Paving the way for lightweight constructions on cruise ships through the LASS-C project

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ABSTRACT

The LASS-C project, "Lightweight construction of a cruise vessel", expanded the concept of making lightweight structures in SOLAS vessels by considering not only superstructures, glass and internal design, but also elements which are part of the hull girder, affecting the ship's global strength. The existing Panamax cruise ship the Norwegian Gem worked as application case in the project where the uppermost five decks were redesigned in lightweight fibre reinforced polymer composite material. Comparing with the previous design, weight savings calculations showed that about 1 200 tons could be saved in load-bearing structures. FEM simulations showed that the weakening of the global strength from using lightweight structures could be compensated by reinforcing the lower decks, still making the residual weight savings economically interesting. Environmental and economic assessments were carried out from a life cycle perspective, proving the lightweight construction has less impact to surroundings and that additional costs would pay back in 2.5 years. The key issue for building ships in plastic composite, namely fire safety, was addressed by performing a risk assessment in line with the method provided for alternative fire safety design and arrangements in SOLAS II-2/17. A preliminary analysis report for the fire safety design was delivered to the Swedish Flag for approval as part of the project.

KEYWORDS: lightweight, cruise vessel, composite, shipbuilding, fire safety

INTRODUCTION

Authorities, the public and customers are increasingly demanding sustainable solutions. It will eventually lead to emission trading, giving environmentally sound transport a competitive advantage. A stronger focus on both energy efficiency and environmental competitiveness has created a large interest world-wide for using lightweight materials in shipbuilding. Any technique that allows for an increased pay load/displacement ratio is obviously also economically interesting, particularly as fuel costs are increasing. The lighter the vessel, the more it can carry, or the less energy it needs for propulsion.

Sweden is, based on the work mainly by Kockums and FMV, a world leading producer of composite military crafts. The non-military vessel market has previously been closed for the usage of combustible construction materials. However, thanks to a new regulation for alternative fire safety design and arrangements (SOLAS II-2/17) in 2002 it is now possible to use such materials also in merchant ships, provided that a sufficient level of fire safety can be demonstrated. Fibre Reinforced Polymer (FRP) composite is a lightweight construction material with a high strength to weight ratio compared to steel. These properties, in combination with low maintenance, lack of corrosion, easy repair, prolonged lifetime and unleashed design possibilities make FRP composite an appealing alternative to steel. LASS, "Lightweight construction applications at sea", was a research project aimed at improving the efficiency of maritime transport by developing and demonstrating techniques for using lightweight materials in ship constructions (www.lass.nu). The project showed that by using FRP composite in merchant ships, a reduction in structural weight of up to 60% is achievable. Life cycle cost assessments showed that the lower fuel consumption per ton-km payload makes additional manufacturing costs pay off in short time of operation [1].
The recent LASS-C project [2], "Lightweight construction of a cruise vessel", was a continuation and expansion of the previous technical platform created within LASS. In the previous LASS project, different lightweight ship construction applications were studied, but cruise ships were not an application case. With consideration to environmental, economic and particularly fire safety aspects, the LASS-C project therefore targeted how lightweight constructions could be implemented in cruise vessels specifically. Furthermore, LASS-C expanded the concept of making lightweight structures in SOLAS vessels by considering not only superstructures, but also load-bearing elements which are part of the hull girder, affecting the ship's global strength. The project involved 15 parties and ended up with a budget of about M€ 1, out of which almost M€ 0.3 was funded by VINNOVA within their program for lightweight materials and constructions.

**OBJECTIVE AND LIMITATIONS**

In order to provide additional momentum to the movement towards lightweight composite constructions in shipbuilding, the goal was to provide demonstrative examples of how composite materials can be used on cruise ships. The ambition was therefore to bring a large cruise vessel, with a FRP composite construction, through the design and approval processes. This was done by redesigning an existing cruise ship to make use of the saved weight when building the upper decks in FRP composite. In combination with calculations of possible weight savings, finite element model analyses and tests were carried out to evaluate mechanical properties. Analyses were also performed considering costs and environmental effects in a long term life cycle perspective (LCC/LCA), since these analyses are of great relevance when determining the potential benefits of lightweight designs. Furthermore, a fire risk assessment was performed since demonstration of an equivalent level of fire safety is the critical point for using the material.

**DEVELOPMENT OF THE NORWEGIAN FUTURE**

A goal for the project was to provide a concrete example of a lightweight cruise vessel design. The technical platform was therefore extended by incorporating the German shipyard Meyer Werft, one of the world’s largest shipyards building cruise vessels. By doing so, more practical aspects for making composite-steel ship constructions were possible to study through the application case the Norwegian Gem. Weight savings calculations were carried out to determine the potential benefits of a lightweight design for the vessel, which formed the basis of a new concept design, the Norwegian Future.

**Weight calculations**

In 2007 Meyer Werft launched the 294 meters (965 ft) long cruise vessel M/S Norwegian Gem. It was built mainly in steel and consists of 15 decks, providing amenities for about 3000 passengers and 1200 crew. Realistic calculations were carried out to estimate how much weight could be saved by using FRP composite in the upper five decks. As input, Meyer Werft provided a general weight distribution of the areas on deck 11 and above, according to Table 1.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Weight [tons]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel structures</td>
<td>2050</td>
</tr>
<tr>
<td>Aluminium structures</td>
<td>310</td>
</tr>
<tr>
<td>Cabins</td>
<td>410</td>
</tr>
<tr>
<td>Balconies (floor)</td>
<td>60</td>
</tr>
<tr>
<td>AC rooms</td>
<td>290</td>
</tr>
<tr>
<td>Galleys/Pantries</td>
<td>200</td>
</tr>
<tr>
<td>Public spaces inside</td>
<td>1090</td>
</tr>
<tr>
<td>Public spaces outside</td>
<td>580</td>
</tr>
<tr>
<td>Technical spaces</td>
<td>110</td>
</tr>
<tr>
<td>The rest</td>
<td>100</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>5200</strong></td>
</tr>
</tbody>
</table>

Steel and Aluminium 2360 t
Outfitting 2840 t
Based on the weight distribution in Table 1, the weight relation between the structures that will be replaced by FRP composite (steel and aluminium structures) and the rest (outfitting) appeared to be approximately 1:1. Using FRP composite instead of steel and aluminium was assumed to reduce the weight of the structures by half, based on [1], but the weight of outfitting was assumed unaffected. The simplistic conclusion was thereby made that the structure/outfitting relation of the new design of the upper decks would be 1:2. As illustrated in Table 1, this leads to an absolute weight reduction of approximately 1200 tons.

The Norwegian Future

A likely scenario is that a ship owner will want to utilize the saved weight in a way that gives the fastest return of investment. In the previous LASS project, weight savings estimations worked as input to calculations of reduced fuel costs. An alternative way to make use of the reduced weight is to gain more space, and thus increase the payload. This became the ambition when Meyer Werft developed a new design for the upper decks. A prerequisite was to also keep the same centre of gravity and thus fulfil the same stability criteria, which would simplify the design process.

The result was a design where decks 1-10 are identical to those on the Norwegian Gem. The layout of the remaining upper five decks was although changed by adding another third of a deck. It was inserted in the position of the previous front third of deck 12. This implies that the front third of all previous decks above deck 11 were shifted upwards, as seen in Figure 1. The basis for this was the 1200 tons saved, out of which 400 tons of additional steel was estimated necessary to strengthen the load-bearing steel hull. The remaining weight reduction of 800 tons were calculated to give a bit more than another third of a deck (FRP composite structures: 265 tons) and its outfitting (86 cabins, 350 m² public spaces and technical spaces: 535 tons). Altogether the new ship will have a weight of 43 150 tons, and hence the same weight as the Norwegian Gem. The vertical centre of gravity will be equal for the two vessels but the longitudinal centre of gravity will be slightly different, which although could be easily adjusted by modifying the load cases or through a different layout.

Figure 1  Illustration of the design changes made to the Norwegian Gem to form the novel design of the Norwegian Future. (GA: Meyer Werft)

Hence, the Norwegian Future obtains an increased tonnage (volume) by 3000 gt and an additional payload of 10 M€/year by accommodating an additional 200 passengers and 20 crew. The design expansion is possible since all load-bearing structures of the upper decks from deck 11 were designed in lightweight FRP composite instead of steel, which saved 1200 tons in weight.
Global strength

Except from the realistic weight calculations above, some further investigations were necessary to account for the introduced novelty. A very important complication brought in by the new design, compared to previous examples in e.g. the LASS [1] and SAFEDOR (www.safedor.org) [3] projects, was the inclusion of decks taking part in the global strength, i.e. constituents of the hull girder. Previous projects have focused on designs where the lightweight construction applications only needed to account for their own weight, wind loads and possibly joints between an upper deck house and the main hull construction. Interfering with the original hull girder design invokes to investigate implications of the new material through Finite Element Model (FEM) analyses. The analyses were carried out by Meyer Werft with the objective to assess the ability of the FRP composite construction to manage global stresses. This is, to our knowledge, the first official report of such calculations.

![Diagram showing global strengths](image)

**Figure 2** The maximum hogging for the Norwegian Gem (top), the Norwegian Future (mid) and the Norwegian Future with increased deck plating (bottom). Equivalent to three.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Norwegian Gem</th>
<th>Norwegian Future</th>
<th>Norwegian Future +</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel mass in tons</td>
<td>16981</td>
<td>15109</td>
<td>15196</td>
</tr>
<tr>
<td>Max usage equivalent stress</td>
<td>0.96</td>
<td>1.31</td>
<td>1.26</td>
</tr>
<tr>
<td>Hogging</td>
<td>353</td>
<td>458</td>
<td>444</td>
</tr>
</tbody>
</table>

*With increased deck plating to fulfil strength and buckling criteria.*

The distribution of global stresses in the novel design was studied through a FEM analysis where mass was distributed only to the steel elements and the dimensions of shell elements in composite were kept as original. As presented in Figure 2 and Table 2, the analysis showed that it is necessary to increase the deck plating to fulfil strength and buckling criteria. An increased vertical deflection of 91 mm or 26% was still obtained at the keel line in the maximum hogging load case, which is a lot but manageable and still economically interesting. Buckling of the bulkheads could be solved by using buckling stiffeners, but a 26% increase in deflection would lead to a necessary re-dimensioning of all local details which are critical with regard to fatigue. There will also be areas where the arrangement and sizes of doors and openings would need to be completely redesigned. The loss of bending stiffness is primarily due to the loss of effective hull girder height. Interesting at this stage is the question if the composite material could generally handle the loading induced by the large deformation or if more effort needs to go into reinforcing the steel decks to reduce the vertical deflection. A central note is that a reinforced steel structure still seems to give sufficient weight savings to be economically interesting.
ENVIRONMENTAL AND ECONOMIC LIFE CYCLE ASSESSMENTS

The material used for manufacturing cruise ships is traditionally steel, as for any large ship. From a manufacturing point of view, steel is the most economical structural material. However, a ship will continue to cause costs and also environmental impact in other parts of the life cycle, e.g. when disposing of the ship and through maintenance in operation. For this reason, environmental and financial costs are nowadays often investigated over the whole lifetime in Life Cycle Assessment (LCA) and Life Cycle Cost assessment (LCC). The former covers the impact on the environment from all parts of the life cycle; from the initiation and production phase via the operation phase and to disposal, and the latter investigates the economic impact over the lifetime. With the life cycle perspective, interest is growing for implementing structural materials on ships which could decrease the environmental impact and also generate cost savings. LCA and LCC were therefore performed for the new ship design (the Norwegian Future) and compared with the traditional construction (the Norwegian Gem) as part of the LASS-C project.

Environmental life cycle assessment, LCA

The importance of environmental protection and increased awareness of possible environmental impacts throughout the whole lifecycle of products has led to a demand to develop methods to better comprehend and assess these negative impacts. In response, a technique developed called Life Cycle Assessment, LCA. It considers environmental aspects and potential impacts associated with a product in all phases of its life. The current LCA method builds on experiences and calculation tools developed within the former research project LASS and is based on the Simapro software tool. One of the goals of the performed LCA was to demonstrate and confirm that the method is applicable for environmental life cycle evaluation of cruise ships. Important to note is that comparison of results from different LCA studies is only possible if the assumptions and context of each study are the same.

The analysis was carried out by the Royal Institute of Technology, based on a master thesis [4], with the goal to investigate the environmental impact by the original superstructure on the Norwegian Gem and to compare it with the impact by the novel FRP composite design of the Norwegian Future. The reduction in weight was assumed to be utilized as increased payload capacity, resulting in an increased number of cabins, as described above. With this follows an increased number of passengers, which will bring more profit to the ship owners. The fuel consumptions of the two ship versions are hence identical since the weight of the ships are approximately the same.

Starting by comparing the manufacturing phase between the original steel design and the FRP composite structure showed that the original design has much larger environmental impacts than the novel design, except in the fossil fuels category. Figure 3 shows the ratio of different environmental impact categories of the two ships and displays relative large differences in all other categories.

![Figure 3](image_url)
However, in general it is not the manufacturing phase that leaves the largest environmental footprint but the operational phase. Figure 4 shows that the operation phase has considerably higher influence on the environment than the manufacturing phase, which in some cases is even impossible to distinguish in the figure.

![Figure 4](image)

**Figure 4** Comparison of characterized environmental footprint from manufacturing and operation phase for the two ships.

From the figures above it is although not possible to determine the difference in impact between the ships. The measured categories were therefore summed up and shown in relation to each other when evaluating the entire life cycle, as illustrated in Figure 5. Different waste scenarios were considered to account for uncertainties regarding disposal of FRP composite; only the least gratifying result for FRP composite is presented here, representing waste scenario 1 in [4]. The general result was that the traditionally built Norwegian Gem has larger environmental impacts than the Norwegian Future in each individual category. The difference was although not as large as in the manufacturing phase in several of the categories. Furthermore, a large impact comes from the operation phase, where a huge amount of fuel is consumed for the life cycle for both two types of ships. Therefore the fossil fuel values of the two designs are not very different and both ships largely influence the climate change, ozone layer and fossil fuels categories, since these are closely connected with fuel consumptions.

![Figure 5](image)

**Figure 5** Single score life cycle comparison of environmental impact.

In conclusion, it was found that the construction in FRP composite material has less impact to surroundings for the whole life cycle in general. It was also concluded that the operation phase contributes the most to the overall impact of a cruise ship life cycle.
Economic life cycle cost assessment, LCC

Pros and cons from an economic point of view were also collected and carefully estimated in a life cycle cost assessment (LCC) in order to determine the potential financial benefit of lightweight cruise vessel designs. The analysis was carried out by the Royal Institute of Technology and was based on experiences and calculation tools developed within the former LASS project. Since it is a comparative analysis, unchanged cost elements were not included, e.g. cost for hull structure, machinery, interior, outfitting or on-board crew. As for the environmental impact analysis above, costs were identified over the whole life cycle, starting with initial costs. These costs include design, planning and development of manufacturing devices and were spread over the first year. The following year, costs for production apply. The ship was assumed to operate for a period of 25 years with operational costs. Finally, the ship is disposed, resulting in a cost or payback assumed for a period of one year.

For a comparative study as this, a key value is the break-even point, i.e. when the costs of the original superstructure on the Norwegian Gem are equal to the costs associated with novel superstructure in FRP composite on the Norwegian Future. To determine this, cost calculations for materials and production of the original superstructure of Norwegian Gem were based on information regarding material content provided by Meyer Werft and material costs according to Kockums AB. The latter partner also provided information on material content and cost for the new FRP composite design of the Norwegian Future. The initial cost was set to 10% of the material, based on earlier studies [5]. This resulted in manufacturing costs of the superstructures at 175 MSEK and 309 MSEK, respectively. For the operation phase, fuel consumption was estimated to 6 900 000 tons over 25 years, i.e. 276 000 tons/year, for both the Norwegian Gem and the Norwegian Future. After the lifetime, costs and incomes emerge from disposing the ship structures. Recycling of steel and aluminium was estimated to give an income of 500 €/ton (www.demolitionscrapmetalnews.com, September 2008), while landfill for the insulation generates a cost of 1 000 SEK/ton [6]. For the sandwich structure, incineration with energy recovery is a possible alternative. The cost for disposal of the composite structure was further based on knowledge from scrapping a Danish composite ship [7] at a cost of 180 €/ton, including cutting, incineration and landfill. In summary, disposal of the ship designs will affect the total costs as presented in Table 3, where costs from all phases are concluded.

From the summarized results it is visible that the operation cost is dominating, but note that this cost applies to the whole cruise ship and the other costs are connected only with the superstructure.

<table>
<thead>
<tr>
<th>Cost element (MSEK)</th>
<th>Norwegian Gem</th>
<th>Norwegian Future</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production</td>
<td>175</td>
<td>309</td>
</tr>
<tr>
<td>Operation</td>
<td>45 512</td>
<td>45 512</td>
</tr>
<tr>
<td>Disposal</td>
<td>-12</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total cost</strong></td>
<td><strong>45 675</strong></td>
<td><strong>45 824</strong></td>
</tr>
</tbody>
</table>

Additional information from Meyer Werft provided basis for further calculations of financial differences, resulting from an additional net income per additional passenger of 107.5 $/day. This yields a total increased income of 7 740 000 $/year (based on 360 operational days/year, 200 additional passengers, the same crew passenger ratio as before and no increased fuel consumption). With an increased cost of 134 MSEK for building the FRP composite superstructure, a break-even is reached after about 2.5 years. If the lightweight material would have been used to decrease the structural weight, the reduced fuel consumption would have led to a break-even after 5.9 years.

ALTERNATIVE FIRE SAFETY DESIGN

Both from different design perspectives as well as from environmental and economic viewpoints, lightweight FRP composite is an appealing alternative shipbuilding material compared to conventional steel. However, at the same time as cost effectiveness and optimization of available resources drives transport development, human safety is of highest concern. The design expansion described above is possible since all load-bearing structures from deck 11 will be made in lightweight
FRP composite instead of steel. The fact that FRP composite has some characteristics very different from steel implies effects on safety. Risks will not necessarily be greater but inevitably different. A reduction in topside weight, obtained by the lightweight material, could for example have a positive effect on damage stability. Risks associated with collision and grounding, which represent the greatest risks on a ship, could thus be reduced [8, 9]. On the other hand, the fact that FRP composite is combustible could have a negative effect on fire safety, unless sufficient safety measures are taken.

Isolation at sea has made fire risks a major concern in shipping and this is also the key issue when considering ship structures in FRP composite. The main introduced difference in fire safety is that the material is combustible, as opposed to steel which by definition is non-combustible. The international code regulating safety of life at sea, SOLAS [10], does not allow making load-bearing structures in combustible material, according to prescriptive requirements. However, a new regulation (SOLAS II-2/17, hereafter referred to as Regulation 17) came into force 2002 which provided an opening for alternative construction solutions if fire safety can be proven at least equivalent to that of a conventionally built ship. It is thus not an exception but an alternative way to fulfil the fire safety requirements of SOLAS. As part of the LASS-C project, a method to assess fire safety when making claim to Regulation 17 was developed which embraces the novelty of FRP composite. It was applied to the Norwegian Future, as further delineated below, and resulted in a preliminary analysis report documented by SP [11] and submitted to the Swedish Transport Agency for approval in principle.

**Method to assess fire safety in FRP composite constructions**

For FRP composite to become a viable maritime construction material, effects on fire safety from using the material need to be revealed, additional safety measures may be required and an analysis demonstrating and documenting sufficient fire safety is necessary. In Regulation 17, descriptions are summarized for how such analysis should be carried out and more detailed guidelines are found in MSC/Circ.1002 [12], hereafter referred to as Circular 1002. They stipulate that the analysis (hereafter referred to as “Regulation 17 assessment”) should be performed by a design team selected to mirror the complexity of the task. The procedure of the analysis can be described as a two-step deterministic risk assessment using performance-based methods of fire safety engineering to compare the fire safety of the alternative design with the level of fire safety obtained by prescriptive requirements [13]. The two major steps to be performed are (1) the preliminary analysis in qualitative terms and (2) the quantitative analysis. In the first step, the design team is to define the scope of the analysis, identify hazards and from these develop design fire scenarios as well as develop trial alternative designs. The different components of the preliminary analysis in qualitative terms are documented in a preliminary analysis report which needs an approval by the design team before it is sent to the Administration for a formal approval. With the Administration’s approval, the preliminary analysis report documents the inputs to the next step of the Regulation 17 assessment, the quantitative analysis. Now the design fire scenarios are quantified and, since there are no explicit criteria for the required level of fire safety, outcomes are compared between the trial alternative designs and a prescriptive design. Accordingly, the prescriptive design is a reference design, complying with all the prescriptive fire safety requirements. The documented level of fire safety of the alternative design is therefore not absolute, but relative to the implicit fire safety of a traditional design, which is likewise a product of the implicit fire safety level in prescriptive regulations. Accounting for uncertainties when comparing fire safety levels, the final documentation of the Regulation 17 assessment should demonstrate whether a safety level equivalent to that of a prescriptive design is achieved by the proposed trial alternative designs.

Regulation 17 was developed to undertake innovative design solutions, typically high atriums and long shopping promenades on cruise vessels, without compromising with fire safety. The regulation is in that sense employed to make safety more attractive, but it can also be used to make fire safety more cost-efficient, i.e. to accomplish the same level of fire safety at a lower cost or to increase fire safety at the same cost. In the present case, all steel divisions of several decks on a large cruise vessel have been redesigned in FRP composite. Above all, the material is combustible and the fire integrity will be fundamentally affected, which implies significant effects on fire safety. Making claim to Regulation 17, an evaluation of the alternative fire safety design should be based on Circular 1002, which has been identified as a type of risk assessment. However, in order to establish whether the fire
safety of a design with FRP composite can be regarded at least as safe as prescriptive requirements, it has been judged that the risk assessment needs to be more elaborated than what is outlined in Circular 1002 [13]. It is namely not evident how fire risks in such a novel design should be assessed to adequately display effects on fire safety. For one thing, all fire safety requirements are made up around steel designs, leaving many implicit requirements unwritten. To further complicate the comparison of safety levels, prescriptive requirements have unclear connections with the purpose statements of their regulations and also with the fire safety objectives and functional requirements of the fire safety chapter, which are supposed to define “fire safety” [13]. A Regulation 17 assessment involving FRP composite should hence not only comply with what is stipulated in Circular 1002, but must also be of sufficient sophistication to describe the introduced novelty in terms of fire safety.

As part of the LASS-C project, a more elaborated method for the first step of the Regulation 17 assessment was developed, which comprises all the requirements of MSC/Circ.1002 but brings the analysis to a higher level [13]. The main differences introduced by the new approach (marked green in Figure 6) are the way verification needs are identified as well as the way these differences in fire safety are collected and rated. Furthermore, since the sophistication of the following quantitative analysis needs to be more elaborated in the present application case, the way fire scenarios are specified is also different. The revised approach and the way it was applied to the Norwegian Future are described subsequently.

![Figure 6](image)

**Definitions of scope**

As described above, the preliminary analysis in qualitative terms can be divided in the three main parts: definitions of scope, development of fire scenarios and development of trial alternative designs. The first part consists of three main bullets. Initially, the scope of the current case of alternative fire safety design is simply presented and the regulatory prescribed reference design is defined. Thereafter follow a definition the base design, i.e. the foundational alternative design against which the coming evaluations will be made and to which additional safety measures may be added. In the present case, the scope of the Regulation 17 assessment was the Norwegian Gem with hull and structural elements in the upper five decks designed in FRP composite. The Norwegian Future works as the base design.
and the corresponding ship built in steel works as the prescriptive design. Except what has been described above, a fundamental condition for the base design was to nowhere in the interior allow a composite surface without thermal protection. The FRP composite divisions were assumed insulated sufficiently to be classified as Fire Resisting Divisions that maintain fire resistance for 60 minutes (FRD-60), according to the International Code of Safety for High-Speed Crafts [14]. The fact that the material is a much better thermal barrier than steel could be advantageous from a fire safety perspective, since the material better will contain heat in an enclosure [15]. Interiors, fire protection systems and equipment were assumed equal in the two designs and in agreement with SOLAS requirements.

The next bullet is a key for the following assessment since it is meant to identify the areas of impaired fire safety which need to be regained in an alternative way. However, Circular 1002 only describes to identify deviated prescriptive fire safety requirements and associated functional requirements to identify differences in fires safety. As described above, for a FRP composite design this is not sufficient since all fire safety requirements are made up around steel designs, leaving many implicit requirements unwritten. Furthermore, the fire safety objectives and functional requirements of the fire safety chapter are not fully covered by the regulations purpose statements and these are not fully covered by prescriptive requirements (hence identification of implicit effects on fire safety may be necessary in any Regulation 17 assessment) [13]. Based on the above weaknesses in regulations, it was suggested that the identification of effects on fire safety includes the following additional components when evaluating FRP composite designs:

- evaluation of how fulfilment of fire safety objectives and functional requirements are affected;
- evaluation of how the fire safety structure is affected;
- evaluation of how the fire safety properties are affected; and
- evaluation of how a fire development is affected.

The revised approach thus undertakes the investigation of potential effects on fire safety from a broader perspective. Applying it to the Norwegian Future firstly identified a number of challenged regulations in the fire safety chapter of SOLAS. External and unprotected surfaces will not fulfil the functional requirement in Regulation 4 to restrict the ignitability of combustible materials as well as painted steel surfaces. Since painted steel is not a fire hazard there has not been any reason to regulate this matter in prescriptive requirements and the base design therefore fulfils all prescriptive requirements. This is a great example of where the base design goes beyond the steel-based regulations. Similarly, all prescriptive requirements of Regulation 5 involving enclosures are complied with but fulfilment of a regulation functional requirement (Reg. 5.1.3) could be claimed weakened as it states to restrict the use of combustible materials. The scope of Regulation 6 also comprises enclosures and the first stages of a fire, which is when people could be exposed to toxic smoke. Even if all the prescriptive requirements of this regulation are complied with and the aim of the regulation is the first stages of a fire in spaces where people work or live, the production of smoke and toxic products may not be as limited as in a prescriptive design. This should therefore be accounted for when comparing safety levels, even if the regulation can be considered complied with.

In the next part of SOLAS II-2 the main challenges regard Regulations 9 and 11. Regulation 9 prescribes main vertical and horizontal zones as well as internal bulkheads, where necessary, to be made up by A-X divisions, which implies steel or equivalent material should be used. Reg. 3.43 defines steel or equivalent material as a non-combustible material which, by itself or down to insulation provided, has structural and integrity properties equivalent to those of steel. The base design achieves equal structural properties and the added thermal insulation in divisions and penetrations makes it exceed the requirements on integrity by all means. However, even if structural and integrity properties in divisions are achieved FRP composite is combustible. This is also the only deviation to Regulation 11, which prescribes the hull, superstructures, structural bulkheads, decks and deckhouses to be constructed of steel or other equivalent material. The risk of collapse and the fact that a (protected) non-combustible material replaces steel gives reason to further assess safety equivalency. (Good structural behaviour of the FRP-composite in a real fire, even with local delamination occurring in the composite due to high temperature, was documented at SP in a full scale cabin fire test [16])
The preceding evaluations of the base design revealed several important effects on the implicit level of fire safety that need to be verified. When it comes to the fire safety objectives in SOLAS II-2, the base design may fulfill some of the objectives superior to a traditional design due to its improved thermal insulation. The focus on safety of human life in the fire safety objectives makes it topical to address, not only the safety of passengers, but also the safety of fire fighters and crew. Investigating the functional requirements for the whole fire safety chapter in SOLAS especially indicated that the risk when adding more combustible materials needs to be accounted for. Effects on the fire safety structure mainly concerned the exposure and effect parts of the fire protection strategy and invoke thorough verification since the changes will affect many protection chains. The following analysis of fire safety properties showed that in particular human intervention, complexity in the fire protection strategy, reliability and vulnerability will be affected. The implications for safety may, however, not be very significant for all of these properties. When the revealed differences were viewed in the context of fire dynamics it was established that the ignition and first stages of a fire in an enclosure will be unaffected by a change to FRD-60. In case the circumstances allow a fire to progress, it will reasonably be better contained in the structure within the first 60 minutes. In case of fire that ability could e.g. give the advantage of an increased time for escape as the temperature in the staircases and escape routes would be significantly lower. The conditions in the base design if a fire develops past 60 minutes may although be worsened, in comparison with a traditional design. Fire safety will also be affected in case a fire includes external surfaces, which will go from being non-combustible in a steel design to combustible but protected in the base design.

Development of fire scenarios

In the next part, the development of fire scenarios, the changes in the suggested approach stem from weaknesses in the descriptions in Circular 1002, the above changes and from the sophistication of the forthcoming quantitative analysis. In the first bullet, the hazard identification, the design team meets in a systematic brainstorming session where fire safety is thoroughly investigated in each space of the novel design. At this stage it is important to recognize how the previously identified differences in fire safety will affect the different kinds of fire hazards in the individual spaces. A new logistical process was therefore added to the new approach, where all pros and cons from a fire safety perspective are collected in a “Procon list”. This document works as input to the hazard identification to recognize how the differences in fire safety result in actual fire hazards or improvements and how these work along with other fire hazards at different stages of a fire scenario. Further differences in fire safety which are identified during the development of fire scenarios are also added to the Procon list. In the present application case, fire hazards were identified in two separate workshops held at SP Technical Research Institute of Sweden with participants from the design team.

Figure 7  (a) Tabulation of the fire hazards from the hazard identification. (b) Fire hazard ratings of the spaces in the FRP composite construction. (c) A different but more useful enumeration of fire hazards where pros and cons with the base design were rated from a fire safety perspective.

In the hazard identification, fire hazards are naturally organized in different categories, as illustrated in Figure 7. This tabulation normally automatically fulfills the stipulation in Circular 1002 to enumerate fire hazards in three different incident categories. The guidelines are although quite vague in this area. What Circular 1002 could be aiming at when stipulating an enumeration into incident classes, and what is more useful, is to rather identify and categorize the plausibly worst fire developments in the spaces, based on the identified fire hazards. It can be said to constitute some form
of fire hazard rating of the concerned spaces, since only plausibly worst consequences are considered and probability thereby is included to a very limited extent. Despite this, and although it is founded on value judgement, this new fire hazard rating provides an indication of the fire risks as perceived by the design team. The fire hazard rating was performed for the spaces involved spaces on the Norwegian Future (see Figure 7) and proved useful when selecting fire hazards to form design fires and event trees, which define the fire scenarios. Before the selection, another process was although added, where the collected differences in fire safety in the Procon list were reviewed and rated (see Figure 7). The first priority when selecting fire hazards should be to include as many of those differences in fire safety between the prescriptive design and the base design as possible. Particularly the highly rated differences in fire safety need to be considered in fire scenarios whilst less significant differences alternatively could be managed qualitatively. Thereafter, hazards that significantly will affect the fire development should be taken into account in the fire scenarios. Finally it should be a goal to include as many of the identified hazards as possible and, hence, not only the hazards resulting in the most severe consequences. In the selection process in the present application case, spaces with similar fire hazards were grouped together to cover all the spaces of the alternative design. It resulted in the following selection of representative spaces where similar fire developments are assumed:

2. Corridors; 5. Lounges; 10. Machinery spaces;
3. Stairways; 6. Restaurants; 11. Funnel and Casing; and

In the following fire scenario specification, relevant failure modes affecting a fire development were specified along with a plausibly worst-case uncontrolled design fires for each space group. Thereby, all of the spaces in an alternative design were included in the fire scenarios instead of being represented by a few design fire scenarios.

**Trial alternative designs and final documentation**

The base design usually needs additional risk control measures (RCM) in order to achieve sufficient safety. A combination of risk control measures makes up a risk control option (RCO) and together with the base design different RCOs make up trial alternative designs, as illustrated in Figure 8. In order to develop suitable trial alternative designs, it is important that the suggested RCM’s originate from the identified differences in fire safety and their effects in a fire scenario. It is also during these previous parts that RCM’s are generally identified. In the revised approach it is therefore simply suggested that RCM’s are collected throughout the analysis and combined to suitable RCO’s at the end of the preliminary analysis in qualitative terms. However, new RCM’s can be found further on, certain combinations can be missed and their effects on safety are still not evident. Therefore it is not constructive to eliminate risk control measures or combinations of such. Even if particularly suitable RCO’s could be suggested, it is advised in the revised approach that trial alternative designs are not firmly defined at this stage. Therefore the list of potential risk control measures was simply presented in a categorized form for the Norwegian Future.

![Figure 8](image)

*Illustration of the base design in relation to trial alternative designs.*

The initial aim of the LASS-C project was to cover both steps of the Regulation 17 assessment but the required labour had been underestimated and only the preliminary analysis in qualitative terms was possible to complete within the project. The analysis was documented by SP in a preliminary analysis report [11] which was approved by the design team and submitted to the Swedish Transport Agency.
for consideration. Development of the method for the quantitative analysis, execution of further tests and final documentation of the safety level of the trial alternative designs is instead carried out within the EU project BESST. Flag state to review the final analysis report has not been determined but the above tasks have been projected to be finished and reported before March 2013.

CONCLUSIONS

To provide momentum to the movement towards lightweight composite constructions in shipbuilding, a demonstrative example was provided of how composite materials can be used in cruise ship constructions. A new design was created from the Panamax cruise vessel the Norwegian Gem with the ambition to gain more space from using lightweight constructions. It resulted in the Norwegian Future, with the upper five decks in FRP composite and an added third of a deck with cabins. A life cycle cost assessment showed that the increased initial cost (134 MSEK) from building the ship could pay back in about 2.5 years from the additional payload. The environmental impact was also evaluated from a life cycle perspective and showed that the FRP composite superstructure would decrease the influence, even if the contribution from the operation phase is still significant. Proving that fire safety is equivalent to the prescribed solution is the critical point for using FRP composite in shipbuilding, since the material is combustible. The first part of the prescribed analysis method when making an alternative fire safety design was developed to better capture the introduced novelty in terms of fire safety when using FRP composite. The revised approach was applied to the Norwegian Future and a preliminary analysis report is awaiting approval from the Swedish Flag.

REFERENCES