules:

- Raw material approval: carried out by tests to check the characteristics of the material considered (resin, reinforcement, core materials…). These tests may be performed by the raw manufacturer, another recognised society or by the classification society and validated on the basis of the minimum characteristics defined by the classification society or the raw manufacturer (these tests are generally based on ISO standards or equivalent).

As a rule, after satisfactory completion of tests, a certificate is generally issued by the classification society to the manufacturer for the raw materials tested.

- Works approval of the manufacturer: based on the quality system (complying with ISO 9000 or equivalent) of the manufacturer and on recognition of the production and quality control processes in order to demonstrate the ability to consistently manufacture the raw materials according to the raw material approved. As a rule, upon satisfactory completion of the process, a recognition certificate is issued by the classification society to the manufacturer for the raw materials considered.

B.3.1.2 The main characteristics usually assessed by the classification societies for the raw materials approval are:

a. Resins:
   - In liquid conditions: Density, Viscosity, Thixotropic index, Monomer and Mineral contents, Gel time.
   - In cured condition without reinforcement: Peak exotherm, Volumetric curing shrinkage, ultimate tensile strength, tensile modulus, fracture elongation, ultimate flexural strength, flexural modulus, heat deflection temperature, water absorption.

b. Adhesives:
   - Tensile and shear modulus moduli and elongations,
   - Density, viscosity
   - Volume shrinkage
   - Heat resistance
   - Water resistance
   - Tensile lap shear test taking into account immersion in water and elevated temperature
   - T peel test
   - Measurement of ph
   - Fatigue test

c. Reinforcements: (mat, UD, woven…)

   The mechanical characteristics of reinforcement, made from discontinuous or continuous monofilament fibres, cannot be mechanically tested in their product form and need to be impregnated by resin.

   Three steps of tests may be considered:

   - Mechanical Tests carried out on continuous fibres (it is important to note that the fibre manufacturer is seldom the reinforcement manufacturer): Linear density, average diameter, tensile strength and modulus and elongation
   - “Geometrical” test on reinforcement non impregnated: Mass per unit area
   - Mechanical tests on impregnated reinforcements: Tensile strength, modulus, elongation. For these tests, the fabrication process of the impregnated reinforcement sample may be different from the hull construction process.

d. Prepreg reinforcement:
   - Percentage of reinforcement in mass,
   - Weight per unit area

And after curing process:

- Tensile test on laminate (modulus, elongation, breaking stress)
- Determination of glass transition temperature

e. Core materials:
   - Determination of the density,
   - Shear modulus and ultimate shear strength
   - Compression in the through thickness direction
   - Water absorption
   - Resistance to resin (dimensional and mass control)
   - Heat resistance temperature

Some classification societies may require specific tests for core materials in exposed slamming areas or in fatigue exposed areas.

B.3.1.3 Works approval of the manufacturer

The objective is to assess the compliance of the raw materials manufactured in mass production to the raw materials approved.

This approval carried out by a recognized society and/or by the classification society is based on:

- The quality system of the manufacturer including the organization of production, the personal qualification, the quality controls and testing during mass production, the work instructions, the traceability of the production (inspection recording during production, handling of non-conformities), internal audit carried out by the manufacturer…
- Audit and periodical visits carried out by the classification society.

The scope of the work approval is as a general rule limited to the production of raw materials tested by the classification society.

After satisfactory completion of the works manufacturer, an approval certificate is issued.

B.3.2 Structure design assessment:

B.3.2.1 Hull structure rules:

The second step of the global survey scheme is the hull structure design approval, based on the hull structure rules of the classification society. These rules are generally ordered as follow:

- Definition of structure design principle: including general requirements about the hull structure general arrangements, definition of structure detail construction,…)
- Definition of design loads to be used for the hull structure assessment: Global hull girder loads and local loads
- Definition of structure calculation methodology: approach of structure computation similar to those considered for other type of hull structure (steel or aluminium structure for example)
- Definition of FRP approach for the scantling calculation based on:
- Theoretical methodology to apply to the FRP material analysis
- Breaking values reference characteristics of FRP material
- Scantling criteria: Based on safety coefficients in relation to the breaking stress or strain values reference of the composite and the actual stresses or strains.

Different general basic approaches are considered in the rules of the classification societies for the analysis of the composite materials:

- 1st approach: Approach based on the hypothesis that a composite laminate can be considered as an homogeneous material having mechanical characteristics (mainly young modulus and breaking stresses) defined taking into account the different reinforcement layers in the laminate: According to this theory, the hull scantling may be directly designed by thickness for plates and modulus for stiffeners.

In this case, the reference values of breaking stresses are considered as a global laminate breaking stress.

- 2nd approach: Approach based on a ply by ply analysis, taking mainly into account the compression and tensile stresses or strains in the direction of the fibres of the reinforcements.

In this case, the reference values of breaking stresses are compression and tensile stresses of each layer.

- 3rd approach: Approach based on a ply by ply analysis taking into account the stresses in the direction and perpendicular to fibre, and the interlaminar stresses between layers.

In this case, the reference values of breaking stresses are compression and tensile stresses in the direction of and perpendicular to the fibres of layers, and interlaminar shear stresses between each layer.

As a rule, longitudinal hull girder strength and local strength are examined independently in the rules of the classification society. For large ship, it is reasonable to consider the stress combination between the effects of the global hull structure loads and the local loads. It should be noted that such combination is not possible with the first approach defined here above.

The scantling check is based on the definition of safety factors equal to the ratio between the theoretical breaking stress/strain defined by the different methodology and the actual applied stresses/strain determine by the structure calculation.

Even if it is difficult to directly compare the values of the safety coefficients taken into account in the structure rules of the different classification society (these values being dependent of the values of loads considered, the type of stress considered in the laminate, the theoretical breaking values considered…), these values globally vary from 3 to 3,6.

Some classification society defined also a criterion based on maximum deflection values of the structure (plate and stiffeners).

B.3.3 Specimen tests

The third step of the global survey scheme is the mechanical and physico-chemical tests on laminate panel produced by the yard in charge of the hull construction. The aim of these tests is to show that the mechanical characteristics of the laminates, produced with raw materials and production process used for the hull construction are at least equivalent to the theoretical mechanical characteristics considered during the structure design assessment.

The main mechanical tests, carried out according to ISO standards or equivalent, required by the classification society are:

- Tensile tests
- Bending tests
- Interlaminar shear tests
- Measurement of density and content in fibre

As a rule, the test panel may be taken from hull cut-outs or hull extension tabs or may be produced with the same process of the hull construction (same materials, layup, same process and cure system).

Specific process such as bond strength for the assembly of laminate or hull part may be required to be tested.

B.3.4 Manufacturing and inspection at works:

The fourth step of the global survey scheme is the manufacturing and inspection at works. The assessment of the manufacturer's arrangement for production aims to verify that the hull construction is in compliance with the Rules of the classification society.

As a rule, this assessment is based on:

- Periodical surveys carried out by a surveyor of the classification society during construction in order to ensure that the hull is constructed in accordance with the hull drawing structure examined during the structure design assessment,
- Quality system used by the yard to ensure the conformity of the composite construction in relation with the classification society Rules.

This quality system must define the yard organisation and a manufacturing, testing and inspection plan or equivalent, and specially:

- Reception and reference of raw materials, storage, traceability and preparation of raw materials
- Preparation of raw materials for lamination (preparation of reinforcements, resin…)
- Lamination process and environment (Qualification of operators, temperature and hygrometry, assessment of lamination sequence in relation with drawings…)
- Assembling of hull with stiffeners, other part of hull elements, second bonding or adhesive joints…
- Inspections and testing carried out by the yard during construction
- Procedures for dealing with non-conformities during construction and introducing corrective and preventive actions

B.3.5 Final tests and inspections:

The final tests and inspection, within the scope of hull construction, are provided to confirm:

- The watertightness of hull, tanks and watertight boundaries (carried out by hydrostatic, hydropneumatic, air, hose testings or equivalent),
- The conformity of the construction with the hull design approved.

Non-destructive testing may be used during the final tests (ultra-sonic testing, stereoscopy, radiography…).

B.4 Conclusions

The five main steps defined in B.2.1 are essential in a global certification process of hulls built using composite materials. However, this theoretical global process is limited to list the necessary many sub-assessments and controls to meet the requirements of the classification society requirements and to demonstrate that the hull structure is in compliance with the Rules of these Societies.

In practice, it is often necessary to adapt these schemes, taking into account the numerous interference processes during hull construction in composite modifying the basic characteristics of the composite materials, while maintaining the primary objectives:

- The assessment of the final mechanical properties of the laminates in relation with the theoretical analyse approach considered during the design approval of the structure
- The assessment of hull construction details (assembling of structural components - stiffeners, counter moulds, lamination on hull of bulkheads, bonding of main structural elements…

B.5 References

[1] DNVGL-RU-SHIP, Rules for Classification – Ships
[2] DNVGL-RU-HSLC, Rules for Classification – High Speed and Light Craft
[3] DNV-OS-C501, Offshore Standard – Composite Components
[4] ABS – Rules for materials and welding
[5] ABS – Rules for conditions of classification High-Speed Craft
[6] ClassNK – Guidance for the approval and type approval of materials and equipment for marine use
[7] ClassNK – Rules for the survey and construction of ships of Fiberglass Reinforced Plastics
[8] Lloyd's Register – Rules for the manufacture, testing and certification of materials
[9] Lloyd's Register – Rules and regulations for the classification of Special Service Craft
[10] BV NR320 – Certification scheme of materials and equipment for the classification of marine units
[11] BV NR546 – Hull in composite materials and plywood, material approval, design principles, construction and survey
[12] BV NR600 – Hull structure and arrangement for the classification of cargo ships less than 65m and non-cargo ships less than 90m
[13] MSC-MEPC.1/Circ.4Rev4 – Guidelines On The Organization And Method of Work Of the Maritime Safety Committee And The Maritime Environmental Protection Committee And Their Subsidiary Bodies"

C Methodology for design and approval

C.1 Introduction

Main author of the chapter: RISE

During the RAMSSES project a methodology for design and approval will be developed, aiming for accelerating the market uptake of advanced innovative materials in the maritime sector.

To achieve that RAMSSES follows a multi-level approach to make sure solutions developed in the demos are acceptable and the “smart track to approval” (STTA) can be simplified and shortened in the future: This STTA aims to shorten two main elements of the risk based design process:

- **Risk assessment**. Currently carried out case-by-case, the project aims to introduce “standard risk scenarios” covering a range of similar applications. These can be referred to in the future without the need to carry out extensive quantitative risk assessments.
- **Testing**. As an outcome of a risk assessment, expensive and lengthy physical tests are often required to prove certain functional properties. The database of test results and pre-approved solutions, to be developed in RAMSSES, will avoid the necessity of repetitive tests if a simple qualitative risk analysis shows that relevant results and solutions are already available. In addition, the project will develop numerical or statistical models that may replace certain physical testing in future

Unfortunately the RAMSSES demonstrators cannot follow the STTA yet, as the method is still under development during the project.

Chapter C.2 outlines the regular selection procedure of the applicable rules for the demonstrator cases. Each demonstrator case will go develop and design their solutions according to their needs , their performance will be tested and evaluated using the applicable rules to apply for approval.

In Chapter C.3 a general description of the methodology for design and approval is given and the following chapters provide guidance for the topics of fire safety, mechanical performance, probabilistic damage stability and comfort. For each topic the background and relevance for composite ships is described followed by guidance for both the design considerations and specific criteria for approval of composite ships.

C.2 Rules selection

Main author of the chapter: BV

In Bureau Veritas, rules application depends on the following parameters:

- Date of contract between owner and shipyard
- Type of vessel
- Length
- Gross tonnage
- Material
- Number of passengers
- Navigation

All these parameters will allow to select the relevant rules applicable for the vessel. In addition, national and international regulations may be required.

C.2.1 Type of vessels

Depending of the type of vessel, the designer will select the appropriate regulations and rules for the classification. While there are no universally applicable definitions of ship types, specific descriptions and names are used within IMO treaties and conventions. The following is a non-exhaustive list ship types defined in various IMO instruments:

- A passenger ship is a ship which carries more than twelve passengers. (SOLAS I/2)
- A fishing vessel is a vessel used for catching fish, whales, seals, walrus or other living resources of the sea. (SOLAS I/2)
- Fishing vessel means any vessel used commercially for catching fish, whales, seals, walrus or other living resources of the sea. (SFV 1993 article 2)
- A nuclear ship is a ship provided with a nuclear power plant. (SOLAS I/2)
- Bulk carrier means a ship which is constructed generally with single deck, top-side tanks and hopper side tanks in cargo spaces, and is intended primarily to carry dry cargo in bulk, and includes such types as ore carriers and combination carriers. (SOLAS IX/1.6)
- Bulk carrier means a ship which is intended primarily to carry dry cargo in bulk, including such types as ore carriers and combination carriers. (SOLAS XII/1.1)
- Oil tanker means a ship constructed or adapted primarily to carry oil in bulk in its cargo spaces and includes combination carriers, any "NLS tanker" as defined in Annex II of the present Convention and any gas carrier as defined in regulation 3.20 of chapter II-1 of SOLAS 74 (as amended), when carrying a cargo or part cargo of oil in bulk. (MARPOL Annex I reg. 1.5)
- General cargo ship: A ship with a multi-deck or single-deck hull designed primarily for the carriage of general cargo. (MEPC.1/Circ.681 Annex)
- High-speed craft is a craft capable of travelling at high speed. (SOLAS X/1.2, HSC Code 2000 para 1.4.30)

- Mobile offshore drilling unit (MODU) means a vessel capable of engaging in drilling operations for the exploration for or exploitation of resources beneath the sea-bed such as liquid or gaseous hydrocarbons, sulphur or salt. (SOLAS IX/1, MODU Code 2009 para 1.3.40)
- Special purpose ship (SPS) means a mechanically self-propelled ship which by reason of its function carries on board more than 12 special personnel. (SPS Code para 1.3.12)

source : http://www.imo.org/en/OurWork/Safety/Regulations/Pages/Default.aspx

C.2.2 Length

A limit ship length has been defined by the International Load Line Convention. All vessels of 24 m and more are to have a special marking positioned amidships, see Figure 4. The aim of the Load Line is to fix a maximum legal limit up to which a ship can be loaded. With such limits, the risk of cargo exceedance of cargo is limited as well as insufficient stability and structural overstress.

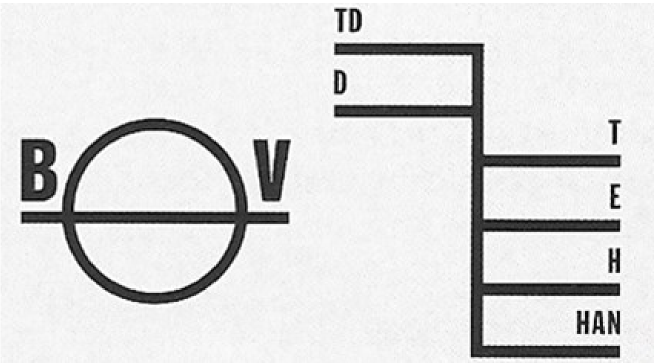


Figure 4: Plimsoll mark

In addition of this Load Line, Classifications Societies have determined several characteristic lengths for the rules application. Unfortunately, such length limits are not uniform from a class to another one and are completely dependent of the Society. For example, in Bureau Veritas, a cargo ship less than 65m will be reviewed in accordance with NR600 and with NR467 beyond. While the limit for a non cargo ship, in BV rules, is 90m. Also, some additional notations will be applied in relation with the vessel length, such as VeriSTAR-HULL, VERISTAR-HULL FAT, etc.

C.2.3 Gross tonnage

The gross tonnage (GT) of a vessel refers to its internal volume and is used to categorize commercial ships. This volume concerns all areas of the vessels and is used as a legal measure to determine regulations, safety rules, registration fees and port charge for vessels. The gross tonnage has been defined in the International Convention on Tonnage Measurement of Ship in 1969.

Due to the shape of ships, the volume used for the gross tonnage calculation can be complicated and GT is expressed in volumetric tons of 100 cubic feet. The gross tonnage is obtained with the following equation:

$$\text{GT (Gross Tonnage)} = \text{K} \times \text{V}$$

Where K = 0.2+0.02xlog10(V) and V = interior volume of a vessel in cubic meters

As an example, the gross tonnage measure is used for the application of SOLAS. For all cargo ships less than 500 gross tonnage, SOLAS does not apply. Rules application can be different if the vessel is less or greater than 500 GT or 1 000 GT.

C.2.4 Material

The following materials are used for shipbuilding:

 Steel	 Aluminium
 Composite	 Wood

Rules and regulations application depends of the materials type. There is no restriction to use metallic material, i.e. steel and aluminium alloy, if design criteria are respected. However, for composite materials, the structural validation is not sufficient, the fire safety requirements are to be validated and for SOLAS vessel the equivalence with metallic material is to be demonstrated.

C.2.5 Number of passengers

According to the SOLAS, in case of international voyage and whatever the length of the vessel, a ship is considered as a passenger ship if the number of passenger is equal or greater than 12. For national voyage, the limit is determined by the flag and can sometimes referred to SOLAS.

Other conventions, such as Special Purpose Ship (SPS) or MARPOL, can give different limits. As example, in SPS Code, damage stability approach will be modified if the number of person onboard is less than 60 persons or greater than 240 persons.

C.2.6 Navigation categories

Some notations, corresponding to different navigation categories, are assigned to vessel depending on the ship intents to operate. These notations are:

- Unrestricted navigation
- Summer zone
- Tropical zone
- Coastal area
- Sheltered area

The classification of the vessel is also depending on the type of voyage. If it is an international voyage or a national voyage, regulations are not the same. For a national voyage, only local administration is applicable.

In case of High Speed Craft, for a voyage from a point A to a point B, it is another applicable code.

C.2.7 Example of a OPV (WP16 and WP17)

Application cases used for WP16 with Naval group and WP17 with DSNS is taken as an example to illustrate the selection of rules. In both cases, shipyards develop a OPV, one with a metallic hull and superstructure in composite materials, Naval Group solution, see Figure 5, and on full composite material, DSNS application, see Figure 6.

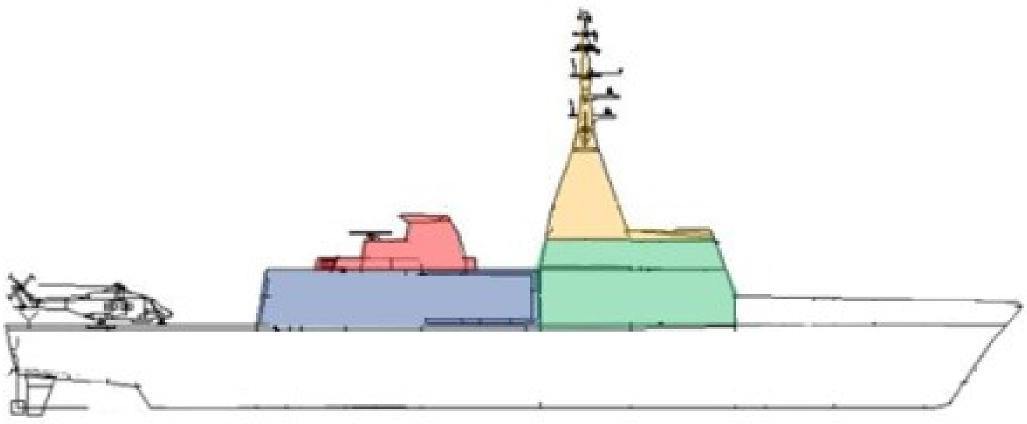


Figure 5: WP16, view of Naval Group application case

Figure 6: WP17, view of DSNS application case

According to BV rules NR467, Part D, Chapter 16, and main characteristics of vessels, following rules are applicable:

Table 1: OPV, applicable requirements

Item		Greater than or equal to 500 GT	Less than 500 GT
Ship arrangement and hull integrity	L ≥ 90 m	• Part B • Part C, Chapter 1 **(1)**	• NR566 **(2)**
	L < 90 m	• NR600 • Part C, Chapter 1 **(1)**	• NR566 **(2)**
Hull	L ≥ 90 m	• Part B • NR396 **(3)**	• Part B • NR396 **(3)**
	L < 90 m	• NR600 **(2)**	• NR600 **(2)**
Stability		• NR566 • Ch 16, Sec 2	• NR566 • Ch 16, Sec 2
Machinery		• Part C • Ch 16, Sec 3	• NR566 **(2)** • Ch 16, Sec 3
Electrical installations and automation	N ≤ 60 **(4)**	• Part C	• NR566 **(2)**
	N > 60 **(4)**	• Part C • Ch 16, Sec 4	• NR566 **(2)** • Ch 16, Sec 4
Fire protection, detection and extinction		• See Tab 2	• See Tab 2

(1) Applicable requirements with respect to discharges and scuppers. see Pt C, Ch 1, Sec 10, [8].
(2) Application of these requirements are to be applied except that specific rules for passenger ships are not to be taken into account.
(3) In addition, requirements of NR396, Chapter 3 apply if $V \geq 7{,}16\Delta^{1/6}$ where V is the ship speed, in knots, and Δ is the displacement of the ship, in tons.
(4) The number of persons N is defined in [1.2].

Note 1:
NR396: Rules for the Classification of High Speed Craft.
NR566: Hull Arrangement, Stability and Systems for Ships less than 500 GT.
NR600: Hull Structure and Arrangement for the Classification of Cargo Ships less than 65 m and Non Cargo Ships less than 90 m.

Table 2: OPV, applicable requirements for fire safety

		Greater than 1000 GT	Between 500 and 1000 GT	Less than 500 GT	
				Unrestricted navigation	Restricted navigation
Steel or aluminium material	N ≤ 60	• Part C, Chapter 4 • Ch 16, Sec 5	• NR566	• NR566	• NR566
	N >60 **(1)**	• Part C, Chapter 4 • Ch 16, Sec 5	• Part C, Chapter 4 • Ch 16, Sec 5	• Part C, Chapter 4 • Ch 16, Sec 5	• NR566 • Ch 16, Sec 5
Composite material	N ≤ 60	NA **(2)**	• NR566	• NR566	• NR566
	N >60 **(1)**	NA **(2)**	NA **(2)**	NA **(2)**	• NR566 • Ch 16, Sec 5

(1) Offshore patrol vessels with more than 200 persons will be subject to special consideration by the Society.
(2) The present Chapter does not include this case (NA = not applicable).

For this example, existing rules cover the structure of the OPV however, the fire safety requirements are not applicable. This restriction is due to the SOLAS regulation, material used is to be equivalent to steel. The solution to solve this restriction is to perform an alternative design study, based on a risk analysis according to MSCI/Circ.1455.

C.3 Methodology for design and approval

Main author of the chapter: BV and RISE

The RAMSSES project is elaborating and testing a new approach to achieve a "Smart Track to Approval" (STTA) for innovative solutions, including new materials. This will be fed into the maritime rule making processes in the form of common positions and project guidelines. RAMSSES partners are also contributing to the development of cross-industry guidelines e.g. for new materials.

The "Smart Track to Approval" is to be:

- Simple,
- Generic,
- Readable by shipyards, engineering, naval architects, …
- Applicable to all RAMSSES demonstrator cases.

The STTA principle is based on the experience gained during previous research or commercial projects, by sharing knowledge with other industrial sectors, i.e. aeronautics, railway and automotive, by using existing database and by standardizing results.

The STTA is composed of two layers: one led by the classifications societies and one led by the shipyards, engineering or design offices, see Figure 7. The STTA will be a first step to prepare an Approval In Principle (AIP), leading to the certification or the classification of a vessel or a part of the vessel. The STTA is developed in the RAMSSES project to propose an alternative to the prescriptive rules concerning the introduction of innovative materials in the shipbuilding industry. Figure 7 resumes the process and gives the main steps of the STTA.

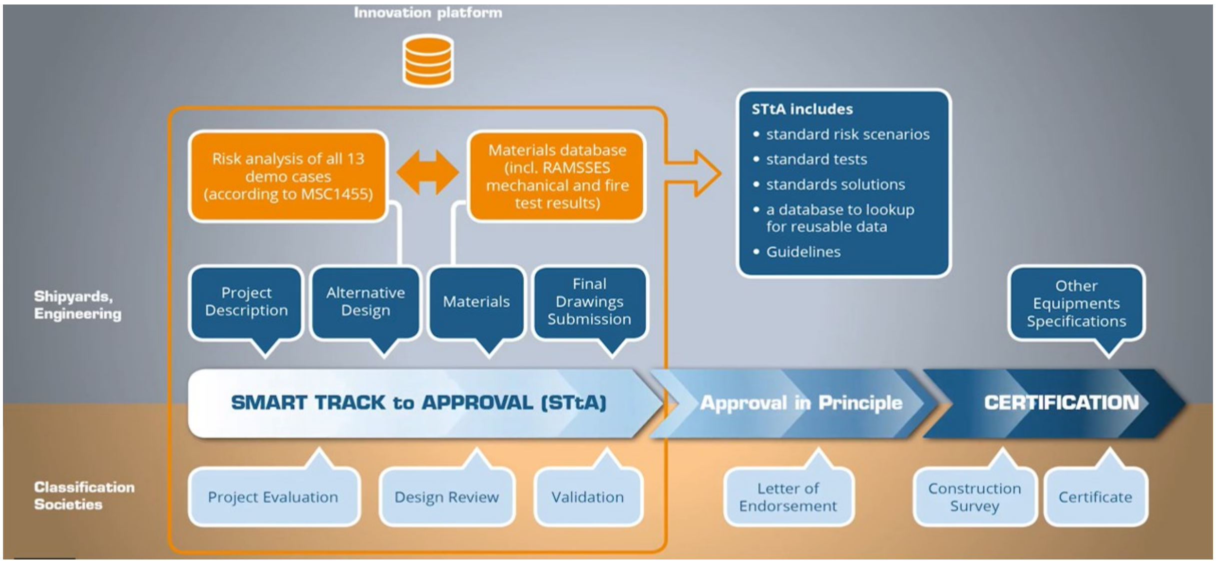


Figure 7: Smart Track to Approval, process overview.

The ambition is that the STTA will mainly be used for alternative design solutions performed in accordance with the circular MSC.1/Circ.1455, see Figure 8. In the context of RAMSSES, several risk analyses are carried out to demonstrate the feasibility of new concepts, to validate different design options, to confirm the performance of innovative materials and to prove equivalent fire safety compared to conventional structures. All risk analyses will be supported by numerical simulations, such as Finite Element Analysis, Computational Fluid Dynamics, evacuation simulations, thermo-mechanics calculations, etc. Model or full scale test for the RAMSSES demonstrator cases, will be used to verify the assumptions in the assessment.

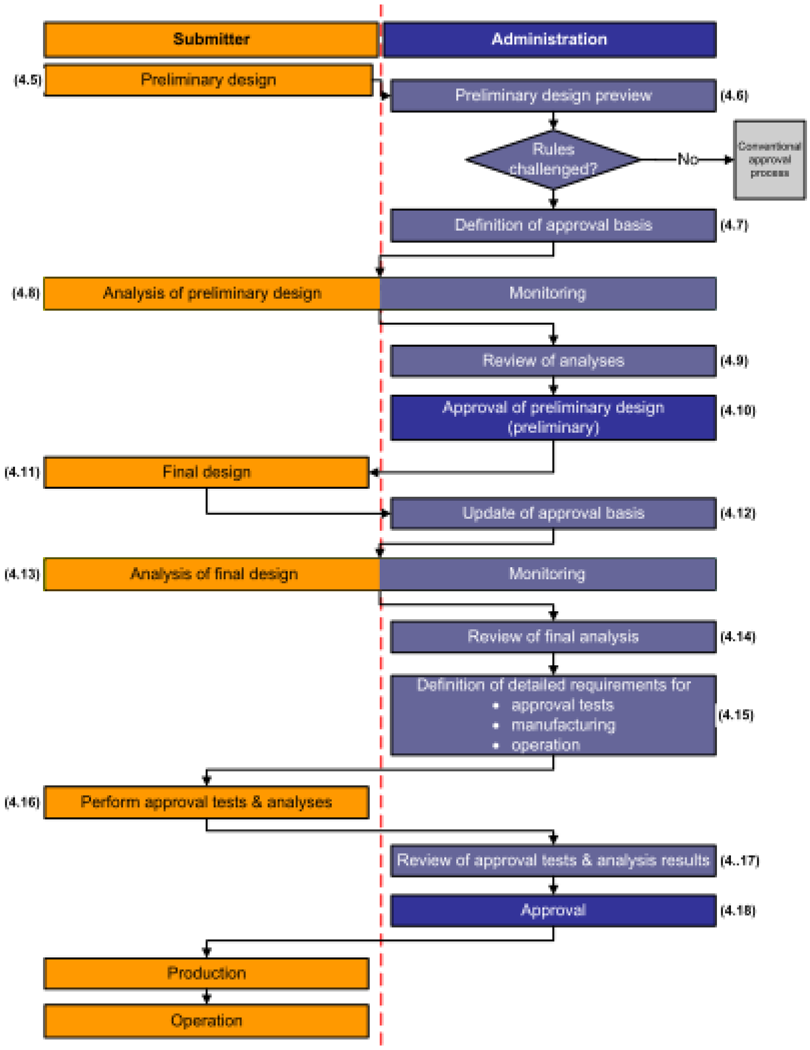


Figure 8: Design and Approval Process [14].

From the results of demonstrator case risk analyses, the STTA will propose standard risk scenarios, standard tests, standard solutions and a database to lookup for reusable data. The quantitative analyses are currently carried out on a case-by-case basis. The objective aims to develop standard risk scenarios covering a range of similar applications. These can be referred to in the future without the need to carry out extensive quantitative analyses or tests. The definition of standard risk scenarios will be based on the demonstrator cases developed in RAMSSES.

The standard risk scenarios will cover the following aspects:

- Fire safety,
- Stability, including damage stability,
- Materials,
- Structural arrangement.

For example, when evaluating fire safety for FRP composite structures, the encountered challenges are often similar. Standard risk scenarios developed in the project cover several applications and include scenarios defining suitable reaction to fire properties for external and internal surfaces as well as required fire resistance for internal and loadbearing bulkheads. As an input to the fire risk assessment, significant testing is often required to prove the functional properties. The second objective of the STTA is therefore the creation of a materials database, named RAMSSES Knowledge Repository, see Figure 9. It is a web browser based platform on invitation access (https://repository.ramsses.eu/) In addition to descriptions of the maritime materials, it will define for example fire safety, mechanical and acoustic properties of materials tested standardized tests. A large number of tests, mechanical and fire tests, will be performed during the 4 years of the RAMSSES project on a multitude of materials, composites and metallic. The database of test results and pre-approved solutions, to be developed in RAMSSES, should avoid the necessity of repetitive tests if a simple qualitative risk analysis shows that relevant results and solutions are already available. In addition, numerical or statistical models will be developed during the project that may replace certain physical testing in the future. The approach will be documented in a project guideline, which may form the basis for future modified class rules. The feasibility of this procedure will be demonstrated in a showcase, using a RAMSSES demo case as reference.

The experience and procedures developed in RAMSSES need to be fed into the rule making process, with the final goal to implement the findings into new rules and regulations in the medium to long term. On the short term RAMSSES could deliver input to the evaluation of MSC.1/Circ.1574. Input to IMO and SOLAS needs to involve flag states, which are represented in the IMO. This will be achieved through consortium members working closely with their national authorities, like RISE (Sweden), Bureau Veritas (France), DSNS and NMTF (Netherlands). In addition to that, two other channels will be used: class societies, represented by IACS and shipyards represented by SEA Europe, have an advisory role as Non-Governmental Organization at IMO. NMTF as a national shipbuilding association member of SEA Europe and Bureau Veritas as a member of IACS will serve these channels as well.

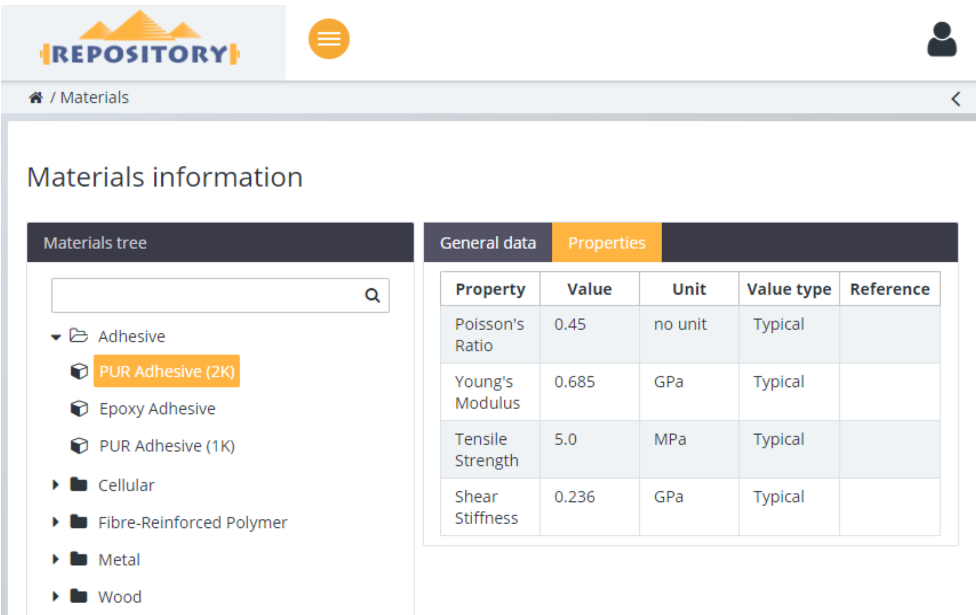


Figure 9: RAMSSES Knowledge Repository platform (https://repository.ramsses.eu).

C.4 Fire safety

Main author of the chapter: RISE

C.4.1 Background

A major part of the communication strategy in RAMSSES is the dissemination and exploitation of information and results. Dissemination, which is not only understood as all activities related to outbound information flow, but also includes organising an inbound information flow to the RAMSSES consortium, with the aim to improve the work of the project, to create future ideas for material innovation and to enhance the related knowledge base with external data and information. This is summarized in the third strategic objective of the project, which states that "*RAMSSES will contribute to support the innovation capabilities of the consortium members and the maritime sector.*"

In order to achieve the strategic objective mentioned above, the Communication Management Group (CMG) has been assigned with relaying relevant information and knowledge to the Innovation Management Group (IMG), as illustrated in Figure 10.

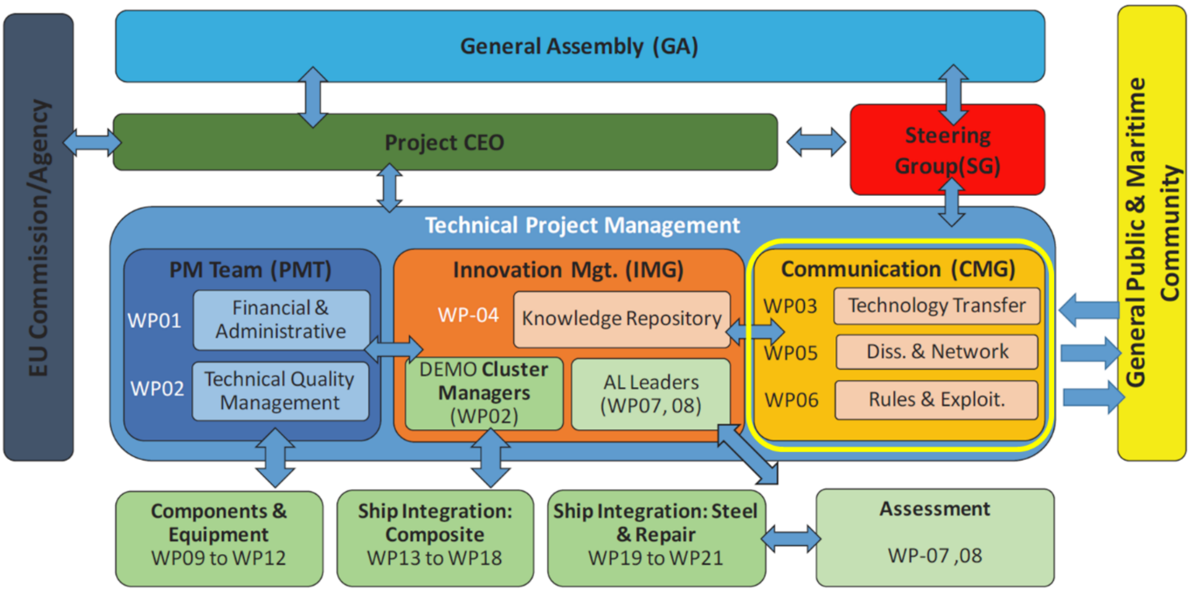


Figure 10: RAMSSES management structure. The CMG is highlighted in yellow. Its objective is not only related to spreading results of the project to the desired targets, but also to relay valuable information and results to the IMG.

The core strategic element for the innovation management is the Common Knowledge Repository. It will apart from providing a means to store information, which is intended for outbound information flow (e.g. input to rule making bodies), also contain relevant information that will be shared between the RAMSSES partners, thus making it a strategic instrument for the project's dissemination and exploitation measures.

The purpose of the methodology herein is to support the innovation capabilities of the consortium members by accentuating the most relevant regulations affecting the design of FRP composite ship structures in furtherance of a more practical approach that ultimately may serve as a basis for achieving equivalence in practice. The methodology is written with the designer in mind and not the approving administration, for which guidelines already exist (see e.g. MSC/Circ.1002 or MSC/Circ.1574).

C.4.2 Prescriptive or performance-based approval

Fire safety standards for merchant ships are defined in SOLAS Chapter II-2. The cornerstone of SOLAS Chapter II-2 is *regulation 2* which details the *fire safety objectives and functional requirements*, forming the basis for all the following fire safety regulations. In the context of fire safety, approval is achieved either through compliance with prescriptive requirements laid out in SOLAS Chapter II-2 parts B, C, D, E, and G, or through the performance-based approach described in SOLAS Chapter II-2 part F and further detailed in relevant guidelines, e.g. MSC/Circ.1002 or MSC.1/Circ.1455. More specifically, the functional requirements defined in SOLAS Chapter II-2 Reg.2 are met when:

a) the ship's design and arrangements as a whole comply with Chapter II-2 parts B, C, D, E, and G;
b) the ship's design and arrangements as a whole have been reviewed and approved in accordance with part F; or
c) parts of the ship's design and arrangements comply with Chapter II-2 parts B, C, D, E, and G and the remaining parts have been reviewed and approved in accordance with part F.

Conventional ship design and approval thus implies compliance with the prescriptive requirements specified in SOLAS Chapter II-2 parts B, C, D, E and G. These parts cover prevention of fire, suppression of fire, escape, operational requirements and special requirements. The use of fibre-reinforced polymer (FRP) in ship structures is a deviation from conventional shipbuilding and generally also from prescriptive requirements. This means that approval through part F is necessary. This part includes only one regulation, Regulation 17 *Alternative design and arrangements*, applying to non-conventional ship designs and fire safety arrangements (not complying with all the prescriptive requirements). This alternative performance-based approach is not an exemption but a different way to fulfil the fire safety requirements. The principle of this regulation is that the alternative design and arrangements shall provide a degree of safety not less than that achieved by compliance with all the prescriptive requirements. This should be shown by an engineering analysis in line with MSC/Circ.1002. For approval of large vessels in composite or when the design affects many other areas than fire safety, it is however more appropriate to follow the process described in MSC/Circ.1455.

C.4.2.1 MSC.1/Circ.1574

A supplement to the Guidelines on alternative design and arrangements for fire safety (MSC/Circ.1002) are found in MSC.1/Circ.1574: Interim guidelines for use of Fibre Reinforced Plastic (FRP) Elements within Ship Structures: Fire Safety issues. The Interim guidelines are intended to ensure that (1) a consistent approach is taken with regard to fire safety for ships making use of FRP elements in their structures and that (2) the level of fire safety afforded by the provisions in SOLAS chapter II-2 is maintained.

Some critical aspects the guidelines are that:

- FRP elements can be approved through SOLAS II-2/17;
- An FRP element is "a structure which may be removed without compromising the safety of the ship";
    - 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.

Deviations from the guide lines should be identified and additional assessments be performed, as appropriate."

- The alternative design and arrangements shall meet the fire safety objectives and functional requirements in SOLAS chapter II-2.
    - Where SOLAS II-2/5.1.3 states that "The use of combustible materials shall be restricted."

C.4.2.2 Review of relevant regulations

According to regulation 17, alternative design and arrangements for fire safety should provide a degree of safety at least equivalent to that achieved by compliance with prescriptive requirements. The assessment should therefore include an identification of the prescriptive requirement(s) which the alternative design and arrangements will not comply with (regulation 17.3.2). The regulations should be clearly understood and documented along with their functional requirements (paragraph 5.1.2).

Potential regulatory deviations and their effect on the achievement of functional requirements are covered extensively in MSC.1/Circ.1574. The purpose here is to accentuate the most relevant regulations in furtherance of a more practical approach for designing FRP composite ship structures, which ultimately may serve as a basis for achieving equivalence in practice.

If generalizing, there are three main aspects of fire safety which are affected by the introduction of FRP composite structures and which need to be properly managed:

I. **Fire growth potential**, i.e. the reaction to fire properties of exposed internal and external FRP composite surfaces AND how fire development will be affected when the combustible materials of the FRP composite structures become involved;
II. **Fire containment**, i.e. avoidance of fire spread by the FRP composite structures; and
III. **Structural integrity**; i.e. the impact on load-bearing capabilities and global strength by potential deterioration of FRP composite structures.

Each of these aspects is further discussed below, with reference to relevant regulations and test procedures in the Fire Test Procedures (FTP) Code, used to ensure sufficient performance of ship building materials.

C.4.2.2.1 Fire growth potential

Prescriptive requirements related to reducing fire growth potential are specified in SOLAS chapter II-2, Regulation 5 (henceforth referred to as regulation 5). For the purpose of this methodology, fire growth potential was divided in four parts:

- Ignitability
- Flammability
- Smoke generation potential and toxicity
- Increased amount of combustible materials

C.4.2.2.1.1 Ignitability

In accordance with the functional requirement in SOLAS II-2/4.1.4, the ignitability of combustible materials shall be restricted, but there are no prescriptive requirements relevant for exposed surfaces related to this functional requirement. In case a design with FRP composite entails that surfaces would be left uncovered, it may be noted that they generally have restricted ignitability. This may for example be determined through a test in accordance with EN ISO 11925-2. There is no test to verify restricted ignitability in the FTP Code [Evegren, Hertzberg, 2017].

C.4.2.2.1.2 Flammability

Interior surfaces

According to regulation 5, exposed interior surfaces in accommodation spaces, service spaces and control spaces shall have *low flame-spread* (LFS) characteristics in accordance with FTP Code, part 5.

The potential for flame spread of a material is tested in equipment where an irradiating panel provides heat input to a surface in order to initiate flaming combustion. The IMO typical example of such equipment is shown in Figure 11. Fire is initiated where the distance between panel and sample is the shortest, i.e. where the irradiation intensity is the highest. The radiation level decreases at the test specimen from left to right in Figure 11, and the extreme burning point to the right, i.e. the point with the lowest irradiation level for sustained combustion, is given as a measure of flame spread for the material. The speed of the flame front movement is also quantified in an appropriate way. There are also criteria regarding the peak heat release as well as of the total evolved effect, which if they are not met with a certain margin introduce further requirements in respect to smoke and toxicity generation, i.e. the material must also be tested in accordance with FTP Code, part 2.

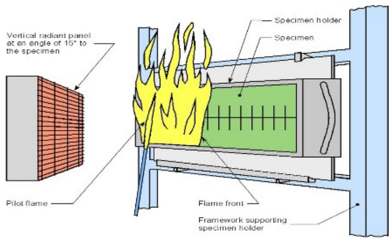


Figure 11: Test for flame spread according to part 5 of the 2010 FTP Code

The test for surface flammability is generally not passed if an FRP with traditional polymer material, e.g. polyester or epoxy, is left untreated or uncovered. In spaces where requirements for low flame-spread characteristics apply, it is therefore often necessary to provide additional safety measures to ensure that

Flame-spread is principally a surface phenomenon, more so for conventional structures made from steel where the total amount of combustible materials is limited to the outermost layers. The importance of the substrate should however not be overlooked, in particular when considering sandwich-structured composites. A structural element with a combustible core will behave differently during fire than a corresponding steel structure, even if they have similarly low flame-spread characteristics. More specifically, the combustible core will as time passes, and the fire intensifies eventually start to burn and contribute to the fire. Low flame-spread characteristics, and thereupon compliance with relevant provisions in regulation 5, may therefore not be a sufficient indicator for sandwich structures with combustible cores. It is in view of this generally reasonable to invoke a higher set of standards specifically for FRP in lieu of what is prescribed in regulation 5.

One such set of standards is detailed in FTP Code, part 10. It is applied for interior surfaces and furniture in the HSC Code and is commonly known as the “room corner test” (ISO 9705). It is an important standardized piece of equipment for testing material potential for Heat Release Rate (HRR) and smoke, schematically pictured in Figure 12. The material to be tested is mounted on walls and ceiling of a full-scale room and a propane gas burner is positioned in one of the inner corners, providing a 100 kW fire for 10 minutes and 300 kW for the following 10 minutes. The HRR and smoke production rate are continuously measured and the criteria that apply are similar to those in the Cone Calorimeter.

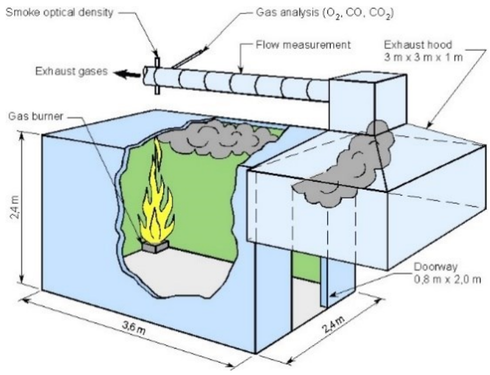


Figure 12: Schematic picture of a Cone Calorimeter

The room corner test includes further complexities of a fire than the test for surface flammability, most notably the significant effects of enclosure fire dynamics, making the test generally harder to pass than the test for spread of flame; in general, materials which pass the room corner test also satisfy low flame-spread requirements.

Any material passing the room corner is thus a good candidate for providing a high degree of fire safety as conditions are more demanding in fire enclosures than in the open. The test method is notoriously challenging for combustible materials, and as a result high-speed vessels constructed from FRP are typically protected with non-combustible panels in order to satisfy FRM criteria.

External surfaces

There is no requirement in SOLAS for external surfaces to have low flame-spread characteristics. It is however clear that the application must be considered when evaluating effects on fire safety from flammability of FRP composite material. For external FRP composite surfaces, a fire protective coating giving low flame-spread characteristics will restrict fire growth in large scale, thus preventing external fire spread. This has previously been demonstrated in a large-scale standardized test method for building façade systems (SP-Fire 105), during which an FRP composite panel treated to achieve low flame-spread characteristics was subjected to the fire source specified in the method, which could represent a fully developed cabin fire emerging through a large balcony opening. The exposed FRP composite surface was protected from involvement in the first critical minutes, and in later stages, contribution to the fire was relatively small. This could give time for fire-fighting crew to arrange and carry out suitable efforts. Continued exposure of the FRP composite panel did not give a large contribution or fast fire growth in the panel.

The results from the large-scale test referenced above reinforce the soundness of requiring low flame-spread characteristics for exterior surfaces in accordance with the smaller-scale test method described in Part 5.

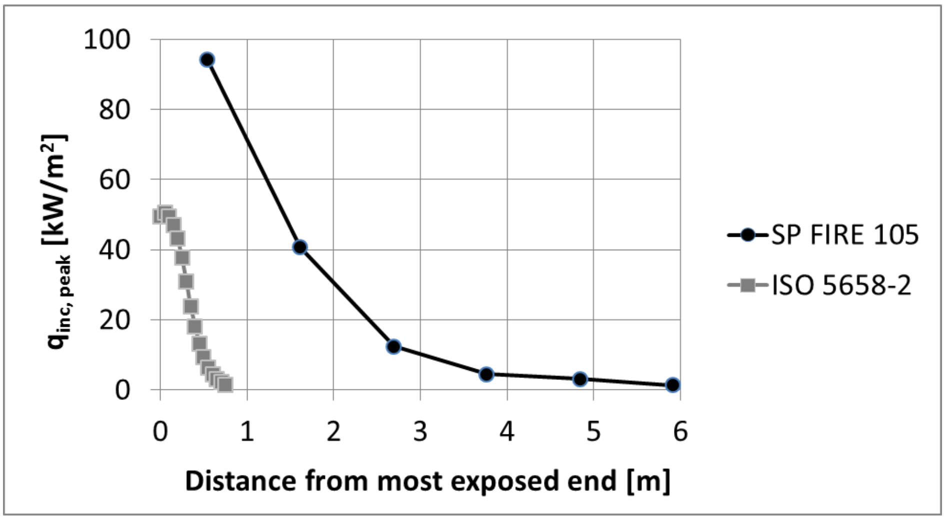


Figure 13:

C.4.2.2.1.3 Smoke generation potential and toxicity

In evaluations of materials it is often relevant to combine properties of fire behaviour (fire growth, fire spread, etc.) with materials' potential for smoke generation and toxicity. For maritime applications, the "smoke box" is used for smoke and toxicology measurements, based on part 2 of the 2010 FTP Code. For SOLAS applications this test is only required if results in the test for spread of flame are insufficient. In this method, a 0.5 m^3 closed cubic box (Figure 14) is used for exposing a small (75 mm x 75 mm) sample for irradiation and measuring continuously gases and smoke opacity in the box. Criteria concern maximum amount of smoke produced and maximum concentrations of the following gaseous species: CO, HCl, HF, NO_x, HBr, HCN and SO_2, as given in the 2010 FTP Code. The test proceeds for 10 minutes if a maximum has been observed in the smoke obscuration level; otherwise the test proceeds for another 10 minutes. The toxicity levels when the smoke obscuration reached its peak value are used as the result from the test.

Figure 14: Smoke box equipment

C.4.2.2.1.4 Increased amount of combustible materials

SOLAS intends to restrict the use of combustible materials (SOLAS II-2/2.2.1.3 as embodied in SOLAS II-2/5.1.3) but this is not completely managed through prescriptive requirements. In accommodation and service spaces there are restrictions for surface materials. They must fulfil requirements on a maximum calorific value of 45 MJ/m^2, recommended to be determined by ISO 171639, and their volume shall not exceed the equivalent of a 2.5 mm veneer. What is not captured by these requirements, except that they only apply in certain spaces, is that a relatively large amount of combustible materials is represented by furniture, loose fittings, and luggage. For such materials there are no restrictions. An IMO guideline has been developed to limit the total amount of combustible materials in accommodation and service spaces, MSC/Circ.1003. However, the guideline is not referenced in SOLAS, use of it is optional and interpretations of it tend to be flexible. Thus, the intention to restrict the amount of combustible materials in interior spaces is not well managed by prescriptive requirements, even with the guideline accounted for. With regards to FRP composite it is nevertheless clear that most relevant structures will deviate from the existing requirements stated above. At least if they are left uncovered in accommodation and service spaces. If thermal insulation is fitted on the FRP composite it can be claimed that the insulation is the surface material to which the requirements apply. The requirements can thereby be considered achieved. A fire risk assessment should nonetheless consider that a combustible material behind the insulation or approved surface material will eventually affect a fire, even if not during its growth stage.

For external areas there are few requirements related to combustible materials. Restrictions apply to combustible materials on cabin balconies, unless balcony sprinkler is provided in line with MSC.1/Circ.1278. No other external areas are considered in the regulations. The intention to restrict the amount of combustible materials in external areas is hence rather ineffective. The background is that external areas traditionally have been seen as bare non-combustible steel decks and therefore routinely have been assumed to have little or no fire risk. However, the continuing evolution of passenger ships has led to increased use of combustible materials. A guideline has therefore been developed for evaluation of fire risk of external areas on passenger ships (MSC.1/Circ.1274), but this is not compulsory or often applied.

It is clear that the allowed amount of combustible materials is undefined in prescriptive requirements. In a safety assessment it is still relevant to inventory the increased amount of combustible materials when using FRP composite structures. This can be done in comparison with a conventional ship, e.g. by comparing the increased area of exposed combustible surfaces in external areas. Such evaluations have shown that FRP composite structures can pose a quite limited addition of combustible surfaces in some external areas, such as a cruise vessel leisure deck. Other external areas are sparsely furnished or bare and the added FRP composite surfaces represent most of what is combustible. The objective of such a comparison should not be to conclude that the increased amount of combustible materials is restricted (as an argument for compliance with SOLAS II-2/2.2.1.3). It should rather provide for further quantification of the effects on fire safety by assessing the potential for fire spread to combustibles and the associated consequences17, 41.

C.4.2.2.2 Structural integrity and fire containment

Fire safety related to containment of fire and structural integrity are covered in SOLAS Chapter II-2 Regulation 9 and 11, respectively (henceforth referred to as regulation 9 and regulation 11).

C.4.2.2.2.1 Structural integrity

According to regulation 11, materials used in the ship’s structure shall ensure that structural degradation due to fire does not occur. In order to maintain structural integrity of the ship, it is explicitly stipulated in that the hull, superstructures, structural bulkheads, decks and deckhouses shall be constructed of *steel or other equivalent material*, which is further defined as *"any <u>non-combustible material</u> 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."*

Non-combustible material is a material which neither burns nor gives off flammable vapours in sufficient quantity for self-ignition when heated to approximately 750°C. Non-combustibility, which is not limited in time, is tested in accordance with FTP Code, part 1, where a specimen is exposed to 750°C in a cylindrical furnace, as depicted by Figure 15, during which temperature increase, flames and weight loss are measured to determine combustion.

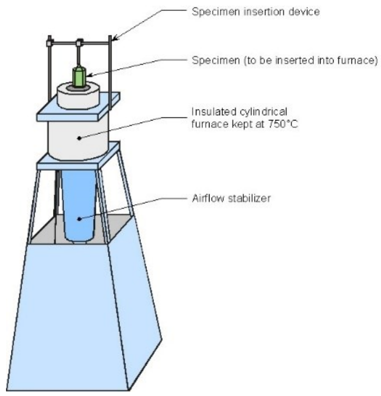


Figure 15: Combustibility test equipment according to part 1 of the 2010 FTP Code

C.4.2.2.2.2 Fire containment

Non-combustibility is per SOLAS a required material property with respect to structural integrity, but also a prerequisite for classification according to integrity and insulation standards for thermal and structural boundaries, which are properties related to fire containment, and thus regulation 9.

Aside from having to meet the non-combustible criterion, certain thermal and structural boundaries need to provide insulation as well as flame and smoke integrity. Of the three categories–A, B, and C–of which only the former two need to meet further requirements than non-combustibility, class A divisions are associated with most demanding performance criteria, requiring them to:

a) prevent the passage of smoke and flame to the end of the one-hour standard fire test (see Figure 16); and
b) be insulated with approved non-combustible material such that the average temperature of the unexposed side will not rise more than 140 °C above the original temperature, nor will the temperature, at any one point, including any joint, rise more than 180 °C above the original temperature, within the time listed below

[14]	class "A-60"	60 min
[15]	class "A-30"	30 min
[16]	class "A-15"	15 min
[17]	class "A-0"	0 min

These performance criteria do not disqualify FRP per se, as it is entirely feasible for sandwiched-structured composites to satisfy (a) and especially (b)[1] under the test conditions specified in part 3. It is however more difficult for such structures, as it currently stands, to qualify as non-combustible in accordance with part 1, which is a prerequisite for all thermal and structural divisions.

[1] The requirements specify that "A" class divisions need to "be insulated" which is a result of assuming that structures are constructed from steel or equivalent material. FRP composite generally have excellent insulating properties.

The fire resistance of thermal and structural divisions is tested and validated in accordance with FTP Code, part 3, by exposing the specimen to a well-defined temperature that increases over time. Typical standardized time-temperature curves are used as reference for the temperature in the furnace as depicted in Figure 16.

An “A-60” class division for example corresponds to fire resistance class [R]EI 60[2], a naming convention used for building components or constructions that achieve 60 minutes of

- load-bearing capacity **(R)**;
- integrity **(E)**; and
- Insulation **(I)**.

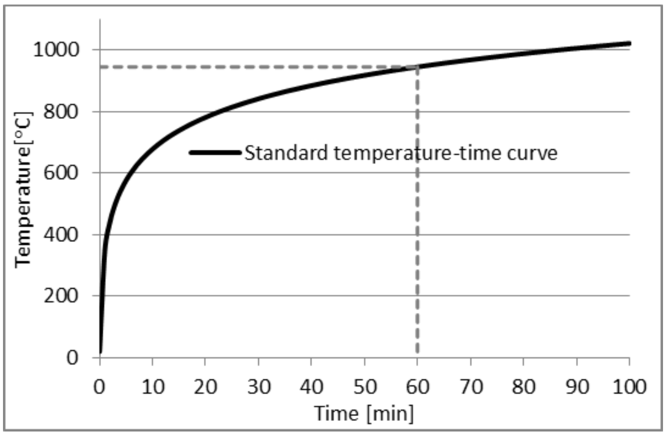


Figure 16: Standard fire time-temperature curve (ISO 834)

C.4.2.2.2.3 FRP composite standards for fire containment and structural integrity

As has been documented above, the provisions in regulation 11 distinctly define non-combustibility as a prerequisite for structural integrity, disqualifying FRP as a prescriptive solution in ship structures. Structural integrity and hence regulation 11 are intimately linked to regulation 9, which covers fire containment. The latter leaves no opening for ships making use of FRP composite in their structures without invoking a different set of standards for thermal and structural boundaries, i.e. one that is not predicated on non-combustibility. Although absent from SOLAS Chapter II-2, such standards have long been the convention for high-speed water vessels.

In the High-Speed Craft (HSC) Code the divisions corresponding to “A” class divisions in SOLAS are referred to as Fire Resisting Divisions (FRD). The main difference is the requirement for an “A” class division to be constructed with non-combustible material, which does not apply to an FRD[3]. The structural fire resistance test, described in FTP Code, part 11, is basically identical to the test required for “A” class divisions, i.e. Part 3, except for an additional load-bearing requirement. This

[2] “A” class divisions are not tested for load-bearing capacity (R), but it is implied by virtue of presumed construction material, i.e. steel or other equivalent material. Although “A” class divisions always have load-bearing capacity, their end-use does not always require it.

[3] It is worth noting that the requirements for FRD specify that materials shall be non-combustible *or fire-restricting*. A Fire Resisting Division can in fact be constructed with non-combustible material, but the “or” clause leaves an opening for combustible materials as long as the materials conform to the requirements as set out for fire-restricting materials (FTP Code, part 10).

requirement implies that FRD decks and bulkheads shall withstand the standard fire test while subjected to transverse and in-plane loading, respectively, thereby incorporating both structural integrity and containment of fire criteria in the test method. An FRD deck or bulkhead structure must sustain the specified static loading whilst exposed to fire in a large-scale furnace for 30 or 60 minutes in order to be certified as FRD30 or FRD60, respectively.

There are, in addition to abovementioned performance criteria, prerequisites that have to be met in order for structures to qualify as FRD. According to test requirements in FTP Code, part 11, materials used in Fire Resisting Divisions shall, assuming they are combustible, be *fire-restricting*[4] (FRM) in accordance with FTP Code, part 10 (ISO 9705). FRM relates to a material's propensity to contribute to fire and ultimately the potential for fire growth, a topic covered in previous sections. FRM is, similarly to FRD, normally only applicable for high-speed craft, and not covered or required by any of the regulations in SOLAS Chapter II-2. In the context of SOLAS vessels, HSC standards like FRD and FRM merely serve as a guidance and a benchmark owing to the lack of specific provisions in SOLAS related to use of FRP composite in ship structures.

A detail worth noting is that an element constructed from combustible material may on no occasion be regarded as an "A" or "B" class division, even if it consists of a combustible core with load-bearing capacity and membrane protection provided by non-combustible material, whereas structural elements consisting of FRP composite can achieve FRD if the main structure fulfils the performance criteria specified in part 11, and is subsequently used in conjunction with fire-restricting material (FRM) panels. The distinction between satisfying part 11 performance criteria and achieving FRD is important to bear in mind, because as mentioned previously, aside from the part 11 performance criteria, there are also prerequisites that have to be met, i.e. materials shall be non-combustible or fire-restricting (FRM). Figure 17 illustrates the two ways of achieving FRD for FRP composite.

[4] Fire-restricting [material] should not be confused with fire resisting [divisions].

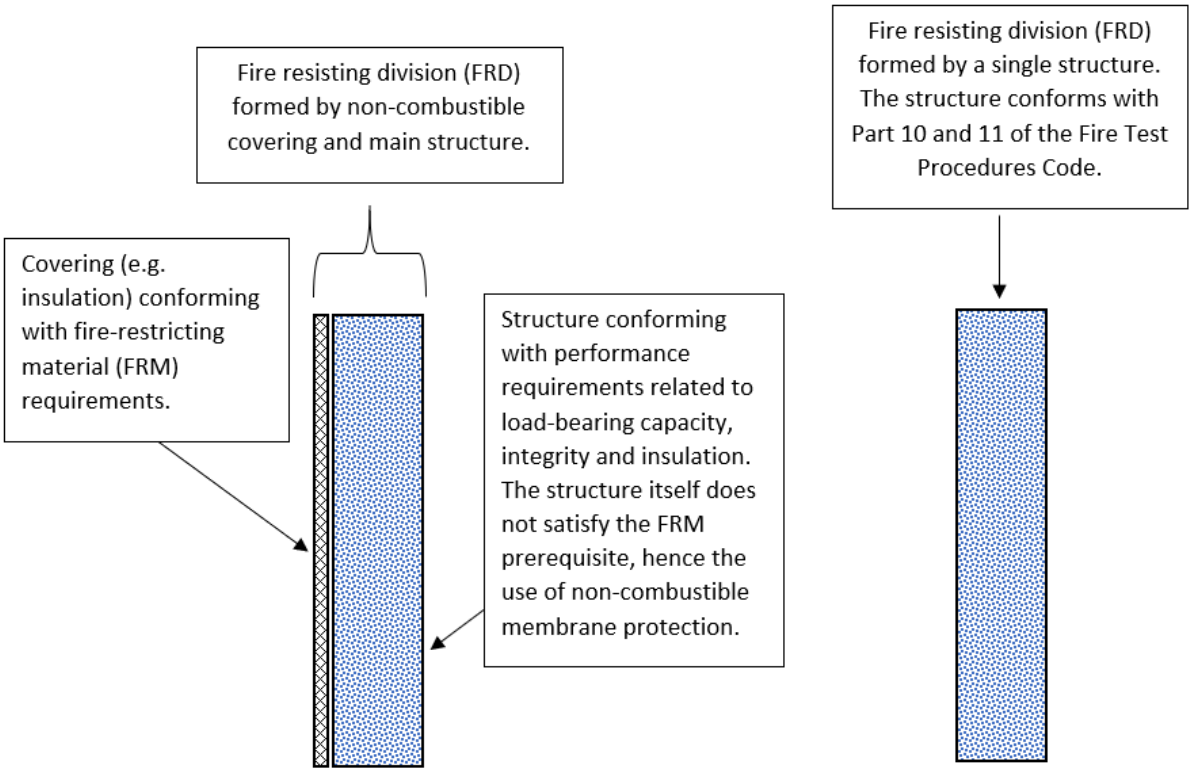


Figure 17: Two different structural FRP composite configurations that achieve FRD

Furthermore, although FRM compliance is necessary in order to meet the threshold for FRD compliance, it can in some circumstances be sufficient to conform only to the performance criteria applicable for FRD and not the prerequisite concerning FRM. At a minimum, such structures would need to have surface materials with low flame-spread characteristics in accordance with part 5 in order to meet the fire safety objectives and the functional requirements as set out in SOLAS chapter II-2. This is particularly appropriate for external combustible surfaces which are not covered by SOLAS Chapter II-2.

C.4.2.2.2.4 Summary of performance and requirements

A summary of the requirements and performances of various structural divisions is given in Table 3.

Table 3: Summary of requirements and performance for "A" class divisions, "B" class divisions and Fire Resisting Divisions.

	B-0	B-15	A-0	A-15	A-30	A-60	FRD30	FRD60
Material	Steel or other equivalent material						FRP composite	
Fire test procedure	Part 3						Part 11	
Prerequisite	Non-combustible (Part 1)						Non-combustible (Part 1) or fire-restricting (Part 10)	
Restricted ignitability	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Fire growth potential	LFS	LFS	LFS	LFS	LFS	LFS	FRM	FRM
Non-combustibility	∞	∞	∞	∞	∞	∞	(30)	(60)
Structural (R)	-	-	(60)	(60)	(60)	(60)	30	60
Integrity (E)	30	30	60	60	60	60	30	60
Insulation (I)	0	15	0	15	30	60	30	60

Note: Technically, low flame-spread characteristics (LFS) is not a requirement for "A" or "B" class divisions, hence highlighted in blue. LFS is however a requirement for exposed surface materials and they are typically attached to or painted on "A" and "B" class divisions.

C.4.3 Alternative approval procedure

C.4.3.1 MSC/Circ.1002

The procedure for a regulation 17 assessment is summarized in the regulation and further described in MSC/Circ.1002 (IMO 2001). It can be described as a two-step deterministic risk assessment, illustrated in Figure 18, consisting of:

1. preliminary analysis in qualitative terms; and
2. quantitative analysis.

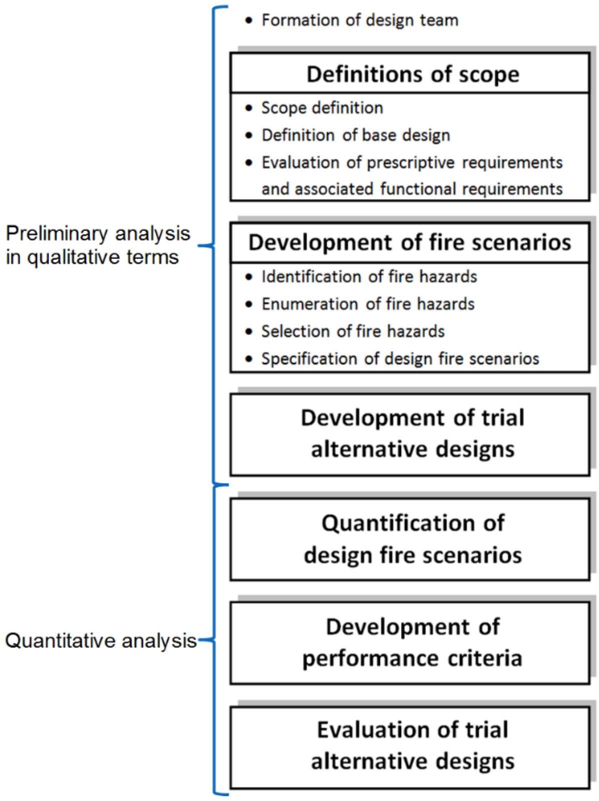


Figure 18. Procedure in accordance with MSC/Circ.1002.

In the first part the scope of the analysis is defined, fire hazards are identified and from these design fire scenarios as well as trial alternative designs are developed. Those steps are documented in a preliminary analysis report, which needs approval before the trial alternative designs are evaluated by the developed fire scenarios in the quantitative analysis. There are no explicit safety criteria but outcomes are compared between the trial alternative designs and a prescriptive design (complying with relevant prescriptive requirements). The final documentation of the engineering analysis should with reasonable safety margin ensure that the fire safety of the final alternative design and arrangements is at least equivalent to that of a prescriptive design.

For further guidance it is relevant to consider guidance notes for MSC/Circ.1002 (e.g. ABS 2010), the general guidelines MSC.1/Circ.1455 (IMO 2013) and guidelines for building fire risk assessment (e.g. ISO 2012, SFPE 2006).

C.4.3.2 Development of fire scenarios

In MSC/Circ.1002, the development of fire scenarios is initiated by an “Identification of fire hazards”, which at least should determine: pre-fire situation, ignition sources, initial fuels, secondary fuels, extension potential, target location, critical factors and relevant statistical data (IMO 2001). These conditions and characteristics may simply be listed but can also be the output from a standardized (What If?, FMEA, HAZOP, etc.) or applied procedure (e.g. Breuillard and Corrignan 2009). However, instead of an identification of hazards, the process rather becomes a way to incorporate effects from the (already identified) hazards into fire scenarios.

According to MSC/Circ.1002, the fire hazards should be enumerated into one of the three incident classes localized, major and catastrophic. These incident classes are meant to signify the effect zone of the fire hazards, i.e. if the fire is confined in an area, the ship or spreading outside the boundaries of a ship (IMO 2001). The instruction to tabulate fire hazards into these incident classes can, however, seem illogical with the standard definitions of hazard and incident within risk management (e.g. Kaplan and Garrick 1981). A hazard is namely merely a source of danger whilst the incident classes represent degrees of consequences. Such depend on the existence and function of risk control measures, which means that hazards are not necessarily related to outcomes (Evegren 2010a).

If identified fire hazards are nevertheless to be enumerated in the specified classes, it could be claim that they correspond to the required hazards categories. ‘Ignition sources’, ‘initial fuels’ and ‘secondary fuels’ then represent localized fire hazards whilst ‘extension potentials’ represent major fire hazards. However, truly major or catastrophic fire hazards will be few since the “Identification of fire hazards” focuses at each space and fire spread to adjacent spaces. Hence, in the translation of fire hazards into fire scenarios it is necessary to also consider the potential for escalating fires involving major parts of the ship.

To continue the process, it is useful to define design fires. Probabilities of functioning risk control measures are then ignored, resulting in the plausibly worst fire scenario for each space/area, with account to the introduced hazards. A design fire should consider identified ignition sources and fuels in the space, the potential for oxygen supply and fire spread, and other relevant conditions (see e.g. ISO 2006, Staffansson 2010). Design fires together with conditions and characteristics affecting fire development (failure of e.g. sprinkler system, detection, fire response, window/door) define distributions of fire scenarios. Depending on the aimed level for the quantitative analysis (see section 3.4.3), it can be relevant to categorize the conditions and characteristics. This allows grouping spaces with similar potential for fire development and representing each group by one fictitious space (ABS 2010). In this process it is particularly important that conditions differing between the alternative and prescriptive design are captured. If evacuation analysis is anticipated (e.g. Salem 2010), the categorization should also account for conditions affecting evacuation, e.g. number of exits and maximum walking distance.

When it comes to selection of fire scenarios, fire hazards are still equated with incidents in MSC/Circ.1002. It is instructed to select a range of incidents which cover the largest and most probable range of enumerated fire hazards (IMO 2001). However, priority when selecting fire scenarios should be to include the introduced hazards. This is the purpose of the assessment; to evaluate effects of these hazards on fire safety. If all fire hazards cannot be covered in fire scenarios, the ambition should be to at least include those with potential to give significant effects. Fire hazards which cannot be quantified in fire scenarios should be managed in a different way, for example qualitatively. The Administration should be involved to ensure this and to limit subjective judgement in this process. It should also foresee whether the prescriptive design will represent an acceptable level of safety in the scenarios.

C.4.3.3 Development of trial alternative designs

In a regulation 17 assessment, the fire safety of trial alternative designs is compared to that of a prescriptive design. Something that is not instructed in MSC/Circ.1002, but becomes a practical necessity in this process, is to determine a ‘base alternative design’ at the onset of the assessment (as e.g. in Breuillard and Corrignan 2009, Evegren 2010b, McGeorge et al. 2009). It should be defined as the ship with the introduced alternative solutions, including pre-determined added safety measures. It will thus be the design and arrangements which all trial alternative designs have in common and are based upon. If this is not defined, identification of hazards, development of fire scenarios etc. will have to be done for each trial alternative design, which is both inefficient and unsystematic.

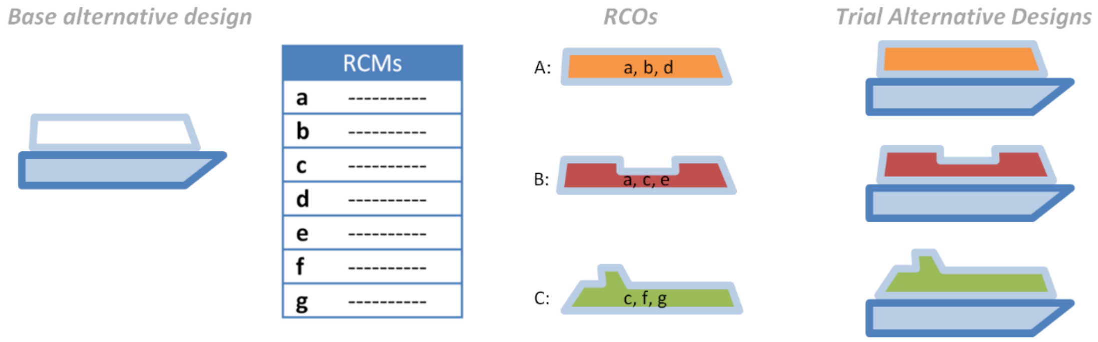


Figure 19: Description of BAD, RCOs and TADs.

The trial alternative designs are supposed to be specified in the preliminary analysis report. However, new risk control measures and suitable combinations can be found later in the assessment, and their effects on safety are not clear. It is therefore difficult to finalize trial alternative designs at this stage; suitable combinations of risk control measures (risk control options) can be suggested, but the trial alternative designs should not be seen as final.

C.4.3.4 Quantitative analysis

C.4.3.4.1 Manage fire hazards independently or safety holistically?

The ultimate requirement for an alternative design is to provide at least the same degree of safety as prescriptive requirements (regulation 17.3.4.2). It may be relevant to quantify safety holistically in one measure but such an assessment would be performed at a very high level. If effects on safety can be separated and managed in smaller 'areas', it will often allow simpler evaluations. The assessment can for example be divided based on affected regulations (e.g. fire growth potential or containment of fire) or functional requirements (e.g. control of air supply or insulation of boundaries). Theoretically, each introduced hazard could be managed independently, but this requires that they are all unconnected.

Large scopes may require dividing quantification in two parts; one part with the fire hazards possible to evaluate independently and one part with the fire hazards that must be quantified together. The hazards managed independently can be those which are judged unlikely to have effects on safety, easily handled by risk control measures or possible to disprove by tests. Other hazards may be necessary to manage independently since they are too uncertain or impossible include in fire scenarios (see e.g. Evegren 2013a).

If hazards are managed independently or in small groups, safety will not be quantified in one holistic measure but sufficient total safety is ensured by achieving at least equivalency within each area. This requires larger safety margins but also less engineering rigor, since it allows evaluating the hazards at suitable levels, as further discussed below.

C.4.3.4.2 Recommendable sophistication of the assessment

The procedure outlined in MSC/Circ.1002 is a typical deterministic risk assessment of design fire scenarios. It is well described in engineering guides to performance-based analysis of fire protection in buildings (e.g. SFPE 2006). In the development of design fire scenarios it is instructed to choose the largest but also the most probable range of incidents. This portion of probability takes the procedure from a worst-case to a plausible worst-case approach. Probabilities are still to a large degree ignored and assumed compensated by the assessment of plausible worst-case scenarios; if performance is superior in these major fires, the design is expected to be advantageous in all less severe scenarios. The uncertainties of this simplification and the undefined measure of conservatism included when developing design fire scenarios although make it unclear as to what risks are really accepted.

MSC/Circ.1002 states that the scope of the assessment depends on the extent of deviations and of the alternative design and arrangements. If safety margins are to be kept reasonable and introduced novelty properly described in terms of fire safety, the assessment may need to be performed at a more sophisticated level. This can be interpreted from MSC/Circ.1002 (6.4.3) but is clearer described in MSC.1/Circ.1455 (4.13.2). A less complicated assessment could also suffice if the base alternative design is simple. Since the term “engineering analysis” generally refers to a certain kind of risk assessment (SFPE 2006), the more general term “regulation 17 assessment” is preferred.

There are many different risk assessment methods of varying sophistication. They are often categorized based on their inclusion of quantitative measures (qualitative-quantitative) or on their consideration to likelihoods of outcomes (deterministic-probabilistic). A categorization which includes these features but depends on how uncertainties are treated with varying sophistication was presented by Pate-Cornell (1996). Based on this categorization and the experience of involvement in over a dozen regulation 17 assessments, it is recommendable to use four levels of assessments, illustrated in Figure 20 and described below.

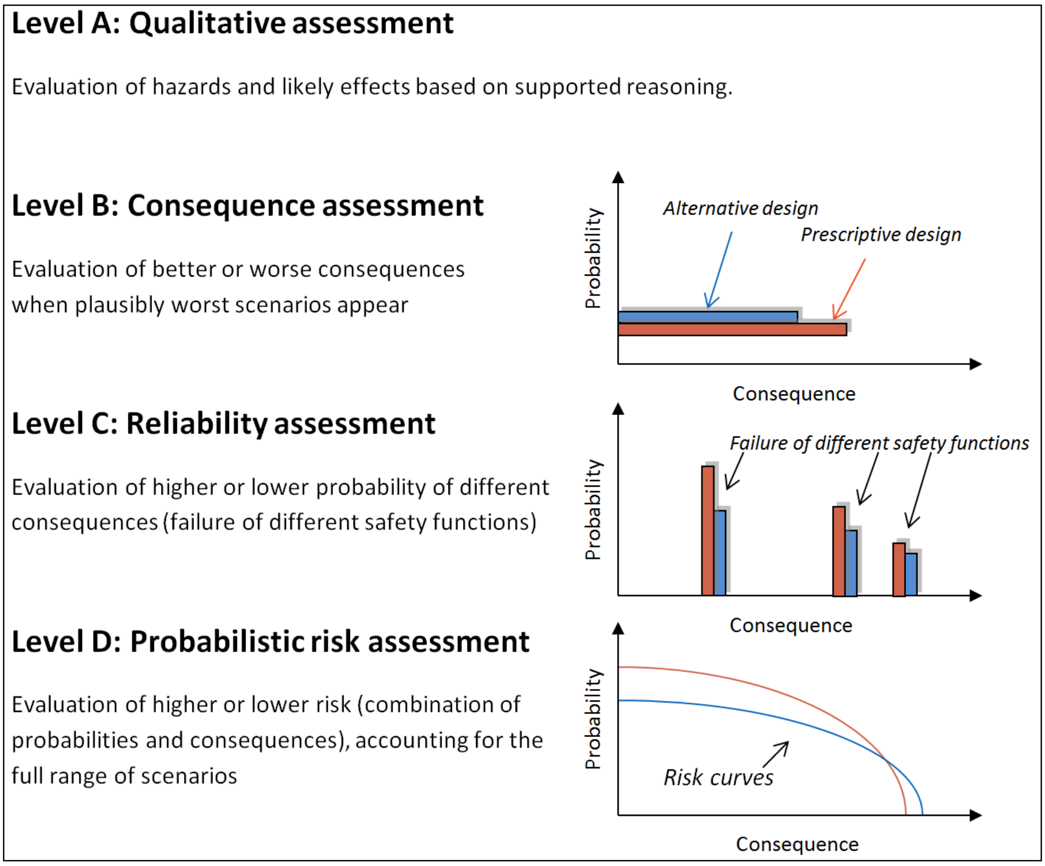


Figure 20: Different levels of risk assessments.

Level A-Qualitative assessment: This level comprises the preliminary analysis in qualitative terms, with identification of hazards and development of fire scenarios. Hazards which are limited (have small effects on fire safety, imply small uncertainties or are easily mitigated with risk control measures) can be managed only qualitatively (see e.g. Evegren 2013b, and Hugosson 2011). Conclusions may be drawn from logic reasoning, statistics, proven solutions, tests, simple calculations etc. (Swedish National Board of Housing Building and Planning 2011). The magnitude of risks cannot be compared at this level and the cost-effectiveness of risk control measures cannot be ranked (Pate-Cornell 1996, level 0).

Level B-Consequence assessment: A pure worst-case approach is an analysis of consequences without consideration to probability. However, since it is meaningless to design according to extremely conservative assumptions, a plausible worst-case approach is often applied, and intended at this level (see e.g. Evegren 2015, Rahm and Evegren 2012, Salem et al. 2015). A guide for such analysis is for example provided in (Rosenbaum 2005). As illustrated in Figure 3, consequences are compared of the scenarios (which should primarily represent introduced hazards), for example in terms of temperatures, visibility and toxic gases (Salem 2010, USA 2012). Probabilities of the quantified scenarios are low and assumed the same in the prescriptive and alternative design. However, there is no attempt to manage probability, quantify uncertainty or judge conservatism of the scenarios. Comparisons of risks and risk-control measures at this level therefore have no real meaning and optimizations are seldom possible (Pate-Cornell 1996, level 2). To limit the measure of conservativism in the design fire scenarios it is useful to give best estimates to conditions which are in common for the alternative and prescriptive design.

Level C-Reliability assessment: Instead of evaluating consequences when plausibly worst-case scenarios appear, evaluation can be made of probabilities of specific consequences (see e.g. Rahm 2011, Rahm 2012). This is for example tradition in design of load-bearing structures, where only the failure probability P_f is determined, i.e. for an assumed fixed consequence (CEN 2002). The selection of consequences should stem from the identified hazards and may advantageously be taken from functional requirements challenged in the regulations, e.g. failure of fire containment or structural integrity. Evaluation is thus made of the reliability of the “safety functions”, as illustrated in Figure 3. These are assumed associated with similar consequences for the alternative and prescriptive design, which is hence opposite from an assessment performed at level B. Common tools for the assessment are event tree, fault tree and Bayesian network. Uncertainties can by use of input distributions be quantified better than at the previous level but holistic comparison of risks and risk-control measures are still impossible.

Level D-Probabilistic risk assessment: A probabilistic risk assessment accounts for the full notion of risk by considering for the whole distribution of consequences and probabilities (see e.g. Evegren 2013a, McGeorge, Höyning and Nordhammar 2009, Povel and Radon 2010, Themelis and Spyrou 2010). The resulting probability density function can be presented as a risk curve, e.g. an FN-curve, illustrated in Figure 3. The dispersion due to knowledge uncertainty and stochastic uncertainty in input data is impossible to distinguish since they are aggregated into the risk curve (Pate-Cornell 1996, level 4). However, it is possible to assign distributions to describe secondary probabilities (Themelis et al. 2011), i.e. uncertainty about probability (Pate-Cornell 1996, level 5). These can be evaluated though Monte Carlo simulations, allowing use of confidence intervals instead of safety margins.

The proposal of different levels to perform an assessment is much in line with the recommendation to manage hazards independently or in small groups. An assessment can include evaluations at several levels; some hazards may be possible to manage at a low level, to exclude them from further quantification at higher levels. Assessments at higher levels can thereby be kept as simple and delimited as possible. Applying a more sophisticated level of risk assessment does not only increase the level of detail and amount of engineering rigor. The documentation also becomes less transparent, and the end result may be harder to comprehend, approve and survey (Breuillard and Corrignan 2009).

C.4.4 Design

Making use of FRP composite in ship structures entails replacing “A” and “B” class divisions with combustible materials. This process is illustrated by the flowchart in Figure 21.

As a first step, the category of division and load-bearing capacity of the conventional structure made from non-combustible material should be identified. Once this has been performed, the relevant test standard for achieving fire resistance for the FRP composite solution can be determined. As an example, an FRP composite structure that replaces a loadbearing “A” class division should satisfy performance requirements detailed in FTP Code, part 11, which corresponds to fire resistance class REI 60.

It should, as a next step, be determined whether covering provided by non-combustible materials (e.g. insulation) is necessary, which is typically only relevant for interior surfaces. Such a structural configuration would imply that the only additional fire safety requirement for the structure is low flame-spread (LFS) characteristics in accordance with part 5. Opting for no covering would however require that low flame-spread characteristics of the surface material should be accompanied with active safety measures, or that the surface material satisfies the requirements for fire-restricting material (FRM) in accordance with part 10. The latter is achieved either through the use of a pre-approved FRM solution, e.g. calcium silica boards, in conjunction with the main structure or by subjecting the structure itself to the test procedures defined in part 10. Both options would, assuming FRM is achieved, result in a Fire Resisting Division.

It is worth recognizing that although surface materials may qualify as LFS or FRM, a fire will eventually reach the substrate, thereby involving the core material as well. This is typically not a critical concern for conventional bulkheads and decks made from non-combustible materials, but by using FRP composite in ship structures, questions regarding the increased amount of combustible materials, i.e. the FRP beneath lining/covering, and structural integrity of the ship during fire may arise. It is therefore generally always better to aim for a higher degree of safety through additional active safety measures, even if they’re not required by prescription. This is particularly important on ships longer than 30 m which are liable to progressive collapse given that load-bearing structures contribute to global strength.

A summary of the performance of divisions formed by non-combustible structures and various FRP substitutes is given in Table 3. This is accompanied by figures (Table 4 and Table 5) which illustrate the structures described in Table 3.

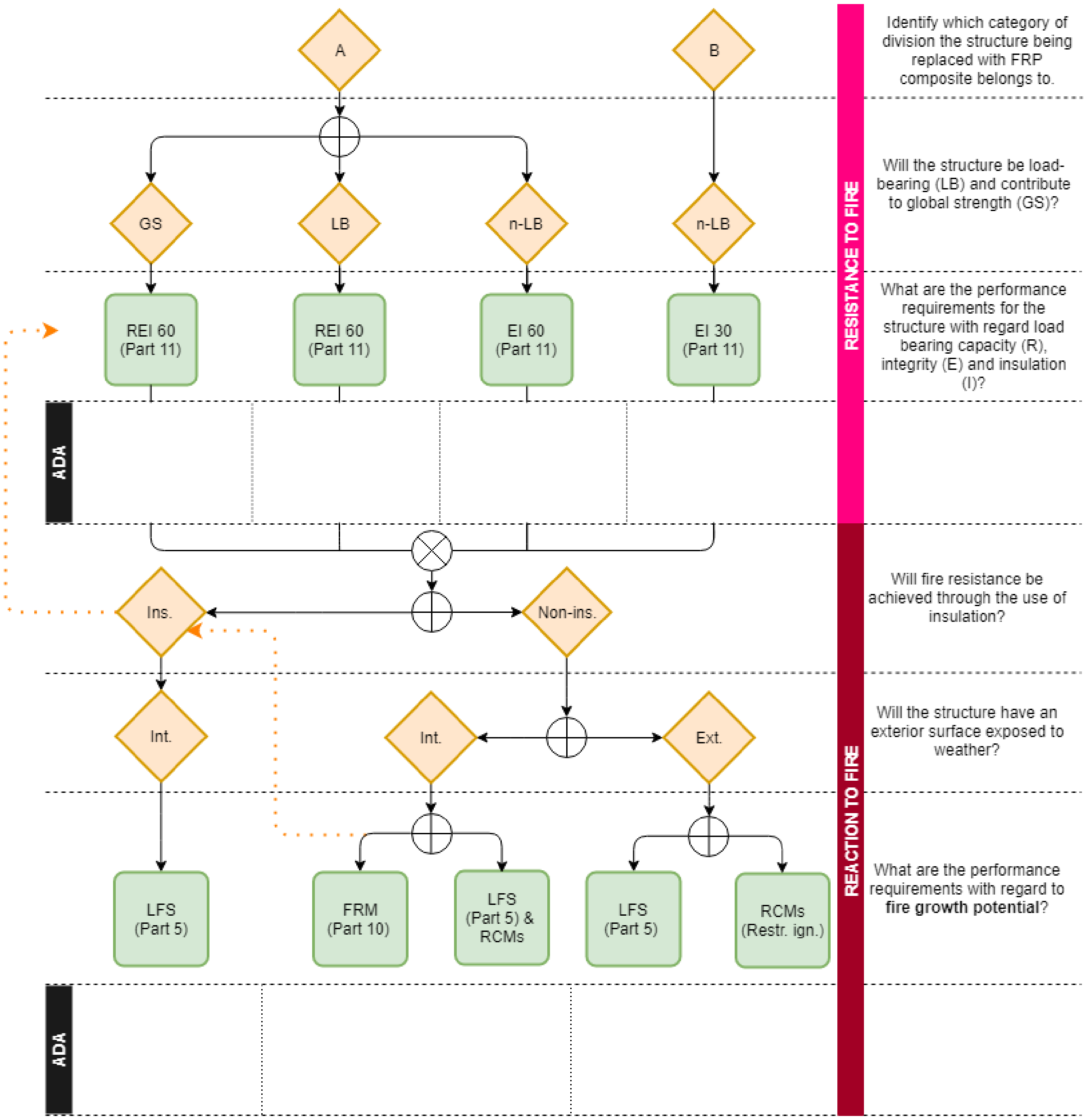
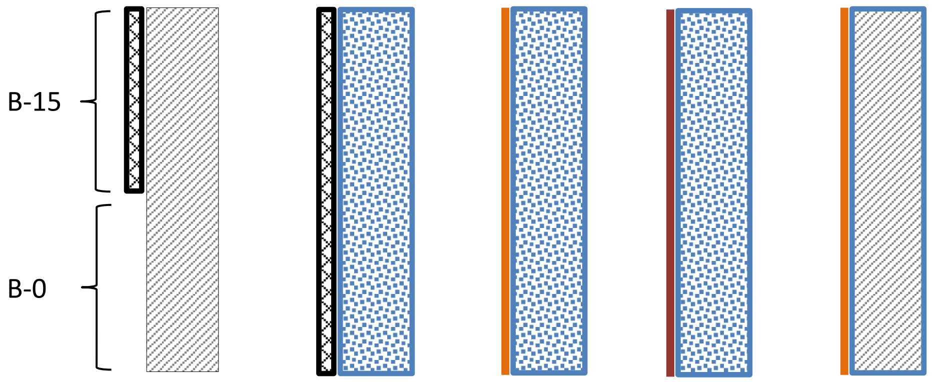


Figure 21: Flowchart illustrating the process of replacing "A" or "B" class divisions with FRP composite structures.

Table 4: Performance of divisions formed by “B” class divisions and various FRP substitutes.

“B” class divisions and FRP composite substitutes



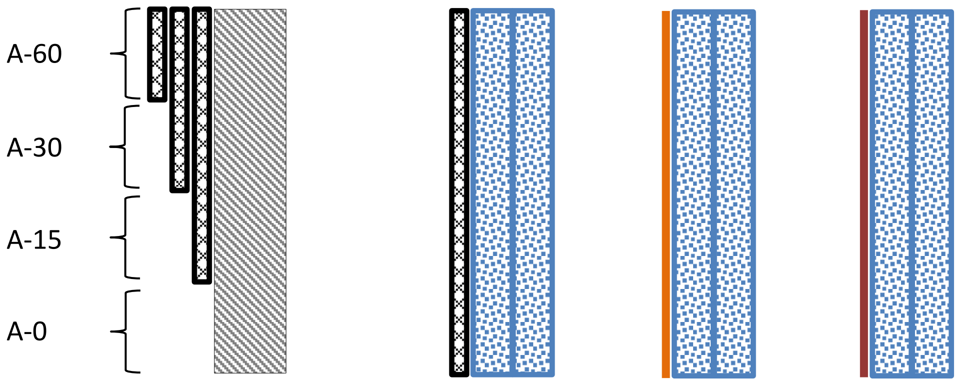
Structure	Conventional according to prescription B-0/B-15	FRP with non-c covering $EI30_{LFS/FRM}$	FRP with FRM surface $EI30_{FRM}$	FRP with LFS surface $EI30_{LFS}$	FRP with LFS surface, Non-c core* B-30
Restricted ignitability	Yes	Yes	Yes	Yes	Yes
Fire growth potential	LFS	LFS/FRM	FRM	LFS	LFS
Non-combustibility	∞	*(<x)**	*(y; y<x)*	*(z; z<y)*	∞
Integrity	30	30	30	30	30
Structural	-	-	-	-	-
Insulation	0/15	30	30	30	(30)

*Only the core is considered to be the structure, to which the non-combustibility requirement applies, and thus becomes a prescriptive “B” class solution if the laminates achieve LFS. Insulation capacity of 30 minutes will inherently be achieved and the solution could thus be claimed to become a B-30 division (not defined in SOLAS) rather than a B-15 division.

Note: Highlighted row in green is the functional requirement and corresponding values that distinguish FRP alternatives from non-combustible structures. In the accompanying figure, from left to right (aligned to square with corresponding columns): “B” class division, composite with covering/insulation, composite with LFS surface, composite with FRM surface, and composite consisting of a non-combustible core with FRP skin and LFS surface.

Table 5: Performance of divisions formed by “A” class divisions and various FRP substitutes.

“A” class divisions and FRP composite substitutes



Structure	Conventional according to prescription	FRP with non-c covering	FRP with LFS surface	FRP with FRM surface, FRM→ FRD60
Restricted ignitability	Yes	Yes	Yes	Yes
Fire growth potential	LFS	LFS/FRM	LFS	FRM
Non-combustibility	∞	*(60)*	*(x_2)*	*(y_2; $y_2 < x_2$)*
Integrity	60	60	60	60
Structural	(60)	60	60	60
Insulation	0/15/30/60	60	60	60

Note: Highlighted row in green is the functional requirement and corresponding values that distinguish FRP alternatives from non-combustible structures. In the accompanying figure, from left to right (aligned to square with corresponding columns): “A” class division, composite with covering/insulation, composite with LFS surface, and composite with FRM surface

C.4.5 FAQ

- It is said that alternative fire safety design needs to achieve the functional requirement: "use of combustible material shall be restricted". How is this possible to achieve when you add more combustible materials/structures?

- With regards to the definition of element; "safety of the ship" is very general. How big can an element be?

- What Flag States are the most positive respectively the most opposed to approval of FRP composite structures, i.e. who should we turn to?

- Are Flag States competent to review and approve FRP composite structures?

- What is the Class role in the approval process of FRP composite structures, and how can this be combined with the Flag role in order to achieve approval of load-bearing FRP composite structures?

- Approval through a Reg 17 assessment seems very costly and time consuming - how will this ever work for a real ship building project?

- Will it ever be possible to build large full FRP composite ships, with consideration to what you stated regarding structural collapse after a long-lasting fire?
- Are there any shortcuts to build a full FRP composite ship today - can structural collapse be addressed?

- How can market uptake of lightweight FRP composite ship structures be accelerated?

- Who should be responsible of performing the fire safety assessment of the FRP composite structures - the yard, shipping company or someone else?

- Why are there not more recommendation in the guidelines wrt structural design, e.g. with dimensions geometries, etc?

C.5 Mechanical performance

Main author of the chapter: BV

C.5.1 Background

C.5.1.1 General methodology for approval of composite structure

Different certification schemes are usually used by the Classification Societies to assess materials and equipment fitted on board ships classed and to assess ships constructions built using composite materials. All these global survey schemes are based on the following steps of assessment:

11. Raw materials;
12. Structure design;
13. Specimen tests of FRP;
14. Manufacturing and testing at works;
15. Final test and inspection of the construction.

These individual steps of assessment are detailed in Annex B of this document

Each step of assessment requires to define the:

- Type testing program and standard to be used or assessment methodology,
- Validation criteria of test results and assessment,
- Body in charge of tests and assessments and responsibilities (manufacturer, independent laboratory or Classification Society);
- Type of certificates granted to certify the assessment process and body in charge to issue these certificates.

C.5.1.2 Composite materials failure mechanisms

C.5.1.2.1 General

In order to evaluate the mechanical resistance of a composite materials, it is important to know the failure mechanisms of this kind of structure. In general, five failures modes have been identified, as show in Figure 22:

1. Longitudinal matrix failure
2. Transverse matrix failure
3. Fibre rupture
4. Fibre matrix debonding
5. Delamination

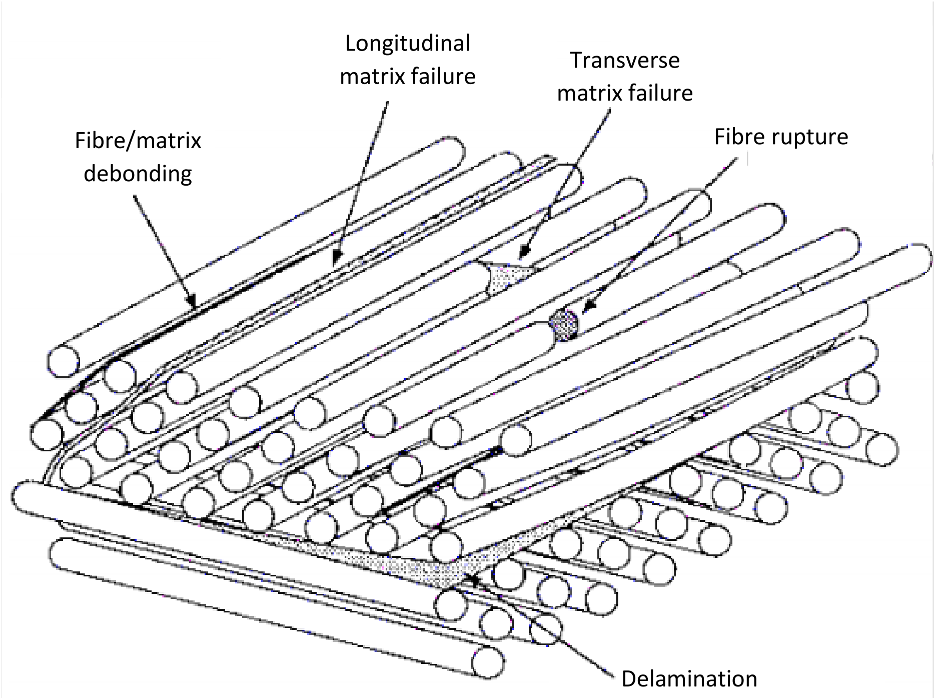


Figure 22 Composite materials failure modes

C.5.1.2.1.1 Matrix failure

The complexity of composite materials lead to several microscopic cracks occurring in the matrix either in longitudinal or transversal direction. When the debonding stress is greater than the shearing resistance, the crack propagates in the perpendicular direction to the load.

C.5.1.2.1.2 Fibre rupture

The fibre rupture occurs when the tensile stress reaches the tensile breaking stress of the fibre in the load direction.

C.5.1.2.1.3 Fibre/matrix debonding

The fibre/matrix interface is the area of load transfer between fibres and matrix. After crack initiation, the crack propagation depends on the nature of the fibre/matrix adhesion. In case of Uni-Directional (UD) fibre composite structure, the following cases can be distinguished:

- Strong interface: the crack propagation will be initiated by the fibre or matrix failure and extends with no obstacle. The rupture is brittle.
- Weak interface: the debonding will occur over a very long distance in the matrix.
- Intermediate interface: the crack will deviate in the perpendicular plane leading to the debonding of the matrix at the interface.

C.5.1.2.1.4 Delamination

In addition to failure mechanisms detailed above, the damage between two layers is called delamination. The delamination process is the result of a chronology of various damage types. The adhesive and cohesive properties at the matrix and fibre interface manage the chronology of this failure. The delamination progresses essentially by interlaminar cracking leading to the separation of the laminate in two parts. This failure mode contributes to a large degradation of the mechanical properties of the structure.

C.5.1.2.1.5 Rupture levels

Two ruptures level can be considered in the design assessment process:

1. First Ply Failure (FPF)
2. Last Ply Failure (LPF)

The first ply failure causes a loading redistribution in the laminate, not always leading to the collapse of the structure. FPF criteria are given by a linear analysis while non-linear analysis will lead to LPF.

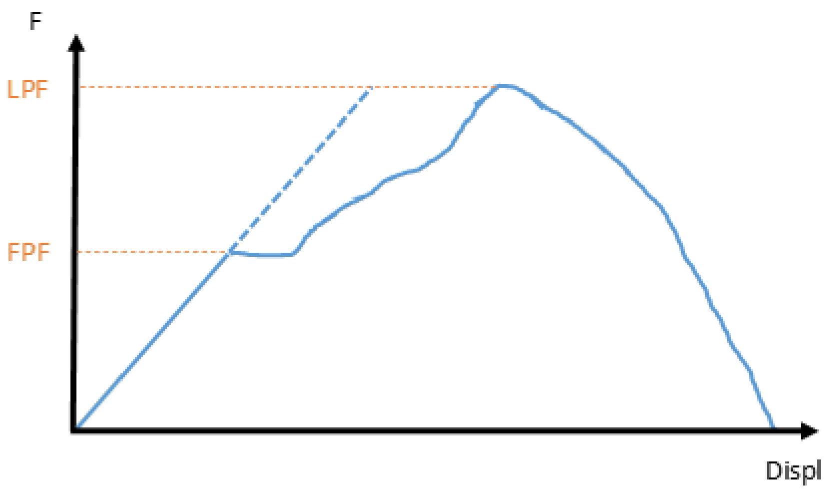


Figure 23 Composite materials rupture levels

Bureau Veritas criteria are based on the First Ply Failure approach for composite materials structure.

C.5.1.2.2 Failure criteria

In general, failure criteria are obtained from tensile and shear mechanical tests and are used for combined stresses. Such criteria give an envelope of the linear elastic area for a laminate under combined stresses. Two criteria families can be defined:

- Energetic criterion: Tsai-Hill, Tsai-Wu, Hoffman
- Phenomenological criterion: Hashin, Puck

These criteria can be easily used for the post-processing of Finite Element Models.

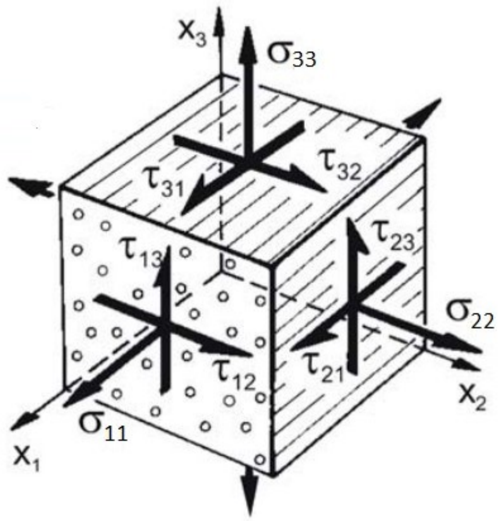


Figure 24 Definition of 3D stresses in a UD laminate

C.5.1.2.2.1 Tsai Hill

The Tsai-Hill criterion is a quadratic and interactive stress-based criterion that identifies failure, but does not distinguish between modes of failure in tension or compression. Failure occurs whenever the following condition is satisfied:

$$\frac{\sigma_{11}^2}{\sigma_{br11}^2} - \frac{\sigma_{11}\sigma_{22}}{\sigma_{br11}^2} + \frac{\sigma_{22}^2}{\sigma_{br22}^2} + \frac{\tau_{12}^2}{\tau_{br12}^2} \geq 1.0$$

The coefficients σ_{ij} and τ_{ij} of the Tsai-Hill criterion are computed as follows:

σ_i , τ_{12} : Actual stresses, in N/mm2, in the considered local ply axis induced by the loading case considered,

σ_{bri} , τ_{br12}: Ply theoretical breaking stresses, in N/mm2, in the local ply axis.

In a Finite Element Analysis (FEA), the failure index is computed as follow:

$$\text{Failure Index} = \frac{\sigma_{11}^2}{\sigma_{br11}^2} - \frac{\sigma_{11}\sigma_{22}}{\sigma_{br11}^2} + \frac{\sigma_{22}^2}{\sigma_{br22}^2} + \frac{\tau_{12}^2}{\tau_{br12}^2}$$

C.5.1.2.2.2 Tsai Wu

The Tsai-Wu Criterion is a quadratic, interactive stress-based criterion that identifies failure and taking into account tensile and compression breaking stresses. Failure occurs whenever the following condition is satisfied.

$$F_1\sigma_{11}+F_2\sigma_{22}+F_{11}\sigma_{11}^2+F_{22}\sigma_{22}^2+F_{66}\tau_{12}^2+2F_{12}\sigma_{11}\sigma_{22}\geq 1.0$$

The various coefficients F_{ij} of the Tsai-Wu criterion are defined in terms of known/measured strengths of the composite material:

σ_i , τ_{12} : Actual stresses, in N/mm2, in the considered local ply axis induced by the loading case considered,

σ_{brci} : Ply theoretical breaking stresses in compression, in N/mm2, in the local ply axis,

σ_{brti} : Ply theoretical breaking stresses in tension, in N/mm2, in the local ply axis,

τ_{br12} : Ply theoretical breaking stresses (absolute value), in N/mm2, in the local ply axis.

With:

$$F_1=\frac{1}{\sigma_{brt11}}+\frac{1}{\sigma_{brc11}}$$

$$F_2=\frac{1}{\sigma_{brt22}}+\frac{1}{\sigma_{brc22}}$$

$$F_{11}=-\frac{1}{\sigma_{brt11}\sigma_{brc11}}$$

$$F_{22}=-\frac{1}{\sigma_{brt22}\sigma_{brc22}}$$

$$F_{66}=\frac{1}{\tau_{br12}\tau_{br12}}$$

The interaction coefficient F_{12} can be defined in one of two different ways. If a biaxial failure stress ($\sigma_{11}=\sigma_{22}=\sigma_{biax}$) is used, F_{12} is computed as follow:

$$F_{12}=\frac{1}{2\sigma_{biax}^2}\left[1-\left(\frac{1}{\sigma_{brt11}}+\frac{1}{\sigma_{brc11}}+\frac{1}{\sigma_{brt22}}+\frac{1}{\sigma_{brc22}}\right)\sigma_{biax}+\left(\frac{1}{\sigma_{brt11}\sigma_{brc11}}+\frac{1}{\sigma_{brt22}\sigma_{brc22}}\right)\sigma_{biax}^2\right]$$

Otherwise, the interaction coefficient F12 is computed as $F_{12}=f^*\sqrt{F_{11}F_{22}}$

where f* is a user-specified constant, -0.5 ≤ f* ≤ 0.

If the Tsai-Wu criterion is selected for a FEA, the coefficient f* is to be defined and the failure index r for the Tsai-Wu criterion is:

$$\text{Failure Index}=F_1\sigma_{11}+F_2\sigma_{22}+F_{11}\sigma_{11}^2+F_{22}\sigma_{22}^2+F_{66}\tau_{12}^2+2F_{12}\sigma_{11}\sigma_{22}$$

C.5.1.2.2.3 Hoffman

The Hoffman criterion is an extension of Tsai-Hill theory by considering values in tension and compression:

$$F_1\sigma_{11}+F_2\sigma_{22}+F_{11}\sigma_{11}^2+F_{22}\sigma_{22}^2+F_{66}\tau_{12}^2-F_{12}\sigma_{11}\sigma_{22}=1.0$$

Bureau Veritas composite materials rules are based on this criterion.

C.5.1.2.2.4 Hashin

The Hashin criterion identifies four different modes of failure for the composite material: tensile fibre failure, compressive fibre failure, tensile matrix failure, and compressive matrix failure.

If $\sigma_{11} \geq 0$, the tensile fibre failure criterion is:

$$F_{brtf}=\left(\frac{\sigma_{11}}{\sigma_{brt11}}\right)^2+\alpha\left(\frac{\tau_{12}}{\tau_{br12}}\right)^2 \geq 1.0$$

If $\sigma_{11} < 0$, the compressive fibre failure criterion is:

$$F_{brcf}=\left(\frac{\sigma_{11}}{\sigma_{brc11}}\right)^2 \geq 1.0$$

If $\sigma_{22} \geq 0$, the tensile matrix failure criterion is:

$$F_{brtm}=\left(\frac{\sigma_{22}}{\sigma_{brt22}}\right)^2+\alpha\left(\frac{\tau_{12}}{\tau_{br12}}\right)^2 \geq 1.0$$

If $\sigma_{22} < 0$, the compressive matrix failure criterion is:

$$F_{brcm}=\left(\frac{\sigma_{22}}{2\tau_{br23}}\right)^2+\left[\left(\frac{\sigma_{brc22}}{2\tau_{br23}}\right)^2-1\right]\frac{\sigma_{22}}{\sigma_{brc22}}+\left(\frac{\tau_{12}}{\tau_{br12}}\right)^2 \geq 1.0$$

Note, the Hashin equations include two user-specified parameters: and τ_{23}.

- α: User-specified coefficient that determines the contribution of the longitudinal shear stress to fibre tensile failure. Allowable range is 0.0 ≤ α ≤ 1.0, and the default value is α = 0.
- τ_{23}: Transverse shear strength of the composite material in the 23 plane.

C.5.1.2.2.5 Puck

The Puck criterion identifies fibre failure (FF) and inter-fibre failure (IFF) in a unidirectional composite. FF is based on the assumption that fibre failure under multiaxial stresses occurs at the same threshold level at which failure occurs for uniaxial level. IFF is subdivided into three failure modes, A, B and C, see Figure 25. Mode A occurs when the lamina is subjected to tensile transverse stress, whereas modes B and C correspond to compressive transverse stress. The classification is based on the idea that a tensile stress $\sigma_t > 0$ promotes fracture, while a compressive stress $\sigma_c < 0$ prevents shear fracture. For $\sigma_c < 0$ the shear stresses τ have to face an additional fracture resistance, which increases with σ, analogously to an internal friction. The distinction between modes B and C is based on their failure angles, which are 0° for mode B and a different value for mode C. In addition, failure mode C is considered more severe, since it produces oblique cracks and may lead to serious delamination.

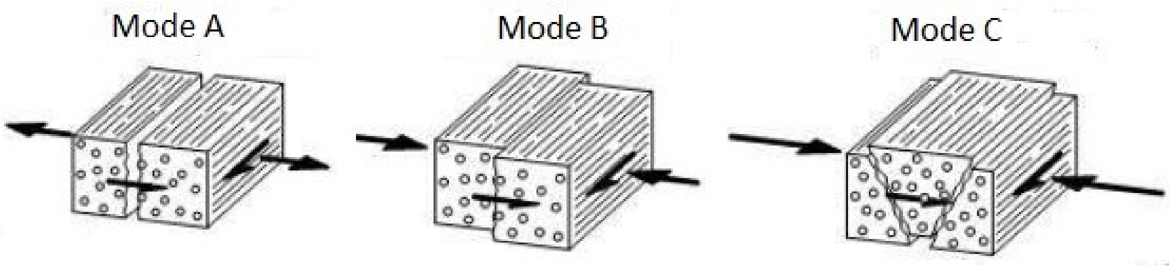


Figure 25 Composites failure modes

Equations for Puck criterion determination are given in Table 6.

Table 6 Equations for Puck criterion (Puck and Schürmann, 1998)

Type of failure	Failure Mode	Failure Condition ($f_{E(FF)}$ *or* $f_{E(IFF)}$)	Condition for validity
Fiber Failure (FF)	Tensile	$\frac{S}{\varepsilon_{1T}}=1$	if $S \geq 0$
$S=\varepsilon_1+\frac{v_{f12}}{E_{f1}}m_{\sigma 1}\sigma_2$	Compressive	$-\frac{S}{\varepsilon_{1C}}+(10\gamma_{21})^2=1$	if $S<0$
Inter Fiber Failure (IFF)	Mode A	$\sqrt{\left(\frac{\tau_{21}}{S_{21}}\right)^2+\left(1-p_{\perp\parallel}^{(+)}\frac{Y_T}{S_{21}}\right)^2\left(\frac{\sigma_2}{Y_T}\right)^2}+p_{\perp\parallel}^{(+)}\frac{\sigma_2}{S_{21}}+f_w=1$	$\sigma_2 \geq 0$
	Mode B	$\frac{1}{S_{21}}\left(\sqrt{\tau_{21}^2+\left(p_{\perp\parallel}^{(-)}\sigma_2\right)^2}+p_{\perp\parallel}^{(-)}\sigma_2\right)+f_w=1$	$\sigma_2<0$ and $0 \leq \left\lvert\frac{\sigma_2}{\tau_{21}}\right\rvert \leq \frac{R_{\perp\perp}^A}{\lvert\tau_{21c}\rvert}$
	Mode C	$\left[\left(\frac{\tau_{21}}{2\left(1+p_{\perp\perp}^{(-)}S_{21}\right)}\right)^2+\left(\frac{\sigma_2}{Y_C}\right)^2\right]\frac{Y_C}{(-\sigma_2)}+f_w=1$	$\sigma_2<0$ and $0 \leq \left\lvert\frac{\tau_{21}}{\sigma_2}\right\rvert \leq \frac{\lvert\tau_{21c}\rvert}{R_{\perp\perp}^A}$
Definitions	$p_{\perp\parallel}^{(+)}=-\left(\frac{d\tau_{21}}{d\sigma_2}\right)_{\sigma_2=0}$ of (σ_2,τ_{21}) curve, $\sigma_2 \geq 0$	$p_{\perp\parallel}^{(-)}=-\left(\frac{d\tau_{21}}{d\sigma_2}\right)_{\sigma_2=0}$ of (σ_2,τ_{21}) curve, $\sigma_2 \leq 0$	
Parameter relationships	$R_{\perp\perp}^A=\frac{Y_C}{2\left(1+p_{\perp\perp}^{(-)}\right)}=\frac{S_{21}}{2p_{\perp\parallel}^{(-)}}\left(\sqrt{1+2p_{\perp\parallel}^{(-)}\frac{Y_C}{S_{21}}}-1\right)$	$p_{\perp\perp}^{(-)}=p_{\perp\parallel}^{(-)}\frac{R_{\perp\perp}^A}{S_{21}}$	$\tau_{21c}=S_{21}\left(\sqrt{1+2p_{\perp\perp}^{(-)}}\right)$

C.5.1.3 Testing

The "classical process" for the testing of composite materials structure in shipbuilding can be represented by a pyramid as indicated on the Figure 26. The pyramid test is composed on 4 levels:

1. Raw materials homologation
2. Material coupon tests
3. Specimen tests
4. Full scale tests

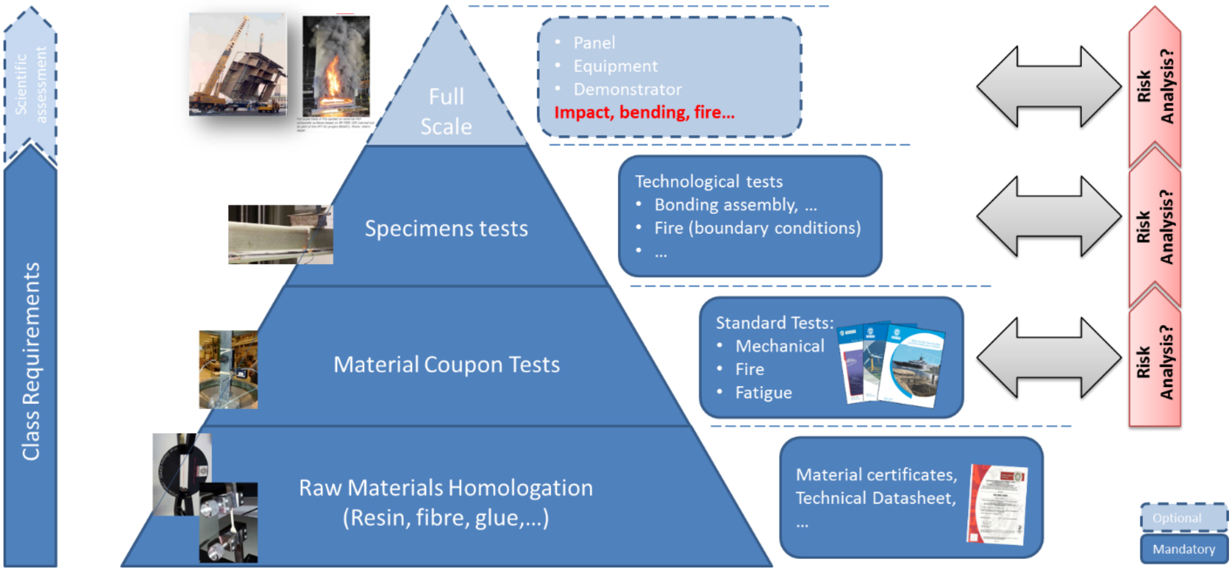


Figure 26 Composite materials pyramid tests

In general, tests are required by the Classification Society in the scope of the classification and/or the certification however, sometimes, tests are required by the risk analysis, especially in the case of an Alternative Design study.

C.5.1.3.1 Raw material homologation

The purpose of raw material homologation is to check the compliance of the characteristics of the materials used for the structure with the requirements of the relevant rules of the Classification Society.

The homologation of raw materials conditions one of the main requirements allowing the hull construction marks to be granted by the Classification Society within the scope of the classification and/or certification.

For composite, principal raw materials are:

- gel-coats and resin systems,
- reinforcement fabrics,
- core materials for sandwich laminates,
- adhesives.

Bureau Veritas rules NR546 give minimum required mechanical test for raw material homologation, see **Fehler! Verweisquelle konnte nicht gefunden werden.** in Annex C.10.1

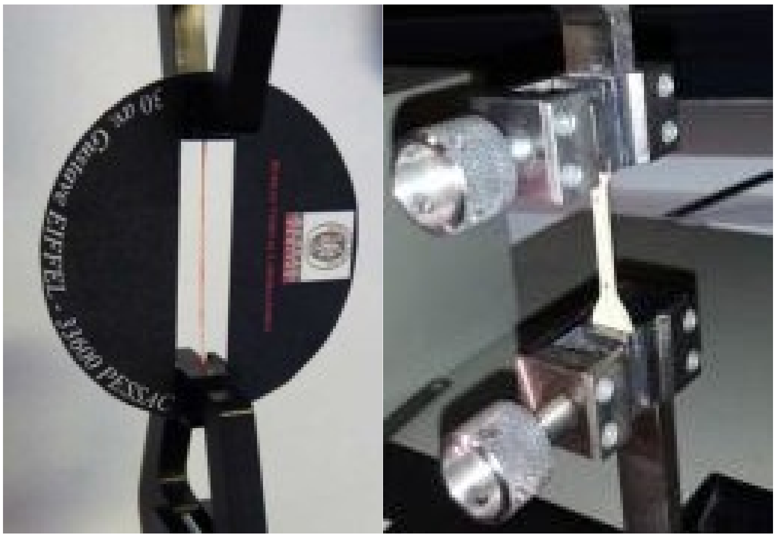


Figure 27 Examples of tensile raw material tests

The homologation of raw material is to be performed in accordance with HBV type approval process composed the two following successive phases:

- Design type approval: To review the technical documentation and mechanical characteristics proposed by the supplier in compliance with the rule requirements.
- Work's recognition: To assess the compliance of the raw materials manufactured in series with the design type approval. => Quality system certification (9000 series), fabrication procedures, audit, …

The process is more detailed in NR320 Certification Scheme of Materials and Equipment for the Classification of Marine Units [1].

C.5.1.3.2 Material coupon tests

Material coupon tests objective is to compare mechanical and physicochemical tests results with theoretical properties used for design assessment review.

Mechanical and physicochemical tests are to be performed on test panels produced by the shipyard and representative of the construction of the hull.

To be representative of the yard production methods and of the hull structure under classification and/or certification, each test panel is to be:

- manufactured from the same raw materials as the hull;
- manufactured by the same methods as the hull and in the same environment, and particularly with the same heat curing cycle, when applicable;
- a composition equivalent to the laminates used for the hull or the side shell in type and arrangement of layers Material coupon tests;

- mechanical tests are to be carried out in the Society's laboratories or in a laboratory recognized by the Society.

Figure 28 Example of tensile coupon tests

Bureau Veritas rules NR546 give minimum required mechanical type test for laminates, see **Fehler! Verweisquelle konnte nicht gefunden werden.** in Annex C.10.2

C.5.1.3.3 Specimen tests

Specimen tests are required on a case by case basis depending on the uncertainty. This kind of test is especially required for bonding assembly, "non-standard" joining technics, non-conventional design, new materials, etc.

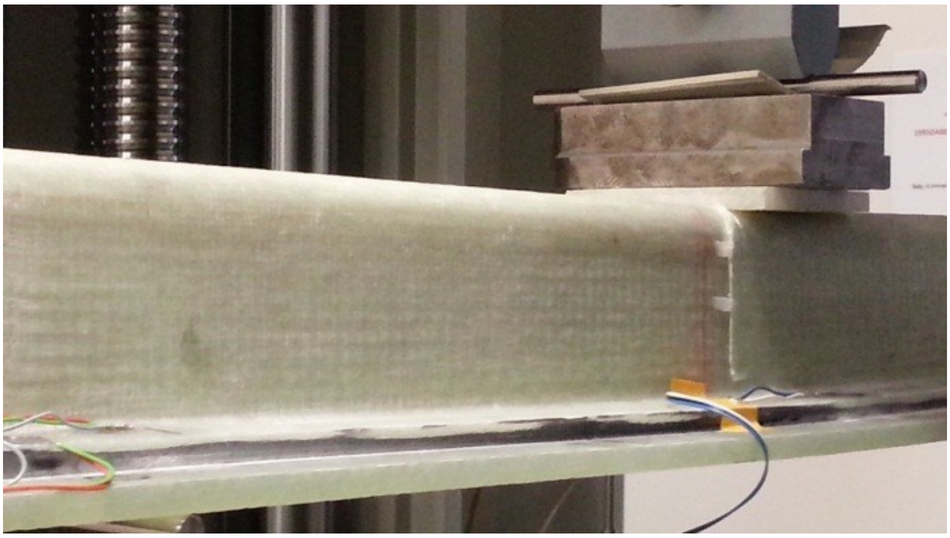


Figure 29 Example of a bonding joint 3-points bending test

Based on a discussion with the designer/shipyard and depending on the type of loads, tensile tests, bending tests or combined tests can be required for the validation. In general, numerical simulation will be performed in parallel to evaluate stresses, strains, displacements and to compare results with tests.

C.5.1.3.4 Full scale tests

In general, full scale tests are not required by the class because they are difficult to carry out and can be very expensive. However, full scale tests can be useful to validate a structure in the framework of a research project for a scientific assessment. Full scale test may be required by the Risk Analysis.

C.5.2 Design

C.5.2.1 Existing rules

Following existing rules have been investigated to evaluate applicability and limits of vessels built in composite materials:

- NR396: Rules for the Classification of High Speed Craft [6];
- NR467: Rules for the Classification of Steel Ships [7];
- NR500: Rules for the Classification of Yachts [8];
- NR600: Hull Structure and Arrangement for the Classification of Cargo Ships less than 65m and Non-Cargo Ships less than 90m [9];
- NR546: Hull in Composites Materials and Plywood, Material Approval, Design Principles, Construction and Survey [10].

C.5.2.1.1 NR396

Vessels designed in accordance with rules NR396 have the class notation HSC or High Speed Craft.

C.5.2.1.1.1 Scope of application

This Code applies to:

- **passenger craft** which do not proceed in the course of their voyage **more than four hours** at operational speed from a place of refuge; and
- **cargo craft of 500 gross tonnage** and upwards which do not proceed in the course of their voyage **more than eight hours** at operational speed from a place of refuge when fully laden.

In addition to the cargo craft these rules also apply as far as appropriate to cargo craft of less than 500 tons gross tonnage.

C.5.2.1.1.2 Structural strength

Structure can be metallic or **Fibre-Reinforced Plastic** (FRP) and should be capable of withstanding the static and dynamic loads which can act on the craft under all operating conditions in which the craft is permitted to operate, without such loading resulting in inadmissible deformation and loss of water tightness or interfering with the safe operation of the craft.

For structure in FRP, the main raw materials are to be homologated by a Classification Society. It may be accepted as equivalent that main raw materials should be individually inspected by the Classification Society. In such a case, each batch being used is submitted to tests, the conditions and scope of which are stipulated by the Classification Society's surveyor.

In general, for craft with length L > 65 m or speed V > 45 knots, the scantlings of transverse structures are to be verified by direct calculations. For all other craft, the Classification Society may, at its discretion and as an alternative to the requirements of this article, accept scantlings for transverse structures of the hull based on direct calculations.

C.5.2.1.2 NR467

C.5.2.1.2.1 Scope of application

NR467 gives the requirements for the assignment and the maintenance of classification for **seagoing ships excluding composite materials vessels**.

C.5.2.1.3 NR500

C.5.2.1.3.1 Scope of application

NR500 applies to yachts intended for pleasure cruising and not exceeding 90 m in length.

Yachts exceeding 100 m in waterline length are considered by the Classification Society on a case by case basis of NR467 Rules for the Classification of Steel Ships and NR500.

Yachts covered by the NR500 Rules are designated with the following service notations:

- Yacht when the ship is not engaged in trade;
- Charter yacht when the ship is engaged in trade.

Note 1: Yachts hired without crew are not considered as engaged in trade.

The requirements of these Rules cover sailing yachts and motor yachts, of mono-hull type or catamaran type, built in steel, aluminium, **composite materials** or plywood.

For charter yacht carrying **more than 12** (and less than 36) passenger, the requirements and arrangements within the scope of classification and/or certification may be different from requirements of international conventions (in particular Solas). The Flag Administration may request that international convention be applied instead of the NR500 requirements.

For private yacht **under 300 UMS**, the requirements and arrangements within the scope of classification and/or certification may be different from requirements issued by the Flag Administration. The Flag Administration may request that Flag Rules be applied or recommended instead of the NR500 requirements.

C.5.2.1.3.2 Structural strength

The requirements are applicable to **yacht hulls** made totally or partly of **composite materials** or plywood and are to be applied together with NR546 in particular for:

- raw materials analysis;
- individual layers and laminate analysis;
- stiffener analysis;
- principle of hull structure analysis;
- hull construction, survey, mechanical tests and raw;
- material homologation.

Local scantling of panels, secondary stiffeners and primary stiffeners, and global hull girder longitudinal strength and global strength of catamaran are to be checked in accordance with NR500 and NR546.

Attention is drawn to the selection of building materials which is not only to be determined from strength consideration, but should also give consideration to structural fire protection and associated class requirements or Flag Administration requirements where applicable.

C.5.2.1.4 NR 600

C.5.2.1.4.1 Scope of application

NR600 Rules contain the requirements for the determination of the hull scantlings (fore, central and aft parts of the ship) and structure arrangement applicable to the following type of ships built in steel, aluminium, or **composite materials**:

- cargo ships with a length L less than 65 m
- non-cargo ships with a length L less than 90 m

A cargo ship is a ship liable to carry cargoes and having a deadweight greater than 30% of the total displacement. These ships are fitted with cargo holds, tanks and lateral ballast tanks used in non-loaded conditions (i.e. bulk or ore carriers, oil or chemical tankers, container ships, general cargo ships, ...). As a rule, the value of the block coefficient is greater than 0.75.

A non-cargo ship is a type of ship other than cargo ships defined here above, or ships having a deadweight greater than 30% of the total displacement and not fitted with lateral ballast tanks used in non-loaded navigation condition.

Specific additional requirements applicable to ships built in composite and/or plywood materials are defined in NR546.

C.5.2.1.4.2 Structural strength

The requirements for the determination of the hull scantlings are applicable to ship hull made totally or partly of:

- steel (ordinary or high tensile);
- aluminium alloys;
- **composites materials**;
- wood (strip planking or plywood).

Ships built with different hull materials (traditional wooden construction for example) are to be specifically considered on a case-by-case basis.

Attention is drawn to the selection of building materials which is not only to be determined from strength consideration, but should also give consideration to structural fire protection and associated class requirements or Flag Administration requirements where applicable.

The global hull girder strength and the local strength are examined independently. For steel and aluminium ships, the combination of global hull girder strength and the local strength may be carried out when the global stress is greater than 0,35 Ry (Yield stress). For ship built in **composite materials**, a combination with the global hull girder stresses for the local scantling analysis may be carried out when deemed necessary by the Classification Society, on a case-by-case basis.

C.5.2.1.5 NR546

C.5.2.1.5.1 Scope of application

The requirements of NR546 are applicable to ships having their hull and superstructure totally or partly made of composite materials or plywood.

The purpose of this Rule Note is to define the general requirements for hull scantling and arrangements, with respect to:

- Raw material;
- Methodology of composite and plywood calculation;
- Hull structure calculation approach;

- Classification and /or certification process.

C.5.2.1.6 Summary

The table below resumes the applicable rules for vessels built in composite materials with limits of scope.

Table 7: Summary of applicable rules for vessels in composite materials

Rules	Steel	Composite Materials	Limit of scope
NR396 HSC	Yes	Yes	Passengers craft: *voyage < 4h from a refuge* Cargo craft ≥ 500GT*: voyage < 8h from a refuge*
NR467 Steel Ships	Yes	No	All seagoing ships excluding composite materials vessels
NR500 Yachts	Yes	Yes	Ship length < 90m Ship length ≥ 90m, see NR467
NR600	Yes	Yes	Cargo ship length < 65m Non-cargo ship length < 90m
NR546 Composites	No	Yes	All equipment and ships in composite materials

In summary, from structural side, actual rules do not allow to build composite materials vessel greater than 90m or only on a case by case basis, except HSC if the voyage is less than 4 hours from a refuge.

C.5.2.2 Monitoring

C.5.2.2.1 SHM definition

SHM or Structural Health Monitoring is a process using Non Destructive Testing (NDT) for damage detection and the control strategy of engineering structure. The objective of SHM is to evaluate the integrity, the health and the maintenance time of the monitored structure.

The interest of monitoring composite structures is to follow the evolution of the behaviour in operational condition and to anticipate failure and maintenance phases. By measuring a large amount of parameters, embedded or in contact sensors are able to predict any issue. The preventive scheme is privileged to the curative scheme.

For large vessel in composite materials, SHM will allow to follow the structure behaviour in live, to evaluate stress and strain level, the effect of humidity, of the temperature, the failure modes (delamination, fibre crack,…), etc. No rules require SHM installation, only load indicator are required for cargo vessels or accelerometer for HSC. These systems are more for decision support than structure surveillance.

C.5.2.2.2 Sensor technologies

A lot of SHM technologies exist or are under development for composite materials applications. Below some of them are detailed.

C.5.2.2.2.1 Acoustic Emission (AE)

Transducers listen for acoustic signals generated by cracks, delaminations or fibre breakage.

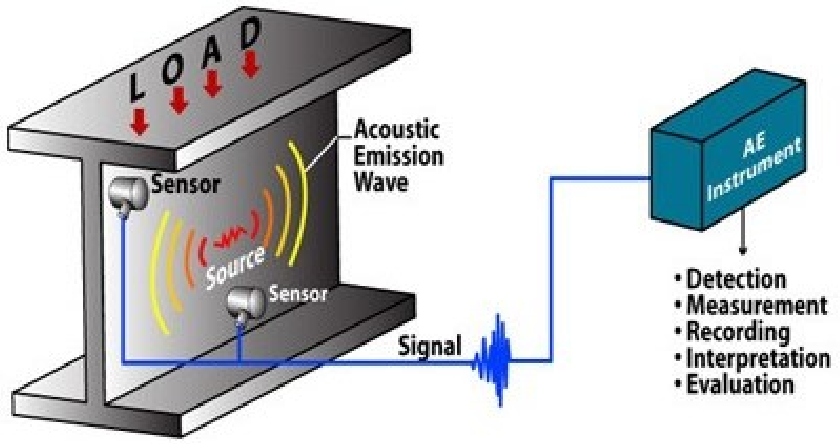


Figure 30 Acoustic Emission passive transducer

C.5.2.2.2.2 Acousto-Ultrasonic (AU)

Low-frequency acoustic pulses are sent through a part and received by a grid of piezoelectric sensors. Damage causes a change in the reflected acoustic energy.

C.5.2.2.2.3 Comparative Vacuum Monitoring (CVM)

The smallest air flow can be detected when galleries alternating between atmospheric pressure and vacuum (enabled by Teflon manifold patch) are breached by a crack or resin micro-cracks.

C.5.2.2.2.4 Fibre Bragg Grating (FBG)

Fibre-optic cables embedded in the structure use alterations in the refractive index of an optical fibre to measure temperature, strain and vibration as well as acoustic and ultrasonic signals for crack and damage monitoring.

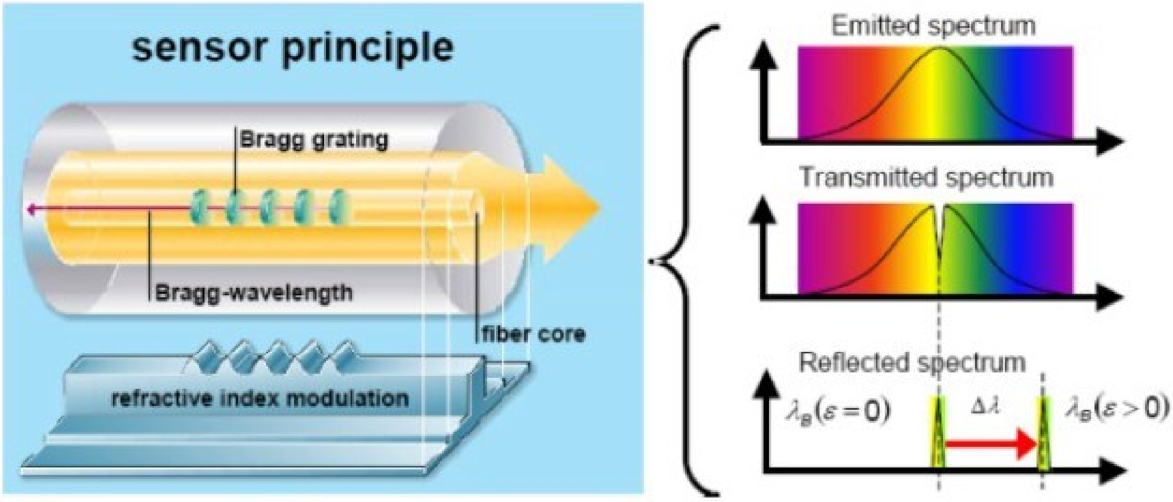


Figure 31 Fibre Bragg Grating

C.5.2.2.2.5 Impact Damage Detection System (IDDS)

This system uses two combined methods:

a) optical intensity measurement before and after impact, using optical fibers to assess damage, and
b) shock wave measurement for impact localisation via FBG sensors.

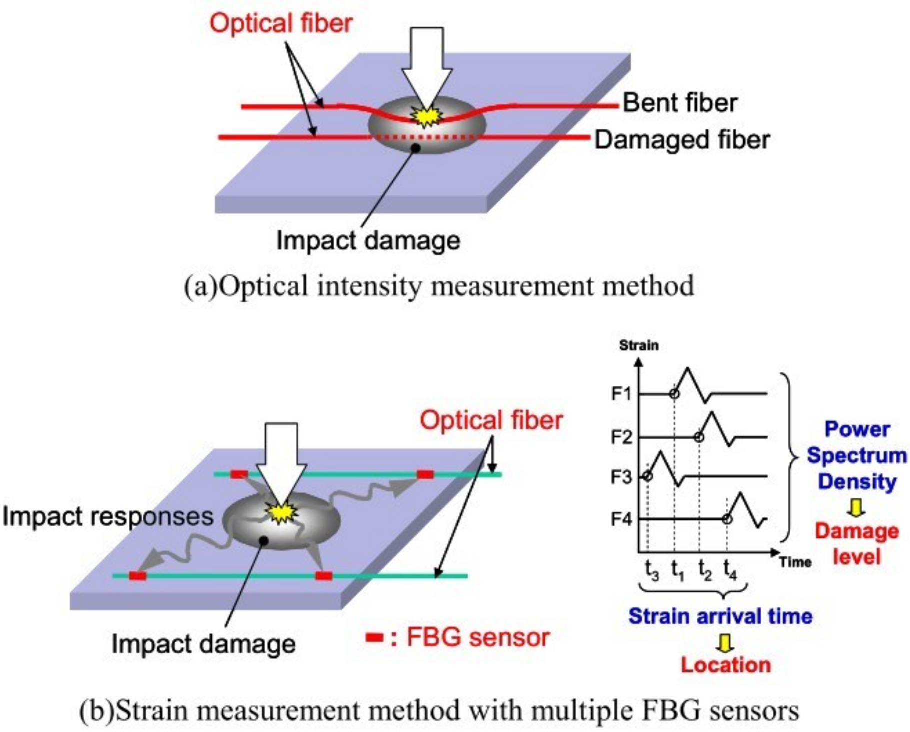


Figure 32 Impact damage detection system

C.5.2.2.2.6 Imaging Ultrasonic (IU)

Miniatured and integrated ultrasonic wave transducer generates a signal that passes through the material. Changes in wave reflection indicate flaws or damage.

C.5.2.2.2.7 Strain Gauge (SG)

Strain gauges bonded on an element aim at measuring the deformation by translating it in to variation of electrical resistance. Strain gauges have also been designed to be integrated into the structure during the composite material manufacturing process.

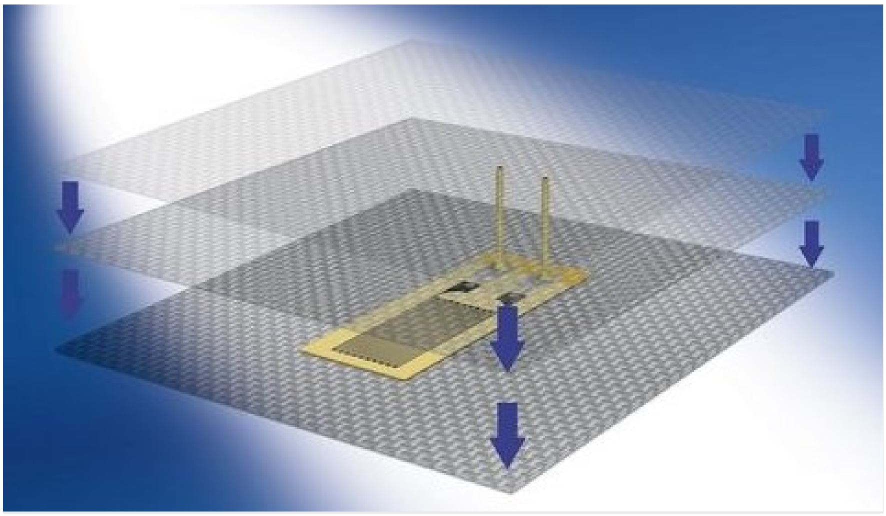


Figure 33 Embedded strain gauge in composite material

C.5.2.2.2.8 Quantum Resistive Sensors (QRS)

The QRS (Quantum Resistive Sensors) sensors have the particularity of being incorporated into the core of the material being controlled during its manufacture without changing its physical properties. This technology is based on the addition of carbon nanotubes (CNT) in the resin of a composite material or on the surface, or inside of an adhesive joint, directly during its fabrication. Thanks to their small dimensions (1 to 2 µm thick), QRS sensors can provide in situ monitoring without loss of mechanical properties, without generating new defects and preserving the homogeneity of the matrix. The characteristics of the sensor can be adjusted by the fraction of CNT in the resin or the amount of resin and CNT in the sensors. QRS sensors are able to inform on mechanical stress or strain and can react on humidity, temperature,…

C.5.3 Approval

C.5.3.1 Proposal of a general approach to take into account for “large-length” ship in composite material

C.5.3.1.1 General

For ships built in composite materials, the hull scantling is to be defined by an approach that combines the overall hull girder loads and the local loads, as considered for large length ships in steel. The need to use this approach is mainly due to the low values of mechanical characteristics of composite materials as compared to steel.

This proposal will be amended in the two main BV Rules dealing of this type of ship:

- NR546: Hull in composite materials;
- NR600: Hull structure and arrangement for cargo ships less than 65 m and non-cargo ships less than 90 m.

It is helpful to remember the general approach for "large-length" ship in steel material summarised briefly in the two successive steps as follow:

a) <u>Overall hull girder strength scantling check:</u> Check of the structure submitted to the overall bending moments and shear forces induced by the hull girder loads in still water (induced by the hull buoyancy and internal loading cases), and waves.

[18] The check is mainly based on buckling criteria and maximum stresses in the structure members contributing to the longitudinal strength of the hull girder.

b) <u>Local strength scantling check:</u> Check of the structure submitted to the local loads taking into account admissible stresses defined in relation to the type of structure element (plate, secondary or primary stiffener), and the location of the element. For structure element contributing to the hull girder strength, these admissible stresses incorporate the value of the global stress induced by the overall bending moments.

It can be also noted that the rules defined also minimum values of the midship section modulus and inertia to ensure that the global stresses induced by the maximum still water bending moment combined to the wave bending moments are lower than the prescribed rules values.

C.5.3.2 Approach proposal for "large" composite ships

It is proposed to keep the overall hull girder strength scantling check as defined here above in a). In addition, two main methods, in development for the future Bureau Veritas Rules, may be used for the local strength scantling check as suggested below.

C.5.3.2.1 1st method

The first methodology in development may be summarized as follow for hull structure element contributing to the global strength and submitted to local loads:

1) Calculation of:
   - The global bending moments and shear forces in still water: These values are to be defined for the different loading and navigation (departure or arrival) conditions considered, and
   - The local loads induced by sea pressures and/or internal pressures. As a rule, the dynamic sea pressures (slamming and side shell impact), test loads and flooding loads are considered without combination with the global bending moment. See below C.5.3.2.3.
2) Definition by the Designer of the longitudinal distribution of still water bending moments and shear forces for the different provided loading cases. When these values are not available, the values defined in the BV Rules may be considered for preliminary assessment.
3) Calculation of the geometric characteristics of the main section of the hull: these characteristics may be evaluated using the dedicated conventional software developed by Bureau Veritas (Mars software) taking into consideration the different Young modulus of each composite structure element of the main section. The geometric characteristics calculation is carried out taking into account an arbitrary Young modulus for the whole

section, and the sections of each element are weighted by the ratio Young modulus of the considered element divided by the arbitrary Young modulus.

4) Calculation of the elongation for the structure element contributing to the hull global strength induced by the global hull girder loads, and of the equivalent tension/compression forces.
5) Calculation of the local bending moments and shear forces for the structure element considered induced by the local loads.
6) Combination of the moments and forces defined in 4 and 5 steps in order to deduce the elongation and stresses in each layer of the laminate according to BV NR546, set out below for information.
7) Check of the safety factors (See C.5.3.3).

The strains and curved deformations of the laminate median plane are obtained from:

$$\begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \\ K_x \\ K_y \\ K_{xy} \end{bmatrix} = \begin{bmatrix} AB \\ BD \end{bmatrix}^{-1} \begin{bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x.10^{-3} \\ M_y.10^{-3} \\ M_{xy}.10^{-3} \end{bmatrix}$$

Where:

ε_x^0: Tensile or compression strain of the laminate median plane in X direction

ε_y^0: Tensile or compression strain of the laminate median plane in Y direction

γ_{xy}^0: Shear strain of the laminate median plane in XY direction

K_x : Curved deformation of the laminate median plane around Y axis

K_y : Curved deformation of the laminate median plane around X axis

K_{xy}: Curved deformation of the laminate median plane around Z axis

With $[A\ B\ D]^{-1}$ the reverse global rigidity matrix of the laminate considered, and forces and moments calculated at point B according to the Figure 34 hereunder:

- N_x: Tensile or compressive force in the longitudinal axe of the hull induced by the global bending moments;
- N_y: Tensile or compressive force in the transversal axe of the hull induced by Poisson's effect under N_x;
- M_x: Bending moment induced by local loads, to be calculated at point B;
- M_y: Secondary bending moment induced by Poisson's effect under M_x;
- T_{yz}: Shear force induced by local loads.

[19]

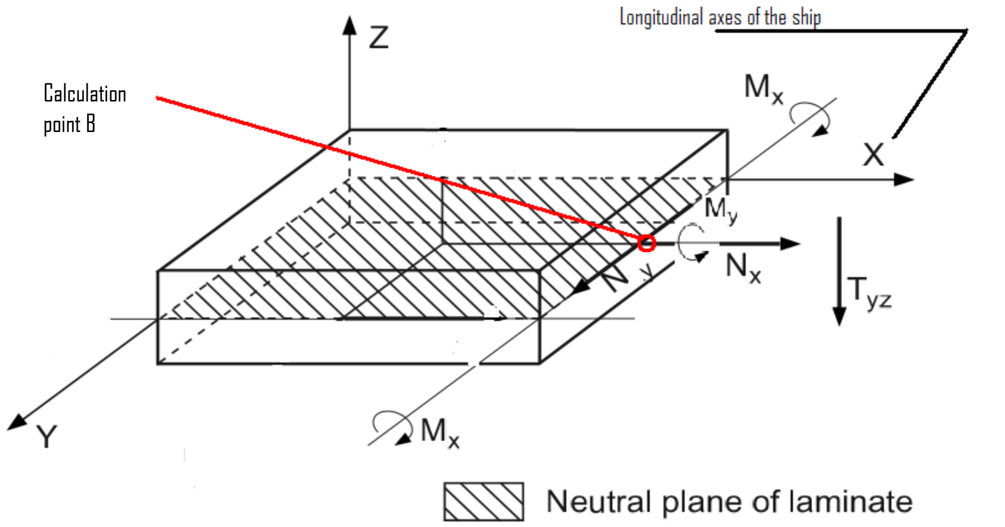


Figure 34: Forces, moments and calculation point A location

The strains and stresses in the individual layers in their own axis of fibre may be determined as defined in BV NR546, taking into account their position in relation with the median plane of the laminate.

Calculations are to be performed on both sides A and B for panels. For stiffeners submitted to global hull girder and local stresses, the same approach may be considered.

C.5.3.2.2 2nd method

A finite element model may be also considered. The main advantage of this method is to simplify the stresses combination in each layer of the laminate induced by global and local loads and the check of the safety factors defined in C.5.3.3. The main inconvenience is the difficulty to define the degree of freedom and the global loading of the model.

C.5.3.2.3 Additional cases

According to Bureau Veritas Rules NR600, the combination of the global hull girder loads and the dynamic sea pressures (slamming and side shell impact), the testing loads and the flooding loads are not taken into account.

Consequently, these local loading cases are to be examined independently, taking into account the specific safety factors defined in C.5.3.3.

C.5.3.3 Safety factors

It is proposed to consider the same approach used in the Rules of Classification Societies for "large-length" in steel materials, in other words, to define different sets of safety factors for the stresses induced by the following loading cases:

a) Hull girder loads acting alone
b) Combination of hull girder and local loads
c) Local loads acting alone (dynamic sea pressures, tests and flooding).

According to the theoretical calculation of composite materials defined in the Bureau Veritas Rules NR546, the proposed safety factors are defined on the following basis:

- Type of stresses considered

Three types of stresses are considered: Main stresses in each individual layers (stresses parallel or perpendicular to the fibres), combined stresses in each individual layers induced by main stresses and buckling stresses in the whole laminate.

- Minimum rule safety factors

The safety factors are defined as the ratio between the theoretical breaking stresses of each individual layers and the applied stresses induced by the loading cases.

For the buckling check, the safety factors are the ratio between the theoretical buckling stress of the whole laminate and the actual compression stress induced by the global loads.

The safety factors are defined in relation with partial safety factors as follow, taking into account:

- C_V: the ageing effect;
- C_F: the composite fabric process and reproducibility of the fabrication;
- C_R: the type and the direction of the main stresses apply to the fibre of the composite;
- C_i: the type of loads;
- C_{CS}: the combined stress in the layers;
- C_{Buck}: the buckling factor of the laminate.

The three type of stresses and associated safety factors considered are as follow:

1. Main stresses in the individual layers:

The minimum rule safety factor SF in each layer is to fulfill the following condition:

$$SF = C_V \,.\, C_F \,.\, C_R \,.\, C_i$$

[20]

2. Combined stresses in the individual layers:

The minimum rule safety factor SF_{CS}, applicable to the combined stresses in each layer, is to fulfil the following condition:

$$SF_{CS} > SF_{CSiapp}$$

where:

$SF_{CS} = C_{CS} \,.\, C_V \,.\, C_F \,.\, C_i$

SF_{CSiapp}: Equal to the positive value of: $SF_{CSiapp}=\frac{-b\pm\sqrt{b^2+4a}}{2a}$

With: $a=\frac{\sigma_1^2}{|\sigma_{brc1}\sigma_{brt1}|}+\frac{\sigma_2^2}{|\sigma_{brc2}\sigma_{brt2}|}-\frac{\sigma_1\sigma_2}{|\sigma_{brc1}\sigma_{brt1}|}+\frac{\tau_{12}^2}{\tau_{br12}^2}$

$$b=\frac{\sigma_1(|\sigma_{brc1}|-|\sigma_{brt1}|)}{|\sigma_{brc1}\sigma_{brt1}|}+\frac{\sigma_2(|\sigma_{brc2}|-|\sigma_{brt2}|)}{|\sigma_{brc2}\sigma_{brt2}|}$$

σ_i , τ_{12} : Actual stresses, in N/mm2, in the considered local ply axis induced by the loading case considered,

σ_{bri} , τ_{br12}: Ply theoretical breaking stresses, in N/mm2, in the local ply axis, as defined in NR546 Sec 5, [10].

Note: The combined criterion SF_{CSiapp} is obtained from the following equation:

$$SF_{CSiapp}^2 .F_{ij} . \sigma_i . \sigma_j + SF_{CSiapp} . F_i . \sigma_i > 1$$

3. Buckling stresses in the whole laminate:

The minimum buckling rule safety factor SF_B, applicable to the whole laminate panel or stiffener is to fulfil the following condition:

$$SF_B \geq C_{Buck} .\cdot C_F . C_V . C_i$$

The values of the partial safety factors are as follow:

1) Ageing effect factor C_V:

C_V takes into account the ageing effect of the composites and is generally taken equal to:

C_V = 1.2 for monolithic laminates (or for face-skins laminates of sandwich);

C_V = 1.1 for sandwich core materials.

2) Fabrication process factor C_F:

C_F takes into account the fabrication process and the reproducibility of the fabrication and is generally taken equal to:

C_F = 1.10 in case of a prepreg process;

C_F = 1.15 in case of infusion and vacuum process;

C_F = 1.25 in case of a hand lay-up process;

C_F = 1.00 for the core materials of sandwich composite.

3) Type of load factor C_i:

C_i takes into account the type of loads and is generally taken equal to:

C_i = 1.0 for local external sea pressures and internal pressures or concentrated forces;

C_i = 0.8 for dynamic sea pressures (slamming loads on bottom and impact on flat bottom on forward area) and for test pressures and flooding loads;

C_i = 0.6 for impact pressure on side shell and on platform bottom of multihull;

C_i = 1.4 for hull structure check under global hull girder acting alone;

C_i = 1.2 for buckling under global hull girder acting alone;

C_i = 0.8 for hull structure check taking into account the combination of hull girder and local loads.

4) Partial safety factor for combined stresses C_{CS}, to be taken equal to:

C_{CS} = 1.7 for unidirectional tape, bi-bias, three-unidirectional fabric;

C_{CS} = 2.1 for the other types of layer.

5) Partial safety factor C_{Buck}, for buckling:

C_{Buck} = 1,45

6) Type of stress factor C_R:

C_R takes into account the type of stress in the fibres of the reinforcement fabrics and the cores and is generally taken equal to:

Table 8: C_R values

Type of stress	Orientation between stress and fibre	C_R values				
		UD, bi-bias	Woven roving	Mat	Synthetic core	Balsa core
Tensile or compressive	Parallel	2.1	2.4	2	2.1	2.1
	Perpendicular	1.25	NA			1.2
Shear stress	Parallel to the fibre or interlaminar	1.6	1.8	2.2	2.5	2.5

C.5.3.4 Hull girder flexibility

It is necessary, due to the low value of the Young modulus of composite materials, to consider a flexibility criteria of the hull girder in addition to the stresses criteria defined here above.

This new criteria can be defined as follow:

$$Fl = (M \,.\, L^2 / 10 \,.\, E \,.\, I).10^{-3} < 0{,}30\%.L$$

Where:

Fl: Theoretical deflection, in m, at the midship section of the hull girder, considering a still water and wave bending moments distribution as defined in NR600;

M: Global bending moment, in KN.m (Still water plus waves);

L: Length of the ship, in m;

E: Value of the arbitrary Young modulus, in N/mm2, considered for the calculation of the inertia of the midship section;

I: Inertia, in m^4, of the midship section.

C.5.3.5 *Assessment of hull construction details (assembling of structural components by gluing connections)*

Adhesive structure connections are generally checked by direct calculation taking into account the shear force applied to the joint. The main parameters to consider are the surface and the geometry of the joint and the mechanical characteristics of the adhesive joint.

The process of survey scheme for the adhesive structure connection is to be as defined in C.5.1.1, including:

- Raw material assessment,
- Structure design assessment,
- Specimen test on sample representative of the hull connections,
- Final inspections.

The scantling of adhesive joint is based on safety factors equal to the ratio between the theoretical breaking shear stress of the joint and the applied shear stresses induced by the loading cases.

As a rule, the value of the shear breaking stress to consider is to be taken equal to the minimum value of the:

- Shear breaking stress of the bonding resin specified by the manufacturer, corresponding to the initial yield (the initial yield may be determined on the basis of shear stress-strain curve as the intersection of a line tangent to the linear elastic region and a line tangent to the non-linear plastic region of the curve), or
- Theoretical interlaminar shear breaking stress value of the first layer of the components bonded together.

Other values of shear breaking stress deduced from mechanical tests representative of the gluing joint may be considered by the Society.

The safety factors are defined in relation with partial safety factors as follow, taking into account:

- C_F: the gluing process;
- C_i: the type of loads (see above).

The minimum rule safety factor SF in the adhesive joint is to fulfil the following condition:

$$SF = 2.4 \,.\, C_F \,.\, C_i$$

With :

C_F equal to:

1.4 in case of a vacuum process with rising curing temperature;

1.5 in case of vacuum process;

1.7 in the other cases;

C_i: as defined in C.5.3.3

C.6 Probabilistic Damage Stability

Main author of the chapter: NMTF

Note: this chapter still need revision (regarding details specific to composite ships), which will be included in Deliverable 6.5

C.6.1 Background

C.6.1.1 History of stability requirements

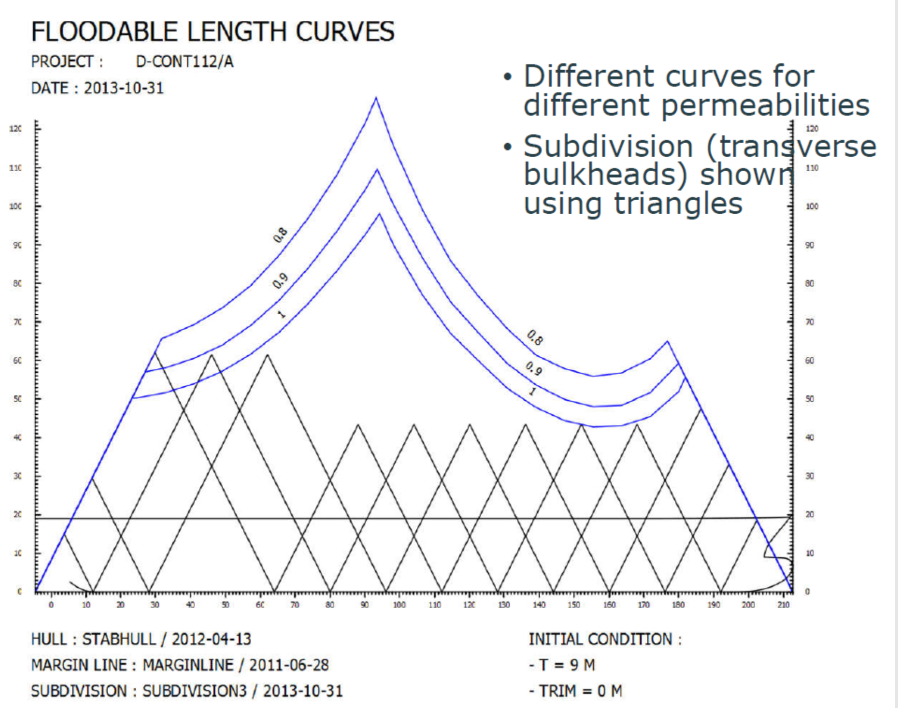
Unfortunately history has known a series of ship accidents with many casualties where loss of watertight integrity, caused by hull damage, resulted in flooding of multiple compartments, capsize and/or sinking of the ship. In case of a flooding incident, the ship should stay afloat and upright to ensure that passengers and crew can remain on board and return to port safely for repairs, to contain onboard cargo and to reduce spills and pollution to a minimum.

The first attempts to regulate ship damage stability performance precede the sinking of the Titanic:

> "All vessels, whether propelled by steam or sail, should possess a margin of strength over and above that which is required to enable them to perform the work for which they were designed and built. A chain, a bridge, or any other structure, the failure of which would entail the loss of human life, invariably has a considerable reserve of strength provided; in other words, the admitted working load is always much less than the computed strength, or the strength ascertained by actual test; certainly it is no less important that the hull of a vessel should contain a similar reserve.
>
> ...
>
> "7. Ocean-going steam-vessels which carry passengers should be additionally protected by having efficient bulkheads, so spaced that, when any two compartments be filled with water, the vessel will still remain in a seaworthy condition, and two at least of the amidships bulkheads should be tested by water pressure to the height of the deck next above the water-line.
>
> International Marine Conference, Washington, 1889

At that time damage stability calculations were purely deterministic and the ship safety was considered sufficient if the ship remained seaworthy whit any combination of two compartments flooded. The sinking of the Titanic in 1912 learned that it was also necessary to define requirements for the watertight subdivision and compartments. This has led to "The International Convention for the Safety of Life at Sea", signed in 1914, but due to World War I it did not enter into force as intended on July 1st 1915.

A few years after the establishment of the United Nations, in 1948, the International Maritime Organisation (IMO) was established as a permanent international body with the task to develop regulations that are followed by all shipping nations. IMO's first task was to adopt a new version of the International Convention for the Safety of Life at Sea (SOLAS), the most important of all treaties dealing with maritime safety. This was achieved in 1960. In this convention requirements were included for the floodable length, which determines how far apart transverse bulkheads can be placed, as well as stability criteria.



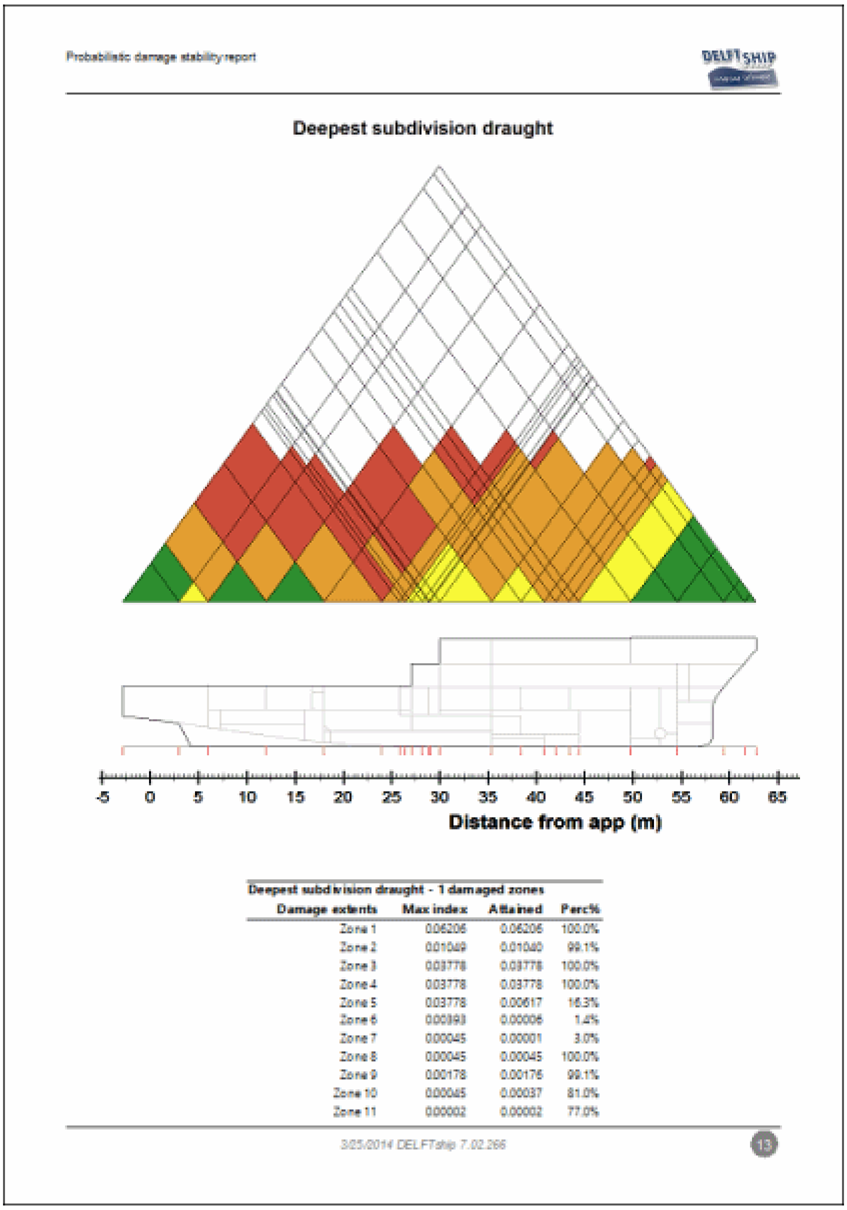
Nowadays the floodable length curves are not relevant for the current damage stability rules, but sometimes they are still used in the initial design phase to determine how far the transverse bulkheads can be placed apart such that the 'margin line' remains dry.

The concept of probabilistic damage is first introduced by the German Professor Kurt Wendel in the late 1950s. He described an alternative method for considering the damage stability of a ship based on damage statistics and introduced a new assessment method that allowed the definition of a global safety level through which the stability characteristics of ships of different size and type could be quantified.

For the probabilistic damage calculation, all possible damage situations have to be considered. For each situation the probability of the damage, the transverse and vertical extent of the damage and the probability of survival are calculated and multiplied. Then a summation over all damage situation results in a so-called Attained index "A", which should be not less than a Required index "R". The Required index is a Rule formula based on the subdivision length and the number of passengers.

The outcome of the calculation is an indication for how likely a ship will remain afloat, without sinking or capsizing, as a result of an arbitrary collision in a given longitudinal position of the ship. Using this method it is possible to allow that certain damage situations have a very low probability of survival, as long as the probability of occurrence is low as well.

In 1992 probabilistic damage stability rules for cargo vessels over 100 m length came into effect, while in July 1998 their coverage was extended to vessels from 80 m



Deepest subdivision draught - 1 damaged zones

Damage extents	Max index	Attained	Perc%
Zone 1	0.06206	0.06206	100.0%
Zone 2	0.01049	0.01040	99.1%
Zone 3	0.03778	0.03778	100.0%
Zone 4	0.03778	0.03778	100.0%
Zone 5	0.03778	0.00617	16.3%
Zone 6	0.00393	0.00006	1.4%
Zone 7	0.00045	0.00001	3.0%
Zone 8	0.00045	0.00045	100.0%
Zone 9	0.00178	0.00176	99.1%
Zone 10	0.00045	0.00037	81.0%
Zone 11	0.00002	0.00002	77.0%

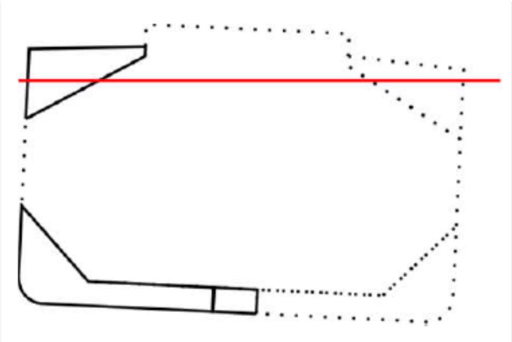
By drawing the triangles all possible damage situations can be visualised. The colour in this image depicts the probability of survival.

C.6.1.2 Deterministic vs probabilistic damage stability calculations

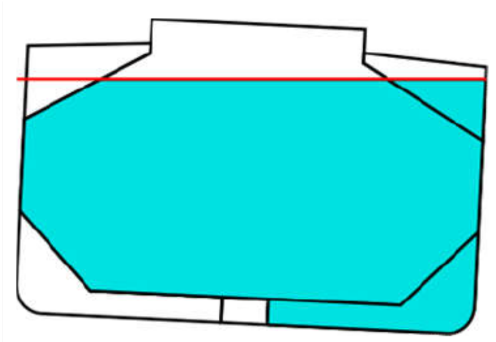
Damage stability calculations were deterministic:

- Requirements for stability with a limited number of damaged compartments
- Compliance measured with given criteria, which the ship design either passes or fails.

In the deterministic approach the ship stability is calculated for each damaged configuration, using the “lost buoyancy” or “added weight” method. The results of these calculations are easy to understand; each damaged configuration has its own draught, trim, heel and stability and can be plotted in stability curves and compared with the acceptance criteria.



"Lost buoyancy" is when damaged rooms are removed from the buoyant hull while displacement is kept constant



"Added weight" is when the floodwater is loaded to the rooms and the displacement increases

C.6.2 Design

C.6.2.1 Current Regulations

This guideline will focus on ships within the scope of SOLAS.

- SOLAS, Chapter II-1, Part B- 1

Other IMO instruments with stability requirements for specific ship types are:

- MARPOL - tankers
- IGC – gas carriers
- IBC – bulk carriers
- SPS 2008 – special purpose ships
- POLAR code

C.6.2.2 Points of attention for composite ships

Considering the probabilistic damage calculation for a composite ship, the method remains the same. However, the volume of water ingress could be different due to a number of reasons.

- The permeability of watertight compartments is different due to the differences in geometry of the hull structure, see Figure 35. This can be easily accounted for in the volume calculation.
- The composite material might have different performance in collision, resulting in different size of damage extent compared to a steel ship. The estimation of damage extend is now based on a statistical database of ship flooding accidents, with measured damage size from steel ships only. Creating a new statistical basis for damage extent for composite ships requires further research and is considered out of scope for the RAMSSES project.

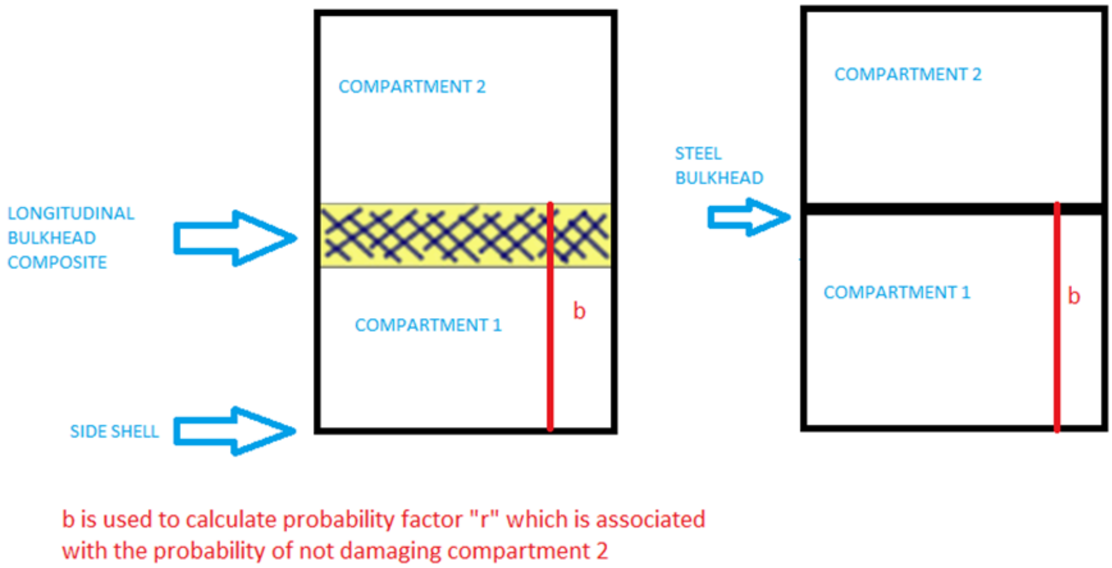


Figure 35: Comparison of volume differences of composite vs steel ships

C.6.3 Approval

C.6.3.1 Best reference approval method

No need to develop specific rules for damage stability calculations for composite vessels, the current method is usable if differences in the volume calculation are taken into account.

C.6.3.2 Recommendations for further research

There is a need for research on correct estimation of expected transverse and vertical damage extent for composite ships, but there is no statistical information available yet. Experimental results and simulations will allow to evaluate consequence of collision and grounding for composite hulls.

C.7 Comfort

Main author of the chapter: NMTF

Note: this chapter still need revision (regarding composite specific application), which will be included in Deliverable 6.5

C.7.1 Background

C.7.1.1 The human perception

The evaluation of vibration (and noise) levels in terms of habitability or comfort are highly subjective to the perception of individuals, consequently it is difficult to find a threshold applicable to the average human being. The perception of individuals is dependent on their initial expectations as well as on what their senses tell them, which influences the evaluation (by these individuals) of the level of comfort for a certain location. For example: given a certain noise and vibration level, any individual will classify the comfort level significantly lower if he or she can not only feel the vibration but also see it by means of shaking monitors or displays. Another example of erroneous evaluation by humans is related to the overlap of the frequency ranges of noise and vibration, see also Figure 36

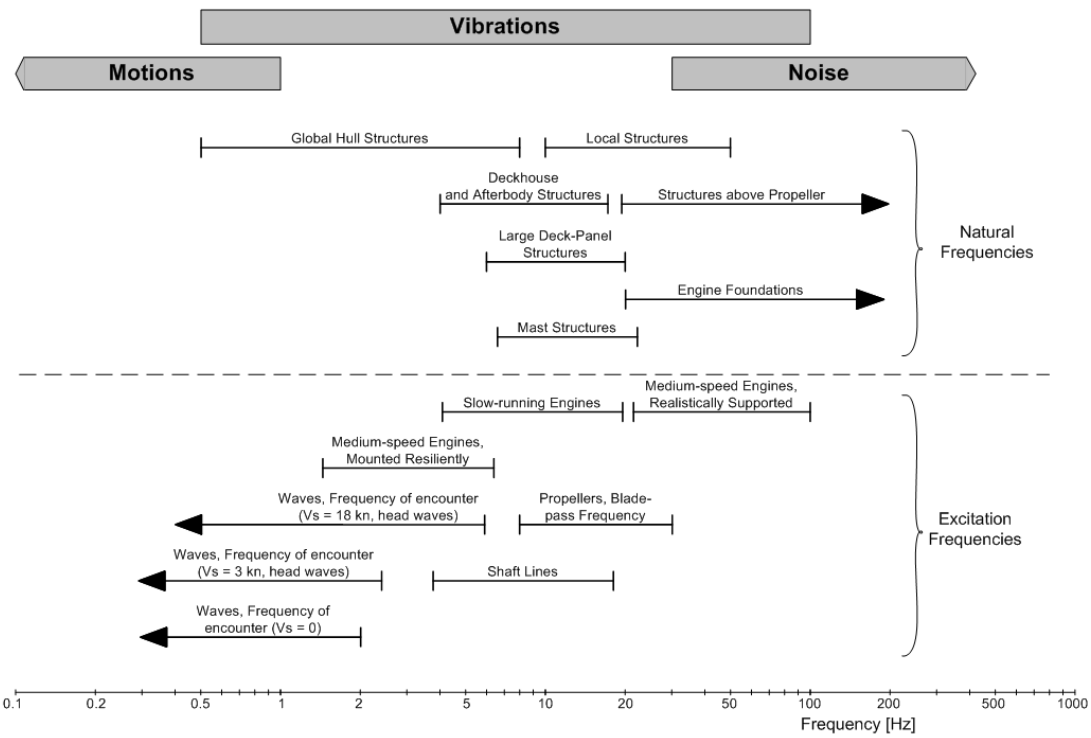


Figure 36: Common frequency ranges in shipbuilding applications

Since both phenomena involve oscillating motion one could imagine that for the overlap-frequencies (high frequency vibration and low frequency noise) it is hardly possible to distinguish which of the two phenomena is causing adverse effects, it could even be possible that when humans complain about high vibration levels, the vibration levels are well below the acceptable limits while the noise levels are not. A good example is for instance the feel of a loud bass drum on your chest, the feel of vibration is probably caused by resonance of internal organs, see Figure 37. This figure shows the major resonances of the human body. A resonance occurs when the excitation frequency is equal to the natural frequency of the oscillating object. When the frequencies in Figure 37 are compared to those in Figure 36 it should be clear that ship vibration can be very annoying for the crew and/or passengers on board.

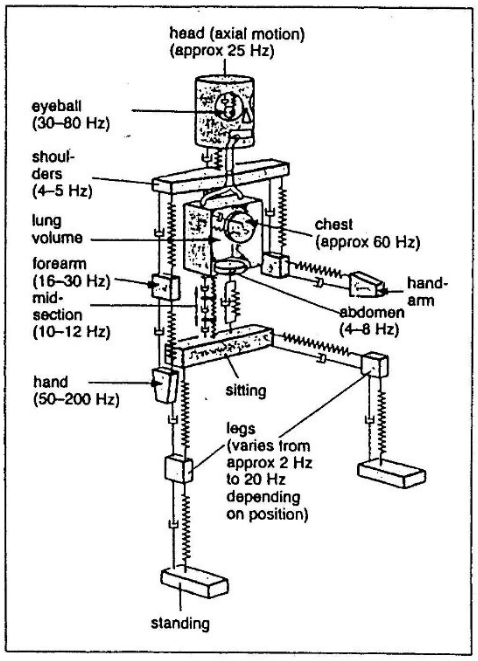
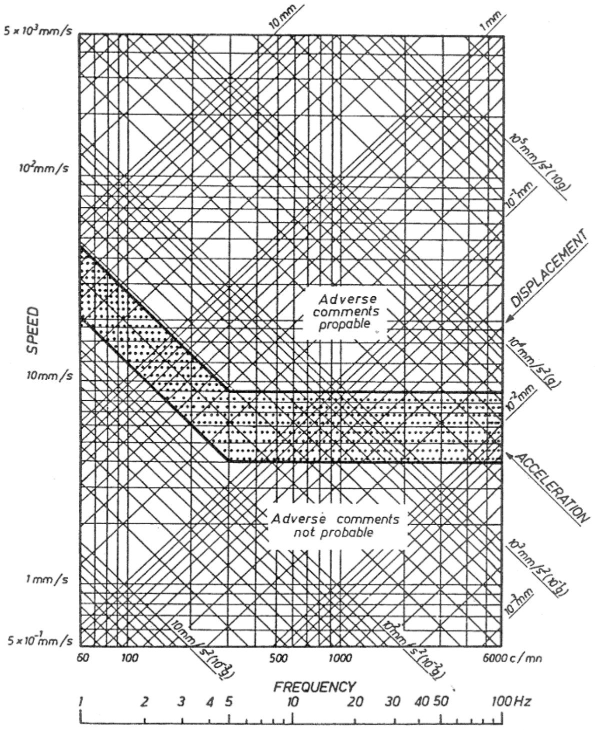


Figure 37: Natural frequency ranges of the human body

C.7.1.2 Development of vibration acceptance criteria

In terms of comfort on board, the rise of the cruise market in the last decades led to advanced developments by classification societies in this field. Most, if not all, classification societies now have voluntary class notations with additional requirements regarding acceptable noise and vibration levels for improved comfort. Obviously this subject needed particular attention for passenger ships, additional requirements for other ship types have followed.

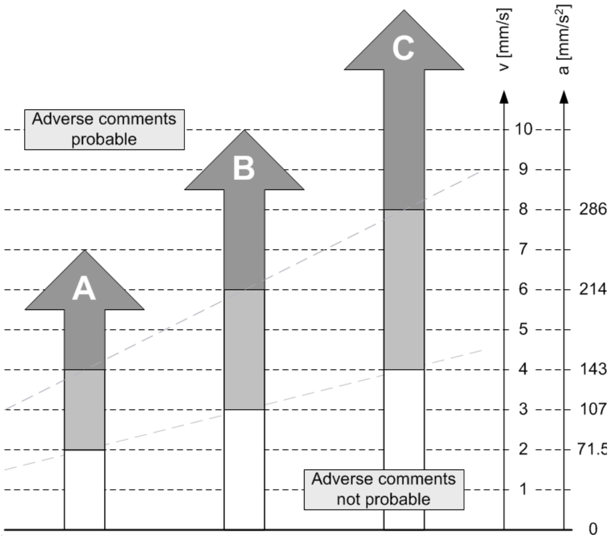
In the past the classification societies (e.g. BV [12] & [13], DNV [14]& [15][15], LR [16]) provided only some guidelines or guidance notes, to help ship designers constructing comfortable solutions. These guidelines were all based on research and experience of the classification societies and on international standards (such as ISO 6954:1984 [11], see Figure 38a). These guidelines typically mention that they are to be interpreted as a recommendation only; it is still up to both the yard and customer to determine which requirements they select as part of the specification and for which areas the requirements are applicable. The location of the areas of applicability is very important; it would not make sense to apply the same comfort requirements in the engine room and accommodation area. In contrast with the old version, the new version of ISO 6954 describes different levels of acceptable vibrations for 3 types of locations but still leaves room for interpretation; for example classification A could be passenger cabins, B crew accommodation areas and C working areas (see Figure 38b).



CURVE	FREQUENCY RANGE	
	1 to 5 Hz	5 to 100 Hz
Upper	Peak acceleration (1) = 285 mm/s²	Peak velocity (1) = 9 mm/s
Lower	Peak acceleration = 126 mm/s²	Peak velocity = 4 mm/s

(1) Peak value is the maximum repetitive value, see ISO 4867.

(a)



	Area Classification					
	A		B		C	
	mm/s²	mm/s	mm/s²	mm/s	mm/s²	mm/s
Values above which adverse comments are probable	143	4	214	6	286	8
Values above which adverse comments are not probable	71.5	2	107	3	143	4
NOTE The zone between upper and lower values reflects the shipboard vibration environment commonly experienced and accepted						

(b)

Figure 38: ISO 6954 Standard, comparison of 1984 (a) and 2000 version (b)

The ISO Standards are developed using a lot of research to the human reaction to whole body vibration, how to measure & report vibration, the effect of mechanical vibrations and shocks on human health & performance, including motion sickness and irritation or discomfort. Even the differences which appear in the perception of vibrations by sitting, standing or recumbent persons or the sensitivity to horizontal or vertical vibrations can be taken into account, for each situation a different frequency weighting curve is derived (see ISO 2631, [17]).

Since January 2000 this knowledge is incorporated into the ISO 6954 Standard [11], the response is no longer evaluated per frequency and r.m.s.[5] values are used instead of 0-peak values. On one hand the evaluation of the habitability has become much easier with the revision of this standard. However, on the other hand troubleshooting vibration problems often requires frequency information, which is now completely lost (see Figure 38b). Most of the guidelines and voluntary class notations are still based upon the ISO Standard 6954:1984

C.7.1.3 Acceptance criteria for noise

IMO recognizes that high noise levels onboard ships could affect seafarers' health and impair the safety of the ship. The purpose of the Code therefore is to limit noise levels and to reduce seafarers'

[5] r.m.s. is short for Root Mean Square or the square root of the arithmetic mean (average) of the square's set of values and a measure of the energy content. For a sinusoidal signal r.m.s.-value is $\sqrt{2}$ times the zero to peak value of the sine wave.

exposure to noise. Therefore the non-mandatory Code on noise levels onboard ships, IMO resolution A.468(XII), is promoted as a mandatory code as per July 2014.

C.7.2 Design

To prevent complaints due to reduced comfort or structural damage due to fatigue, excessive vibration should always be avoided. This requires knowledge of the concepts of vibration, methods to analyse and control the response/behaviour of vibrating systems and of course a specification of acceptable vibration levels.

Apart from natural frequency checks in comfort-critical areas, design for vibration (or noise) is not a common practise in shipbuilding. For noise predictions statistical models can be used and for vibrations it is usually sufficient to check the most important natural frequencies.

However, due to the specific nature of a composite material, the strength characteristics might be different in each direction (orthotropic), while steel is normally anisotropic. This complicates the calculation of natural frequencies a bit, since the composition of the material needs to be taken into account in more detail.

C.7.2.1 General methodology

Noise control

The most common noise mitigating measures are the application of:

- Insulation material
- Absorption material

Vibration control

Vibration control in the design stage of a system, structure or ship is the design for vibration suppression in order to comply with given requirements for acceptable vibration levels. The following 5 general guidelines (as numbered in Figure 39) will help the designer to keep the vibration levels as low as possible:

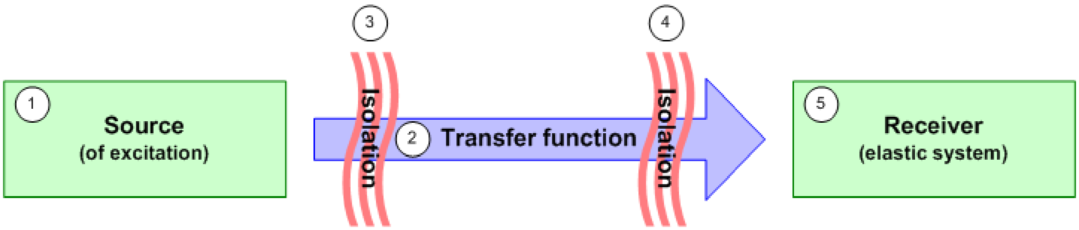


Figure 39: Schematic view of a vibrating system

1. Prevent large excitation forces; in practice this means a careful hull and propeller design in order to reduce magnitude of the pressure pulses imposed by the rotating propeller(s) on the ships hull, or the calculation of thrust bearing forces and whirling behaviour for the complete propulsion installation to find the best shaft alignment. This corresponds with less available energy to induce vibration. Low excitation forces should always have the highest priority in ship vibration control,

however low excitation forces alone do not guarantee a low vibration level. In case of resonance the comfort limits are easily surpassed.

2. Prevent (near) resonances; by the adjusting mass and stiffness properties of the elastic system the designer can shift the natural frequency away from the excitation frequencies to increase the margin[6] with resonance condition. Alternatively the frequency and amplitude of the source of excitation can be adjusted in order to keep the forced response at an acceptable level. Another way of changing the transfer function is by modifying the damping properties, for example by choosing a different construction material such as composites with visco-elastic properties. When resonance occurs the system response is approximately 90° out of phase with the excitation force and almost completely dominated by damping (see Figure 40).

3. Isolate the source from the elastic system; e.g. the creation of an impedance jump[7] by applying passive or active vibration isolation, such as resilient mounting of engines to reduce the magnitude of the free forces introduced into the structure through the engine foundation.

4. Isolate (a part of) the elastic system from the source of excitation; e.g. when sensitive equipment is installed. Again both passive and active isolation methods can be applied.

5. Finally, the response of the elastic system can be reduced if necessary by changing the elastic system; e.g. the addition of passive masses to the structure can help reduce the vibration levels when other adjustments to the structure are too expensive or complicated. This mass is tuned to the resonant frequency of the system and behaves as a dynamic absorber (see Figure 41). This solution should only be considered as a last resort, dynamic absorbers only have effect at a single frequency and in a particular direction. In addition to that one should keep in mind the extra mass and costs as well as the potential of shifting the problem to another frequency.

[6] Rule of thumb: natural frequencies and excitation frequencies should not be within a 20% margin depending on the method of calculation.

[7] The mechanical impedance of a point on a structure is the ratio of the force applied to the point to the resulting velocity at the point. It is a measure of how much a structure resists motion when subjected to a given force, and it is the reciprocal of mobility. The mechanical impedance of a structure varies in a complicated way as frequency is varied. At resonance frequencies, the impedance will be low, meaning very little force can be applied at those frequencies. Therefore it would not be good to have a foundation resonance near the running speed of the machine. In practice this means that a discontinuity in stiffness is required, resulting in boundaries where energy reflection occurs, e.g. resilient mounting of engines.

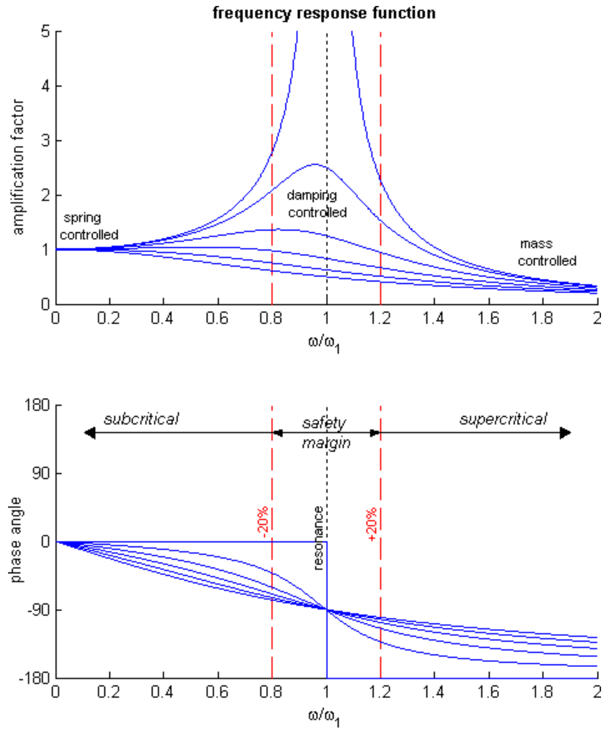


Figure 40: frequency response function of a single degree of freedom system

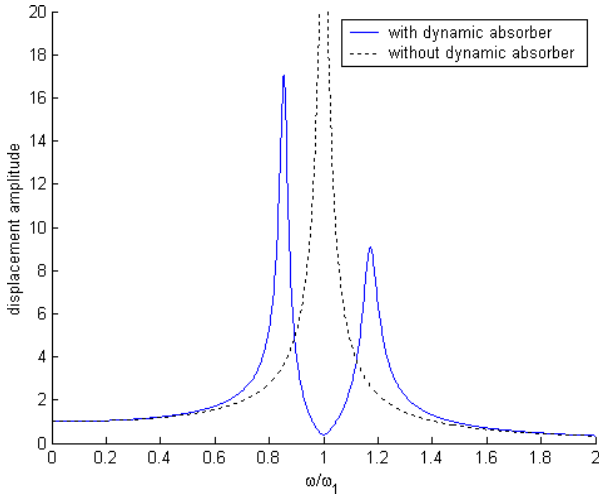


Figure 41: frequency response function including a dynamic absorber mass

C.7.3 Approval

Performing validation measurements (noise and vibration) during sea trials, and check for compliance with acceptance criteria as agreed in the shipbuilding contract. This method is irrespective of the materials used.

C.8 References

[1] Design of Marine Structures in Composite Materials, C.S. Smith, Elsevier Applied Science

[2] Structures composites, Calcul des plaques et des poutres multicouches, C. Decolon, Hermes Science

[3] Les critères de dimensionnement des structures en composite, Sigmeo

[4] Progress in the Puck Failure Theory for Fibre Reinforced Composites : Analytical solutions for 3D-stress, A. Puck, H.M. Deuschle

[5] NR320, NR320 Certification Scheme of Materials and Equipment for the Classification of Marine Units, Bureau Veritas

[6] NR396, Rules for the Classification of High Speed Craft Surname, Bureau Veritas

[7] NR467, Rules for the Classification of Steel Ships, Bureau Veritas

[8] NR500, Rules for the Classification of Yachts, Bureau Veritas

[9] NR600, Hull Structure and Arrangement for the Classification of Cargo Ships less than 65m and Non-Cargo Ships less than 90m, Bureau Veritas

[10] NR546, : Hull in Composites Materials and Plywood, Material Approval, Design Principles, Construction and Survey, Bureau Veritas

[11] "*Guidelines for the overall evaluation of vibration in merchant ships*", ISO Standard 6954, 2000

[12] "*Recommendations designed to limit the effects of vibrations on board of ships*", Guidance Note: NI 138 A-RD3, Bureau Veritas, 1979

[13] "Buil*ding and operation of vibration-free propulsion plants and ships*" Bureau Veritas, Guidance Note: NR 207 SMS E, 1987

[14] "*Guidelines for prevention of excessive ship vibration*", H. Johannessen, K.T. Skaar, SNAME Transactions, Vol. 88. pp. 319-356, 1980

[15] "*Prevention of harmful vibrations in ships*", Det Norske Veritas, 1983

[16] "*Guidance Notes on acceptable vibration levels and their measurement*", Lloyd's Register of Shipping, 1990

[17] "*Guide for the evaluation of human exposure to whole-body vibration*", ISO Standard 2631, 1997

C.9 Indexes

C.9.1 Index of tables

C.9.2 Index of figures

C.10 Annexes

C.10.1 Annex B: Raw material homologation tests

Bureau Veritas rules NR546 give minimum required mechanical test for raw material homologation, see Table 9.

Table 9: Type approval tests for raw materials

Raw material	Property / Characteristics	Required value	Recommended test method/ Required value
Polyester gel coat (cured) **(1)**	Tensile: • modulus (N/mm²) • elongation at break (%)	• ≥ 3000 • ≥ 2,5	ISO 527 or equivalent **(2)**
	Water absorption (mg) over 28 days	≤ 80	ISO 62 Method 1 or equivalent **(3)**
Resin systems **(1)**	Density	Manufacturer nominal value ± 1%	ISO 1183 or equivalent
	Tensile: • modulus (N/mm²) • elongation at break (%)	≥ 85% of the values given in Sec 4, Tab 1	ISO 527 or equivalent **(2)**
Adhesive **(11)**	Tensile: • modulus (N/mm²) • elongation at break (%)	Manufacturer nominal value ± 10%	ISO 527 ASTM D 638
	Shear: • modulus (N/mm²) • elongation at break (%)	Manufacturer nominal value ± 10%	ISO 11003-2 ASTM D 3983 NF EN 14869-2
Yarn	Weight per unit of length (tex)	Manufacturer nominal value ± 10%	ISO 1889 or equivalent **(4)**
Chopped strand mat	Weight per unit of area (g/m²)	Manufacturer nominal value ± 10%	ISO 3374 or equivalent **(5)**
	Tensile tests on laminate: • modulus (N/mm²) • elongation at break (%)	as per the present Rules	ISO 3268 or equivalent
Woven roving and unidirectional	Weight per unit of area (g/m²)	Manufacturer's nominal value ± 10%	ISO 4605 or equivalent **(6)**
	Tensile tests on laminate: • modulus (N/mm²) • elongation at break (%)	as per the present Rules	ISO 3268 or equivalent **(7)**
Pre-preg	Percentage of reinforcements in mass (%)	Manufacturer's nominal value ± 5%	ISO 1172 or equivalent **(6)**
	Weight per unit of area (g/m²)	Manufacturer's nominal value ± 5%	ISO 10352 or equivalent **(6)**
	Tensile tests on laminate: • modulus (N/mm²) • elongation at break (%)	as per the present Rules	ISO 3268 or equivalent **(7)**
	Determination of glass transition temperature	Manufacturer's nominal value ± 5%	ISO 11357-2 or equivalent **(1)**

(1) Curing process of the samples to be specified by the Manufacturer.
(2) Length of sample: 150 mm.
(3) Distilled water at 23° C. Circular sample of 50 mm diameter and 3 mm thickness.
(4) Three samples of 1 m length.
(5) Six samples 300 mm x 300 mm.
(6) Three samples 300 mm x 300 mm.
(7) Tensile tests are to be carried out in the two main directions of reinforcement. To test fabrics other than pre-preg, samples are to be made with a resin of an approved type. As a rule, samples are to be made with at least three layers of the fabric to be approved. Measurements of percentage of reinforcement in mass are to be carried out on samples submitted to tensile test.
(8) Three samples 100 mm x 100 mm x plate thickness.
(9) It may be requested, for foam used in sandwich panel cured with a heat process, that test foam samples be subjected to the same heat process before the test.
(10) Three samples 150 mm x 150 mm x thickness (minimum volume = 500 cm³ per sample).
(11) Curing process and material of sample pieces to be specified by the Manufacturer

C.10.2 Annex C: Mechanical type tests

Bureau Veritas rules NR546 give minimum required mechanical type test for laminates, see Table 10

Table 10: Mechanical type tests

Panels	Test types - Standards	Quantity of test pieces	Size of test pieces, in mm **(1) (2)**
Monolithic	Tensile test: ISO 527	• 5 in lengthwise direction of panel • 5 in crosswise direction of panel • 2 test pieces for calibration	Length: 400 Width: • 25 where e < 25 • 30 where 25 < e < 30 • 35 where 30 < e < 35, etc.
	3-point bending test: ISO 14125	• 5 in lengthwise direction of panel • 5 in crosswise direction of panel • 2 test pieces for calibration	Length: 200 Width: • 25 where e < 25 • 30 where 25 < e < 30 • 35 where 30 < e < 35, etc.
	Measurement of density: ISO 1183 Reinforcement content in weight: ISO 1172 **(3)**	4 samples	30 x 30
Sandwich	3-point bending test ISO 14125	• 5 in lengthwise direction of panel • 5 in crosswise direction of panel • 2 test pieces for calibration	Length: 1000 **(5)** Width: 2 · e
	For both skins: Tensile test: ISO 527, or equivalent **(4)**	• 5 in lengthwise direction of panel • 5 in crosswise direction of panel • 2 test pieces for calibration	Length: 400 Width: • 25 where e < 25 • 30 where 25 < e < 30 • 35 where 30 < e < 35, etc.
	For both skins: Measurement of density: ISO 1183 Reinforcement content in weight: ISO 1172 **(3)**	4 samples	30 x 30

(1) The Society may request additional tests with other sizes of test pieces.
(2) e : Thickness, in mm, of the piece under test.
(3) For laminate test panels reinforced with carbon and/or para-aramid fibres, the standard ASTMD3171 may be used.
(4) Where both skins of the sandwich panel are fairly similar, tensile and density tests may be confined to one of the two skins.
(5) The distance between the fixed rollers is to be not less than 600 mm (It is recommended to use a value roughly equal to 800 mm).