FATIGUE SENSITIVITY ANALYSIS
OF A SHIP STRUCTURAL DETAIL

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ABSTRACT

In the paper, a FEM analysis used for fatigue assessment, based on the rules, was done. The approach for fatigue assessment in the early design stage of the ship structure has been developed. To overcome the challenges due to limited information in the early design stage, generic structural elements and predefined fatigue-critical details were chosen. This allows for the development of a common approach for different ship types, which is also applicable for optimization purpose.

KEYWORDS: Fatigue, ship structure, sensitivity analysis.

1. INTRODUCTION

Ship structures are usually built to a defined set of details, which are documented by classification societies, owners or the builders. Details include stringer and frame intersections, bulkhead and stiffener connections (watertight and non-watertight), penetrations, cutouts etc.

The increasing importance of fatigue strength for maritime structures has resulted in corresponding research activities and recommendations for design, fabrication and operation of maritime structures to counter the increased risks described above. These worldwide research efforts have produced an amount of publications that it is impossible to give a comprehensive overview. The best starting point for a less extensive literature surveys remains the proceedings of the ISSC (International Ship Structure Conference). In reality, fatigue problems appear after a certain number of load cycles, often only after months or even years of operation. The feedback for design is then often slow. Experiments allow accelerating the time scale in applying realistic loads at a much higher frequency and observing then fatigue problems (after the same number of load cycles) in much shorter time, namely hours or days.

Over several decades, test data were accumulated for many typical ship structures and these data have been used by classification societies (along with feedback from fatigue damages on actual ships) to compile catalogues of stress increasing factors. These catalogues allow a simple, pragmatic approach to structural design. The structural designer can compute macroscopic nominal stress using long established and widely available standard tools for structural analysis. The catalogues then give a correction for the influence of a discontinuity (like a weld or a corner) allowing to transform fatigue strength into a changed upper limit for the static stresses. The approach is pragmatic, but not applicable to structures which are not (yet) found in the catalogues. This poses problems each time new structural details or new materials are used.

Design of ships is an interactive process, where major decisions are made in an early design stage covering for instance main dimensions and
Based on a scientific and engineering approach, fatigue-critical structural details and important characteristics of the ships are assessed. The scientific approach is based on damage statistics of fatigue failures in ship structures, and aims to identify critical structural details and corresponding loading modes. In the European Project IMPROVE the review is concentrated especially on tankers, and is extended to cover Ropax and LNG ships based on an engineering approach. The engineering approach is based on pre-existing know-how and knowledge. The study is focused on special features of different ship types which are further developed in the Improve project. The main results of this study are the identification of generic and ship-type-dependent features in fatigue assessment. This is the basis for the development of the fatigue approach for early design stage.

The important calculus is focused on the hot-spot and notch stress level, and it is based on the results of extensive FE-analysis of typical structural detail, performed in SDG, as sensitivity analysis.

In general, there are several approaches for fatigue assessment. The commonly used methods can be divided into different groups according to the applied strength parameters and corresponding response analysis, (see [4]). In this figure, starting from left to right side, the methods are divided to the global and local approaches. The global approaches, such as nominal stress approach, are based on main dimension of the structure. These approaches are easy to apply, but their practical applications for complex ship structures are limited. Therefore, the use of more advanced approaches taking into account local parameters are preferred and applied (ISSC 2003, IACS 2008 [7], [8]). These methods in ship design are structural hot-spot stress and notch stress approaches. The fracture mechanics approaches with J-integral or stress intensity factors are not commonly used in the design stage due to the extremely time-consuming structural analysis.

Weakness of the structural hot-spot stress and notch stress approaches is that they require structural analysis in a detailed level. This can be obtained by applying the finite element method, which is however time consuming and, thus, not suitable for the early design stage. At present there is no common and simplified approach for fatigue assessment which can fulfill the requirements of early fatigue design.

Estimating the production cost is a fundamental part of ship design. Traditionally, shipyards employ empirical methods to estimate the cost of a new ship, as ships typically are one-of-

Traditional dimensioning of ship structures followed simple semi-empirical formulae giving directly the thickness of plates of stiffeners or a required section modulus. Fatigue strength, however, requires a more detailed stress analysis. Complex ship structures are increasingly analyzed using 3D finite elements models. These models allow a realistic distribution of loads and capture the interaction between the main structures. Usually the whole ship hull with its main structures is modeled using plate elements. Secondary structures like stiffeners are modeled simplified using truss elements. The analysis gives global nominal stress distributions for coarse grids. For fine grids, effects of effective width and geometry of the structure are also captured.

Local finite-element models serve to determine the stress increase due to geometry of the structure.

Usually plain-strain plate elements suffice to determine the notch stress at plate edges of holes. For hot-spot stress at weld toes and plate structures, all plate elements of volume elements are employed.

Volume elements require more effort, but consider the stiffness and load distributing effect of the weld better. The definition of the hot-spot stress requires the evaluation of the linear stress component over the plate thickness. This is automatically given for plate elements. For volume elements, an elegant solution is arranging only one element over the plate thickness. Then intermediate nodes are necessary at the element edges to capture the bending properly. Using only 2 integration points over the thickness yields directly the linear stress component. This can then be extrapolated to the plate edge to give the hot-spot stress. The loads for the local finite-element models come either from prescribed external stresses or deformations. These are taken either from a defined initial state or from a global analysis.

In the paper, an approach for fatigue assessment in the early design stage has been developed. To overcome the challenges due to limited information in the early design stage, generic structural elements and predefined fatigue-critical details are applied. This allows for the development of a common approach for different ship types, which is also applicable for optimization purposes.

Based on a scientific and engineering approach, fatigue-critical structural details and important characteristics of the ships are assessed. The scientific approach is based on damage statistics of fatigue failures in ship structures, and aims to identify critical structural details and corresponding loading modes. In the European Project IMPROVE the review is concentrated especially on tankers, and is extended to cover Ropax and LNG ships based on an engineering approach. The engineering approach is based on pre-existing know-how and knowledge. The study is focused on special features of different ship types which are further developed in the Improve project. The main results of this study are the identification of generic and ship-type-dependent features in fatigue assessment. This is the basis for the development of the fatigue approach for early design stage.

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Estimating the production cost is a fundamental part of ship design. Traditionally, shipyards employ empirical methods to estimate the cost of a new ship, as ships typically are one-of-
a-kind products and orders are won based on early bids, i.e. naval architects must estimate costs a priori and within relatively short time (order of several days). Most of these traditional cost estimate approaches are related to the ship weight, which in turn is estimated based on ship type and main dimensions as well as installed power and equipment and outfit.

Design for fatigue leads to much more elaborate structural design and assembly procedures.

In ISSC 2009 Committee III.2 Report, [9], fatigue design methods for ship and offshore structures are discussed. For ships, rule-based-methods for fatigue evaluation are proposed by classification societies, and a comparison of the different fatigue methodologies provided by BV, DNV, GL, KR, LR and NK is summarised. The IACS Common structural rules (CSR) for Oil Tankers and Bulk Carriers Hull structure, published in January 2006, ([7, 8]) have been effective for new-builds since the 1st of April 2006 and it has been evaluated extensively.

International Institute of Welding (IIW) provides fatigue recommendations of welded components and structures, including the effect of weld imperfections with respect to fatigue. The codes cover all current methods of verification, as e.g. component testing, nominal stress, structural stress and notch stress methods, as well as fracture mechanics assessment procedures. The safety philosophy covers the different strategies, which are used in various fields of application and gives a specified choice for the designer, see [6]. The main areas of update are the structural hot-spot stress concept, which now allows for an economic and coarser meshing of finite element analysis, the extension of the effective notch stress concept to welded aluminium structures and numerical assessment of post weld treatments for improving the fatigue properties. In [6], Hobbacher presents the update of the recommendations for polishing welds to reduce notch stresses. The structural weight is virtually unaffected, but the construction costs are naturally significantly higher. Thus a cost estimate following the traditional approach with traditional empirical coefficients based on yesterday’s practice underestimates costs. New approaches to cost estimates need to be developed to reflect modern design-for fatigue, design-for-production approaches in ship building. Such approaches are pursued worldwide at a few places and also subject to a research and development in Project IMPROVE.

The development of the approach for fatigue assessment requires a balanced approach for load, response and strength with sufficient accuracy. However, the approach should overcome the challenge of limited information of structural details in the early design stage. Simplification is also needed to obtain a generic approach, which is applicable for optimization purposes and can be linked to the existing design tools. The existing design tools have suitable databases of general geometry of structure and load specifications. These design tools can be also applied to analyze primary and secondary stresses of hull girder, and they should be exploited to fatigue analysis. Therefore, this study is focused especially on the analysis of local stresses. The main challenges are the transformation of the response from existing design tools and the calculation of fatigue effective stresses in critical structural details with sophisticated assumptions. This requires pre-defined structural details, which are generic, but however define the fatigue strength of the hull girder.

Fatigue failures are usually detected in inspections of classification societies. While fatigue problems are frequent, catastrophes due to fatigue are quite rare, because micro-cracks take usually a long time (sometimes months to years) before progressing to structure failure. They are then typically detected and rectified at an early stage. The inspection requires surveyors (representatives of the classification society inspecting on-board) to look at the structures up close. This poses problems in narrow spaces.

Some characteristics affecting the fatigue strength of the hull girder are strongly depended on the ship type. The use of the ship is defining the main dimensions of the ship, shape of the hull girder, geometry of the main frame and the steel arrangement. Sailing routes i.e. weather condition and service speed can be different between different ships. These differences affect mainly wave and cargo induced fatigue loading and response of hull girder in nominal stress level. Structural details and connections are quite similar between different ship types. However, to obtain optimum space for cargo transporting, special structural elements such as pillars have been applied in some ship types.

A structure of a slopping plate of the tank belonging to a LNG carrier is sensitivity analysed according to the variation of the structural scantlings.

2. STRUCTURAL MODEL

The aim of the sensitivity analysis is to study the effect of the structural scantlings on the structural hot spot stress factor. The analysis is focused on the end of slopping plate marked by the red circles in figure 1. The modelled structure is part of bottom and side structure of LNG carrier. The analysis is focused on the ends of tank top and slopping plates marked by the red circles in figure 1. The model includes, in the longitudinal direction, between two web frames, and in the
transverse direction, part of the bottom and side structure. In the sensitivity analysis the scantlings such as thickness of tank top, bottom and slopping plates are varied. The topology of the structure is fixed to simplify the analysis.

Calculus was done with COSMOS/M. The FEM model has almost 300000 degrees of freedom. The mesh was done according to [6]. The 8 nodes quadrilateral elements were used. In the interested area, the length of the elements is less than 0.5 of the thickness.

The structure is modeled using shell elements. The elements types are parabolic quadrilateral shell elements. The bottom, double bottom, side and double side stiffeners, i.e. HP profiles, were modeled with L-profiles. The L-profiles have same cross-sectional area, moment of inertia and neutral axis position as the HP profiles. However, the equivalent profile may be determined according to [4].

The displacement restraints are applied to the selected boundaries of the model (see Fig. 1).

The plane A is clamped and the symmetry boundary condition is applied for the planes B and C. The corresponding displacement restraints are given in table 1.

<table>
<thead>
<tr>
<th>Plane Description</th>
<th>Displacement</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>u_x  u_y  u_z  θ_x  θ_y  θ_z</td>
</tr>
<tr>
<td>A</td>
<td>Clamped</td>
</tr>
<tr>
<td>B</td>
<td>Symmetry</td>
</tr>
<tr>
<td>C</td>
<td>Symmetry</td>
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Three different loading cases are applied for free boundary of the model (see fig. 3). The load shall be modelled so that the loaded boundary remains plane. This can be obtained by coupling the degree of freedom of the nodes in the boundary. Alternatively, the rigid plates can be used in loaded ends. The unitary resulted loads i.e. forces and moments are added to the neutral axes of cross-section to avoid additional bending.

The load was modelled so that the loaded boundary remains the plane. The forces and moments resultants that are applied in figure 4 are unitary.

The 9 stations (sets of scantlings data models) for the sensitivity analysis are presented in table 2. The notations in table 2 are according to the symbols from figure 5. The order dimensions presented in figure 5 are considered constant during the sensitivity analysis. That is: Flat_1 (200x12), hp_1 (340x12), t_2 (16 mm), t_4 (20 mm).

### Table 2. FE models for sensitivity analysis.

<table>
<thead>
<tr>
<th>Model name</th>
<th>Geometry</th>
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<tbody>
<tr>
<td></td>
<td>t_1</td>
</tr>
<tr>
<td>SPlate_1_i</td>
<td>17</td>
</tr>
<tr>
<td>SPlate_2_i</td>
<td>21</td>
</tr>
<tr>
<td>SPlate_3_i</td>
<td>30</td>
</tr>
<tr>
<td>SPlate_4_i</td>
<td>21</td>
</tr>
<tr>
<td>SPlate_5_i</td>
<td>21</td>
</tr>
<tr>
<td>SPlate_6_i</td>
<td>21</td>
</tr>
<tr>
<td>SPlate_7_i</td>
<td>21</td>
</tr>
<tr>
<td>SPlate_8_i</td>
<td>21</td>
</tr>
<tr>
<td>SPlate_9_i</td>
<td>21</td>
</tr>
</tbody>
</table>

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### 3. RESULTS

Stress distributions at hotspot areas are determined according to the paths presented in figure 4.

The naval rules give a general background for the rule requirements for fatigue control of ship structures, and to provide detailed recommendations for such a control. The aim of the fatigue control is to ensure that all parts of the hull structure subjected to fatigue (dynamic) loading have an adequate fatigue life.
Fig. 1. The structural model for the sensitivity analysis of the end of the slopping plate and planes for boundary conditions.

Fig. 2. Finite mesh in the hot-spot area.
Calculated fatigue lives, calibrated with the relevant fatigue damage data, may give the basis for the structural design (steel selection, scantlings and local details).

Furthermore, they can form the basis for efficient inspection programs during fabrication and throughout the life of the structure.

To ensure that the structure will fulfill its intended function, fatigue assessment, supported where appropriate by a detailed fatigue analysis, should be carried out for each individual type of structural detail which is subjected to extensive dynamic loading. It should be noted that every welded joint and attachment or other form of stress concentration is potentially a source of fatigue cracking and should be individually considered.

According to [6], the structural hot spot stress $\sigma_{hs}$ is determined using the reference points and extrapolation equations for different refinement mesh. For coarse mesh with higher-order elements, as was used in this paper, having lengths equal to plate thickness at the hot spot, evaluation of stresses at mid-side points or surface centres, respectively, i.e. at two reference points $0.5t$ and $1.5t$, and linear extrapolation is done with the formula

$$\sigma_{hs} = 1.5 \sigma_{0.5t} - 0.5 \sigma_{1.5t}$$  (1)

**Fig. 3.** Load cases for FE – models.

**Fig. 4.** Paths for extrapolation for hot-spot points.
Fig. 5. Geometry of FE model for end of slopping plates.
For the structure analysed in the paper, according to the upper formula, stress variations in the hot spots along the paths were obtained according to the linear variation (linear extrapolation) in figure 6.

Fig. 6. Stress variation in the hot spot area.

4. CONCLUDING REMARKS

Fatigue cracks tend to occur in highly stressed regions with remarkable change in geometry, such as connection between longitudinal and transverse structures. The highest occurrence of fatigue cracks were mainly observed amidships, where the maximum bending moment occurs.

The geometry of structural details has a huge influence on the fatigue strength. Three generic structural elements can be identified that can cover hull girder structures: stiffened plates, girders and pillars. However, it is important to notice that the loading mode of the structural elements is different depending on its location within the hull girder and ship type. The number of different structural details is relatively large causing challenges to obtain the generic approach for the early design stage. Based on the results from the review of fatigue damage statistics, it can be concluded that the end of longitudinal stiffeners, particularly beam brackets and cut-outs are the most critical details. Important are also the ends of slopping plates, which are fatigue-critical in the case of LNG ships. Several different fatigue-critical details lead to the conclusion that some sophisticated grouping of structural details will be required in the fatigue approach for the early design stage.

Fatigue for maritime structures has far more implications and aspects than ‘just’ the experimental and numerical aspects of mechanical investigations. Ultimately, engineering research is expected to yield better products and better procedures to support these products (from design to operation). A wider view shows many facets that need to be addressed. In my personal view, we will only succeed if we address the topic with a wider view, without reducing the importance of focused or even fundamental research.

In general, analysis of structural discontinuities and details to obtain the structural hot spot stress is not possible using analytical methods. Parametric formulae are rarely available. Thus, finite element (FEM) analysis is mostly applied.

For FEM analysis, sufficient expertise of the analyst is required.

For many joints between circular section tubes, parametric formulae have been established for the stress concentration factor $K_{hs}$ in terms of structural hot-spot stress at the critical points (hot spots). Hence the structural hot spot stress $\sigma_{hs}$ becomes:

$$\sigma_{hs} = K_{hs} \sigma_{nom}$$

where $\sigma_{nom}$ is the nominal axial membrane stress in the braces, calculated by elementary stress analysis.

For the structural joint, nominal stress is the stress calculated in the sectional area under consideration, disregarding the local stress raising effects of the welded joint, but including the stress raising effects of the macrogeometric shape of the component in the vicinity of the joint. Overall elastic behaviour is assumed.

In simple components, the nominal stress can be determined using elementary theories of structural mechanics based on linear-elastic behaviour. Nominal stress is the average stress in weld throat or in plate at weld toe as indicated in the tables of structural details.

Nevertheless, the structural hot-spot stress is frequently determined by extrapolation from the reference points mentioned before, particularly at points showing an additional stress singularity such as stiffener ends.

The structural or geometric stress $\sigma_{hs}$ at the hot spot includes all stress raising effects of a structural detail excluding all stress concentrations due to the local weld profile itself. So, the non-linear peak stress $\sigma_{nip}$ caused by the local notch, i.e. the weld toe, is excluded from the structural stress. The structural stress is dependent on the global dimensional and loading parameters of the component in the vicinity of the joint. It is determined on the surface at the hot spot of the component which is to be assessed.

Structural hot spot stresses $\sigma_{hs}$ are generally defined at plate, shell and tubular structures.

The structural hot spot stress approach is recommended for welded joints where there is no clearly defined nominal stress due to complicated geometric effects, and where the structural discontinuity is not comparable to a classified structural detail.

The following considerations focus on extrapolation procedures of the surface stress, which are nearly the same in measurement and calculation.

Firstly the stresses at the reference points, i.e. extrapolation points, have to be determined, secondly the structural hot spot stress has to be determined by extrapolation to the hot spot point. The structural hot spot stress may be determined using two or three stress or strain values at particular reference points apart from the hot spot in direction of stress. This is practically the case of points placed at the distances of 0.5 t and 1.5 t from the hot spot point, where t is plate thickness. The structural hot spot stress at the
hot spot is then obtained by extrapolation, according to the equation (1).

For the LNG structural joint analysed in the work, the stress concentration factor \( K_{hs} \) has values placed in the range: \( 1.5 < K_{hs} < 4.0 \).

This means that during the static or quasistatic calculus of the LNG structure, for a certain load case, the values obtained for stress in the hot spot point, for a coarse mesh will be multiplied by \( K_{hs} \) to obtain the structural hot spot stress \( \sigma_{hs} \) (according to equation 2).

Identification of the critical points (hot spots) can be made by:

- a) measuring several different points,
- b) analysing the results of a prior FEM analysis,
- c) experience of existing components, which failed.

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