Parameter Controlled Optimization of Grillage Shaped RoRo Deck Structures

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ABSTRACT

Achieve an accurate ship design in a short time is only feasible by using powerful ship design tools. But the features of common design tools, concerning the structural design, are not satisfying today. This paper presents a new structural design method for RoRo vessels, which is integrated in a ship design tool. The method is able to dimension and optimize RoRo-deck structures by using simple beam grillage calculations. Thereby structural design aspects can be treated more effectively during the RoRo ship design process.

KEY WORDS

Design; Steel; FEM; Deck; Optimization; RoRo

INTRODUCTION

The initial design process takes place in the time between the inquiry for a new ship and the signing of the building contract. During this phase, which takes approximately 4 to 6 weeks, the aim is to achieve a proper, technically feasible and competitive design. This can only be achieved by using strong and reliable software tools, combined with a lot of experience. Due to the variety of typical problems arising during ship design, the task is performed with highly specialized ship design software. In this paper a new method implemented in such design software is presented to improve the initial ship design process. One important part of the ship design is the structural design. Critical parts of the ship structure are determined, the main frame is developed and the lightship weight as well as the ships center of gravity is estimated. For these tasks, actual ship design software tools only have limited features, which are not optimally integrated in the other methods for e.g. the hull form design and statutory stability calculations.

In consequence the structural design is performed with separate steel design and strength analysis tools. The data consistency with the ship design software must be assured manually, which is error-prone and time consuming. Due to the limited design time, strength calculations are performed only when they are absolutely necessary. Many parts of the structural design are set based on experience. Consequently, large parts of the structural design are based on empirical data and formula. Especially for these parts, the quality of the design depends only on the quality of the empirical data and on the expertise of the designing engineer. This reduces the quality of the overall ship design. By giving the designer additional and better integrated initial steel design tools, the dependency on external tools is decreased and the overall ship design is improved simultaneously.

For this purpose, a strength calculation method, capable of handling finite beam elements under various loads has been implemented in a ship design tool. This allows the dimensioning of basic ship structures integrated in the ship design environment without switching the software. Building on that, a specialized method has been developed to perform semi-automatic parameter studies for the optimization of grillage shaped decks of RoRo vessels. To realize the necessary large unsupported deck areas, such decks are usually stiffened by a grillage of high-webbed and massive longitudinal and transversal T girders. Here the optimization of the girder dimensions offers a large potential for savings. But also for other specific parts of the ship structure, for any kind of ship type, an integrated strength calculation method offers new ways of structural dimensioning and optimizing within a ship design tool during the initial design phase.

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METHODOLOGY

In the following, the theoretical background of the developed RoRo deck calculation and optimization method is described.

Software Framework E4

The method is implemented in the ship design system E4. The system contains a method database for the ship design, which is used and developed further at Hamburg University of Technology. The initial idea for the development of the software has been described in 1994 by Bühr and Krüger [1] or by in 2003 by Krüger [2]. E4 provides the designer with various calculation methods to allow a holistic, overall ship design. Methods are included concerning main dimension determination, hull form development, main frame description, light ship weight and loading condition determination as well as manoeuvring and sea keeping simulations. All methods obtain the required basic data out of a common database and store their results in it after calculation. Thereby a consistent and up-to-date overall ship design is assured at any time. The focus for all methods in E4 is on fast and accurate calculations as well as on empirical data and rough approaches where suitable. The features of the software match those of commercial initial design tools such as NAPA or AVEVA Initial Design.

Until now the lack of strength calculation methods in E4 forces the steel designer to use external FEM and structural analysis tools for such calculations. Besides the arising costs for software purchase and license fees, this implies always an additional modelling effort before the intended calculations can be performed. Interfaces between the two programs can help, but the daily practise shows that they barely work without any error. In consequence the E4 steel design model has to be reworked manually to consider the obtained results. By improving the design software with strength calculation capabilities, all problems related to data handling, model reworking and interfacing can be omitted.

Besides theses advantages, the implementation of strength calculation tools brings some other advantages. Firstly it is possible to model the steel structure automatically based on the hull form and the ships compartmentation. For the automatic modelling a fixed standard has to be followed which assures that the models are accurate. Certainly such modelling is only feasible and wanted for specific, recurring structural parts such as e.g. decks for rolling cargo. Secondly with specific structures, modelled automatically, an optimization is possible where multiple versions of the structure are calculated and evaluated to achieve an optimum regarding weight, dimensions or used capacity of the structure. And thirdly - which is the most interesting part for ship design software - the tools can be fully integrated in the design system. In consequence the considered structural parts become a variable design parameter and their influence on e.g. the freeboard deck height, the damage stability determination, the ships weight can be considered in ship design.

Beam Grillage Theory

The steel structures treated during the initial design are usually basic parts of the ship structure such as the mainframe or cargo hold areas. The detailed steel design is performed later in the design process. Most of the common shipbuilding structures consist of relatively thin-walled plates stiffened with small and large profiles. The small profiles are stiffening the deck and preventing the deck from buckling. The large girders are dissipating the loads in the surrounding structure. Decks for the rolling cargo in RoRo vessels have to be built preferably without pillars or other obstacles. This leads to very large unsupported lengths and therefore high-webbed and heavy girders. To perform rough strength calculations, especially such structures can be modelled and calculated adequately with simple beam grillages. Calculation methods based on the beam theory are easy to implement, very fast, easy to operate and the necessary modelling work can be automated. Therefore they can be integrated well in the initial steel design process.

To allow such calculations a beam grillage method is developed and implemented in the design software E4. The implemented method including solver and optimizer is written in the programming language FORTRAN. The theoretical background for the solver is extracted from the explanations of Lehmann [3], Fricke [4], Hughes [5] and Klein [6].

Used element type

The beam grillage consists of simple finite beam elements (see Figure 1) which can be loaded vertically to their extent. The start node i and the end node j of each element have 3 degrees of freedom. Namely there are the rotations around the 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 IY, the torsional moment of inertia IT and the element length l are needed to calculate the node displacements with the implemented solver.
In finite element analysis the task is always to calculate the deformations and rotations of the nodes. In the simplest case this leads to solution of the linear equation system (1):

$$ P_K = \bar{K} \cdot \bar{u}_k $$

(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:

$$ \begin{cases} P_{zi} \\ M_{xi} \\ M_{yi} \\ P_{zj} \\ M_{xj} \\ M_{yj} \end{cases} = \begin{bmatrix} 12K_y & 0 & -6K_y \cdot l & -12K_y & 0 & -6K_y \cdot l \\ K_T & 0 & 0 & 4K_y \cdot l^2 & 6K_y \cdot l & 0 \\ 0 & 12K_y & 0 & K_T & 0 & 6K_y \cdot l \\ 0 & 0 & 4K_y \cdot l^2 \end{bmatrix} \begin{bmatrix} w_{zi} \\ \varphi_{xi} \\ \varphi_{yi} \\ w_{zj} \\ \varphi_{xj} \\ \varphi_{yj} \end{bmatrix} $$

(2)

With the choice of this element-stiffness-matrix the deformation due to shear is neglected and the axial deformation, which is independent from the bending deformation, is excluded. The global stiffness matrix $K$ in global coordinate system is assembled based on correctly (according to the node numbers) overlaid element-stiffness-matrices considering the different local coordinate systems of each element.

**Basis function**

The underlying basis function which describes 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.

$$ w(\xi) = \begin{cases} (1 - 3\xi^2 + 2\xi^3) & w_{zi} + \left( -\xi + 2\xi^2 - \xi^3 \right) \cdot \varphi_{yi} \\ + (3\xi^2 - 2\xi^3) & + \left( \xi^2 - \xi^3 \right) \cdot l \cdot \varphi_{yj} \end{cases} $$

(3)

with $\xi = \frac{x}{l}$
**Loads**

On the modelled structure, different load types can be applied. It is possible to apply point loads on the nodes as well as point loads, constant and linear line loads on the elements. The influence on the node displacements 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 Figure 2.

![Figure 2: Applicable Loads](image)

**Resulting bending line and distributions**

After calculating, the node displacements, the rotations and the reaction forces in the beam mountings are determined by the method considering the boundary conditions. Subsequently the respective bending line, bending moment and shear force distributions are calculated and plotted. The resulting bending line and distributions for the continuous beam example in Figure 2 are shown in Figure 3.

![Figure 3: Bending Moment & Shear Force Distribution](image)
Example

In the following parts of the paper, a main frame of a typical RoRo vessel is taken as an example to illustrate the performed preprocessing, calculation and optimization steps. The decks of the vessel are loaded with trailers as shown in Figure 4.

Figure 4: RoRo Vessel Example

Grillage Derivation

The intended purpose of the method is the usage during initial design, where no or only little information about the steel structure is given and the first idea of the main frame is set. Therefore a grillage calculation must be possible based on the main frame only. Here the method helps to determine roughly the scantlings of the high-webbed longitudinal and transversal girders stiffening a typical deck for rolling cargo. Besides the deck weight, the minimum achievable web height of the large girders is of high importance for the initial design, since it has a big influence on the overall ship design.

From main frame to 3D model

The RoRo deck structure is modeled based on the main frame as a grillage of beam elements representing the main transversal and longitudinal girders. This is done according to Figure 5 by extruding the main frame into the longitudinal direction. Depending on the longitudinal frame spacing, the main frame is copied several times. In a next step, beam elements are placed at the positions of the girders. The elements are connected by nodes at the intersection points of the girders.
The number of copies is chosen depending on the dimensions of the rolling cargo type, which is loaded on the respective deck. In the example given, the most demanding load case for the girders is a row of trailers located directly on the transversal girder with their axles. Figure 6 shows this load case and also the resulting beam grillage with loads applied and boundary conditions set. It is suitable to keep the calculation model small by using a symmetry condition in the longitudinal direction. Hence the main frame is copied 4 times in the longitudinal direction with a frame spacing of 3000 mm. By this, one trailer row loads the 3rd transversal girder while a symmetry condition can be assumed at the nodes of the 1st and the 5th frame.

**Beam properties**

The treated RoRo deck as well as the majority of shipbuilding structures consist of relatively thin-walled plates stiffened with profiles. To derive a calculation model as shown in the precedent chapter, the deck is transformed into a grillage of beam elements where each element represents the properties of the real deck. For the calculation, the input values to be determined are the cross-section area, moment of inertia and torsional moment of inertia. The deformation of the deck is governed by the large longitudinal and transversal T girders. So these girders combined with a piece of the attached deck plating are transformed to beam elements. The mentioned part of the deck is called effective breadth of the deck. It depends on the
unsupported length of the girder and the spacing between two girders. Using the concept of the effective breadth considers the fact, that plates attached to a girder are not fully effective for the bending (shear lag effect). The influence of the smaller stiffeners on the global deformation is neglected. The described principle of transforming a stiffened deck into a grillage is shown exemplary in Figure 7 for one beam element.

The effective breadth of the plate is determined according to DNVGL [7]. Depending on the applied loads, the effective breadth is obtained from empirical formulae. This class guideline is a simplification of the effective breadth determination method according to Petershagen [8], where the breadth is determined correctly as a function of the moment distribution. This theory should be utilized for more detailed investigations. For the use in initial structural design the simplification of the effective breadth determination according to DNVGL is assumed to be suitable.

The moment of inertia around the y axis is calculated with simple formula for composed cross sections. The torsional moment of inertia is calculated with the simple formula (4) for the torsion of composed and open cross sections. Such sections consist of several rectangles with the breadth b and the thickness t.

$$I_T = \frac{1}{3} \sum_i b_i \cdot t_i^3$$  \hspace{1cm} (4)
Parameter Optimization

While optimizing a RoRo deck, a unique optimum is difficult to define. Or in other words, the optimum depends on the needs of the design and the objective of the designing engineer. For one RoRo design it might be useful to minimize the ships steel weight and achieve a higher deadweight. For another design it might be favorable to minimize the girder height of the deck, which shifts the ships center of gravity downwards to the baseline, because the whole ship structure above the optimized deck moves downwards, too. This leads to a better stability behavior of the ship. And for a third design only the displacement of the deck might be of interest.

In the majority of cases it is a mixture of these optimization goals. In either case the main objective of the structural optimization is, to use the deck structure to capacity. Otherwise the structure is either too heavy or overloaded. So potential savings are wasted or repairs become necessary.

Therefore a deck optimization tool must include a lot of different optimization goals and give the designer the possibility to optimize the one desired parameter in a given range. In the implemented deck optimizing tool, the variable parameters of the used T girders are web height, web thickness, flange breadth and flange thickness. These 4 dimensions can be varied between a given minimum and maximum value for the longitudinal and transversal girders respectively. The plate thickness of the RoRo deck is not part of the optimization, since it must be determined according to the DNVGL [9] depending on the type of the rolling cargo.

Then the deck structure is loaded with all desired loads and the stress into the structure is calculated for each optimization step. The number of valid solutions is limited by

1. The given minimum and maximum dimensions of the T-girders
2. The maximum allowed displacement of the grillage
3. The maximum absolute stress in the structure.

To use the structure to capacity, 100% of the permissible stress should be reached in the deck structure. For the high-webbed girders in RoRo deck structures this stress is defined according to DNVGL [9] as:

$$
\sigma_{perm} = \frac{165}{k} \frac{N}{mm^2}
$$  \hspace{1cm} (5)

The material factor k depending on materials yield stress $R_{eH}$ is defined as:

$$
k = \frac{295}{R_{eH} + 60}
$$  \hspace{1cm} (6)

Knowing the allowed input parameters and resulting output value ranges, an optimization can be started. With the choice of these limits, the resulting desired optimum can be strongly influenced. Various optimization aims can be pursued with the method. Amongst others, e.g. the following optimization strategies could be of interest while treating a RoRo deck and are chosen in the paper to illustrate the possibilities.

1. Minimize grillage weight + maximize used capacity + constant girder height
2. Minimize girder height + maximize used capacity

For the optimization process an algorithm is developed, which uses the Tangent Search Method from Hilleary [10]. By using this method for optimization, the results converge to a local minimum depending on the given start values and increment of the search.
RESULTS

By using the described initial design methods, shipbuilding structures can be calculated and their necessary dimensions determined. The developed optimization method allows the systematic optimization of RoRo cargo decks.

Limitations of the Used Methods

The following assumptions are made for the implemented method and have to be kept in mind while interpreting the results later on.

1. The deformations of the analyzed structures are relatively small and therefore the relation between the loads and the deformation can be assumed to be linear
2. Deformations due to shear are neglected
3. Cut outs in the girders are not considered
4. The torsional moment of inertia is determined very roughly and does not consider the influence of e.g. closed parts of the cross-sections
5. Bending of the stiffened plate field due to the deck loads is not considered at all

Because of the assumptions and simplifications, the method should only be used for the rough strength calculations in initial and basic design. It cannot and is not intended for replacing a detailed FEM strength analysis, with much more complex models and more precise results!

Strength Calculation Method

With the help of the strength calculation method, the steel designer can model, load and calculate beam and grillage structures. In addition new more specialized design methods are developed to minimize the necessary modelling work and improve the optimization capabilities.

Ship deck structures with large unsupported lengths have relatively high and therefore heavy longitudinal and transversal girders to absorb and dissipate 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 local deckloads and the global loads applied by the 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. The beam grillage is applied with typical loads for a RoRo deck. Those are axle loads for trailers, trucks, cars or fork lifters of the rolling cargo defined in the building specification. After calculation the node deformations, loads in the bearings and the deformation of the grillage are known. Following the RoRo vessel example given before, the respective grillage derived from the deck structure and the resulting bending line is shown in Figure 8.

![Figure 8: Derived Beam Grillage & Resulting Bending Line](image-url)
The resulting bending moment and shear force distributions for the grillage are shown in Figure 9. The stress in the deck structures depends on the bending moment distribution in the elements and the section modulus according to the deck layer and the flange layer of the elements cross-section. The resulting stresses for the grillage of the RoRo example are shown in Figure 10.

**Figure 9: Resulting Bending Moment & Shear Force Distributions**

**Figure 10: Stress in Deck & Flange Layer**

**Method validation**

The results of the strength calculation method including node deformations and rotations as well as the bending line, bending moment and shear force distributions are validated with ANSYS and the tool SEBBES. The latter is software for the analysis of girder grids and has been developed at the Institute of Structural Analysis of the Leibniz University in Hannover, Germany [11].

**Resulting Optimization Method**

Based on the initial grillage derived from the main frame, the parameters described in the chapter Parameter optimization are varied from the optimization method. The user may manually check explicit values or optimize the grillage automatically using the implemented optimization algorithms. Here the parameters web height and thickness, flange width and thickness of the longitudinal and transversal girders as well as the longitudinal frame spacing are varied automatically. All parameters, the resulting maximum displacement and the stress in the grillage are kept within user-defined limits. Amongst all possible solutions a local optimum is searched depending on the intended optimization goal.
Referring to the example given in the previous chapters, some achievable results are shown below. Here the results for the first proposed optimization strategy \textit{Minimize grillage weight + maximize used capacity + constant girder height} are shown. The limits for the optimization parameters are set to the values given in Table 1:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Web</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min height</td>
<td>400 mm</td>
<td></td>
</tr>
<tr>
<td>Max height</td>
<td>2000 mm</td>
<td></td>
</tr>
<tr>
<td>Min thickness</td>
<td>5 mm</td>
<td></td>
</tr>
<tr>
<td>Max thickness</td>
<td>15 mm</td>
<td></td>
</tr>
<tr>
<td>Flange</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min breadth</td>
<td>100 mm</td>
<td></td>
</tr>
<tr>
<td>Max breadth</td>
<td>300 mm</td>
<td></td>
</tr>
<tr>
<td>Min thickness</td>
<td>5 mm</td>
<td></td>
</tr>
<tr>
<td>Max thickness</td>
<td>25 mm</td>
<td></td>
</tr>
<tr>
<td>Longitudinal Frame Spacing</td>
<td>3000 mm</td>
<td></td>
</tr>
</tbody>
</table>

Based on these parameters, the grillage weight is minimized for a constant girder web height, while it is used to capacity preferably ($\sigma_{\text{max}} = \sigma_{\text{perm}}$). The calculation is repeated several times, varying the web heights between the set minimum and the set maximum height. Here the web heights of the transversal and longitudinal girders are equal for each step. The resulting weight per meter in longitudinal ship direction of the longitudinal and transversal girders is shown against the web height in Figure 11. The weight of the deck plating and the small stiffeners is not included. Grillage variants where the resulting stress reaches higher values than the maximum permissible stress on the left side of the diagram ($\sigma_{\text{max}} > \sigma_{\text{perm}}$) are drawn with a dotted line. Variants with a permissible stress higher than the max resulting stress on the right side of the diagram ($\sigma_{\text{max}} < \sigma_{\text{perm}}$) are drawn with a dashed line.

![Figure 11: T Girder Weights against Web Height](image-url)
The diagram shows, that for the given RoRo deck example, a girder height of 1000 mm leads to the minimum weight. However a girder height of e.g. 800mm is not much heavier. Considering the weight of the steel in the surrounding structure which could be removed by choosing the smaller web height, this might be a lighter solution. Here the designer may now weigh up the different options and choose a desired one. For different longitudinal frame spacing than 3000 mm, the calculation must be repeated with adapted input parameters, because the dimensions of the deck plating and the small stiffeners must be changed. They both scale with the unsupported span between the large T girders and are determined e.g. with a rule scantling tool such as Poseidon ND from DNVGL.

DISCUSSION

Calculation Methods in Ship Design Software

Implement various calculation and simulation methods in design software has been practiced since years. Nevertheless it has been done more for other disciplines than the steel design. To name a few, in ship design software usual standard methods are e.g.:

1. The determination and optimization of the ship’s hull form with CFD calculations
2. The prediction of the ship’s behavior at sea with seakeeping simulations
3. The propeller design based on numerical wake analysis

All these methods are accurate, fast and well integrated in the design process. In the field of structural design the use of modern numerical and computational methods within ship design software is the exception. Some ship design tools include steel structure modeling and in the best case a possibility to transfer this structure to a FEM tool. The calculation can be performed in the external tool. But methods to calculate, simulate or optimize the ship structure, which are fast and accurate enough for basic design usually are not included.

Even though the dimensions and the design of many structural parts have a strong influence on ships steel weight, stability and the overall design, the steel structure is barely used as a ship design parameter. During initial design, where main dimensions and specification are changing constantly, the ability to predict accurately the influence of design changes on steel weight and center of gravity is a strong advantage.

Application of the Method during Design

On one hand the used capacity, the weight or the dimensions of the deck structure can be optimized in any desired direction. On the other hand a ship designer may use the results gathered 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 above 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 performed very early in the design where detailed steel structural information is not available. The direct calculation methods presented here, give the designer the necessary tool to treat such questions.

CONCLUSIONS

With the methods described in this paper, the initial steel design capabilities of the ship design software E4 are improved. It is possible to calculate basic shipbuilding structures such as the grillage shaped RoRo cargo decks and optimize systematically their dimensions. The calculation models are defined automatically based on the main frame only. In consequence the basic dimensions of the steel structure can be changed easily and become available as a variable design parameter for the overall ship design. The methods are very fast, easy to handle and are working on the same common design database as the other ship design methods. This reduces the need for external strength calculation tools for the initial steel design and therefore the overall design time.
REFERENCES


