# Simulation Driven Structural Design in Ship Building

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## Summary

The traditional naval ship design process relies on limited design data on the major structural design drivers when making key decisions in the Concept and early Preliminary Design phase of a project. This largely subjective approach, albeit using the best engineering judgement, can result in inefficiency and sometimes even significant structural problems being locked-in from the start, with the consequence of increased weight and unnecessary complexity, as well as higher design and manufacture cost in the end product, compared with one where the design has been optimised. Simulation driven design acts to solve these problems by providing naval architects with a greater and more in-depth understanding of the design drivers at the concept phase, thus enabling more informed design decisions to be made at this critical stage. It is facilitated by the use of structural simulation, such as finite element analysis (FEA) working in conjunction with optimisation technology, that yields 'right first time' designs. This paper highlights the problems of the traditional design process and discusses the merits of the simulation driven design process. This is supported by examples of how it has been applied to local structures on the UK's Queen Elizabeth Class (QEC) Aircraft Carrier. The paper also discusses how the process can be applied at an earlier stage and expanded to whole ship design and the work that is planned to achieve this.

## 1.0 Introduction

### 1.1 Traditional Naval Ship Design Process

Naval ship structural arrangements are rarely optimised for weight and cost from the outset because for these large and complex vessels the initial focus is entirely centred on defining a hull envelope, general arrangement and powering solution that will meet the operational requirements and budget of the customer. Although the major whole life cost and performance-driving decisions are made during Concept and early Preliminary Design phases [1, 4], their impact on the structural arrangement tends to be assessed subjectively and from a top-down perspective, by undertaking manual design iterations with limited data or by adapting existing designs in order to obtain a realistic weight estimate of the eventual structural arrangement. As structural weight can typically form 40-50% of the total lightship for a naval vessel this is the minimum necessary in order to demonstrate feasibility of a concept design. However, this approach can lead to the following problems:

- Undesirable constraints placed upon the structural arrangement by high-level design decisions being locked-in as the project advances in design maturity from contract award to Preliminary Design and into Detailed Design.
- A higher likelihood of costly iterative change being required in the later design and build phases with consequent pressures on resources and programme.
- The resulting structural design being sub-optimal in terms of weight and cost to manufacture and a poor compromise of design parameters.

Solving these problems would result in more efficient, low cost platforms.

Within the commercial sector, a well-defined operational profile and a strong learning curve achieved as a result of a frequent turnover of designs, typically solves the above problems. The Naval sector is rarely able to benefit from a similar learning curve for a number of reasons:

- The turnover of designs is much less frequent.
- There is an increasing trend for naval vessels to be designed for a multiplicity of roles due to acquisition and operating costs limiting the number of platforms and thus putting pressure on designers to achieve maximum leverage.
- There is the added requirement to protect the vessel against a variety of above surface and underwater weapon threats as well as the normal seagoing environmental loads [2].
- The required design solutions tend to be such significant extrapolations of historical and published data that they have effectively been started from a ‘blank sheet of paper’ to produce a bespoke solution, as is the case with some recent UK naval ship programmes.

All of these factors invariably lead to difficulties in converging on optimal solutions in the early stages of the engineering lifecycle, with the result of considerable change or ‘design churn’ and higher engineering costs in the later stages.

In order therefore to accommodate the above issues and work towards the same efficient low cost platforms achievable in the commercial sector an alternative to the traditional design approach is required that does not rely on a time consuming manual design iteration and instead informs designers to enable them to focus on high level engineering decisions.

### 1.2 An Alternative Approach

A means of automatically selecting the optimum ‘right first time’ design from all possibilities is required. This can be achieved through the use of optimization algorithms that take into account the overall design objective and the design constraints and then determine the optimum values for the design variables in order to satisfy them. This approach has been proven to work effectively in industries such as aerospace and automotive and is readily applicable to the ship building industry. For example competition in the cruise ship market and the increasing number of novel concepts, has prompted a more sophisticated approach to the design of structures for these ships, with optimisation techniques being applied to demonstrate weight savings in the order of 10% compared with designs produced by the most experienced engineers using the traditional approach [3].

Using optimisation-based simulation early on is the fundamental basis of the simulation driven design process. This paper demonstrates how the process of simulation driven design has already been successfully used to produce local design solutions on the QEC Aircraft Carrier and provides discussion on how it can be expanded to the whole ship level with the aim of solving the previously stated problems.

## 2.0 Simulation Driven Design Process and Methods

### 2.1 Exploring the Design Space

When designing any structure the end product will be required to meet an objective (e.g. minimise mass) and a set of constraints (e.g. stress must not exceed an allowable). This is achieved through the manipulation of design variables (e.g. geometry). Different combinations of design variables produce different design solutions and the space in which all these variable combinations reside is known as the design space. Within all design spaces there is one combination of variables that forms the optimum solution where the constraints are met whilst minimising or maximising the objective function. The challenge to any designer is finding this optimum.

The traditional structural design process relies on the optimum solution being found through prior knowledge, engineering experience and simple trial and error. For complicated design problems this approach can lead to lengthy and costly design cycles in which the end product may never be the optimum and may not be as efficient in terms of cost and performance as may be desired.

The fundamental problem with the traditional design approach is that it is impossible to take into account all design possibilities, either because there is insufficient time to do so or because some design possibilities simply cannot be conceived based on engineering knowledge and experience. This inability to fully explore the entire design space means that the optimum solution to complex design problems will rarely be found by traditional design methods.

As an example take an arbitrary steel structure where some of the members are described by 10 design variables and that it takes 1 second to perform a structural analysis of each design. In order to manually explore all design possibilities (and hence manually find the optimum solution) it would take 1010 seconds or 317 years! Clearly this is not practical.

The simulation driven design process utilises structural simulation combined with optimisation technology to intelligently explore, mathematically and logically, the design space in order to identify the optimal, right first time design. This process results in fewer design iterations, which in turn results in a shorter design cycle, whilst ensuring an optimum structural solution. A faster turnaround of design ideas also allows a greater number of design starting points to be considered and enables trade-off studies to be undertaken rapidly.

## 2.2 Simulation Methods

This part of the design process can either take the form of simulating the ship structure using a set of rules based design calculations, or by using finite element analysis of the structure or indeed both. Within an optimization algorithm the variables can be passed through both hand calculations and FEA at the same time in order to achieve as much fidelity as possible.

Traditionally, with the exception of integrated structural analysis toolsets such as MAESTRO [5], analytical methods such as FEA have only been used to validate and refine existing designs, but this is an extremely poor use of a very powerful technology. In simulation driven design FEA can be enabled at the very beginning of the design process to ensure that the detailed assessments of structural concepts that result from FEA can be used in assisting with the design rather than just validating and refining it.

Whatever method is used, the corner stone of the process is optimisation. It is optimisation technology that transforms structural simulation tools into design tools that can explore the design space.

### 2.3 Optimisation Technology

The optimisation technology within simulation driven design can be split into four key methods:

- Free form or 'topology' optimisation
- Free-size optimisation
- Size optimisation
- Shape optimization

Free form or 'topology' optimisation automatically identifies which areas of a package space (in which the structure can reside) are structurally important and structurally redundant under a given set of design loads, objectives and constraints. This method is typically used early on in the design process where the overall package space is defined and maximum freedom of design within that space is still allowed.

As an example topology optimisation could be used to identify the best location for structural bulkheads (structurally important areas within a package space) and the best locations for openings within those bulkheads (structurally redundant areas within a package space).

Figure 1 below provides an illustration of the topology optimisation principle where load paths are 'grown' and redundant material 'removed' between two loaded hardpoints within a package space to form an optimal structure.

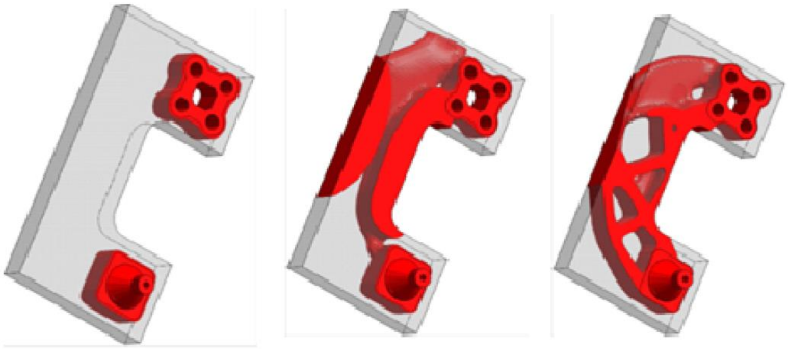

**Figure 1: Defining Optimum Structural Layout using Topology Optimisation**

Free-size optimisation acts in a similar way to topology optimisation, indicating areas of structural importance and redundancy within a package space. The difference is that free size optimisation acts to freely vary the thickness of existing structure rather than physically removing or 'growing' structure within a package space. An example of this method can be seen in Figure 2 below, where an aircraft rib structure has been optimised using the free-size method.

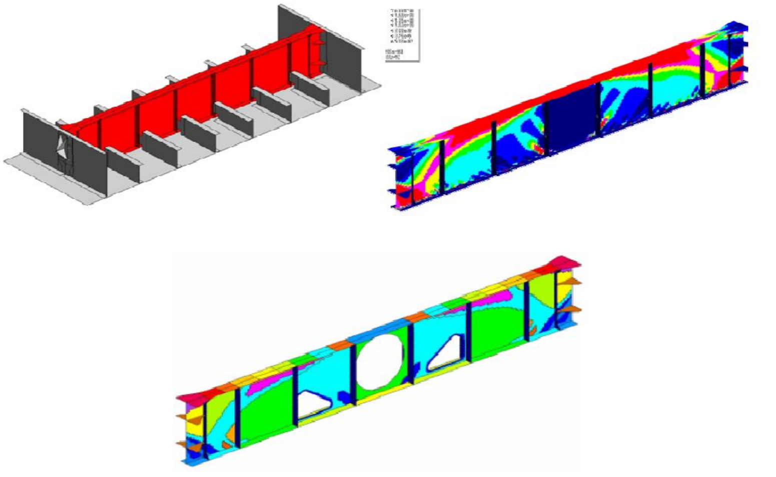

Figure 2: Free-Size Optimisation of an Aircraft Rib

Size optimisation allows for pre-defined structures to be optimised by automatically changing dimensional values (e.g. plate thickness or stiffener dimensions) in the structure.

Shape optimisation is similar to size optimisation in that it varies the dimensions of structural features. However, instead of changing a dimensional value within an equation or FE model it acts to change the shape of an FE mesh used to describe a structural feature such as a radius corner on an opening.

Both size and shape optimisation can build on the structure defined by topology or free-size optimisation, or be used to refine an existing design concept that has originated from other means.

Size optimisation can be applied to both FEA and non-FEA based simulation methods as it involves setting dimensional values as variables. Topology, free-size and shape optimisation are FEA dependant methods as they rely on structural package spaces being discretely divided up with finite elements.

Although optimisation methods can be used at any stage in a design process their application early on in the design process results in a more efficient distribution of material and load. This has the knock on effect of minimising stress concentrations, which is one of the main causes of remedial work later on in the design process.

## 3.0 Existing Alternatives to the Traditional Design Process

Currently the only alternative to the traditional design process that is known to exist in the ship building industry, that also makes use of optimisation and structural simulation technology, is one that focuses on the ‘fine tuning’ of pre-conceived structural arrangements. The ‘fine tuning’ is akin to the size optimisation technology stated previously, where, for example, the plate thickness and stiffener dimensions are changed in order to reduce mass and fabrication cost whilst meeting design constraints. MAESTRO is an example of a tool that promotes this alternative approach to the traditional design process.

Although the existing applications can be extremely powerful design tools they are unable to address the following key questions:

- What should the starting structural layout be to achieve an optimum solution?
- What is the optimum shape of structural features?

A simple example would be that of an opening in a bulkhead: the surrounding plate thickness can be finetuned to achieve an ‘optimum’ solution, but what if the true optimum involves moving the opening a couple of metres from its current position or changing the corner radii of the opening? Solving this problem requires more than just size optimisation.

The simulation driven design process as described in Section 2 addresses the above questions in the following manner:

- Firstly a design optimisation stage is introduced before the ‘fine tuning’ stage that makes use of the ‘free form’ optimisation technology (topology and free-size) to determine optimum structural layout.
- Secondly a shape optimisation process is introduced that can be used in parallel with size optimisation to provide maximum flexibility in ‘fine tuning’ the design.

## 4.0 Current Industry Applications

For many years simulation driven design has been successfully applied in the aerospace and automotive industries primarily to reduce product mass in order to improve product efficiency. This need to reduce mass has been driven by increasingly stringent governmental environmental legislation and customer demand.

Within the aerospace industry Airbus has been a high profile adopter of simulation driven design, adopting the process as early as 2002 [8] for design work on wing ribs for the A380. The company has continued to increase its use of the process over the years and now has an optimisation centre dedicated to applying the process to the design of all structural components.

Within the automotive industry Jaguar Land Rover have been keen adopters of optimisation technology in the design of vehicle components, extending the technology to account for design robustness to ensure a robust optimum solution [9]. The fast growing car industry in China has also recognised the benefits with SAIC having adopted the process for the development of their current vehicle range [10].

Within the aforementioned companies simulation driven design has been introduced into the design process through the use of the following software tools: Altair Optistruct [6] for free form, size and shape optimisation and Altair HyperStudy [7] for FEA solver independent optimisation and optimisation involving robustness.

Within the ship building industry the demands for design improvement are less clear cut and the problems that need to be solved require a more complicated solution than simply saving mass. Within this industry cost is the primary driver and it is the raw material and fabrication cost where there is significant room for improvement.

Simulation driven design can help to reduce raw material cost by enabling lighter more efficient structures and can also reduce fabrication cost by reducing structural complexity through making more efficient use of the ship structure and minimising the need for remedial work late on in the design process.

It can also help reduce engineering design costs through minimising the number of design cycles and helping to eliminate the need for costly, late design changes that may have resulted from ill-informed design decisions early on.

## 5.0 Application to the QEC Aircraft Carrier

The UK's QE Class Aircraft Carriers are being produced and delivered by the Aircraft Carrier Alliance (ACA), in one of the largest engineering projects currently being undertaken in the UK. The ACA is an innovative partnering arrangement between BAE Systems, Thales UK, Babcock and the Ministry of Defence.

The above track-record of the use of simulation driven design provided the ACA with the confidence to fund a pilot exercise on a section of structure of the vessel, during which time Altair engineers had the opportunity to familiarise themselves with the principles of steel ship design.

The main driver for exploring the capabilities of this technology was the lack of background data in the UK on naval vessels of this size (i.e. lack of pre-formed ideas of what structural solutions should look like) and the sheer number and complexity of load cases, which together made intuitive design decisions difficult to make.

The following sections detail examples of how simulation driven design has been use on the QEC Aircraft Carrier.

### 5.1 Double Bottom Structural Arrangement

The double bottom structure of the ship is required to support significant loads from external hydrostatic pressures and dynamic loads induced by large equipment items that reside on the double bottom.

As part of the QEC project's "Confined Space Access and Escape Arrangements Policy" there was a requirement to route access openings through the floors in the double bottom. In order to identify the optimum locations for these openings, topology optimisation was employed to identify areas of redundant structure that could accept access openings without compromising structural performance.

Figure 3 below illustrates an example topology optimisation result for a double bottom floor along with a conservative design interpretation of the topology result.

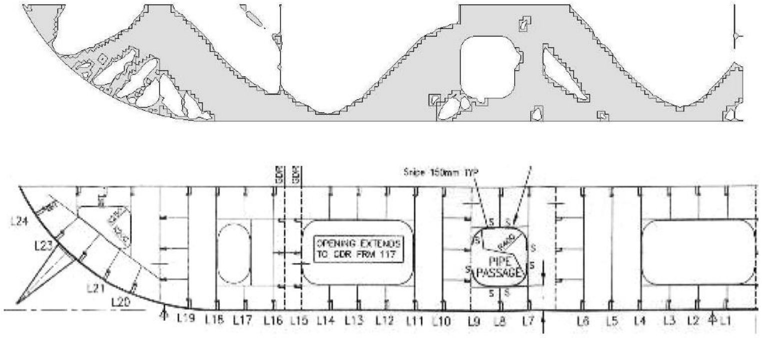

**Figure 3: Topology Optimisation and Resulting Design Interpretation for a Typical Double Bottom Floor**

Following the interpretation of the topology optimisation, size and shape optimisation was employed to fine tune the shape of the openings so as to improve the stress response of the structure.

In addition to aiding in the placement of openings the topology optimisation acted to minimise the steelwork mass required to meet the design targets. The final proposed design was 9% lighter than the baseline design (despite a conservative interpretation of the topology results) and met all design targets, while the baseline design failed to meet the stress targets. This combination of meeting project policy needs in terms of access openings and reducing mass was a ‘win-win’ solution for the project as at the time there was also a drive to reduce overall steel mass.

### 5.2 Flight Control Module

The QEC flight control (FLYCO) module is located on the aft island and is home to the equipment and personnel that assist in the control of aircraft operations (see Figure 4). The FLYCO structure comprises a large glazed area supported between an upper and lower sponson structure. These sponson structures are required to meet natural frequency and deflection targets and are therefore subject to the interactions of mass and stiffness.

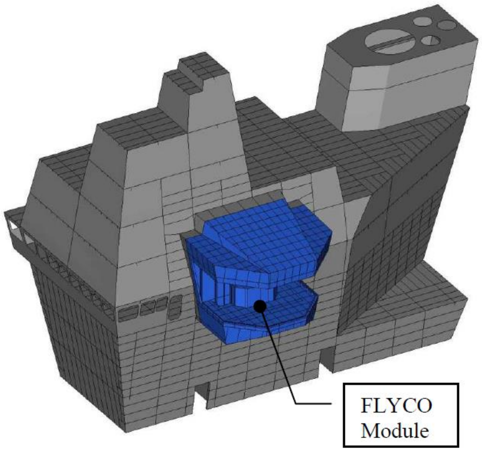

**Figure 4: Aft Island with FLYCO Module**

In order to satisfy the design requirements simulation driven design was employed to achieve a ‘right first time’ solution to the internal structural arrangement of the FLYCO module. Topology optimisation was first employed to identify the optimum global positioning of stiffening webs within the package envelope of the module. This was then followed by a further round of topology optimisation to identify the optimum load paths within those webs, such that openings could be cut without compromising structural performance (Figure 5).

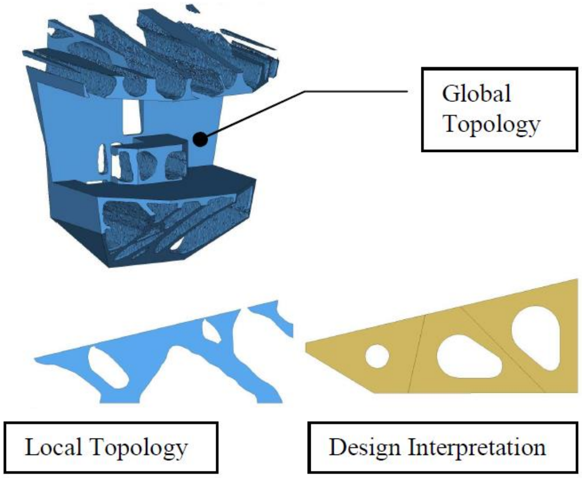

**Figure 5: Global and Local Topology Optimisation Results**

Finally, size and shape optimisation was employed to fine-tune the plate thicknesses and opening sizes to minimise mass and design complexity whilst meeting design targets.

The outcome was a structure that met the natural frequency, deflection, stress and buckling targets whilst being 16% lighter than a traditional design and using less piece-parts, resulting in reduced fabrication cost.

### 5.3 Stern Platform

The QEC stern platform is a cantilevered structure subject to significant slamming loads and therefore needs to be integrated into the main ship structure in such a way as to minimise stress concentrations and the risk of buckling (Figure 6).

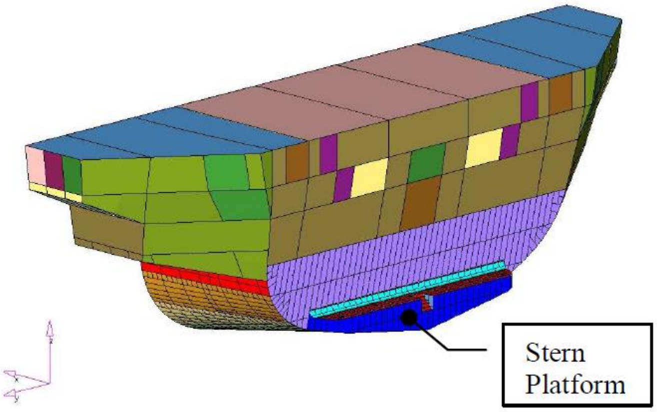

**Figure 6: FE Model of QEC Aft End Incorporating the Stern Platform**

The ACA conceived three design solutions (Figure 7) involving the use of insert plates and wanted to identify the solution that would result in the thinnest and least number of inserts. Ordinarily such a task would require a large number of trial and error analyses, with no guarantee of achieving an optimal solution.

FE models of the three concepts were created followed by size and shape optimisation of the various piece parts that formed the different solutions. The process enabled rapid identification of the solution that resulted in both the minimum number of inserts and the minimum insert thickness.

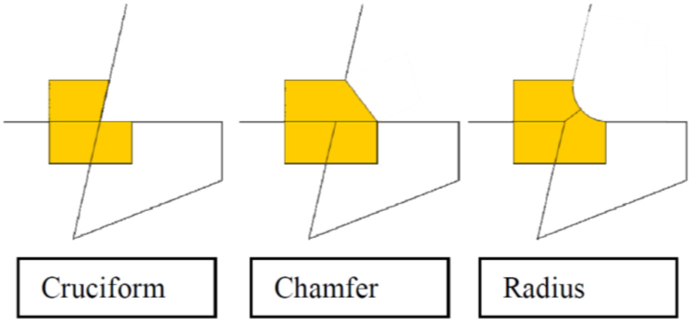

**Figure 7: Three Proposed Design Solutions**

The results of the optimisation are detailed in Table 1.

| Design variant | % Reduction in peak stress compared to 'cruciform' | Maximum Insert Thickness (mm) | Minimum Number of Inserts |
|---|---|---|---|
| 'Cruciform' | - | 45 | 43 |
| 'Chamfer' | 13% | 58 | 37 |
| 'Radius' | 26% | 31 | 36 |

**Table 1: Stern Platform Optimisation Study Results**

As indicated in Table 1 the 'radius' design proved the best solution, exhibiting peak stresses 26% less than the 'cruciform' design and having the least number of inserts and the thinnest inserts.

Reducing the number of piece parts and mass of material required has resulted in a design that is less costly to manufacture through the savings made in raw material and fabrication cost.

## 5.4 Transverse Bulkheads

The transverse bulkheads (known as 'bents') that run between the flight deck and 2 deck above the 30m wide hangar bay are subject to high stresses under ship racking loads. The problem is compounded by the need for multiple, large access openings through the bulkheads. Figure 8 below illustrates an exaggerated FEA deflection plot result of a typical 'bent' under racking loads, showing the multiple openings. The large hangar space can be clearly seen in the middle of the plot.

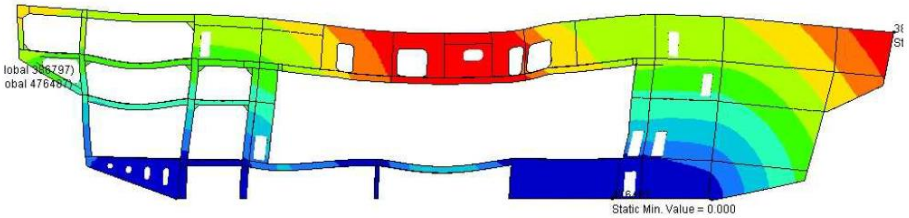

Figure 8: Typical Racking Load Deflection Plot

Given that simulation driven design was not employed from the outset for these structures, it was found that multiple stress concentration issues arose in way of openings and structural discontinuities that required a rapid solution.

In order to rapidly identify what size and shape of door opening or plate insert to employ across the bulkheads simulation driven design was used in the form of structural size and shape optimisation on FE models of the bulkheads. For a given bulkhead, multiple stress concentration issues could be solved simultaneously enabling the interactions between the different stress concentrations to be accounted for. This approach resulted in all the stress concentration issues being solved with the minimum possible insert plate thickness.

For the example shown in Figure 8, eight stress concentration issues were identified following an FE analysis of the structure. These eight issues were then simultaneously solved using a single optimisation run that involved changing plate thicknesses and corner radii in order to reduce stresses to acceptable levels. The optimisation took six iterations to converge on a solution and ran in approximately 20 minutes on a desktop PC.

This example illustrates how simulation driven design can be used to rapidly solve problems late on in the design process. At the stage in the design programme when the analysis was undertaken, the access openings were fixed in location and the general arrangement had developed without optimisation of the opening locations.

A great deal of work took place in the early stages to prove the feasibility of placing access openings in these highly loaded structures. However, had a simulation driven design approach been used earlier then perhaps an alternative solution would have been revealed that would have resulted in less detailed design work having to be undertaken to achieve and acceptable design.

Very often the general arrangement development progresses with inadequate input of structural considerations and without quantifying the cost and complexity of having to live with those decisions, which only emerge later in detailed design.

## 6.0 Proposed Future Applications

BAE Systems are planning to embark, with Altair Engineering and a University team, on a 3 year research project to identify how best the simulation driven design process can be applied to whole ship design starting at the concept phase and running through to the detailed design phase.

The previous examples have illustrated that simulation driven design has merit in solving local structural design problems. One objective of the future work will be to demonstrate that the same processes can be applied to whole ship design.

The first task will be to firmly establish the capabilities and tools that are currently in use such that they can be included in any simulation driven design process. The focus here will be to ensure that the product of previous research work is not unnecessarily repeated.

The follow-on task will be to look at toolset integration, in particular how rule-based design tools can be interfaced with optimisation software, FEA, CAD, CFD, cost models and shipyard operational enablers and constraints. Including all these factors will enable all relevant variables to be included and all stakeholders to have a sense of input to the design process and ownership of the resulting solutions. This will all help contribute to ‘right first time’ design decisions and provide an auditable log of all design parameters and constraints.

It is envisaged that topology and free size optimisation could be used in conjunction with whole ship FE models to conduct trade-off studies at the concept phase to identify optimum positioning of bulkheads and primary structure. In parallel, size and shape optimisation could be wrapped around rules based hand calculations in order to identify optimum rules based structures.

The application of such technology starting early on in the design process is reliant on whole ship FE models being built quickly and efficiently. Advanced FE model pre-processing tools such as Altair HyperMesh [11] facilitate this. These tools can also be made to integrate with ship concept structural definition tools in order to make the building of whole ship FE models a highly automated and therefore fast process.

Introducing simulation driven design into the design process is not aimed at replacing the experience of naval architects but to complement that experience. The process aims to provide naval architects at the concept phase with as much information as possible to enable them to make more informed design decisions at a crucial time.

## 7.0 Conclusions

Within this paper the shortcomings and problems associated with the traditional ship structural design process have been highlighted. In addition this paper has outlined the concept of simulation driven design and the technology that underpins that process.

The paper has demonstrated by example and through discussion how the technology can provide benefits to ship structural design and manufacture in terms of design and fabrication cost reduction, mass reduction and improved structural performance and efficiency.

It is recognised that the tools and techniques still require significant development in order to be successfully applied to whole naval ship design due to the considerable size of design space involved and further research work is planned to facilitate this.

Overall the benefits of simulation driven design to the naval marine industry can be summarised as follows:

- Reduced structural weight, by minimising redundant material
- Reduced cost per tonne of fabricated steel, by minimising the need for complex local solutions to address stress concentrations and discontinuities (i.e. inserts, brackets and tapered sections)
- Reduced risk of through-life problems such as fatigue cracking through developing simpler structures with fewer ‘complicating features’
- Reduced analysis effort in the detailed design phase as a result of there being fewer emergent problems that have to be solved in order to make the design work in practice
- Improved ability to cope with increasingly complex and sometimes conflicting design requirements that may continue to evolve during the early life of a project

It is the authors’ belief that simulation driven design using the approach described, with its logical, automated ‘explore all design options’ capability represents the future of naval ship design in the UK. It should be noted however that it is not intended to replace experienced naval architects but instead provide them with the tools and freedom to make more informed design decisions at the critical concept phase of a project. It is also recognised that in order for it to be adopted a move away from traditional or established design approaches is required and a greater degree of structural modelling undertaken in the early design stages. This means the deployment of more design resources in the early project stages, demanding a funding commitment that needs to be recognised and acknowledged by projects as a worthwhile up-front investment.

## 8.0 Acknowledgements

The support of Thales Naval UK Ltd., an ACA Industrial Partner, is acknowledged for recognising the potential benefits of and supporting the simulation driven design approach to the QEC Aircraft Carrier. TEX ATC Ltd. is acknowledged for supporting the use of the process for the structural development of the FLYCO module, for which they are responsible.

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## 10.0 Author’s Biographies

**Alan Dodkins** has 30 years experience in naval ship structural design in the marine industry and is employed by BAE Systems Maritime (UK). He is currently seconded to Thales Naval UK Ltd. where he has the role of Delegated Design Authority for Hull Structure on the QEC Aircraft Carrier Programme, a position he has held for the past 7 years. Prior to this he was Structures Engineering Manager for the Type 45 Destroyer and has worked on a number of design and build naval ship programmes as well as R&T projects, in steel, aluminium and FRP materials.

**Tom Goodwin** holds the current position of Product Design Team Manager at Altair Product Design. He is responsible for the delivery of FEA based structural design projects across a broad range of industries with specific emphasis on simulation driven design and the marine industry. He has worked on the QEC Aircraft Carrier project for the last 6 years as both an FE analyst and FEA project manager.