ABSTRACT

A well-founded determination of steel structure scantlings is essential during the early design process of a ship or an ocean structure. In the first 4 up to 6 weeks of a new building project, the major part of the final building costs has to be fixed. Amongst others a proper steel weight estimation is crucial. The weight depends on the structural dimensions which are determined mostly by experience and rarely by direct calculations. Therefore, a simple direct strength calculation tool has been integrated in a ship design software. The tool uses structural and general ship design information. Besides the structural constraints, posed by the project design, the steel designer has to fulfill also the structural constraints posed by the classification societies. Normally they are checked with software solutions provided by the societies. However these software tools are not well adapted to the early design process as various design parameters change frequently. For this purpose a link has been created between a rule scantling tool on one side and a design software on the other. The link allows an automated exchange of steel scantlings and project information. By this the modeling and design work as well as the structure scantling and steel weight determination is performed in the design software tool, while the rule scantling tool is only used for a quick assessment of class conformity. With the help of the mentioned methods, the structure can be pre-dimensioned directly based on the early design model in accordance with the classification rules. Furthermore the steel dimensions can not only be optimized with regard to local and global loads, but also with regard to design boundary conditions. In consequence the early steel design process is improved by a more accurate steel scantlings determination and results in a better optimized steel structure as well as severely reduced time spent on the steel iterations.

KEYWORDS:

Early Steel Design, beam grillage, finite beam element, interface, XML handling

1. INTRODUCTION

1.1. Shipbuilding Environment in Europe

For several decades the European shipbuilding industry is under fierce competition of Asian shipbuilders. Substantially higher labor costs, combined with a difficult funding environment, forced the European shipyards to focus on new and competitive products. They specialized on the building of innovative and technically sophisticated designs, such as RoRo - vessels, cruise vessels, ferries, offshore vessels, naval vessels and mega yachts. Those types of vessels are often custom-made. Consequently the achievable cost savings in the engineering and production process are marginal, compared to the serial production.

The wide influence of a serial production on the costs is shown e.g. by Krüger / FSG [1] in 2003. Fig. 1 out of this paper shows the relation between the cost level and time. The diagram was developed based on cost calculations for a series of 6 RoRo vessels. Within the first 4 weeks of the project nearly 70% of the final costs have already been fixed while only small costs have been generated in this early stage. This illustrates another important aspect that can be extracted from this diagram. Technical decisions, made early in the design process have a strong influence on the final project cost. Errors made during this phase, lead to expensive corrections or extra work in the subsequent project stages. Therefore, the improvement of the early design process offers a large potential for savings.
1.2. Software Framework E4

It is the aim of this paper to describe methods which have the potential to enhance and streamline the early steel design process by reducing engineering man-hours and shortening the design time. The methods are implemented in the ship design method database E4 to extend and improve its early steel design capabilities. E4 is a ship design software which is used and developed further at Hamburg University of Technology. The initial idea behind the development of the software has been executed in 1994 by e.g. Bühr and Krüger [2]. E4 provides the ship designer with various calculation methods concerning main dimension determination, hull form development, main frame steel description, light ship and loading condition determination as well as maneuvering and sea keeping simulations to allow a holistic, overall ship design. The features of the software are comparable to those of commercial initial design tools such as NAPA or AVEVA Initial Design. One basic principle of the tool is that each design method works with data out of a common database. Thereby a consistent and up to date overall ship design is assured.

The first improvement presented in this paper is the integration of simple direct strength calculation capabilities. The second improvement is the implementation of a link to a rule scantling tool.

1.3. Motivation for Strength Calculation During Design

Until now the lack of strength calculation possibilities in E4 forces the steel designer to use external tools for each calculation. This implies an extra effort for modelling, performing the intended calculation and reworking the steel design model according to the results.

By implementing strength calculation possibilities in the design software, all problems related to data handling, model reworking and interfacing are omitted. In a next step it is also possible to automate the modelling work for common applications, to integrate optimization methods and generally to implement new, problem-specific methods.

As stated in chapter 1.1, the focus in this paper is on fast, easy and rough approaches during the early design process. The considered steel structures are global parts of the ship steel structure. The detailed steel design is performed later in the design. To perform rough strength calculations of decks, bulkheads and other global parts it is adequate to apply simple beam theory or beam grillage calculations. These methods are easy to use and very fast. So they can be integrated well in the early steel design process to optimize the overall early ship design.

1.4. Motivation for an Interface to the Rule Scantling Tools

Usually the design information is transferred by paper or digital drawing between the designer and the classification societies. The time spent on the design, the transfer and the review process can be significantly reduced with new efficient mechanisms for sharing and exchanging the design model. The organizations normally involved in this process - the classification society on one side and the designer on the other side – rarely use the same software tools. Therefore some kind of data exchange is necessary. For this several approaches have been pursued in the past, e.g. Polini [3]. Despite many efforts and attempts the shipbuilding industry has not agreed on a common data exchange format yet. In consequence most software tools provide the user with “point-to-point” solution in the form of exchange and interfacing possibilities to the necessary external tools. Such an interface between the cross-section description in E4 and a rule scantling tool of any class is not available yet. Most classification societies provide the designer with software tools such as Poseidon, NauticusHull (DNV GL both), VeriSTAR (BV) or SafeHull (ABS) to assess the structure according to the classification rules.

Without interfacing capabilities the designer has to transfer information and keep two models manually consistent. This time consuming and error prone work is undesirable and should be avoided.

Furthermore a reliable interface allows the designer to use the rule scantling software for the design. If it is possible to transfer a cross-section version from the design software to the classification software and determine the steel scantlings according to the classification rules within a short time, the designer can easily try multiple cross-section. In consequence this helps to achieve better optimized and up-to-date steel scantlings.

Therefore a simplified data exchange with the classification societies and the possibility to use such external software during the design are the motivations for developing an interface between E4 and rule checking software solutions of the classes. Here the first step was the development of an
interface to Nauticus Hull from DNV. In further steps the integrating of other classes is very worthwhile.

2. THEORETICAL BACKGROUND

2.1. The Challenges in Early Design

The early ship design phase which takes 4-6 weeks at maximum is the time between project inquiry and contract signing. Due to this short time the feasible calculations and estimations are limited and have to assure a functional ship design nevertheless. In consequence extensive, detailed and therefore time consuming investigations are usually not possible. This gap between the limited time and the wish to achieve as detailed results as possible is the main conflict which arises during early design.

So the constant improvement of the used design methods and processes for the early design is fundamental. On one hand existing methods can be enhanced, on the other hand the increased computing power of modern PCs allows the integration of new and more computationally intensive methods.

2.2. The Early Steel Design Workflow

A new ship design is usually generated in an iterative process where each single design step depends on previous steps and has to be performed multiple times. This common problem in technical design can be illustrated well by a design spiral. A ship steel design spiral feasible with the design software E4, as a part of the overall design spiral, is shown in Fig. 2.

In the diagram a simplified workflow from the inquiry to the contract signing is shown. It is indicated where the design software with a common database can be used and where selected external tools are needed.

Inquiry

New ship design projects normally begin with the inquiry of a customer and pass through the early design process until a building contract is signed in the ideal case. A design is based on currently available information at project start, which can be amongst others

1. A general arrangement plan
2. A vessel of comparison
3. An outline specification

The subsequent task for the ship designer is to develop a functional ship design based on this data and to produce all necessary information and design parameters for a successful contract signing.

Early Steel Design Spiral

In the ship design amongst others the main dimensions, the hull form, the hydrostatics, the propulsion and the loading conditions are determined. The steel design relies seamlessly on the ship design and contains e.g. the following tasks:

1. The steel scantlings of the main frame are developed using the experience from previous designs and/or the respective steel design tools provided by the classification societies (see chapter 1.4)
2. The longitudinal strength of the global ship hull girder is checked against the global loads in still water and waves for critical cross-sections using the classification tools as well.
3. The further ship structure including decks, bulkheads and other main structural components is determined by experience, by manual calculation or if applicable by using external beam calculation and beam grillage calculation tools.
4. The unsupported lengths between the main steel members and hence the frame spacing in longitudinal and transversal direction have a strong influence on the steel scantlings. The frame spacing which is determined mainly by the ship design is checked, optimized and changed where necessary.
5. The bigger part of the light ship weight is the steel weight of the ship hull which has to be estimated by using the experience from previous designs and by summarizing and extrapolating the weights derived in 1. and 3.
6. Based on all estimated and calculated information the material and production costs can be obtained.

Basic Design Model & Contract Signing

Finally the results of the early design process are a functional basic design model, the core design parameters and the main parts of the production and material costs. The described process relies on a constant and efficient data exchange between ship design, steel design and the utilized external tools to achieve a proper and good overall design.

A drawback of the described workflow is the need of external tools. Here often a double data management, modeling
and a manual or automatic exchange possibility are necessary. This leads to the usual interface problems, the error-proneness and time consuming utilization mentioned already in chapter 1.3 and 1.4. With the two methods integrated in the workflow and described in the following, the dependency on external tools is to be reduced.

2.3. The Strength Calculation Method

To solve most of the structural problems during the early steel design, the use of simple beam calculations is suitable. Calculations based on the beam theory usually are fast, easy to operate and the necessary modelling can be automated quickly. To allow such calculations a simple beam grillage solver is developed and implemented in the design software. Subsequent steel design methods are developed, which are using the solver to calculate and optimize the steel structure for several common application fields during the early steel design.

The implemented beam grillage solver is programmed in FORTRAN. The theoretical background for the solver is extracted from the explanations of Fricke [4], Hughes [5] and Klein [6]. Actual and planed methods which are using the solver are presented in chapter 3.1.

Used Element Type

The beam grillage in the new implemented solver consists of simple finite beam elements (see Fig. 3). The start node i and the end node j of the element have 3 degrees of freedom each. Namely there are the rotations around its local x and y axis as well as the displacement in the direction of the local z axis. As element properties the elastic modulus E, the modulus of shear G, the moment of inertia around the y-axis $I_y$, the torsional moment of inertia $I_T$ and the element length l are needed.

Stiffness Matrix

In finite element analysis the task is always to calculate the deformations and rotations at the nodes. In the simplest case this leads to solution of the linear equation system (1):

$$P = K \cdot u$$  \hspace{1cm} (1)

$P_k$ is the global load vector, $K$ is the global stiffness matrix and $u_k$ is the global deformation vector. Since each node of the implemented beam element has 3 degrees of freedom, 3 equations have to be solved for each node. For a single beam element this leads to the following equation system (2) which has to be solved:

$$\begin{bmatrix}
P_{xk} \\
M_{y,k} \\
M_{z,k} \\
P_{k} \\
M_{y,k} \\
M_{z,k}
\end{bmatrix} =
\begin{bmatrix}
12K_y & 6K_y l & -12K_y & 0 & 0 & -6K_y l \\
6K_y l & 4K_y l^2 & 6K_y l & -K_T & 0 & 0 \\
-12K_y & 6K_y l & 12K_y & 0 & 6K_y l & -6K_y l \\
0 & 6K_y l & 0 & 2K_T & 0 & 0 \\
0 & -K_T & 0 & 0 & 4K_y l^2 & 2K_T \\
0 & 0 & 6K_y l & 0 & 0 & 4K_y l^2
\end{bmatrix}
\begin{bmatrix}
\psi_{xx} \\
\varphi_{xx} \\
\psi_{yy} \\
\varphi_{yy} \\
\psi_{zz} \\
\varphi_{zz}
\end{bmatrix}$$

(2)

With the choice of this “element stiffness matrix” the deformation due to shear is neglected and the axial stiffness, which is independent from the bending deformation, is excluded. The global stiffness matrix K in global coordinate system is assembled based on correctly overlaid element matrices considering the different local coordinate systems of the element matrices.

Basis Function

The underlying basis function to describe the deformation of the beam element is shown in equation (3). The deformation at the normalized coordinate $\xi = \frac{x}{l}$ is given as a function of the node displacements and rotations. Again only the influence of the bending deformation but not the deformation due to shear is included. The torsional deformation is considered independent from the bending deformation.

$$w(\xi) = \frac{1 - 3\xi^2 + 2\xi^3}{(3\xi^2 - 2\xi^3)} w_{xi} + \frac{(-\xi + 2\xi^2 - \xi^3)}{(3\xi^2 - 2\xi^3)} w_{xj} + \frac{\xi^2 - \xi^3}{(3\xi^2 - 2\xi^3)} l \cdot \varphi_{yi} + \frac{\xi^2 - \xi}{(3\xi^2 - 2\xi^3)} l \cdot \varphi_{yj}$$

(3)

Loads

On the modelled structure several different loads can be applied. It is possible to apply loads on the nodes directly or as single loads as well as constant and linear line loads on the element. The influence of single and line loads is relocated to the nodes by considering equivalent node loads. The three degrees of freedom at each single node can be blocked to achieve all necessary boundary condition. A continuous beam with applied loads is shown exemplary in Fig. 4.
After the calculation the node displacements, the rotations and the reaction forces in the beam mountings can be calculated with the help of the boundary conditions. Subsequently the respective bending line, bending moment and shear force can be determined. The resulting bending line and distributions for the beam example in Fig. 4 are shown in Fig. 5

The steel structures used in shipbuilding contain often large party of stiffed panels. To calculate such structures with the beam grillage tool, the necessary input values such as cross-section area or the moments of inertia have to be derived from the stiffed panel according to Fig. 6.

Here the influence of the smaller stiffeners is considered by a higher plate thickness. The effective breadth of the plate is determined according to the GL [7]. The class guideline is a simplification of a method according to Petershagen [8], where the effective breadth is treated correctly as a function of the moment distribution. This theory could be utilized for more detailed investigations.

2.4. The Interface to the Rule Scantling Software Nauticus Hull

Data Handling

Programming an interface always begins with a discussion about the data handling and the complexity of the intended data exchange. The main question is which data exactly and in which format has to be transferred between two software tools?

Objectives for the Interface

In the case of the interface between E4 and Nauticus Hull the discussion leads to the tasks derived in the following:

1. Transfer cross-section data between the two programs and determine rule conform scantlings

Since Nauticus Hull includes only some limited possibilities of modeling transversal steel members, only the longitudinal members of the steel structure are to be transferred between the two programs.

In addition to the information about the longitudinal steel members in the form of cross-sections, a couple of main dimensions as well as the frame table to perform a rule scantling check are needed. This leads to two additional objectives:

2. Transfer the main dimensions
3. Transfer the frame table

With this information given the intended rule scantling check is possible. The steel scantlings can be dimensioned in accordance to the classification rules from DNV. After dimensioning, the interface has to identify the changes made, to modify the respective steel data and to transfer it back. Therefore another task is:

4. Transfer back the dimensioned steel scantlings to the design software

As mentioned in chapter 1.4 it is crucial to avoid errors while transferring data and to save time using the interface. On that account the modeling and adjusting work – and therefore the time spent – in both programs has to be minimized. Otherwise interfaces are not applied by the users. Hence the last task is:

5. Minimize the modeling work as well as the setting of rule and calculation parameters
**Choice of Interface Format**

The usual way an interface works is through a common exchange file. Often such files are ASCII based and therefore readable and editable. The data structure in an exchange file is in most cases defined by the party who programs the interface or in the best case by all parties using the interface.

Nauticus Hull provides only the exchange file format 2dl for interfacing purpose. The structure of the data in the file is exactly defined and documented. But the file only handles the cross-section data. The transfer of main dimensions, program parameters or the frame table is not possible. With regard to the aforementioned interface tasks the data exchange exclusively based on the 2dl format is not adequate.

The rule scantling software stores all ship information including main dimensions, frame table and cross-section data as well as the program settings in readable and editable XML files. The obvious possibility to use those files to perform the exchange of all relevant data led to the following problems to solve:

1. The XML files are not documented
2. The XML files contain large parts of unnecessary data
3. The XML is not an intended exchange format and therefore e.g. the file data structure of the file containing the cross-section data is not fixed from DNV side
4. The possibility to search, read, store, change and write efficiently the files without destroying the XML structure is not implemented in the design software

To compensate the missing documentation and identify the position where and the moment when the information is stored, two file versions have to be compared before and after each performed program step in Nauticus Hull.

The provision of the unnecessary data is avoided by using a default file and only adding and changing data where necessary.

The cross-section data is transferred initially with a 2dl file. As soon as the data structure in the XML file containing the cross-section data is final, the use of the 2dl file will be replaced by the XML file. By this the multiple re-programming of the interface after each XML change is avoided.

Finally a proper XML file handling is implemented while programming the interface.

**The XML Handling**

A proper handling of the XML files while deleting, changing and adding data is essential. The correct handling has to be ensured to work in either case. If the interface produces XML files with an illegal structure or changed content, the consequences may be serious. Therefore, this part shortly describes how XML files are handled in the design software.

Initially each file is read into the memory and the content is stored in a large one-dimensional character array. (See example in Fig. 7)

```
<xml version="1.0" encoding="UTF-8" standalone="yes">
<shiplist>
  <Entry Shiptype="Container">
    <Name>Frl Mayer</Name>
    <Length>100</Length>
    <Breadth>12</Breadth>
    < IMO Numb>1234567</ IMO Numb>
    <Flag>Germany</Flag>
    < Homeport>Hamburg</Homeport>
  </Entry>
</shiplist>
```

**FIG. 7 - XML FILE IN CHARACTER ARRAY**

The content is analyzed and the xml structure is stored into another one-dimensional structure array. (See Fig. 8)

```
Example = "<Name>Frl Mayer</Name>
level = 4
character_array = [4,98,101,103,111,...]
stored_position_numbers = [99,101,111]
```

**FIG. 8 - STRUCTURE ARRAY PREPARATION**

Each tag and attribute in the XML file gets the following information in this array.

- Level of the tag below the first parent
- Position in character array of the leftmost character of the tag name
- Position in character array of the rightmost character of the tag name
- Position in character array of the leftmost character of the tag content
- Position in character array of the rightmost character of the tag content

In the e.g. in Fig. 8 the tag `<Name>Frl Mayer</Name>` has the structure array “address” (4 98 101 103 111). With the help of this “address” the character array may be searched, modified and sorted very efficiently without checking each single character for each operation. In the same time a valid XML structure is assured.
3. ACHIEVED IMPROVEMENTS

With the use of the two new implemented early design methods described in chapter 2.3 and chapter 2.4 the use of external tools during the early design can be reduced significantly according to Fig. 2. The use of external “strength calculation tools” is not necessary anymore since such calculations are possible in the design software now. The use of “rule scantling tools” is improved by the implementation of an interface to one selected tool. Where exactly and how the new methods can be used is described in the following.

3.1. Resulting Calculation Method

With the help of the new grillage solver and direct calculation method the steel designer can model, load and calculate beam and grillage structures. In addition new methods are and will be developed to minimize or omit the necessary modelling work and improve the optimization capabilities.

Deck Optimization Method

Ship deck structures with large unsupported lengths have relatively high and therefore heavy longitudinal and transversal girders to absorb the applied loads. A typical ship type with such large and heavy deck structures is a RoRo vessel for the transport of rolling cargo. Here the optimization of the deck structure offers high potential savings.

Based on the deckloads and the loads applied by the global ship hull girder bending, the deck structure can be optimized regarding to steel weight, rigidity or elastic deflection. The variables in this optimization are the dimensions of the longitudinal and transversal deck grillage main members as well as the respective spacings in between.

Starting with at least one cross-section of the RoRo vessel a 3D cargo space model is extrapolated. Subsequent a beam grillage can be derived from the model for each intended deck to optimize. (see Fig. 9)

The beam grillage is loaded with typical stresses for a RoRo deck. Those are axle loads for trailers, trucks, cars or fork lifters according to the classification societies (e.g. GL [9]) and with respect of the rolling cargo specified by the customer. The resulting bending moment distribution is shown in Fig. 10 and the resulting shear force distribution is shown in Fig. 11.

![FIG. 10 - BENDING MOMENT DISTRIBUTION](image1)

![FIG. 11 - SHEAR FORCE DISTRIBUTION](image2)

The dimensions and spacing of the resulting beam grillage are then varied to find an optimum. The intended optimum goal can be defined by the user.

Benefit From the Deck Optimization

On one hand the efficiency, the weight or the dimensions of the deck structure can be optimized. For example it could be the aim to minimize the girder height of the main deck grillage members. By this the height of the deck above baseline can be lowered and the steel structure above this deck is lowered at the same time as shown in Fig. 12. By this, the center of gravity of the ship is reduced respectively. Another aim could be the inverse case where the ship is not critical to stability and the deck girder height is increased while the overall deck weight is reduced.
On the other hand a ship designer can use the parameters achieved in the rough and fast deck optimization for the stability determination within the global design. In the case of a RoRo vessel the girder height and thereby the height of the main garage deck over baseline has a direct and occasionally drastic influence on the damage stability calculation according to SOLAS and the freeboard deck determination according to ILLC. Both calculations are usually performed very early in the design where detailed steel structural information is not available. The direct calculation method gives the designer the necessary tool to treat such questions.

**Method Validation**

The resulting node deformations and rotations as well as the bending line, bending moment and shear force distribution is validated with the program SEBBES [10]. This is a software tool for the analysis of girder grids which is developed by the ISD (Institut für Statik und Dynamik) of the Leibnitz University of Hannover, Germany.

**3.2. Resulting Interface**

Based on the objectives and data handling concepts derived in chapter 2.4 an efficient interface between E4 and Nauticus Hull is developed.

**Data Transfer Between the Tools**

The following ship and steel design information can be exported from E4 to Nauticus Hull at this time:

- The hull form as DXF file
- The frame table
- The main dimensions

- The cross-section steel data at selected frames including all longitudinal members of the steel structure
- The dimensions, the material and also the necessary rule information (position ID & girder ID) of each longitudinal steel member
- General vessel information such as the rule version in effect, the freeboard type, identification data and other settings Nauticus Hull needs for a rule scantling check

In the opposite direction from Nauticus Hull to E4 only the steel scantlings can be imported. This is suitable since all modeling and settings work is to be done in E4 (chapter 2.4 - objective no. 5), while the rule scantling tool is to be used as a rule checking module. Therefore all changes in steel geometry are to be made in the design software. Subsequent the steel scantlings are checked with the help of the interface.

**Interface Workflow**

This leads to the interface data workflow shown in Fig. 13.
to tank pressure, cargo and wheel loads as well as the global loads due to global hull girder bending and torsion have to be applied manually. For a fast steel concept in early design, rule based default values can be chosen to define limiting values for shear force and bending moment stress on the hull girder in still water and waves.

Based on this data the cross-section steel members are determined automatically according to the classification rules. The changed dimensions of the plates, girders and stiffeners are stored in the XML files. The changed dataset containing ship and cross-section information is checked by the design tool, the existing values are compared with the changed ones and corrected where necessary.

4. CONCLUSIONS

European shipyards design technical demanding and competitive ships in a difficult international environment. This can only be successful by applying fast and accurate early ship design methods. Therefore the applied early design processes and methods have to become faster and at the same time new approaches have to be developed. For that reason ship design software has to be continuously developed further and adapted to the state of the art.

The steel design has substantial influence on the entire ship design. Numerous of variable parameters defined by the steel design are not used yet in the early design process. With the implementation of new steel design methods into ship design software, some of these parameters become easily variable and a designer is able to use them for the improvement of the overall ship design.

The two new early steel design methods presented in this paper have the potential to considerably streamline the design process derived in chapter 2.2. Looking again at the workflow chart shown in Fig. 2 it becomes apparent, that the process is improved at two points.

Firstly the use of external “strength calculation tools“ is reduced, since simple types of strength calculations are now possible with the design software E4. Therefore the time-consuming data exchange, data management and double modeling are omitted. In future the application range of the described calculation capabilities has to be extended to more different and also more complicated parts of the steel design. It is thinkable for example to implement also Shell elements in the solver to be able to model and calculate plane parts of the structure. Furthermore the development of specific structural optimization methods should be pursued.

Secondly the link to the external “Rule scantling tool“ Nauticus Hull allows a semi-automatic steel data exchange. Hereby the time-consuming and error-prone manual data exchange is avoided. The interface transfers all relevant information between the two tools and considerably facilitates the steel scantling determination according to the classification rules. With the help of the interface a rule scantling check, based on a cross-section modeled in the design software, is feasible within 5 minutes. To avoid such costly and complicated point-to-point interface solutions in the future, it is very desirable to seek for a common and widely accepted industry format for exchanging ship design data.

Finally to improve and streamline the described early design workflow, it is an aim to refine the existing design methods and to reduce further the use of external tools. Thereby a media break is avoided, time is saved, errors are prevented and a better ship design is achieved.

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