European Research in Marine Structures

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An overview is presented of the results obtained in Europe by a network with a large number of research groups in the field of Marine Structures during a period of 6 years. The European Union has funded a project aimed at improving the collaboration among European research groups specialized in marine structures, which has led, among other results to a number of benchmark studies organized in 6 main topical areas, namely, Methods and Tools for Loads and Load Effects, Methods and Tools for Strength Assessment, Experimental Analysis of Structures, Materials and Fabrication of Structures, Methods and Tools for Structural Design and Optimization and Structural Reliability, Safety and Environmental Protection. This paper presents an overview of various studies performed, which helps identifying the level of consistency and robustness of different numeric tools used in this field.

1. INTRODUCTION

The European Union has funded MARSTRUCT, the Network of Excellence in Marine Structures, in which 33 research groups from Universities, Research Institutions, Classification Societies and Shipyards have cooperated during 6 years aiming to increase their strength and complementarity. The background was the recognition that each of the existing research groups has some areas of expertise but in general lacks critical mass to deal with the wide variety of problems required to analyze and design marine structures. The network aimed at facilitating cooperation and building the critical mass through inter institution cooperation. This objective was to be achieved through a program for jointly executed research in the area of structural analysis of ships, the sharing of research facilities and platforms and a continuous program of dissemination and communication of research results. The way in which the program was designed contributed to the mutual specialization and complementarity through building up of strengths and the shrinking of weaknesses of the participants.

Although the funding was not negligible, it was aiming at promoting cooperation and thus each institution could only perform limited amounts of basic research. This was an incentive to completing tasks from previously concluded projects or doing joint work with others groups, often intercomparisons of calculation tools or sharing of experimental results or infrastructures.

The activities of the Network cover different areas related with advanced structural analysis such as:

- Methods and Tools for Loads and Load Effects assessment for the various modes of structural response.
- Methods and tools for the analysis of the structural strength and performance, including aspects such as ultimate strength, fatigue, crashworthiness, fire and explosion, blast resistance, and noise and vibration.
- Experimental analysis of structures
- Influence of fabrication methods and new and advanced materials on the structural strength and performance of ships.
- Tools for design and optimization of ship structures.
- Tools and methods of structural reliability, safety and environmental protection of ships, which are organized in the various workpackages of the project.

The project has produced many research results that contributed to advance the state of the art in the various areas relevant to ship structures, which make more than 400 journal and conference papers, 3 journal special issues (Guedes Soares and Das, 2008a,b Guedes Soares, 2011), and 3 books with the proceedings of international conferences (Guedes Soares and Das, 2007, 2009, Guedes Soares and Fricke, 2011). Of particular interest are several benchmark studies produced, namely:

- Comparison of experimental and numerical loads on an impacting bow section

- Comparison of experimental and numerical impact loads on ship-like sections
- Evaluation of slamming loads on V-shape ship sections with different numerical methods
- Comparison of experimental and numerical sloshing loads in partially filled tanks
- Simulation of the behavior of double bottoms subjected to grounding actions
- Round robin study on structural hot-spot and effective notch stress analysis
- Effect of the shape of localized imperfections on the collapse strength of plates
- Parametric study on the collapse strength of rectangular plates with localized imperfections under in-plane compression
- Benchmark study on the use of simplified structural codes to predict the ultimate strength of a damaged ship hull
- Studies of the buckling of composite plates in compression
- Fabrication, testing and analysis of steel/composite DLS adhesive joints
- Simulation and optimization of the ship production process;
- Benchmark on ship structural optimization
- A benchmark study on response surface method in structural reliability
- Modeling strength degradation phenomena and inspections used for reliability assessment based on maintenance planning
- Current practices and recent advances in condition assessment of aged ships

The results of some of the benchmark studies will be summarized here as well as the results of some other specific studies and experimental programs. It is hoped that this may provide a comprehensive view of part of the work done and bring attention to some of the results considered to have applicability in the industry. The paper is organized in the various subject areas indicated above.

2. METHODS AND TOOLS FOR LOADS AND LOAD EFFECTS

The calculation tools and knowledge that will allow the prediction of hydrodynamic loads are essential for design. The main ones focused on both the operational as well as accidental loads on ships, with limited attention to the description of the environment that the marine structures are subjected to. Some attention was devoted to the databases which are the basis to define the design wave climate and also on aspects of prediction of extreme waves and occurrence of abnormal or freak waves.

A limited effort was made in the benchmarking of codes for linear wave induced loads and the main emphasis was concentrated on wave induced loads in flexible ships. Special phenomena like slamming, green water and sloshing were considered and benchmark studies have been made on these topics. This chapter will include a brief description of one such study that had not yet been reported.

Accidental loads due to fires, explosions, collisions and grounding are equally important as design parameters for ships although difficult to predict. Through passive safety measures in the structural design, the safety of ships and the environment can be improved when adequate accidental load models are available. The load modeling includes also the behavior of the damaged ship in waves, an important aspect in the reliability assessment of collision and grounding scenarios.

This chapter will also include an overview of the work done concerning the prediction of the grounding loads as well as the loads due to abnormal or freak waves, which due to their rare nature are also considered as accidental situations.

2.1 Comparison of numerical and experimental slamming impact pressures

Accurate prediction of slamming forces is important to enable their incorporation within methods that evaluate wave-induced motions so that transient induced wave loads can be estimated. Various methods and tools are available and thus a benchmark study was undertaken on the numerical evaluation of pressures and forces acting on impacting two-dimensional sections, comparing with available experimental data obtained from drop tests, with the aim of assessing the quality of predictions obtained from a range of numerical methods.

The bow section attached to a free falling rig, shown in Figure 1, was selected as one of the subjects of investigation due to its ship-like shape and the range of experimental conditions tested. Numerical investigations focused on tests with low (≈0.6m/s) and high (≈2.4m/s) drop velocities, with the variable velocity profile available from the measurements, and 3 angles of heel, namely 0º, 9.8º and 28.3º. The points where pressures were measured using pressure cells, namely P1, P2, P3 and P4, are shown in Figure 1. In addition to pressures, measurements of vertical and, for rolled section impact, horizontal forces were recorded. To ensure 2D flow the total drop section was divided into three parts, namely one measuring section with a dummy section on each side. Further details of the experimentation and measurements are presented by Aarsnes (1996).

A list of the methods used for the modeling of the bow section impact is shown in Table 1, which also includes details of the idealization and modeling of the impact velocity profile. In selecting the methods, both potential and non-potential (or RANS) flow concepts were included.

The Boundary Element Methods (BEM) fall in the potential flow category. They are all based on the same formulation, described by Zhao et al. (1996) as the simplified rather than the fully nonlinear approach, which is a zero gravity potential theory formulation similar to the Wagner method but with boundary conditions satisfied on the real body surface. It accounts for water pile-up, but does not model jet flow. Only the methods denoted as BEM1 and BEM3 account for flow separation from the knuckle. Furthermore each method has used different body and free surface idealizations, as can be seen in Table 1.

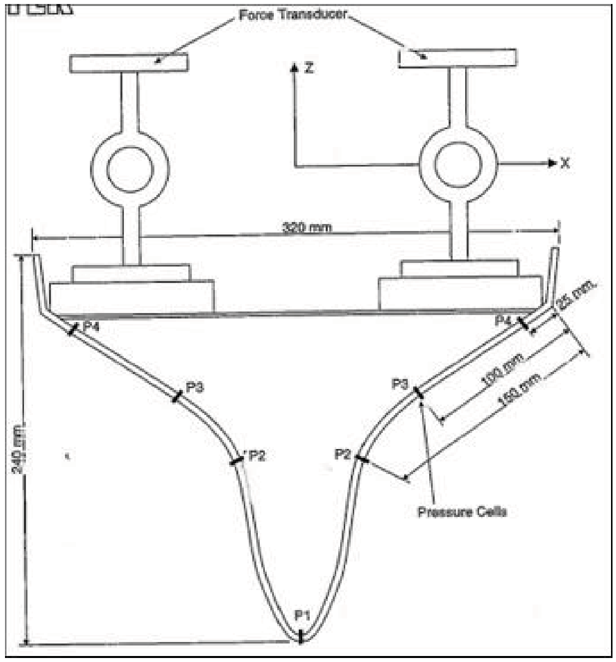

Figure 1: Bow section and test rig (Aarsnes 1996)

Table 1: Details of methodology and idealization

Method	**Idealization and Impact velocity profile**
BEM1 (1)	SB=160, FS=240 (*); imposed velocity profile
BEM2 (2)	SB=301, FS=300 (*); linear approximation to experimental velocity profile
BEM3 (3)	SB=90, FS=50 (*); imposed velocity from experiment
ANSYS CFX (4)	30000 cells; free fall

Method	**Idealization and Impact velocity profile**
FLOW3D (5)	500 x 375 grid + refinements; (a) imposed velocity from experiment (b) constant (c) free fall
LS-DYNA (6)	31250 fluid (8-noded);180 solid shell elements; imposed velocity from experiment
OpenFOAM (7)	42370, 91642 (92k) & 168066 (168k) nodes; velocity imposed from experiment, but smoothed
SPH (5)	250000 particles (diam. 1.75mm); (a) imposed velocity from expt. (b) constant (c) free fall

(*) Segments on SB : Submerged Body, FS : Free Surface
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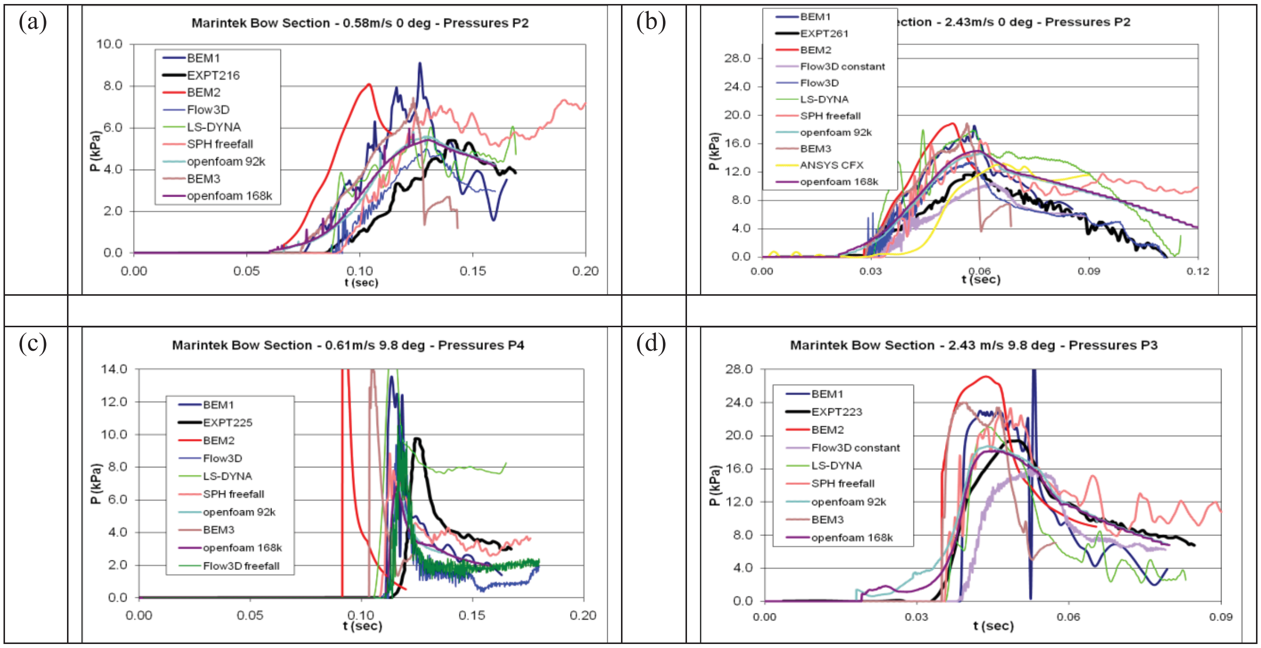


Figure 2: Example of pressure predictions and comparison with experimental measurements, for the bow section shown in Figure 1,at (a) P2, 0.58m/s, 0^{O}, (b) P2, 2.43m/s, 0^{O}, (c) P4, 0.61m/s, 9.8^{O} and (d) P3, 2.43m/s, 9.8^{O}.

The commercially available software ANSYS-CFX, FLOW3D, LS-DYNA and the open source openFOAM fall within the RANS category. A range of mesh densities are used to model the air and fluid domains, as can be seen in Table 1.

It should be noted that LS-DYNA allows for the modeling of both the fluid and body domains, thus can be used for hydroelastic slamming. The final method in the RANS category is the Smoothed Particle Hydrodynamics (SPH) approach developed by Viviani et al. (2009).

Numerical predictions of pressures at all four positions and slamming forces were obtained for all the aforementioned test conditions. A selection of pressures is shown in Figure 2. Pressures and forces predicted by the various numerical methods show differences between each other and the differences become greater with increasing impact speed and heel angle. Different assumptions were used for the impact velocity profile, as can be seen from Table 1. Simulating the velocity profile measured in the experiments, following impact is of vital importance in obtaining accurate pressure estimates at low impact speeds. During the investigations it was noted that use of the actual velocity profile resulted, in general, in oscillations in some RANS based solutions, e.g. FLOW3D and especially in SPH.

The free fall concept, whereby the impact velocity is assigned as initial velocity as the section is about to impact, appears to work well in terms of eliminating such oscillations, especially for SPH; hence, only results for SPH with freefall are provided.

The use of constant speed at higher impact speeds is also suitable. Example of such influences can be seen in the pressures of Figure 2(b), constant vs velocity profile for higher impact speed (compare Flow3D constant vs Flow3D), and Figure 2(c), free fall vs velocity profile for lower impact speed (compare Flow3D freefall vs Flow3D).

All BEM methods show relatively sharp peaks in pressures. They all overestimate by comparison to the experiments. The influence of the velocity profile is evident in the early peak seen from BEM2, for the lower impact speed. BEM1 shows more oscillations compared to BEM3, probably due to the different mesh used for body and free surface idealization. Limited studies on mesh refinement carried out with openFOAM indicate good convergence, in general, for the meshes with 91,642 (92k) and 168,066 (168k) nodes respectively, as can be seen in Figure 2. Overall RANS based methods produce the closest agreement with experimental measurements. In particular, openFOAM appears to provide consistent predictions of good quality, Flow3D and SPH also compare well in spite of some oscillations still being present. There isn't enough data for CFX to make an overall judgment and LS-DYNA can result in some good predictions but not consistently.

The importance of the investigations carried out is the systematic approach followed in assessing the predictions of potential and RANS methods, looking at the influence of impact speed, angle of heel, position along the section contour and mesh sensitivity. The results indicate that there is a need for further investigations, such as the use of the fully nonlinear approach for BEM, use of more refined meshes for some RANS methods, e.g. LS-DYNA, and application to the impact of other sections with available experimental measurements.

More details about the methods and models used as well as more results have been reported by Brizzolara et al. (2008) and Temarel (2009).

2.2 Simulation of the behavior of double bottoms under grounding actions

Grounding as well as collision simulations involve high geometric and material nonlinearities, friction between structural components that slide on one another, material failure and buckling modes of failure of structural components. Taking these aspects into consideration it is obvious that finite element codes offer obvious advantages: the modeling allows the description of complicated geometries, the material modeling is far more realistic rather than the material models that are incorporated in analytical techniques, and it is not necessary to assume a priori the failure modes of the structural components as is needed when using upper and lower bound theorems for the prediction of collapse strength of structures.

However, despite the availability of a number of appropriate FE codes, such as LS-DYNA, ABAQUS, and DYTRAN, there are not widely acceptable guidelines for a FE simulation and in particular for the discrimination of the structure and the definition of the material model. Therefore the use of finite element codes is linked with uncertainties that need special consideration: typical results, such as force vs. penetration curves, strain and stress patterns, even failure modes, depend on the selection of mesh and element type, on the material deformation and failure models.

With respect to the simulation of the behavior of the material there are still uncertainties, in particular related to the failure criteria under multiaxial stress states and the representation of hardening in the plastic range under varying strain rates. Accordingly, it is highly desirable to compare the predictions of independent FE simulations of grounding incidents, in order to quantify the impact of the uncertainties related to the modeling technique and the solvers on the simulations' results. The study conducted aimed at analyzing and quantifying the differences that may arise

i. as a results of the selection of independent parameters, in particular mesh size, relative speed between ship and sea-bed; and
ii. when two independent teams simulate the same grounding.

2.2.1 Selection of independent parameters for FE simulations

Samuelides et al. (2007b) reported on an extensive series of simulations of grounding of a double bottom on a rock, aiming at identifying guidelines that may be used to obtain numerically stable results when simulating grounding incidents with the explicit FE code ABAQUS. The model of the double bottom that was used is shown in Figure 3a and the rigid obstacle that comes in contact with the double bottom is presented in Figure 3b. The investigation was based on simulations employing three different models of the double bottom:

- ✓ a coarse mesh with shell elements having a length of 100 mm,
- ✓ a medium mesh with elements of 50 mm length (see Figure 4), and
- ✓ a fine mesh with shell elements having a length of 25 mm.

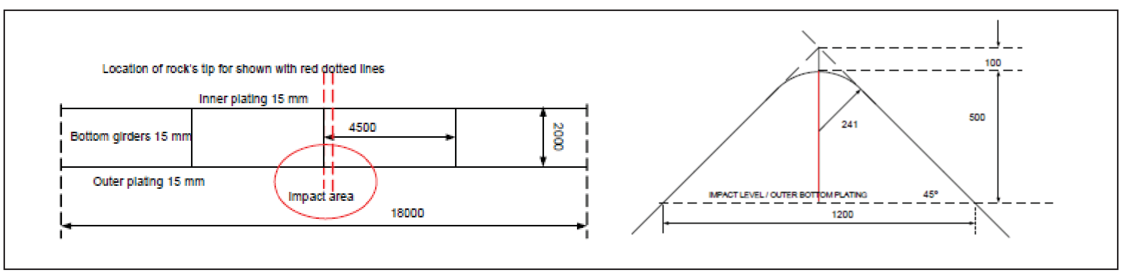


Figure 3a (left): Model of double bottom
Figure 3b (right): Model of rock-conical obstacle

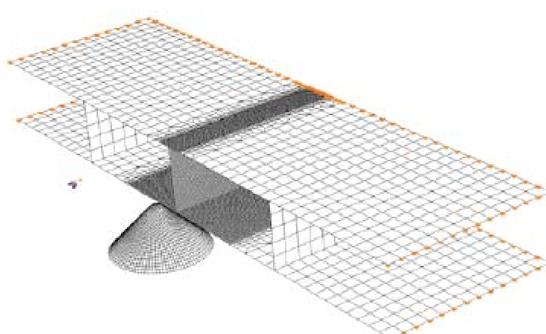


Figure 4: Model of the double bottom with no girders and the conical rock

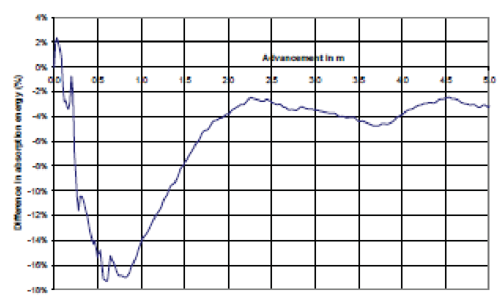


Figure 5: Differences in energy predictions when using 5 vs. 7 through thickness integration points

Preliminary runs revealed that the indenter speed was found to have a small effect on the computed structural response and the calculated resisting forces and it was concluded to use an indenter speed equal to 10 m/s. The elements used for the modeling were reduced integration 4 node shells with 5 through thickness (Simpson) integration points. Figure 5 shows that there is a substantial underestimation of the energy at the initial stages of the contact when using 5 layers instead of 7, but the differences reduce to around 4% in the span where the force response exhibits a steady state, as it happens when the obstacle is moving in the area between the floors. The relative vertical position of the apex of the rock with respect to the outer shell was selected to be 0.5 m. In the transverse direction the indenter was either aligned with a girder or at a distance of 300 mm away from it.

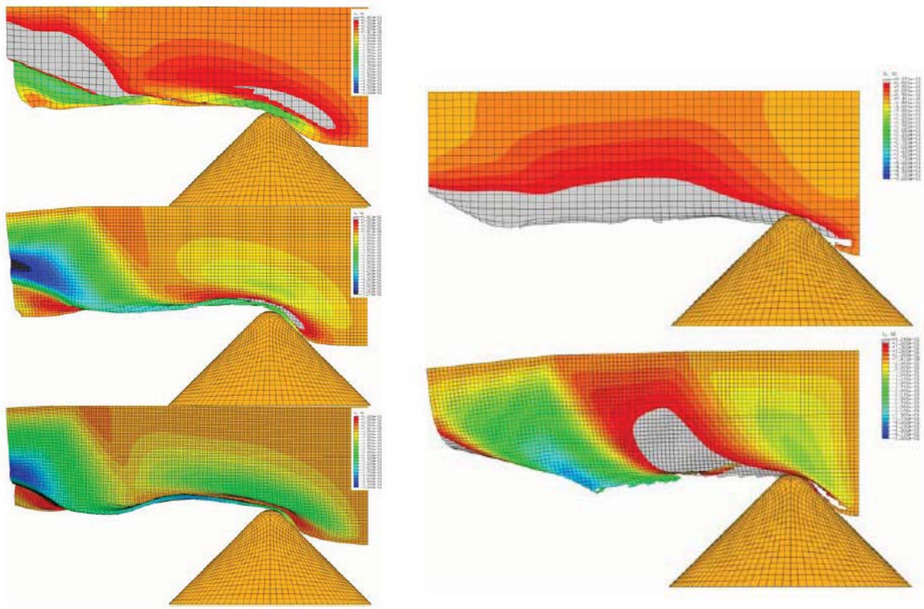


Figure 6: Effect of mesh size on the deformation modes of the girders and out-of plane displacement; with no rupture from top to bottom mesh size is 100 mm, 50 mm and 25 mm (left); with rupture from top to bottom mesh size is 100 mm & 50 mm (right)

The investigation illustrated how the element size affects the mode of response of the girder. When the element size is 100mm the folds of the girder are not as apparent as in the models with the fine and medium meshes (Figure 6). However, in the absence of rupture, the medium and fine meshes produce similar deformation modes and the out-of-plane displacement in the medium and fine models also exhibit similar distributions. Further, the results obtained with the 25 mm and 50 mm meshes exhibit a relatively steady state force when the obstacle is approximately along a distance that extends from a point located 29% from the initial contact until 32% from the end boundary of the model. The mesh refinement studies suggest that a 50mm x 50mm shell elements, with five through thickness integration points, is sufficient for the accurate prediction of the forces. Trial runs indicated that the use of a 25mm square element size in the modeling of a longer structure including four or more floors, currently leads to impractical computational times.

Further simulations were performed considering a material failure criterion based on a maximum strain depending on the size of the element. These runs provided consistent results, particularly concerning the sensitivity of element size on the rupture strain value (50mm square element, 22% rupture strain and 100mm square element, 13.7% rupture strain). The reduction in the longitudinal force magnitude was found to be significant, less than half when the “element failure” was neglected. Figure 7 shows the deformation and failure modes in the plate and girder from the analyses with the 100 and 50mm models. However, despite the reasonably good agreement in the predicted longitudinal force curves, there are differences in the failure modes of the two models. It can be argued that this is the consequence of the ‘damage’ zone being localized along the girder-plate intersection with plastic strain magnitudes well in excess of those required to induce rupture.

2.2.2 Benchmark study

For the benchmark study the FE codes ABAQUS and LS-DYNA were used to simulate a section of the double bottom structure of a tanker subjected to a grounding action. The vessel considered is a 265 m long tanker with a displacement of 150000 tons and her double bottom geometry is shown in Figure 8. Details of the structure may be found in (Zilakos et al. 2009).

A three bay section of the double bottom, with a length of 15 m and spanning the entire breadth at the middle section of the vessel, has been modeled. Three separate models have been constructed in order to examine the effect of the longitudinal stiffening on the grounding action: (a) a model including the girders but excluding all longitudinal stiffeners; (b) a model with longitudinal stiffeners attached to the inner and outer bottom plating; and (c) a model including all stiffeners, i.e. including the flat bar stiffeners in the plating and girders.

The grounding actions have been imposed on the double bottom through the motion of a conical shaped rigid indenter in the longitudinal direction of the ship. Two scenarios of grounding have been studied: impact on a longitudinal girder and also on the plating between two girders. Following previous studies (Samuelides et al., 2007b) the size of the elements were selected 50 mm in the contact area and 200 mm elsewhere.

Prior to examining the predictions from the two codes, it was pertinent to examine the effect of the longitudinal stiffening on the plating and girders for contact aligned with a longitudinal girder or off-girder. Accordingly, the longitudinal and vertical reaction forces are shown in Figure 10, illustrating a gradual increase of the longitudinal force as stiffening is added to the model. Figure 10 shows however that there is only a small increase in the vertical force when comparing the fully stiffened and only on plating stiffened models. As in the case of impact on the girder, it can be seen that the inclusion of the stiffeners leads to significantly higher reaction forces.

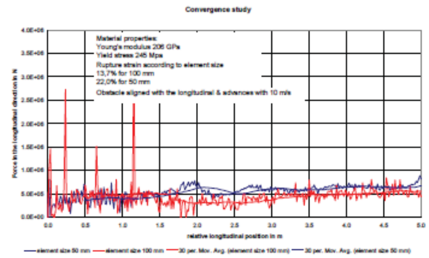


Figure 7: Longitudinal reaction force vs. advancement: effect of mesh size including material failure

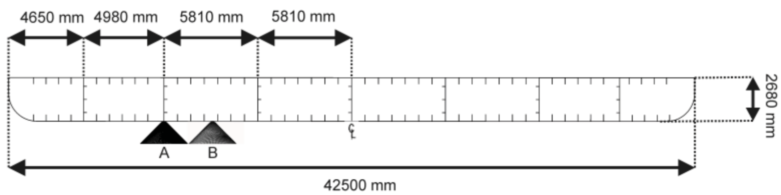


Figure 8: Geometry of double bottom

However, when comparing the fully stiffened and plating only stiffened models, it is evident that the reaction forces are very similar. This is attributed to the 'localized' deformation induced by the impactor without spreading to the neighboring girders which remain almost intact. Clearly this result will change if a wider impactor was used in the simulations or if the penetration depth was larger. In the present work the width of the conical impactor that contacts the outer plating is approximately 1200mm while the distance between the two adjoining girders is 5810mm (see Figure 8).

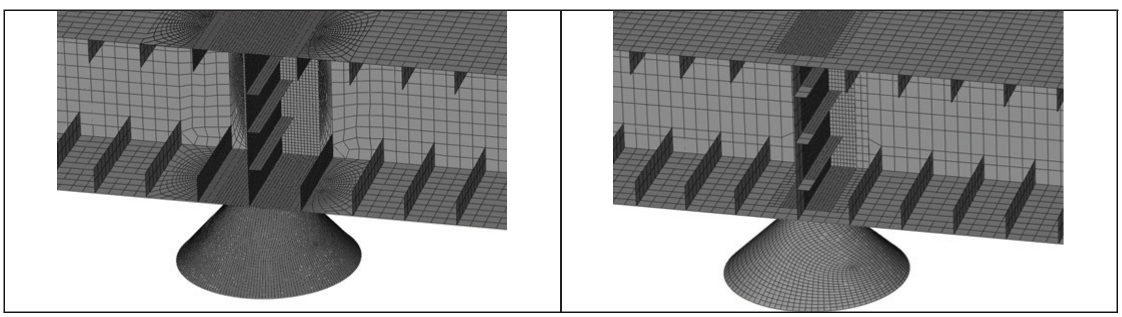


Figure 9: Mesh design in the vicinity of the impact zone for the impact on girder: (left) LS-DYNA model, (right) ABAQUS explicit model.

A key prerequisite for the wider application of the Finite Element Method in the design of ships against grounding and other collision accidents is the reliability of the predictions. In this context, a series of grounding simulations of the double bottom structure were performed independently using the FE codes ABAQUS explicit and LS-DYNA. In order to reduce the uncertainty of the comparison, the same mesh topology and element sizes were used overall, although certain differences in the topology remained in the transition from the fine to coarse mesh regions due to different features in the two codes. In both cases the models were formed with one point quadrature shell elements with 5 through thickness integration points. However the element formulations differed, using in LS-DYNA a popular shell element developed by Belytschko and co-workers while selecting in ABAQUS a finite (logarithmic) membrane strain alternative. The simulations considered two possible scenarios for grounding, that is, impact on a longitudinal girder and on the plating, in-between girders. Results in terms of longitudinal and vertical reaction forces are presented in Figure 11.

The reaction forces computed with the two FE codes for the spaces between two transverse floors were found to differ in the range of 15-30%. There was, however, closer agreement in the force peaks obtained as the impactor crosses each floor present in the model.

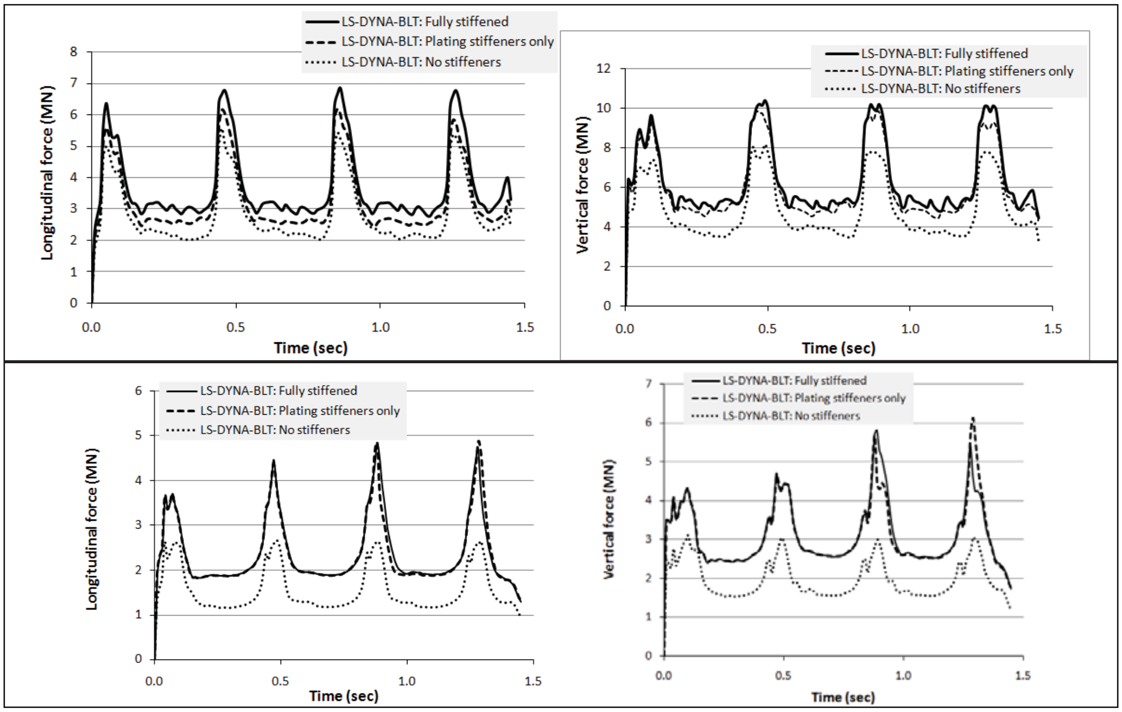


Figure 10: Reaction force versus advancement (speed 10 m/s) illustrating the effect of stiffening elements. Top: Impact on girder, bottom: impact off girder, left: longitudinal force, right vertical force.

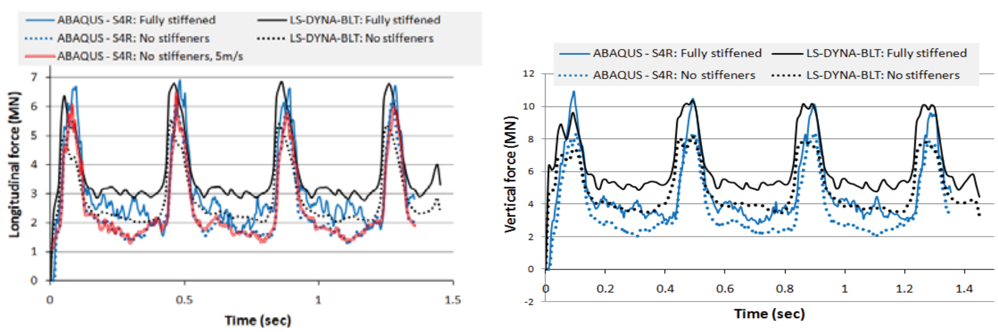


Figure 11: Comparison of independent simulations: left: longitudinal reaction force, right: vertical reaction force

2.3 Load Effects Induced by Abnormal Waves

Current design methodologies do not consider explicitly the wave conditions associated with the encounter of ships with abnormal or freak waves. This is because the probabilistic models describing the waves do not include the abnormal waves that modify the upper tail of those distributions.

Some of the mechanisms that generate abnormal waves have been identified and reviews of the literature about them can be found in Kharif and Pelinovsky (2003) and in Guedes Soares et al. (2003) for example. The definition of which waves should be considered as abnormal ones is also not commonly agreed as discussed in those references, but a criterion adopted by some authors is the ratio of the abnormal wave height by the significant wave height being larger than 2.0.

Although current design methods do not consider explicitly the abnormal wave conditions, Faulkner and Buckley (1997) suggested that the methods to determine the design loads should be revised to account for the effects of the abnormal waves on the ship structure.

In order to consider the structural loads induced by these conditions, a method was proposed by Fonseca and Guedes Soares (2001) to calculate the structural loads induced by deterministic wave traces of abnormal waves, where the ship responses are calculated by a nonlinear time domain seakeeping code. Using this approach the authors carried out several studies related to the responses of a floating platform induced by abnormal waves that were actually measured at the sea. A summary of these studies is presented here, which include also, for comparative purposes, the analysis of the responses induced by design seastates.

The calculations and the model tests were carried out for a Floating Production Storage and Offloading (FPSO) platform. Figure 12 presents cross section lines. The sides are vertical along most of the ship length. The hull shape is similar to a large tanker ship, although with differences in the stern and the bow lines. The length between perpendiculars of the hull is 280.8m, the beam is 46.0m, and the draught is 16.7m, corresponding to a loaded displacement 174,000ton and a block coefficient of 0.87.

A procedure developed by Clauss et al. (2004) was implemented at the seakeeping basin of the Technical University of Berlin to reproduce deterministic irregular wave traces at a specific target position in the tank.

Fonseca et al. (2010) carried out tests with the FPSO model in regular head waves and measured the vertical motion responses, as well as the vertical bending moment. The authors concluded that the heave and pitch motions are well predicted by the code of Fonseca and Guedes Soares (1998) but the relative motion at the fore end of the bow is slightly under predicted, by around 10%.

Clauss et al. (2004) and Guedes Soares et al. (2008) investigated experimentally and numerically the wave effects induced by the New Year Wave (NYW) on the platform. The NYW was measured at the Draupner platform in the Central North Sea, when it was struck by a storm from December 31, 1994, to January 1, 1995 (Haver and Karunakaran,1998, Cherneva and Guedes Soares, 2008, Clauss et al. 2008). The investigation of the platform responses to abnormal waves was generalized in Fonseca et al. (2009), where a set of 20 abnormal waves were systematically analyzed. These wave traces were measured during storms in the Gulf of Mexico, Northern North Sea and Central North Sea.

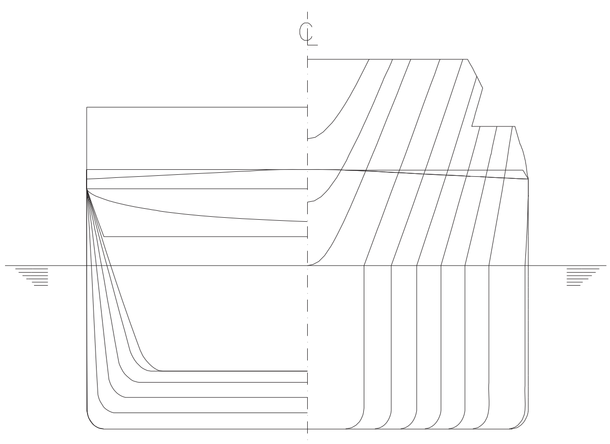


Figure 12: Bodylines of the FPSO

Fonseca et al. (2007) investigated the influence of the length of the FPSO platform on the vertical bending moments induced by the 20 abnormal wave records. They have concluded that the moment peaks normalized by the wave height depend on the abnormal wave length and the maximum responses occur for a wavelength of approximately 75% of the platform length. No correlation was found between the maximum induced moment and the steepness of the abnormal waves.

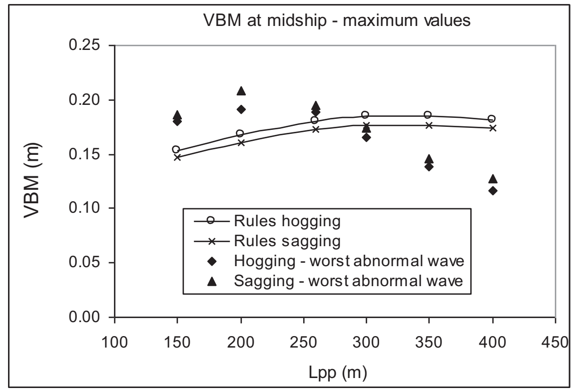


Figure 13: Maximum bending moments for the six FPSOs induced by all abnormal waves. Comparison with rules minimum requirements (from Fonseca et al. 2007).

The calculations were then carried out for a group of six similar FPSOs with lengths between perpendiculars from 150m to 400m. Similar ships mean that the geometric and mass properties are scaled between ships according to Froude scaling.

The authors concluded that the magnitude of the vertical bending moment induced at midship is very much correlated to the relative motion at the bow. In other words, the more the vessel dives the bow into the wave the larger the bending moment. The graph in Figure 13 shows the correlation between the maximum relative motion at the bow and the maximum bending moments induced by all abnormal waves. The results are for the FPSO with 260m between perpendiculars. The correlation is very strong.

3. METHODS AND TOOLS FOR STRENGTH ASSESSMENT

The study of the methods and tools for strength assessment covered the standard finite element analysis and modeling approaches, leading to a best practice document on finite element modeling. In addition to static response, also vibratory response and analysis was considered and various studies were made on ship vibration.

The standard strength assessment approaches were considered, namely ultimate collapse strength, fatigue strength and impact strength. A more limited activity has addressed as fire and blast resistance of structures as well as hull structural monitoring.

This chapter summarized some work done on benchmark studies related with the ultimate strength of damaged ship hulls and with fatigue strength of welded joints.

3.1 Benchmark Study on the use of Simplified Structural Codes to Predict the Ultimate Strength of a Damaged Ship Hull

Some studies on the impact of structural damages on the ship ultimate strength have been by Gordo and Guedes Soares (2000), Ziha and Pedisic, (2002), and Fang and Das, (2004) conducted using simplified methods based on Smith's approach to predict the ultimate longitudinal strength of damaged ships. The approach generally adopted in these studies considers that the elements within the damaged area are removed and the ultimate strength of the ship is recalculated using the simplified methods (see Figure 14). However as no validation of this approach had been made an attempt has been made in this project.

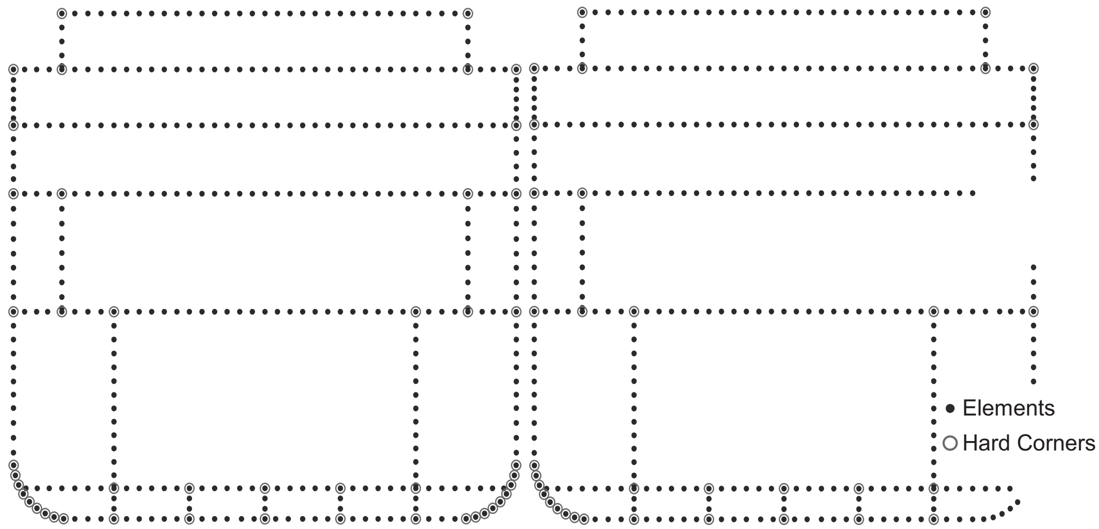


Figure 14: Comparison between the intact section model and the damaged section model for HULLCOLL.

A study was conducted to evaluate the ability of simplified structural analysis methods, based on the Smith (1977) formulation, to predict the ultimate strength of damaged ships. Such methods are now widely accepted as a reliable and fast way to obtain the longitudinal strength of an intact ship. The main difference between the methods used in this work and Smith method is that while the Smith originally used finite element analysis to derive the stress strain relationships for the elements, the simplified methods presented here use simplified analytical approaches to derive that relationship.

In order to extend these methods to damaged ships, first a benchmark study on the intact ship was performed in order for the differences between the methods to be evaluated. Afterwards the methods are applied to the same ship section but with damage, which was defined by removing the structural elements from the affected areas. These, in turn, were obtained from a previous study in which a collision was simulated using a finite element model (Voudouris et al. 2000).

For the damaged ship, the principal axis of the cross-section is rotated compared to the position of the principal axis for the intact ship. Therefore, strictly speaking, it should be necessary to consider combined bending under the action of the vertical bending moment, contrary to the case of the intact ship where the vertical bending moment induces vertical bending exclusively. However the angle of rotation is small and it is assumed that the principal axes in both cases coincide, even though the cross-section is no longer symmetrical.

In Figures 15 and 16 (Guedes Soares et al. 2008) the moment curvature diagrams obtained by all organizations for the sagging and hogging conditions without and with residual stresses respectively are presented. The results obtained with residual stresses have a higher variability in sagging, just as without residual stresses. In the hogging condition the highest differences are around 8% while for the sagging condition the highest differences are around 10%.

Note that in hogging it is the structural elements in the lower part of the hull that are compressed: outer and inner bottom, bottom girders and lower parts of the sides and longitudinal bulkheads, while in sagging it is just the opposite, and the decks are compressed. In all procedures applied in the investigation the stress-strain relationship follows the elastic-plastic behavior of material for tension while the differences appear for compression. The substantial scatter of results for sagging indicate that the differences between the applied procedures to evaluate response of stiffened plates are more significant for more thin plating and slender stiffeners rather than plating of moderate thickness and stocky stiffeners typical for the bottom structure.

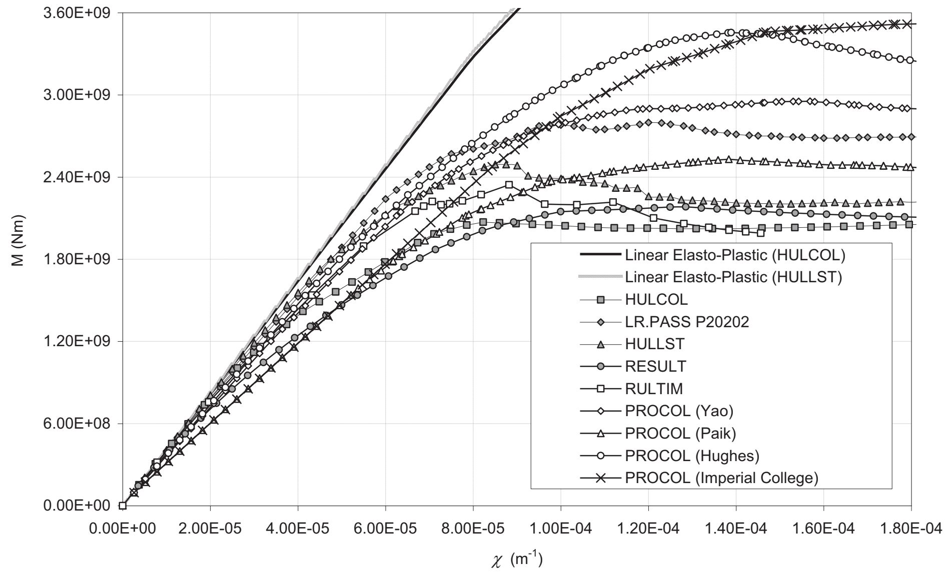


Figure 15: Moment curvature relationship for the sagging condition without residual stresses.

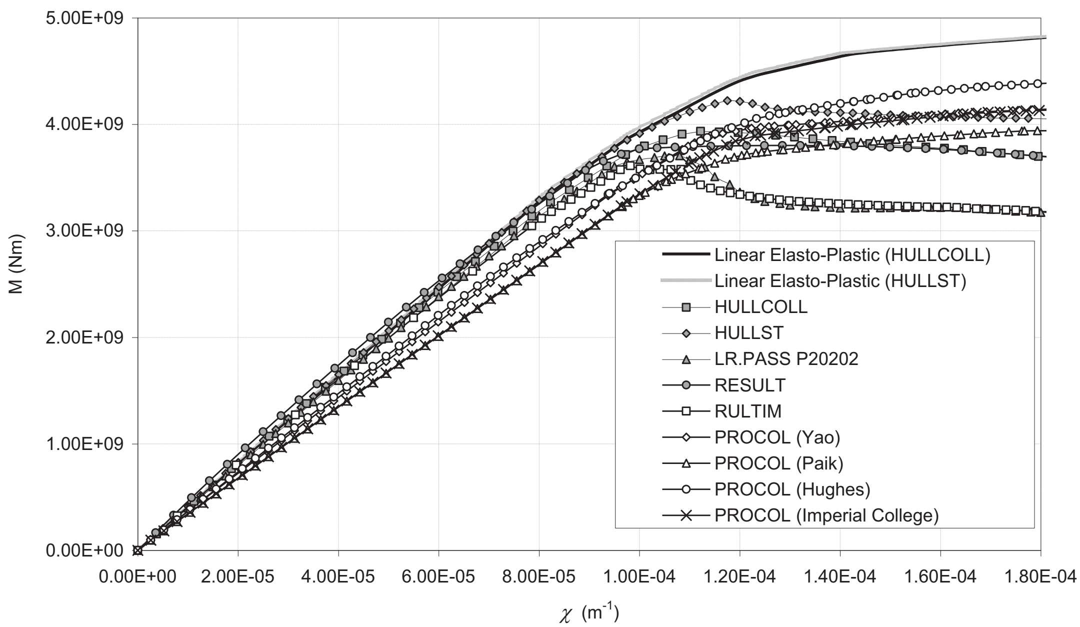


Figure 16: Moment curvature relationship for the hogging condition without residual stresses.

Results obtained for the ultimate strength were compared against each other and with the results of the finite element analysis. Aside from some exceptions, the results of the approximate methods agreed well with each other for the intact and damaged conditions. The simplified methods are more conservative than the finite element analysis in hogging while they seem to give a very good approximation to the result for sagging with some of them overestimating this value.

The simplified methods used in this study compare well with one another for the calculation of the ultimate strength, giving differences that one has come to expect from these types of calculations.

After careful analysis of the ultimate moment it seems that the results present a higher variability in predicting the sagging moment rather than the hogging moment. One should take this in consideration because the strength in sagging is usually the critical condition of ship hulls.

For the damaged ship, the finite element method seems to overestimate the mean value of the simplified methods in hogging, while in sagging it gives a closer value to the mean than the simplified methods themselves. However without experimental analysis it is impossible to say which method is more precise. Therefore this conclusion holds just for the specific case found in this study and it is not possible to say which results are less conservative because it is possible for it to be overestimating the actual resistance of the ship.

Considering the fact that no experimental analysis has been performed, one cannot say if the simplified methods are in fact a useful tool to calculate the resistance of damaged ships. However, considering that simplified methods are accepted as reliable tools for calculating the ultimate moment of intact ships even with the differences shown in these results, and that the results obtained for the damaged ship do not present bigger differences than the intact condition, then, it is possible to say that simplified methods compare well between each other for the calculation of the ultimate bending moment of damaged ships.

3.2 Benchmark Study on the Analysis of Fatigue in Joints

A round robin was performed regarding the computation of structural hot-spot and notch stresses for fatigue assessment. Three details were analyzed by several groups:

- Thickness step at a butt joint maintaining the moulded line so that secondary bending is present under axial loading (5 groups). Figure 17 shows the situation investigated representing the upper deck of a container vessel, where the deck thickness is increased from 20 mm to 30 mm, e.g. in the vicinity of a hatch corner (not included in the model). The stress increase factor due to secondary bending at the weld toe is here approximately K_s = 1.6, which can be well computed with shell and coarse solid models. The deviation between the results of the partners was hence small lying between +5% and -3%.

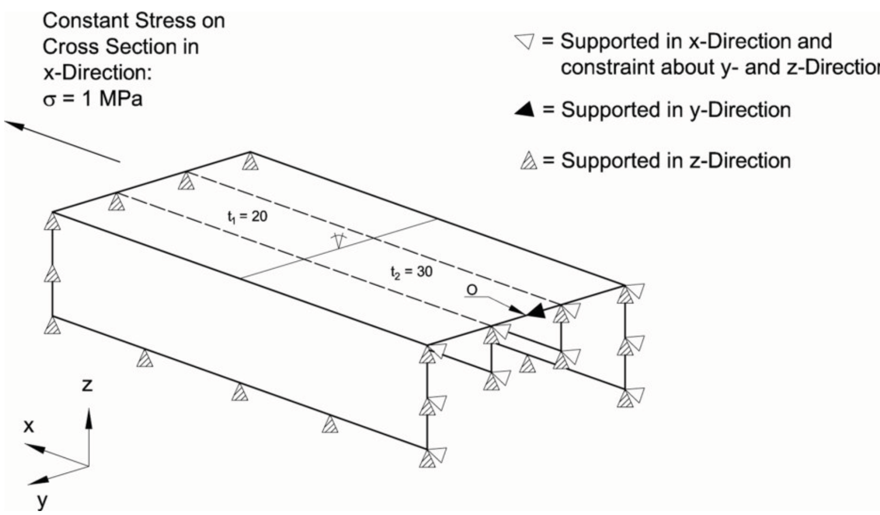


Figure 17: Simplified model for the deck strip of a container ship with thickness step

- Penetration of a longitudinal (T-bar) through a bulkhead (5 groups) with two variants, one conventionally closed with overlapped patches and the other with a T-slotted web. The fatigue-critical point was the connection between the flange and the web or patch, respectively, as well as the end of the stiffener on the flange. Structural hot-spot stresses were analyzed.
- Fillet-welded end of a rectangular hollow section subjected to axial and bending loads (3 groups from MARSTRUCT + 4 groups from International Institute of Welding). Figure 18 shows a quarter model with half of the hollow section (left), a vertical intermediate plate (right) and the fillet weld connection. Fatigue tests have shown weld root cracking so that the round-robin concentrated on the notch stress in the weld root, which was fictitiously rounded with a radius of 1 mm according to IIW recommendations. Table 2 shows some modeling details and the resulting elastic notch stresses. The differences between the results of the partners are quite small except for partner G where automatic meshing has created few elements with relatively long edges in the radial direction at the stress peak, i.e. in the direction of the largest stress gradient. These forced the local stresses to smaller values. Without these results the coefficient of variation is 2-3%.

The results of the round robin are published in Fricke, et al. (2008). In addition, they led to the development of a procedure for the fatigue assessment of fillet welds subjected to throat bending based on a structural weld stress (Fricke and Kahl, 2008).

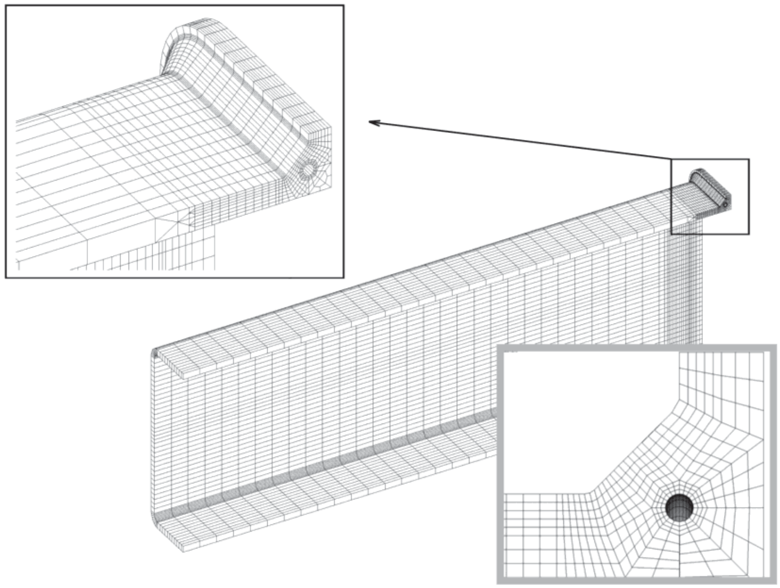


Figure 18: FE model of fillet-welded rectangular hollow section for notch stress analysis

Table 2: Analysis results for hollow section joint (for nominal stress of 100 MPa)

Participant	Program	Element Type (Displacement function and shape)	Element length along circumference	Maximum notch stress [MPa]	
				Tensile LC	Bending LC
A	ANSYS	quadratic (hexahedral)	~ 0.1 mm	888	637
B	ANSYS	quadratic (hexahedral)	~ 0.25 mm	867	601
C	ANSYS	quadratic (tetrahedral)	~ 0.4 mm	913	650
D	ANSYS	quadratic	Not reported	907	642
E	I-DEAS	quadratic (hexahedral)	~ 0.45 mm	914	644
F	ANSYS	quadratic (tetrahedral)	~ 0.2 mm	864	620
G	ANSYS	quadratic (tetrahedral)	~ 0.3 mm	700	600
Coefficient of variation (all results)				8.7%	3.3%
Coefficient of variation (all results without G)				2.5%	2.9%

Another round robin on fatigue assessment was performed. Three details were proposed, but only the first one was analyzed by five groups. It concerns load-carrying fillet welds at doubler plates and lap joints which were also fatigue-tested (see section 4.3). Here, the non-fused root face is parallel to the loading direction so that crack initiation is possible at the weld toe as well as weld root.

A 2D analysis is sufficient here. Different approaches have been applied, including the structural hot-spot stress approach, the structural approaches according to Xiao and Yamada, to Dong and to Poutiainen and the effective notch stress approach. The approaches and first results are published in Feltz and Fricke (2009).The round robin revealed several aspects to be considered in the analysis. These were taken into account in rules and recommendations such as Fricke (2008).

3.3 Benchmark Study on Collision Resistance Simulations of Ship Structures

Due to safety assessment of ships, numerical simulations on ship collisions and groundings are performed increasingly more often. Accuracy of these simulations is crucial when the structural design and optimization for crashworthiness are considered. Therefore, while load task discussed the mechanics of ship groundings as influenced by the material and structural behavior, the task on structural resistance of ship structures analyzed the methods to assess collision resistance of the steel structure; thus it concentrated on the internal mechanics.

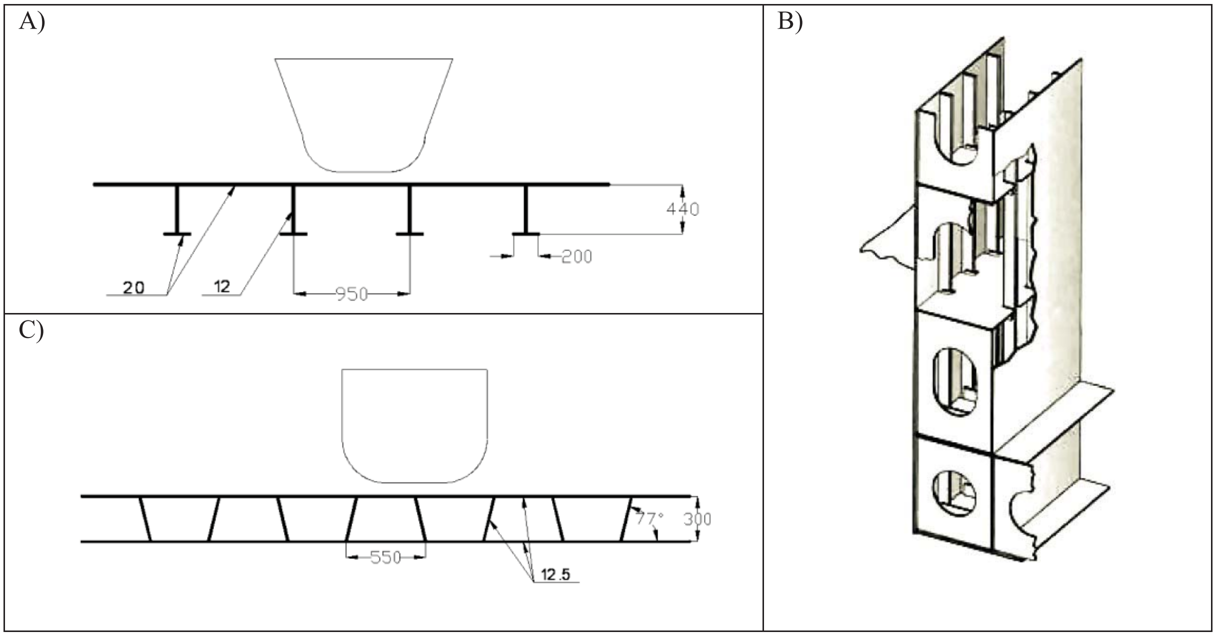


Figure 19: Geometries considered in the benchmark (Ehlers et al., 2008).

A benchmark was set up where stiffened plate, steel sandwich structure and side structure of a ship (see Figure 19) were analyzed by different institutions using the same finite element mesh and software, and material data, but different material relations until failure. The aim of the investigation was to reveal the differences at structural level between the failure criteria proposed by Germanischer Lloyd which is based on thru-thickness plastic strain, the criteria by Peschmann and the RTCL (Rice-Tracey and Crockcroft-Latham) criteria. The numerical simulations were compared with the full-scale collision tests performed during 1997 and 1998 in Netherlands. The investigation is described in depth in Ehlers et al. (2008).

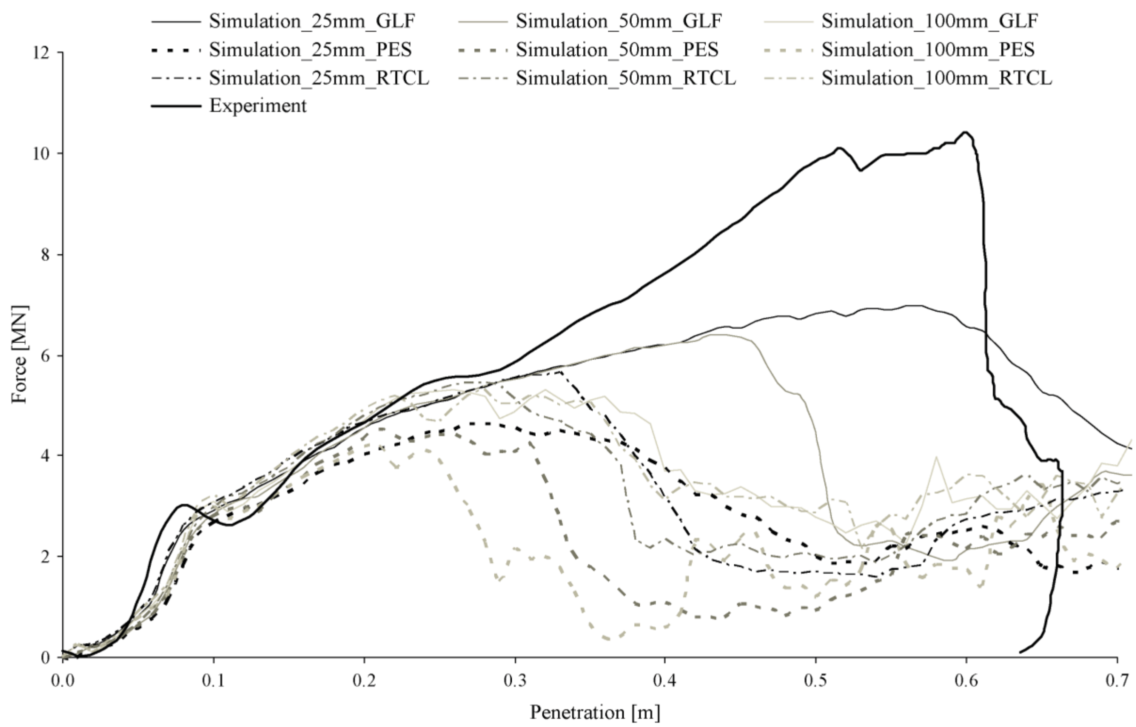


Figure 20: Stiffened plate comparison (Ehlers et al., 2008).

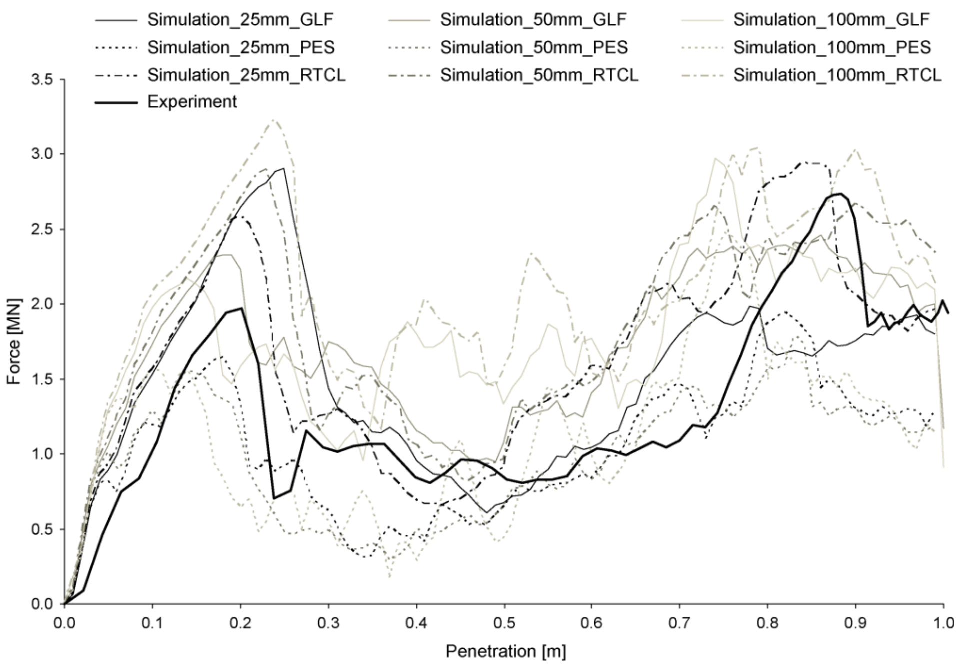


Figure 21: Side structure comparison (Ehlers et al., 2008).

The benchmark study considered three different mesh sizes, i.e. 25mm, 50mm and 100mm. The crack initiation and propagation were modeled in LS-Dyna using the element deletion option. Calculations were performed quasi-statically in displacement control, recording the introduced force; the rigid indenter having the shape of bulb was moved with constant velocity. The boundary conditions at model edges were considered clamped at all four edges. Figures 20 and 21 show the comparison between the simulations and experiments for the stiffened plate and the ship side structure.

Figures 20 and 21 show that the Peschmann and RTCL criterion correlate well in the parts where the failure is not yet occurring. The general trend is that the failure is predicted too early for section 1 while Peschmann criterion works well and RTCL criterion overshoots the force penetration curve for section 3. The results indicate that for coarser meshes (in present case 100mm) the deletion of elements has higher influence than for the finer meshes (25mm and 50mm). Therefore, mesh refinements should be considered in coarse mesh collision simulations. It is also concluded that the mesh size sensitivity might be more important than the material model when the collision simulation accuracy is concerned. Therefore, unified mesh sensitivity equation should be considered, a proposed after the benchmark by Ehlers and Varsta (2009).

4. EXPERIMENTAL METHODS FOR STRENGTH ASSESSMENT

4.1 Test on mild steel box girders subject to pure bending moment

The evaluation of the ultimate capacity of ships under bending moment is a very important issue in the structural design of ship structures, as it is associated with a global failure of the hull and the final result is normally the loss of the ship, its cargo and human lives.

A series of tests were performed to describe the strength of box girders under pure bending moments. The first series of tests intends to compare the ultimate bending moment of box girders made of mild steel (Gordo and Guedes Soares, 2008) with a similar series of tests using very high tensile steel and performed under the EU project FasdHTS (Gordo and Guedes Soares, 2009). These tests allow verifying the increase on the structural efficiency by using high tensile steel and, also, to establish the dependency of the ultimate bending moment due to the variation of the column slenderness of the stiffened panels which are primary elements of the box girders and ship structures. The variation of column slenderness was obtained by having different frame spacing in each box girder, where the slender one has twice the slenderness of the stockiest one.

The test set up for 400mm frame spacing box girder is presented in Figure 22 and it is a typical four point loading test.

The tests showed that the performance of the box girders are as expected and the performance of the high tensile steel model is very good obtaining a global efficiency of 2.28 while the maximum available is 2.56 due to the difference of the yield stress of the two different materials employed. The lower value results from the effect of the increase on the column slenderness of the panel under compression when the yield stress of the material increases.

The column slenderness controls the type of collapse of the structure: high column slenderness leads to more sudden collapse, follow by large discharge of load during the failure of the structure. That was found during the experiments and it is represented by the shedding pattern of both experimental moment curvature curves.

Residual stresses are very important in this type of experiment and the moment curvature curves depend very much on their level according to the manufacturing process. However it is possible to have a good understanding of the behavior of the structure without residual stress by performing a series of loading cycles prior to the collapse of the structure. With those cycles one removes the residual stresses on the panels in tension allowing for the observation of the elastic behavior of the structure, Figure 23. However the residual stresses in the panels under compression cannot be fully removed with this technique, which explains the low tangent modulus near the maximum bending moment.

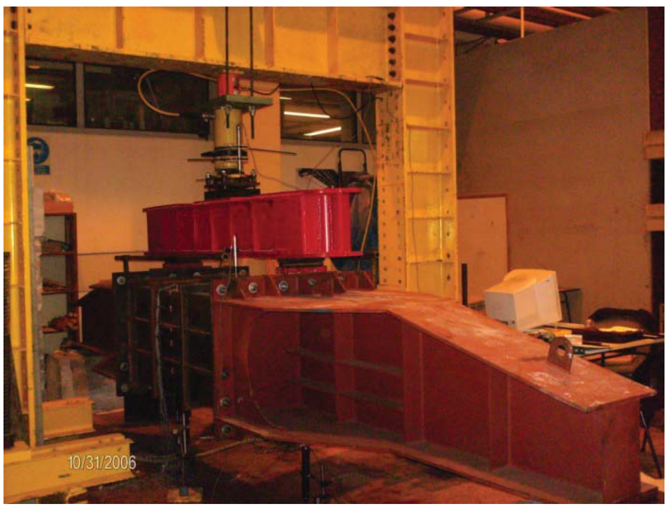


Figure 22: Setup of the test on a mild steel box girder with 400mm frame spacing

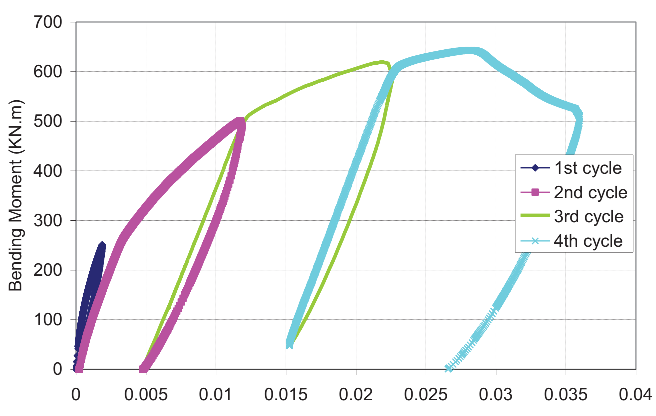


Figure 23: Moment curvature relationship for 200mm frame spacing box girder.

4.2 CORROSION-DEPENDENT ULTIMATE STRENGTH ASSESSMENT OF AGED BOX GIRDERS

A corrosion-dependent analysis of the ultimate strength of aged box girders based on experimental results is presented here. Three multispan corroded stiffened box girders subjected to four-point vertical load are analyzed, idealizing the behavior of midship sections of full ships. The specimens have three levels of corrosion.

4.2.1. Experimental set up of corrosion deterioration

Three specimens, in the form of box girders representing a midship section of ship hull have been tested in a corrosive environment in direct contact with seawater. The dimensions of the specimens are 1400 x 800 x 600 mm. The box girders are made of steel of minimum yield point equal to 235 MPa and the Young modulus of 206 GPa. The specimens were exposed to Baltic seawater without any corrosion protection system (no coating). One of the box girders was tested in cold water and the others in hot water. The box girders were placed in large tanks and seawater was continuously pumped into the tanks. The temperature of the seawater was increased and the oxygen depolarization sub process rate was increased by agitation of the seawater, which resulted in the corrosion rate increase.

To model corrosion rate acceleration, anodic polarization of the metal surface was used. Anodic electric current was supplied by an external source. The test durations were 30 days for experiments with application of external electrical current and 90 days for the test performed without polarization. The models were cleaned of corrosion products once a week.

Figure 24 (a, b) shows the box girders after test with anodic polarization and exposure to hot and cold sea water and the box girder tested in hot water without polarization is shown in Figure 24(c). Detailed information about the corrosion set up is presented in Domzalicki et al., (2009).

A survey of corrosion thickness on the three corroded box girders' plating was analyzed. The corrosion data consists of 636 measurements of corrosion thickness, with 212 measurements collected for each box girder. The as built thickness of measured plates and stiffeners are 4.5 mm. As can be seen from Figure 25, the corrosion distribution is non-uniform and several places are subjected to aggressive corrosion deterioration as can be observed.

Figure 24a, b, and c: Box girders after tests in hot and cold sea water with and without polarization (Domzalicki et al., 2009).

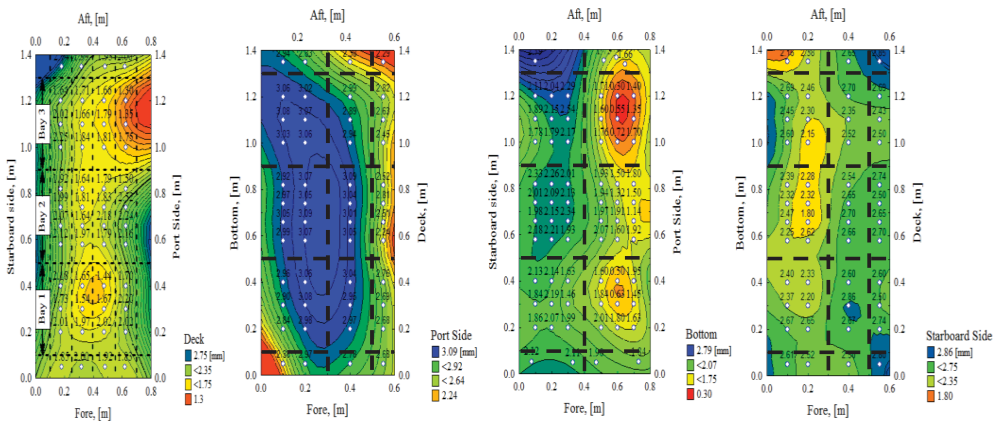


Figure 25: Plating thickness, severely corroded box (Saad-Eldeen et al., 2011a)

Experimental evidence of corrosion, reported by various authors, shows that a nonlinear model is more appropriate than a linear one. The mean value of the measured corrosion depth of the deck plates (0.41, 2.31 and 2.62 mm) of the box girders are compared with the upper limit of the 95 percent confidence interval of the corrosion depth defined by the regression equations developed in (Guedes Soares and Garbatov, 1999) for deck plate of ballast tanks of real tanker ships. This reveals that the initially corroded box matches the 0.2 year of deterioration, while the moderately and severely corroded boxes are related to 17.9 and 23.3 years of deterioration, respectively, considering that the coating life is 0 year (Saad-Eldeen et al., 2011a).

4.2.2. Experimental set up of ultimate strength test

Three ultimate strength tests have been carried out for three corroded stiffened box girders. The use of multiple bays instead of a single bay allows having results that are more realistic by avoiding the effect of the boundary conditions for the central plates, which is due to the eccentricity of load and the interference between adjacent panels.

The box girders have been mounted between two stiff supporting arms using bolt connections. The box girder was subjected to four-point vertical bending moment, in an arrangement similar to the one described in section 4.1. The bottom part is subjected to tension and the upper part, deck, is under compression. The bending moment is kept constant along the box girder, between bolt connections. There are four points for transmitting the load, two are located at the supports of the arms and two are on the boundary between the box girder and the supporting arms. More detailed information is given in (Saad-Eldeen et al., 2010; 2011a; 2011b).

The experimental results of the ultimate bending moment of the tested box girders are given in Table 3 and Figure 26, which show the moment-curvature relationship.

The moment-curvature relationship is linear until the occurrence of buckling or yielding. For the tested box girders, it is noticeable that as the corrosion level increases, the linear range becomes less and the material nonlinearity starts to take place under smaller loads, which gives an indication about the effect of corrosion on the geometrical and mechanical properties.

As may be seen in Figure 26, the slope of the three curves is different, which accounts for the effect of corrosion degradation on the structure flexural rigidity, which directly affected the ultimate bending moment capacity of the box girders.

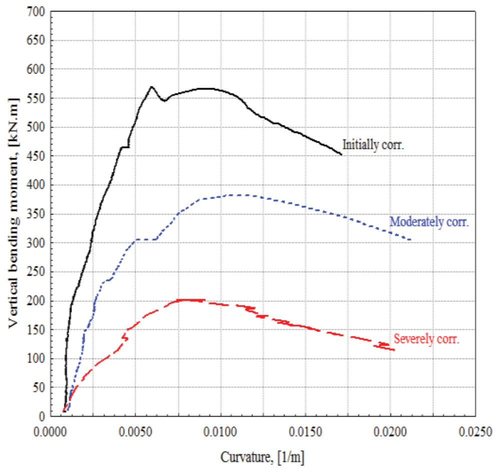


Figure 26: Moment-curvature relationship (Saad-Eldeen et al., 2011c).

By comparing the response of the three box girders in the linear region, it is evident that as the corrosion level increased the curvature also increases for the same bending moment. As a result of the moderate and severe corrosion degradation, the ultimate bending moment that the box girder can withstand decreases by 32.9% and 64.7%, respectively.

The section modulus reduction of the moderate and severe corroded box girders with respect to the initially corroded one is 32.8% and 47.9%, respectively. The section modulus reduction is different in comparison to the ultimate bending moment reduction. This is explained with the non-uniform corrosion degradation distribution, the changes in mechanical properties, and the reduction of the residual stresses (Saad-Eldeen et al., 2011c).

Figure 27: Final collapse mode for initially, moderately, and severely corroded box girders (Saad-Eldeen et al., 2011c).

Table 3: Ultimate bending moment-curvature

Box	Bending moment, kN.m	Curvature, 1/m	%
Initial	568.942	0.0059	**100**
Moderate	381.9777	0.011	67.13
Severe	201.0058	0.0075	35.33

It has been seen that for any box girder, after passing the level of the ultimate bending moment, the curve starts to go down with an increase of the curvature (see Figure 26). This may be explained by the fact that the reduction of the capacity of the structural members result in a very large deformation. The final collapse modes for the three box girders after the test are presented in Figure 27.

4.3 Fatigue Tests

Remarkable fatigue tests related to ships were reviewed and some additional tests were performed in order to

- support the round robin fatigue analyses performed and partially discussed in section 3.2 here, with data for verification purposes
- clarify some open questions in parallel running research projects. These include the residual stress measurements to show how far these could have affected test results.

The fatigue tests were performed on small-scale specimens and components under constant amplitude loading, yielding S-N curves after statistical evaluation. In particular the investigations on following details are notable:

- Fillet-welded ends of rectangular hollow sections subjected to axial and bending loads. These showed weld throat bending and crack from the weld root so that they can generally serve for benchmarks on fatigue assessment approaches considering local stresses in fillet welds. The results are published in Fricke et al. (2006)
- Load carrying fillet welds with loading parallel to the non-fused root faces, occurring e.g. at doubler plates and lap joints. Depending on the throat thickness, fatigue cracks may initiate from the weld toe or the weld root (Figure 28). The correct prediction of the crack initiation site and fatigue strength is a challenge to all fatigue assessment approaches. The test results are shown in Figure 29 and Figure 30 and are published in Fricke and Feltz (2010) and Fischer et al. (2011)

- Joints of bulb flats welded either with a butt-weld filling the whole bulb or with a patch on top. The quality including misalignment affects the fatigue behaviour so that it must be considered during the fatigue assessment. The investigations are published in Notaro et al. (2007).

Figure 28: Investigated doubler plate specimen (left) and lap joint (right) with fatigue cracks at upper left weld

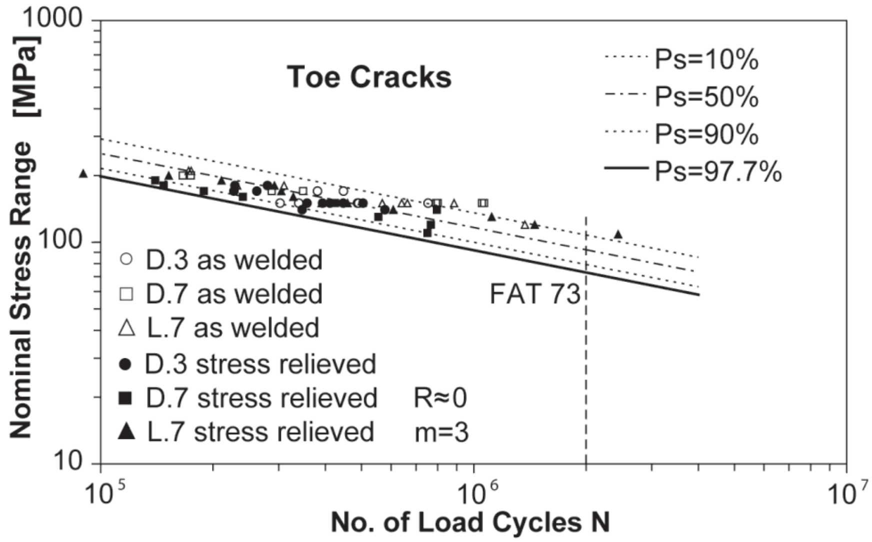


Figure 29: S-N results for doubler plates (D) and lap joints (L) with 3 and 7 mm throat thickness (Frick and Feltz, 2010)

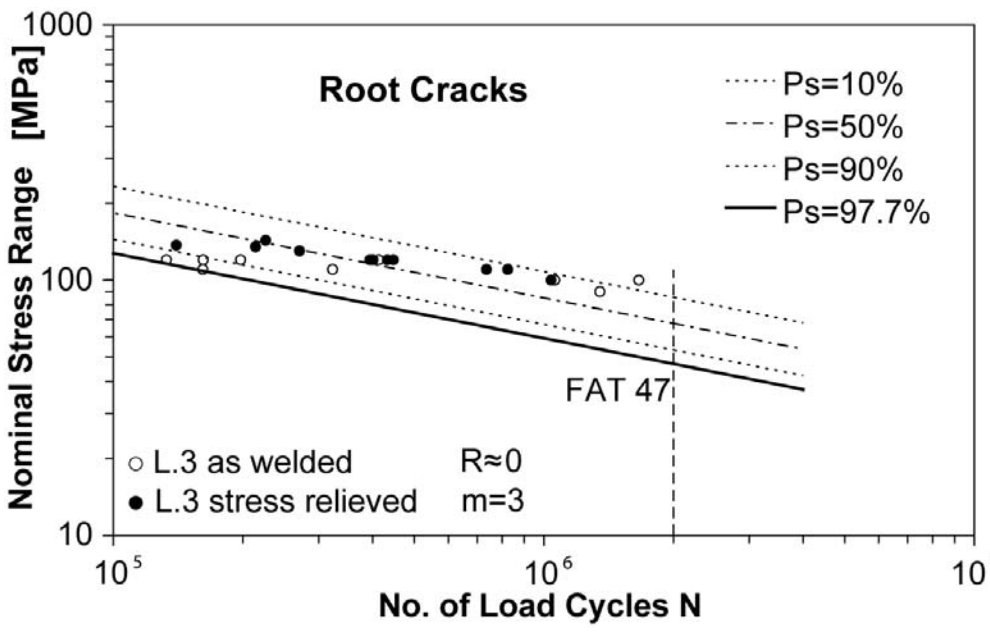


Figure 30: S-N results for all lap joints with 3 mm throat thickness (nominal stress refers to main plate section) (Fricke and Feltz, 2010)

5. METHODS AND TOOLS FOR STRUCTURAL DESIGN AND OPTIMIZATION

The shipbuilding industry usually deals with small series of very large structures with a life-cycle of 20 or 30 years; this means that design choices have an impact which may last for several years and makes design a very critical phase, further complicated by other factors such as:

- the huge volume of data to manage;
- the massive data exchange with many sub-contractors, suppliers and stakeholders;
- the potential significant cost savings both in the building phase and during the whole lifecycle of the ship (repair, maintenance, etc…) made possible by design optimization;
- the strong connection and interdependency with the production process, in a concurrent engineering perspective.

Therefore it is important to have efficient procedures for ship design, among which optimization techniques: these procedures are oriented to structural analysis but also address other multi disciplinary design tools, such as CAD/CAM systems, Classification Societies rule sets, CFD and seakeeping software tools, etc.

During the MARSTRUCT project, the aspects related to both preliminary and detailed structural design have been considered and investigated by identifying, selecting, sharing and improving the existing and available methodologies and tools. Efforts have also been devoted to extend the investigation towards those aspects, such as production and maintenance implications, which more and more are assuming an important role on some decisions taken in the design phase.

The summary reported in this paper describes the *highlights* of the work, with specific reference to three benchmark activities:

1. simulation and optimization of the ship production process;
2. global optimization in the early design phase of a fast ferry;
3. structural optimization of the mid-ship section of a fast ferry.

5.1 Benchmark on simulation and optimization of the ship production process

Production simulation is a powerful technique able to analyze different types of problems and to manage and optimize the production for different time horizons. A benchmark was carried out in the most common use of simulation: the calculation of fabrication time and cost of a ship building block, which is usually one of the steps necessary to set up an efficient production schedule.

In broader terms, production simulation has other applications and can be used for different purposes:

- workshop design:
  - machines/equipment (position, number, capacity, etc.);
  - simulation before investment (make or buy decision);
- definition of production schedules:
  - validation of production plans;
  - decrease of the lead time (identification of bottlenecks);
  - definition of the best production ordering (sequencing);
  - optimization of space allocation in the shipyard;
- production management:
  - balance of the workload (improved personnel and resource planning);
  - improved material management;
  - impact of machine failure;
  - impact of workload and workforce variations.

Nevertheless, in most cases, the purpose of the simulation is to develop the best production strategy by playing on levers such as the distribution of tasks on different work areas, the fabrication sequence within each zone and the quantity of resources used (mainly the number of workers).

In this benchmark, based on a common and agreed specification, two simulation models were independently developed using two different commercial software tools: EM-Plant and Arena; they simulated the production and pre-outfitting process of two consecutive bottom blocks of a ship side in a virtual shipyard with 4 building areas and one single crane (Figures 31 and 32).

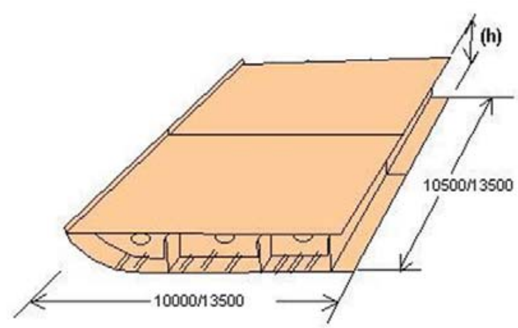


Figure 31: ship portion to build

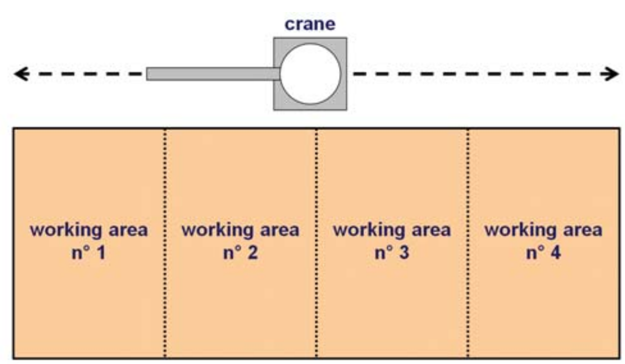


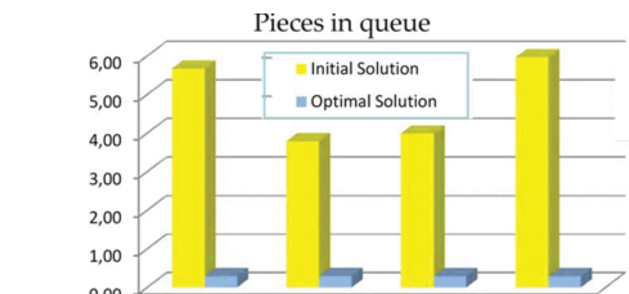
Figure 32: shipyard layout

Even with some different assumptions in the representation of particular aspects of the activity of the workers and of their shifts (two per days, 8 hours each), the two approaches led to consistent results, in terms of resource utilization, lead time and number of pieces in queue.

As a matter of fact, the total production time calculated by the two groups was 92.8 days and 88.5 days, with a difference of only 4.7%.

In the second phase of the activity, the two partners decided to implement an optimization problem in order to increase the efficiency of the production; thanks to the consistency of the results of the comparative phase, the two partners, in order to explore a wider range of solutions, implemented two completely different optimization strategies, consisting of different ranges for the number of workers (carpenters, plumbers, welders), different launching sequences and different constraints on the maximum number of workers per activity.

A certain number of runs were performed, leading to very different (but equally interesting) sets of results; a minimum production time of 49.7 days was reached by one model, while the other led to two solutions, the first with the minimum production cost and a production time of 71.4 days and the second with the minimum production time of 63.6 days. All optimized solutions were characterized by a workload more balanced and a dramatic reduction of pieces in queue as shown in the example results of Figures 33 and 34.



	Area 1	Area 2	Area 3	Area 4
Initial Solution	5,67	3,78	3,99	5,96
Optimal Solution	0,29	0,30	0,29	0,29

Figure 33: Pieces in queue

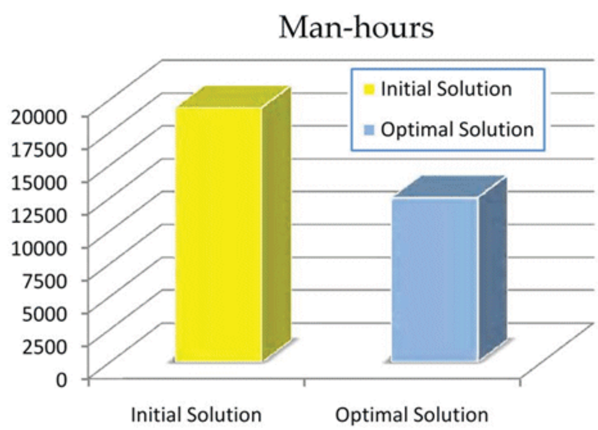


Figure 34: Total man-hours

5.2 Benchmark on global optimization of a fast ferry

A collaborative study was performed to define and validate an innovative methodology for ship design based on an extensive use of optimization techniques, which was applied to the design of a fast-ferry. The methodology consists of a two-level and multidisciplinary optimization. The first level (global level) consists of modifying the ship overall dimensions to reach a global objective. The second level (local level) allows for the definition of the successive designs with a local optimization of each iteration.

The methodology is based on an iterative process built around three tools operated in interaction. A naval architecture software tool is used to generate the ship model at each step of the global optimization and to assess the model (evaluation of hydrostatic properties, ship weight, hull stability, hull resistance, etc.). The midship section of each global iteration is defined and optimized according to Rule constraints with a dedicated tool, with an objective of least weight. The overall process is hosted by modeFRONTIER, which coordinates the tools and performs the global optimization.

ModeFRONTIER is a general purpose optimal design tool developed by ESTECO, able to deal with multidisciplinary problems. It is a state-of-the-art PIDO tool (Process Integration and Design Optimization) that offers a large number of functionalities in terms of process integration, design optimization and post-processing analyses.

The naval architecture calculations were performed by AVPRO. Based on a parametric model, AVPRO can define and assess a 3D model of the ship with a minimum amount of data, in order to comply with the short duration of early design.

The structural optimization of the midship section was performed by LBR5, which performs a 3D structural analysis of a ship portion (usually the midship section), and a scantling optimization of the structural elements (plate thickness, size and spacing of the longitudinal and transversal members), based on different objective functions, as higher inertia, less weight and/or lower cost.

In order to demonstrate the possibilities offered by the two-level and multidisciplinary optimization, the methodology was applied to a fast ferry. The design of a 150 meter long, 7500t displacement ship, accommodating 400 meters of garage truck capacity at a service speed of 30 knots was initiated with AVPRO (Figure 35).

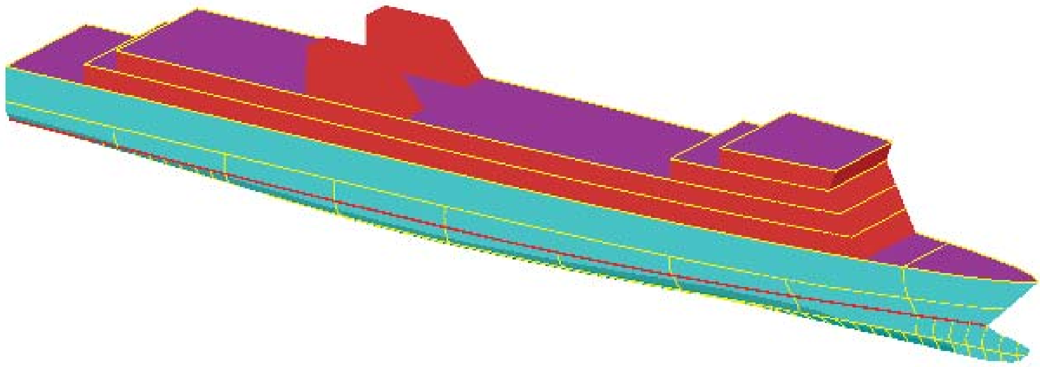


Figure 35: Case study (fast ferry)

The hull resistance was selected as the objective function to minimize. Restrictions were defined for the optimization: minimum garage length (400 meters), correct balance of the ship, basic stability checks.

The two-level and multidisciplinary optimization problem was defined as follows. The first level (global level) consisted of modifying the ship model overall dimensions to reach a global objective of minimal hull resistance, keeping a specified minimum garage length, and considering some feasibility restrictions. The waterline length, waterline beam and draught were the design variables of the global level optimization.

The objective of the second level optimization (local level) was to define an optimal structural design for each global iteration, minimizing the structural weight and complying with standard strength Rules, modifying the scantlings of the midship section (plate thickness and stiffener dimensions and spacing).

Table 4: Results of the two-level optimization

	Initial Design	**Best design**
Length (m)	150	152
Beam (m)	20	18.8
Draught (m)	5	4.3
Parking length (m)	440	421
Propulsion power at 30 knots (kW)	21 400	16 700

The results obtained for the initial design and the final optimized design are summarized in

Table 4. The optimization led to a decrease of 22% of the required propulsive power, complying with all the criteria (vehicle capacity, stability requirements, Rule structural requirements).

The study brilliantly demonstrated the validity and feasibility of an approach based on optimization techniques, and on the interoperability of different tools.

5.3 Benchmark on structural optimization of the mid ship section of a fast ferry

A benchmark on a classical scantling optimization problem was defined and developed by 5 groups. The object of the study was the mid-ship section of a deep-V shaped mono-hull fast passenger-car ferry made of aluminum alloy (FINCANTIERI MDV 1200).

Figure 36: Fincantieri MDV 1200 vessel

Four Rule loading conditions (DNV HSLC 2005) were used, together with a set of 11 design variables and other constraints, such as admissible bending and shear stresses on shell plating and extruded profiles; the objective function was the minimum weight.

The problem of structural optimization was approached in this benchmark with different techniques using a wide range of codes: specialized codes for marine technology, such as MAESTRO and LBR5, general purpose FEM programs, such as PERMAS, general purpose optimizers coupled with FEM codes, like modeFRONTIER with SAMCEF, and the advanced optimization techniques, such as vectorization coupled with genetic algorithms (VOP). An overview of the structural models used can be seen in Figure 37.

Due to code constraints, these approaches have a different number of hypotheses, not all of them coincident with those defined in the benchmark specifications. For example, MAESTRO has its own comprehensive failure criteria, and does not allow users to define their own. On the other hand, generic FEM codes, while they may give more flexibility in the definition of criteria, do not allow the user to easily define the stiffener spacing or their number as a variable. Finally, the analyses based on genetic algorithms have the maximum flexibility but also the greater degree of abstraction. In that sense, in VOP a part of the code for structural evaluation applied in this study was specifically developed, and consisted of several simplifications, such as e.g. consideration of stiffener sizes through area, and not directly through scantlings, or application of rule-based design.

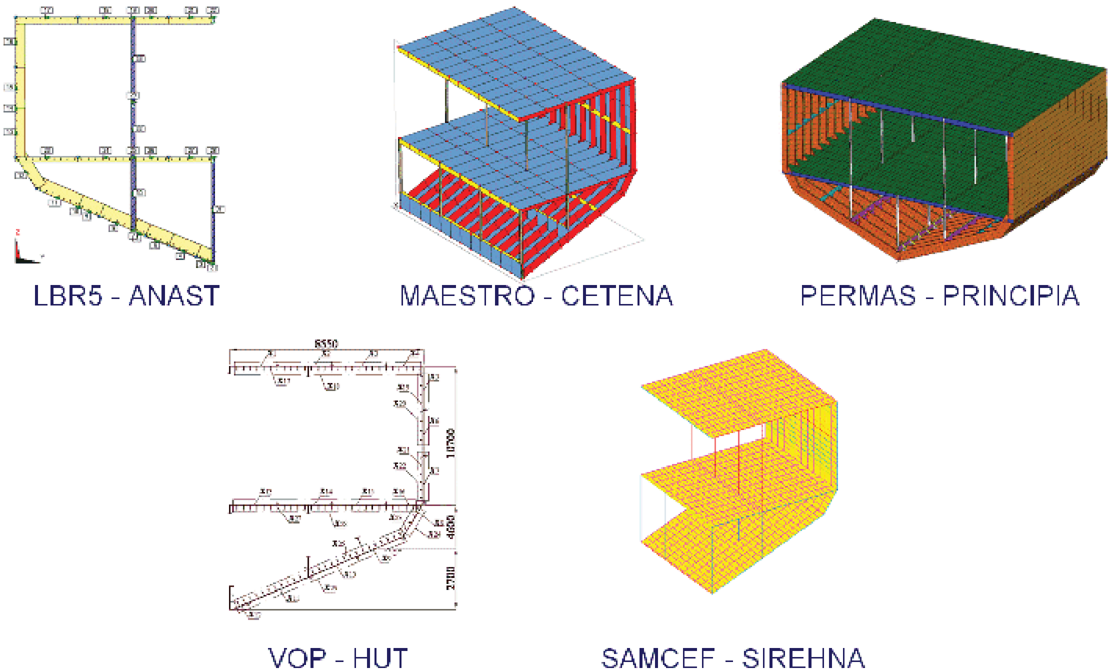


Figure 37: Structural models used in the benchmark

A table detailing the properties of the different codes and analyses performed in the benchmark can be found in Figure 38.

It can be noticed that the largest decrease in weight was obtained applying the modeFRONTIER optimizer linked with SAMCEF, with a 16% result using continuous variables; the actual performance is obviously somewhat lower, due to the *a posteriori* discretization of design variables. The lowest result was 3.4%, obtained with PERMAS, which however did not vary the stiffeners and frames spacing. Other methods obtained weight savings ranging from 10.8% (LBR-5) down to 9.4% (MAESTRO). Indeed, it is significant to mention that the analyses performed with very different methodologies achieved very similar results, with most results close to 10%.

The optimization performed by modeFRONTIER based on genetic algorithms, which allow a wide search within the optimization domain, led to a low thickness of the bottom plates. Yet complying with the specifications of the study, it raised the problem of Rule minimal thickness, which was not explicitly imposed by the study specifications.

This underlines the fact that any simplification of the optimization problem can lead to edge solutions, which can be very sensitive to changes of conditions (as additional requirements), all the more as the implemented algorithm allows for a wide exploration of the optimization domain. More conservative conditions (especially concerning loads) give safer and more robust solutions, and generally speaking a robust optimization study should consider every aspect of the design, and take into account all the constraints and requirements it relates to.

Software used for optimization		MAESTRO	LBR-5	modeFRONTIER and SAMCEF	PERMAS	VOP
Partner		Cetena	ANAST	SIREHNA	Principia Marine	TKK
type of software used for optimization		ship F.E.M. gradient algorithm	ship analytical method gradient algorithm	generic F.E.M. several algo. (see text)	generic F.E.M. gradient algorithm	beam theory Genetic Algorithm
variables	frame spacing	NO	YES (constant)	NO	NO	NO
	n° of stiffeners btw girders	YES	YES	NO	NO	YES
	position of stiffeners btw girders	YES - Δstiff constant	YES - Δstiff constant	NO	NO	YES - Δstiff constant
	stiffeners and girders dimensions	YES	YES	YES	NO (possible)	YES
	web thickness	YES	YES	YES	NO (possible)	YES
	flange thickness	YES	linked to geometry	YES	NO (possible)	YES
	plate thickness	YES	YES	YES	YES	YES
	discrete variable variation	YES	NO	NO (possible)	NO	YES
modelling	ship subdivision in zones	YES	YES	YES	YES	YES
	used for	preliminary design	preliminary design	prel./det. design	prel./det. design	preliminary design
	main element types	"strake"	"strake"	shell - beams	shell - beams	shell
	stiffeners modelling	YES	YES	YES	YES	NO (area)
	bulb modelling	L-equivalent	L-equivalent	L-equivalent	YES	NO (area)
	brackets modelling	"effective span"	accounted for in weight computation	NO (possible)	YES	NO
	local details modelling	NO (possible)		NO (possible)	NO (possible)	NO
analysis	load cases	static	static	static	static	static
	buckling strength	YES	safety factors	check after analysis	check after analysis	check after analysis
	design of experiments	NO	NO	YES	NO	NO
results	global stress	YES	YES	YES	YES	YES
	local stress	NO	YES	YES	YES	Rule-based
	adequacy parameters	YES	NO	NO	NO	Rule-based
performance	final result (continuous variables)	---	10.8%	16%	3.4%	---
	final result (discrete variables)	9.4%	---	---	---	10.6%

Figure 38: Summary of the optimization results

Hence, the study did not claim winners or losers, but certainly showed the possibility for diversity of the available tools, their respective capabilities and challenges. It is worth underlining that, from the user's perspective, such as a shipyard or a design consultancy firm, not all the tools and methods illustrated are equally accessible. MAESTRO, LBR5 and PERMAS are commercially available tools embedding an optimizer. The modeFRONTIER-SAMCEF approach utilizes commercial codes but requires expertise on two environments, while the VOP approach is the most *ad hoc* method, probably viable only for academics.

6. TOOLS FOR STRUCTURAL RELIABILITY ANALYSIS OF MARINE STRUCTURES

A variety of problems have been addressed, using modern tools of structural reliability assessment and in some cases dealing with advances in the tools themselves.

The strength of ships under different damage scenarios and their reliability was studied. Finite element analysis was carried out on a tanker model to find the intact ultimate strength and reliability. Also, analysis based on Smith's method were done on bulk carriers and tankers which according to the statistics were shown to be the types involved in the largest number of grounding and collision accidents. It could be found that in both grounding and collision the ultimate strength reduces noticeably and hence reliable and fast methods of residual strength measurements should be in place. Based on these results a reliability analysis was also carried out which showed that tankers have a relatively higher reliability index compared to bulk carriers with similar damage percentage. Also with collision the probability of failure in sagging is higher than in hogging for both the type of ships, while with grounding accidents the probability of failure is more in hogging than in sagging (Hussein and Guedes Soares, 2009, 2011).

An analytical procedure was presented for designing stiffened panels made of composite material and subjected to longitudinal compression and lateral loadings. To validate this code, its predictions were compared with finite element calculations and published experimental results. A stiffened composite panel of ship structure is investigated to consider the uncertainties associated with basic strength variables, load variable and model uncertainties in strength predictors. The reliability estimate was performed using FORM/SORM and Monte Carlo simulation and the importance of the random variables in the prediction of reliability can be determined through the sensitivity analysis. The parametric study is performed to study the effects of statistical distribution of the important variables. Finally, recommendations are made to provide guidance on applications. It was also shown that the analytical procedure is feasible and very fast for effectively analyzing the stiffened composite panel in the preliminary and reliability-based design stages (Yang et al. 2009, 2011).

Risk based design methods and their applicability as tools for assessing partial safety factors as required for code formulations have been studied. Specific applications to tankers and bulk carriers in order to assess the implications of the new Common Rules as compared with the previous ones have been analyzed. A set of representative ship types have been selected, such as container vessels, bulk carriers and tankers. For these ship types the organization and the control of loading and unloading procedures were identified. Possible strategies for re-ballasting during voyage to compensate for the consumption of fuel were investigated. On this basis a stochastic model is established that can provide the joint distribution of relevant forces in the hull (Rizzuto, 2006).

Probabilistic models have been developed for the hull girder ultimate capacity of the selected ships. They quantified the changes in notional reliability levels that result from redesigning an existing tanker ship to comply with new IACS Common Structural Rules for Double Hull Oil Tankers (Parunov and Guides Soares 2008). The risk-based design principles have been utilized to illustrate how the target risk level and the target reliability level can be obtained for selected ship types (Rizzuto, 2005). Reliability formulations have been developed and applied in the assessment of the safety levels of intact ships subjected to combined sea states (Teixeira, Guedes Soares, 2009) and damaged ship structures due to accidental events (Luis et al. 2009, Rizzuto et al., 2010).

Rizzuto et ala (2010) have examined the various elements that an effective characterization of a design scenario for a ship in damage conditions should include, highlighting the need for a proper accounting of the relationships among such elements. In particular, the dependencies on the damage extension and position of the corresponding static and dynamic loads and of the residual structural capacity of the ship were discussed, as well as the key point of the correlation between the environmental conditions during the accident.

POD curves and methodology for ship structures have been developed, including different inspection procedures. In particular, special attention has been given to rank the inspection techniques currently applied onboard with reference to the various degradation type and to identify which factors influencing inspections performances are the most relevant for each degradation type and to quantify the effects of the factors influencing inspections performances on POD and POS or at least to propose a new adequate procedure for that (Zayed et al., 2008, Lo Nigro and Rizzo, 2008).

Corrosion wastage based on long-term measurement data have been analyzed and modeled to check structural deterioration and limit state functions based on the ultimate strength, accounting for different deterioration mechanisms, including reliability assessment based inspection and maintenance planning (Ok et al., 2007, Garbatov et al., 2008).

Teixeira and Guedes Soares (2008) have studied the ultimate strength of corroded plates with spatial distribution of corrosion also represented by random fields, which were discretized using the Expansion Optimal Linear Estimation method. This preliminary study has indicated that the strength of plates with spatial distribution of corroded thickness is usually lower than the one obtained for uniform corrosion and, therefore, it is expected that this better representation of the corrosion patterns would influence the probabilistic models of the residual strength of ship plates under in-plane compression. Using the non-uniform corrosion in plates, Teixeira and Guedes Soares (2007) have investigated how the number of thickness measurements and their location influence the correct representation of the corrosion patterns and the correct assessment of the ultimate strength of the corroded plates. They showed that taking the average of the measurements to represent the corroded plate thickness in alternative to a more correct representation of the corrosion patterns, can lead to optimistic assessment of strength of the structural elements.

An approach based on the statistical analysis of failure data leading to probabilistic models of time to failure and maintenance planning has been developed. The approach adopted the Weibull model for analyzing the failure data. Based on historical data of thickness measurements or corresponding corrosion wastage thickness of structural components in bulk carriers and the progress of corrosion, critical failure levels were defined. The analysis demonstrates how data can be used to address such important issues as the inspection intervals, condition based maintenance action and structural component replacement. (Garbatov and Guedes Soares 2009).

6.1 Risk based maintenance of deteriorated ship structures accounting for historical data

Planning of structural maintenance of ships based on structural reliability approaches involving models that represent the time development of corrosion deterioration have been proposed as, for example, the one presented in (Guedes Soares and Garbatov, 1998), which was recently calibrated with full-scale data in (Garbatov et al., 2007) and it has also been recently applied to analyse the reliability of a bulk carrier hull subjected to the degrading effect of corrosion. The effect of maintenance actions was modelled as a stochastic process and different repair policies including the ones adopted by the new IACS common structural rules were analysed.

The classical theory of system maintenance describes the failure of components by probabilistic models often of the Weibull family, which represents failure rates in operational phases and in the ageing phases of the life of components. This approach has been adopted in (Garbatov and Guedes Soares, 2009a; 2009b; 2010), where it has been demonstrated how it can be applied to structural maintenance of ships that are subjected to corrosion. The approach is based on historical data of thickness measurements or corresponding corrosion thickness in ships. Based on the progress of corrosion, critical corrosion thickness levels are defined as “failure”, which is modeled by a Weibull distribution. Existing formulations obtained for systems are applied to this case, leading to results that agree with standard practice.

Several sets of corrosion data of structural components of tankers and bulk carriers were analyzed. The analysis demonstrates how this data can be used to address important issues such as inspection intervals, condition based maintenance actions and structural component replacement. An effort is made to establish practical decisions about when to perform maintenance on a structure that will reach a failed (corroded) state. Different scenarios are analysed and optimum interval and age are proposed (Garbatov and Guedes Soares, 2009a; 2009b; 2010).

The optimum age and intervals are based on statistical analysis of thickness data using the Weibull model and some assumptions about the inspection and the time required for repair in the case of failure are considered.

Since failure is unexpected then it may be assumed that a failure replacement is more costly than an earlier replacement. To reduce the number of failures, replacements can be scheduled to occur at specified intervals. However, a balance is required between the amount spent on the replacements and their resulting benefits, that is, reduced failure replacements.

It is assumed the problem is dealing with a long period over which the structure is to be in good condition and the intervals between the replacements are short. When this is the case, it is necessary to consider only one cycle of operation and to develop a model for one cycle. If the interval between the replacements is long, it would be necessary to use a discounting approach, and the series of cycles would have to be included in the model to consider the time value of money.

No account was taken for the time required to perform replacements since they were considered to be short, compared to the mean time between replacements. When necessary, the replacement durations can be incorporated into the replacement model, as is required when the goal is the minimization of total downtime or, equivalently, the maximization of component availability. However, any cost that is incurred because of the replacement stoppages need to be included as part of the total cost before failure or in the total cost of a failure replacement.

Optimal replacement intervals for the set of corrosion data of deck plates of ballast tanks are given in Figure 39(a). It can be seen that the minimum inspection interval is achieved when there is a combination of low corrosion tolerance and extreme total repair cost consequence, which leads to 2 years optimal replacement interval for ballast tank plates. Different variations of corrosion tolerance and total repair cost consequence result in different optimal replacements intervals (see Figure 39 a and b).

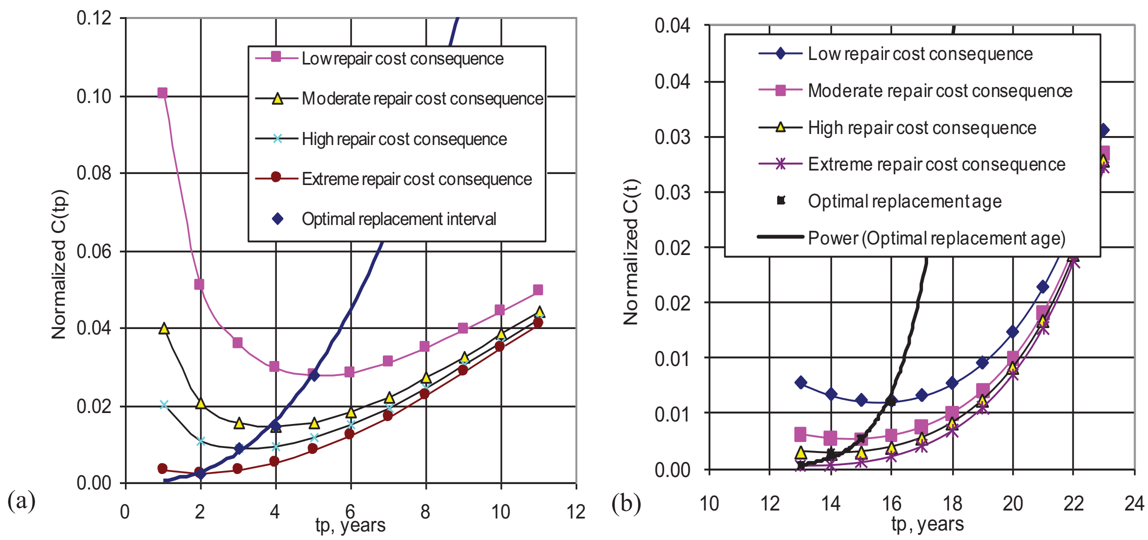


Figure 39: Replacement intervals (a) and age (b), deck plates in ballast tanks, moderate corrosion tolerance (Garbatov and Guedes Soares, 2009b)

The problem of optimal replacement age is similar to the one of replacement intervals except that instead of making replacements at fixed intervals, with the possibility of performing a replacement shortly after a failure replacement, the time at which the replacement occurs depends on the age of the component. When failures occur, failure replacements are made. When this occurs, the time clock is reset to zero, and the replacement occurs only when the component has been in use for the specified period.

The problem is to balance the cost of the replacements against their benefits, and this is done by determining the optimal replacement age for the component to minimize the total expected cost of replacement per unit time.

The optimal replacement age of the deck plates in ballast tanks for various repair consequences, normalized with respect to the expected cost for failure replacement for ballast and cargo tanks, are given in Figure 39(b), from which it can be seen that the optimal replacement ages for different combinations of corrosion tolerances and total repair consequences.

The optimal replacement age accounting for the times required for replacements for the datasets of corroded plates of the structural components subjected to corrosion is shown in Figure 40(a) for deck plates in ballast tanks conditional to moderate corrosion tolerance.

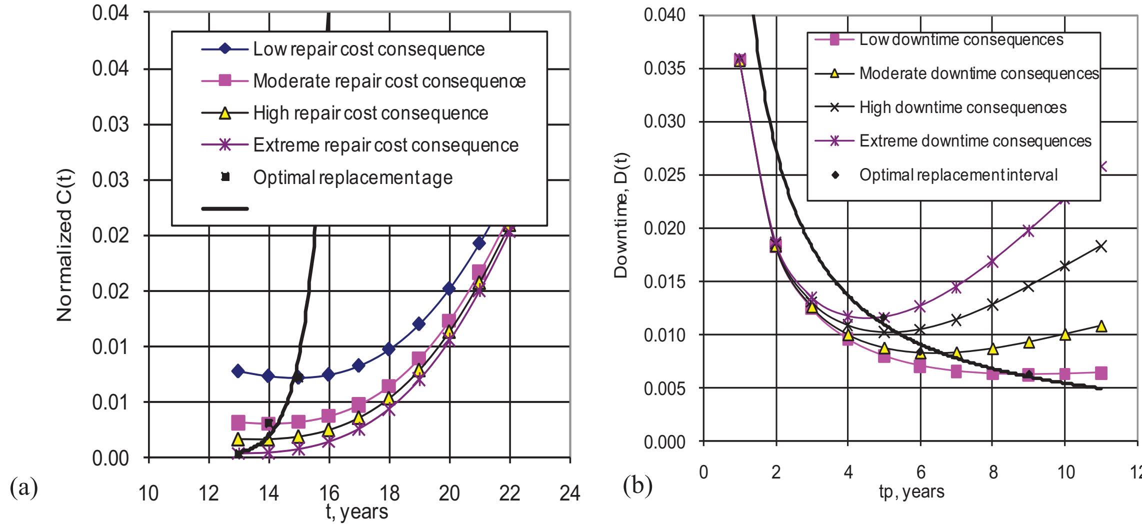


Figure 40: Replacement ages (left), interval (right), deck plates in ballast tanks, moderate corrosion tolerance (Garbatov and Guedes Soares, 2009b)

Due to difficulties in costing or the desire to get maximum utilization of structures, the replacement policy required may be one that minimizes total downtime per unit time or, equivalently, maximizes availability. The problem is to determine the best times at which replacements should occur to minimize total downtime per unit time. The basic conflicts are that as the replacement frequency increases, there is an increase in downtime because of these replacements, but a consequence of this is a reduction of downtime because of failure replacements, and we wish to get the best balance between them. The optimal replacement interval for different corrosion tolerances and downtime consequences result in different optimal replacement intervals for deck plates in ballast tanks conditional to moderate corrosion tolerance, and are given in Figure 40(b), where the solid line shows the optimum replacement interval.

6.2 Structural safety of damaged ships

In the last two decades there has been an increasing interest in using structural reliability methods to assess the safety of ship structures. Most of the applications are related to the assessment of the implicit safety levels of ship structures for different failure modes with the state-of-the-art models and representative uncertainty measures of the strength and load variables (e.g. Guedes Soares et al., (1996), Paik and Frieze, (2001), Bitner-Gregersen et al., (2002)), and to calibrate design formats where a consistent reliability level is required (e.g. Spencer et al., (2003), Teixeira and Guedes Soares (2005), Hørte et al., (2007)).

An important application is on the assessment of the notional probability of structural failure that results from different ship types as well as from different actual concepts of the same ship (Guedes Soares and Teixeira, (2000)). Also, the time dependent degrading effect of fatigue cracking and corrosion on the ultimate moment has also been taken into account in the reliability assessment of different ship types including FPSO structures (e.g. Guedes Soares and Garbatov, (1996a), Garbatov et al., (2004)).

More recently, similar reliability formulations to the ones used for intact ships have been adapted to assess the safety levels of damaged ships structures due to accidental events, as reviewed by Teixeira and Guedes Soares (2010).

In order to be able to determine structural reliability of a damaged ship it is necessary to evaluate the longitudinal strength of the damaged hull girder and to define probabilistic models that can characterize the variability expected from the structural strength estimates.

Guedes Soares et al., (2008) reported the results of a benchmark study in which the strength of a damaged ship hull was calculated with 3D nonlinear finite elements and was compared with the strength predicted by various codes based on the Smith method showing in general a good correlation. This simplified approach based on the Smith method has been used in several studies of reliability assessment of damaged ships (e.g Fang and Das (2005), Luís et al., (2009), Hussein and Guedes Soares (2009) and Rizzuto et al., (2010)).

Fang and Das (2005) have studied the risk level of a ship damaged in different grounding and collision scenarios in different service conditions. They found that the failure probability of the ship damaged due to grounding is far less than due to collision. Moreover it was shown that the ship damaged by grounding or collision is at high risk unless necessary operational precautions are taken in order to reduce the expected loads to which the ship is subjected.

Hussein and Guedes Soares (2009) have studied the residual strength and the safety levels of three double hull tankers designed according to the new Common Structural Rules (CSR) of the International Association of Classification Societies (IACS). Different damage scenarios at side and bottom were considered and the residual strength of the ship in each scenario was calculated. The reliability of the damaged ships was then calculated considering the changes in the still water bending moment and the decrease in the ultimate strength due to the damage.

Luís et al., (2009) performed a reliability analysis of a Suezmax double hull tanker accidentally grounded. The loading of the ship was defined based on the extremes that the ship could find during one voyage of one week to dry-dock through European coastal areas. It was shown that in spite of the reliability being lower in the intact condition for sagging, in the damaged condition it is possible to find lower values for hogging, depending on the location and size of the damaged areas.

In particular, Luís et al., (2009) have assessed the effect of damages around the keel area due to an accidental grounding of a Suezmax tanker, while Rizzuto et al., (2010) have considered damage extents and locations covering all possible grounding scenarios that can occur described by a damage box as a function of the transverse location (*ypd*), transverse extent (*yld*) and vertical extent (*zld*) of the damage, as illustrated in Figure 41. Moreover, Rizzuto et al., (2010) have adopted the IMO (2003) Resolution MEPC 110(49) for the probabilistic characterization of the grounding damage.

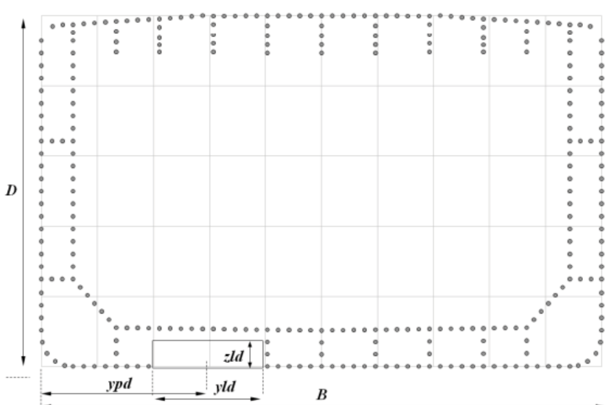


Figure 41: Location and extent of damage due to grounding (Rizzuto et al., (2010))

Figure 42 illustrates the ultimate strength of the ship under sagging bending moment for the different damage cases calculated by the simplified progressive collapse method developed by Gordo et al., (1996), considering the net thickness approach ($t=t_{net}+0.5t_c$) applied to all structural members according to IACS Common Structural Rules (CSR) (Rizzuto et al., (2010)).

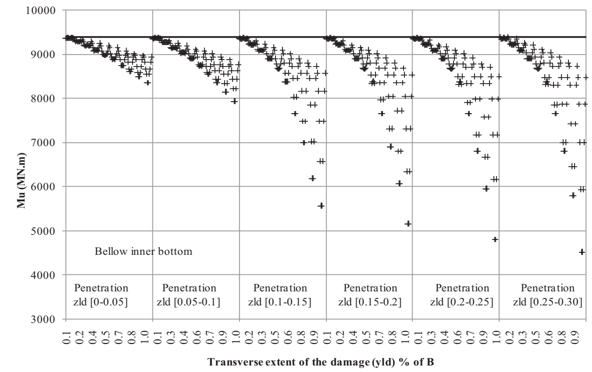


Figure 42: Ultimate strength M_u of the hull girder for the different grounding damage cases. Rizzuto et al., (2010).

In the case of damaged ships the applicable environmental conditions used for assessing wave induced loads are typically taken to be less severe than the North Atlantic model, since groundings and collisions are likely to occur in coastal areas where the traffic density is higher, as done by Luís et al., (2009). Furthermore, a reduced exposure time to the environmental conditions after damage and before the ship is taken to a safe location should be considered when establishing the stochastic model of the extreme wave induced bending moment. Luís et al., (2009) have considered a time period *T* of one week as the voyage duration of the damaged ship to dry-dock and Rizzuto et al., (2010)) have used an exposure time of 24h. Luís et al., (2009) showed that the mean value of the distribution of the extreme values of the vertical wave induced bending moment can reduce by around 15% for a Suezmax tanker when reducing exposure time from one year in the North Atlantic (ATLN) to one week under the environmental conditions of European coastal areas (ECA) (Global Wave statistics (GWS) areas 27, 28 and 30, Hogben et al., (1986)).

The reliability indices of the Suezmax tanker under the two operational conditions, ATLN and ECA, obtained by Luís et al., (2009) are presented in Table 5 (following page) as a function of increasing damages around the keel area.

The ECA condition also considered an increase of 50% of the still water bending moment as a result of the damage. However more accurate predictions of the still water loads that result from the hull rupture and subsequent flooding of ship compartments can be calculated using the approach suggested by Santos and Guedes Soares (2007). It can be seen that in general the reliability in sagging is smaller than in hogging and the reduced wave induced bending moment compensates in most of the cases the reduction in the strength of the ship and the increased still water loads due to the damage. However, since grounding damages affect considerably the strength of the ship under hogging bending moments, the hogging reliability of the ship with large damages around the keel area may be lower than the one of the intact ship in sagging under the ATLN conditions. This suggests that the hogging failure of the ship in ballast and partial loading conditions should be analyzed carefully when assessing the structural safety of ships with grounding damages.

Table 5: Reliability indices of a Suezmax in sagging and hogging

	Sagging			Hogging		
	$M_{u,int}$ / $M_{u,dam}$	ATLN	ECA	$M_{u,int}$ / $M_{u,dam}$	ATLN	ECA
Intact	1.0	1.77	2.15	1	2.12	2.15
Damage (GCD) - 20%	0.985	1.67	1.88	0.957	1.84	1.88
Damage (GCD)	0.982	1.65	1.82	0.948	1.78	1.82
Damage (GCD) + 20%	0.979	1.63	1.74	0.935	1.69	1.74
Major Damage (GCMD) - 20%	0.983	1.66	1.67	0.925	1.61	1.67
Major Damage (GCMD)	0.979	1.63	1.52	0.903	1.46	1.52
Major Damage (GCMD)+ 20%	0.970	1.57	1.36	0.88	1.28	1.36

The variety of damage states, depending on type, location and extension of the damage enlarges considerably the space of possible accidental conditions that in principle need to be considered in the design. A natural evolution in the definition of the damage state is the adoption of probabilistic models that can weigh the various scenarios according to their probability of occurrence.

The various elements that an effective characterization of a design scenario for a ship in damage conditions should include have been discussed by Rizzuto et al., (2010)) using a Bayesian Network model, highlighting the need for a proper accounting of the relationships among such elements. A flooding scenario is characterized in general by static and dynamic global loads, as well as by a reduced capacity. In actual terms, the extension and position of the damage in the hull envelope at the basis of the accident determines the extension of the flooding itself, the static equilibrium position, the sea-keeping performances of the hull (including wave loads) and, last but not least, the residual capacity of the hull girder. Moreover, the sea conditions may be statistically dependent (or not) on the specific accident, i.e. there could be a functional link between the sea state and the occurrence of the accident. All these aspects should be properly accounted for when defining a design scenario, which will be necessarily simple, but also realistic and coherent (in order to be representative). The possible relationships recalled above are presented in Figure 43 for the case of an incident corresponding to loss of containment in the hull envelope.

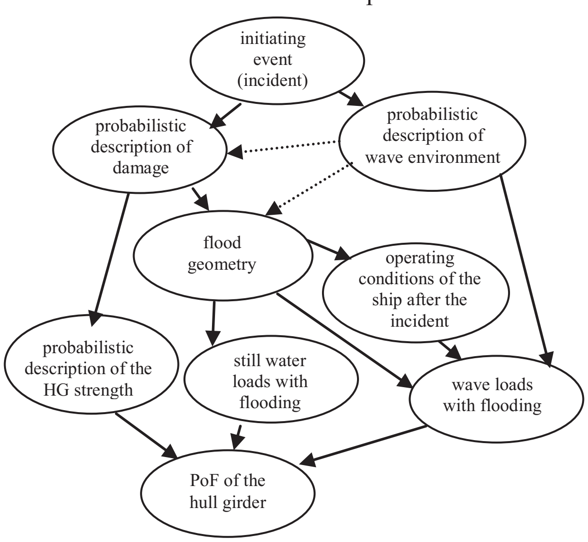


Figure 43: Functional diagram for an incident corresponding to loss of containment in the hull envelope (Rizzuto et al., (2010))

Rizzuto et al., (2010) have considered a specific incident corresponding to a grounding event occurring in the hull bottom at mid-length and creating an asymmetric flooding in Ballast Tank #3 (BT3) portside. This scenario has been considered as the most relevant for the hull girder failure. However in a more general application of BN for identification of critical scenarios, the flooding of all the combinations of compartments of the ship must be analyzed.

Based on this specific scenario**,** Rizzuto et al., (2010) have calculated the probability of failure of the hull girder conditioned to occurrence of flooding in BT3. Such a probability is shown in the second column of Table 3 for different characterizations of the sea environment.

It can be seen that the environmental characteristics influence greatly the results, because of the impact they have on the dynamic component of loads. These results in particular show the paramount importance that establishing a link between damage occurrence and the presence of severe sea states implies on the damage scenario definition.

The probabilities above reported (P(HGF | F.BT3, Grounding)) should be weighted in actual terms by the probability of flooding (only) BT3, conditional to a grounding event (2×1.19%) and by the probability of having a grounding given an incident times the probability of having an incident ($P_{25years}$(Ground.)). The last two probabilities can be derived from tanker incidents data. These calculations are reflected in the unconditional probabilities of hull girder failure (P(HGF)) and associated reliability indices presented Table 6, column 3.

In unconditional terms, probability of failure of the hull girder in the specific damage scenario is very low, which is in line with the results of previous studies performed on the reliability assessment of damaged ships, as recently reviewed by Teixeira and Guedes Soares (2010). On the other hand, this type of probability associated to a single case has not a practical meaning. The conditional probability should instead be regarded as a value to be used in a comparative evaluation within the same class of incidents for the sake of selecting the most representative one. Once the choice has been made, the risk associated to the whole class is in principle to be transferred to the single case (design case).

Even though the specificity of the analysis developed by Rizzuto et al. (2010) did not allow any firm conclusion on the selection of a design scenario for grounding events, the work intended to give a contribution from a procedural point of view for a better treatment of accidental situations in the formulation of design checks in accidental conditions.

In the damaged condition the annual probability of failure ($P_{f\ damage}$) can be defined as the product of the probability of occurrence of a damage scenario i ($P_{damagei}$) times the conditional probability of failure given this scenario ($P_{f\,|\,damage\ i}$), and accumulated over the number of relevant scenarios.

$$P_{f\ damage} = \sum_{i=1}^{all\,scenarios} P_{f\ damagei} = \sum_{i=1}^{all\,scenarios} P_{damagei} \cdot P_{f|damagei} \quad (1)$$

In practice a very limited number of scenarios need to be considered since for most of them $P_{damagei}$ or $P_{f|damagei}$ are not relevant.

Table 6: Probability of failure of the intact and damaged hull girder

	Sea environment	P (HGF|F.BT3,Grounding)	P (HGF)
Intact Ship	North Atlantic (ATLN) T=25 years (IACS Rec. 34)	-	3.08E-02 (β=1.87)
Damaged Ship	South Africa (SA) (GWS Area 85), T=24h	4.18E-04 (β= 3.34)	1.09E-06 (β= 4.74)
	SA (SD truncated) ($H_s \geq 7.5$ m), T=24h	6.50E-02 (β= 1.51)	1.69E-04 (β= 3.58)
	ATLN, (IACS Rec. 34), T=24h	1.38E-03 (β= 2.99)	3.61E-06 (β= 4.49)
	ATLN (SD truncated) ($H_s \geq 7.5$ m), T=24h	5.36E-02 (β=1.61)	1.40E-04 (β= 3.63)
	P (Flooding of BT3 | Grounding) = 0.0119 (BT3 portside)		
	P_{annual}(Grounding)= 4.64E-03	$P_{25years}$(Ground.)= 0.11	

7. CONCLUSIONS

This paper has presented an overview of the results obtained in the MARSTRUCT project by a large number of European research groups. The summary, necessarily brief and limited, has covered a set of studies that have produced interesting results, some of which are unpublished yet and others briefly summarize published results. Each of the topics is aimed at being self contained in the method and conclusions obtained, although the details are not covered.

The general set of problems treated will give a flavor of what are considered relevant present day problems related with marine structures, from load assessment to strength assessment and experimentation and to design and safety evaluation. The reference list will hopefully allow the follow up of more details regarding each of the studies.

8. ACKNOWLEDGEMENTS

The work reported has been performed within the project ‘‘MARSTRUCT’’-Network of Excellence on Marine Structures’’ (http://www.mar.ist.utl.pt/marstruct/) and has been partially funded by the European Union through the Growth program under contract TNE3-CT-2003-506141. This paper has been written within the activities of MARSTRUCT VIRTUAL INSTITUTE, (www.marstruct-vi.com).

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Discussion

Wei-Cheng Cui, Visitor

I am honored to be invited by the SNAME Papers Committee to write a formal discussion of the paper, "European Research in Marine Structures," by Carlos Guedes Soares et al. The paper is long and contains many research findings. By reading the paper my knowledge on marine structures is greatly updated. I think the paper is a very valuable reference for research students and even professionals.

In Europe it is a very good practice to organize experts together to attack a problem of common interest. It has the advantage of sharing the facilities and reducing the repetition of human resources. This paper provides an overview of the results obtained in Europe by a network with a large number of research groups in the field of Marine Structures during a period of 6 years. It covers a very wide areas of research topics and for the purpose of clear presentation, the authors organized them into 6 main topical areas, namely, Methods and Tools for Loads and Load Effects, Methods and Tools for Strength Assessment, Experimental Analysis of Structures, Materials and Fabrication of Structures, Methods and Tools for Structural Design and Optimization, and Structural Reliability, Safety and Environmental Protection. Due to the limit of space, each of the topics can only be presented in a brief manner, including only the main research findings and conclusions. Many references provided in this paper may compensate this shortcoming for those readers interested in a specific topic.

In terms of the current scientific research on marine structures, the paper covers the most important research fields for marine structures established before this project started. Many numerical and experimental investigations have been carried out and the results and conclusions obtained from the project deepen the current understanding of each of the topics studied. It can be said that this research represents the current state of the art. However, it contains no significant technical breakthroughs or new research directions. The authors, or more widely the researchers, who participated in this project should not be blamed, as this is a characteristic of modern science built on the foundation of western philosophy.

One of the significant differences I have found between western and eastern philosophy is that western philosophy pays more attention to the details of each part and then constructs the whole picture by reasoning from the parts. Oriental philosophy, on the other hand, pays more attention to the overall picture rather than the details of each part. The influence of this philosophical difference in science can perhaps be more clearly seen by comparing western and Chinese medical science. With regard to the problems studied in this project, if one asks critically why do we need to investigate these problems and are they really important to ensure the safety of marine structures, the answer may not be so positive as is implied by the authors of the paper.

Let us take one typical problem of ensuring a designed ship of adequate safety in its future service time. The problem can be roughly separated into three parts: the future loading process, the stress analysis for a given loading, and the damage process from an unknown loading history - because it is a future event.

Philosophically, the future loading process can never be known. There is no theoretical relation between the past environmental condition and the future environmental condition since future environmental condition is greatly influenced by human activities on Earth. Figure1 shows the Green House Gases (GHG) change over the last 650,000 years, cited from

Intergovernmental Panel on Climate Change (IPCC) 4th Assessment (AR4) Report. From this figure, one can see that the increase of GHG during the period from 1970 to 2004 reaches up to70% above levels from a very long period in the past. Recent frequently-occurring extreme environmental disasters provide another piece of evidence for this unpredictable statement. Therefore, extrapolation from past statistics to derive the future design load involves a large uncertainty. Let us assume this uncertainty is of the order of ε1=1.0.

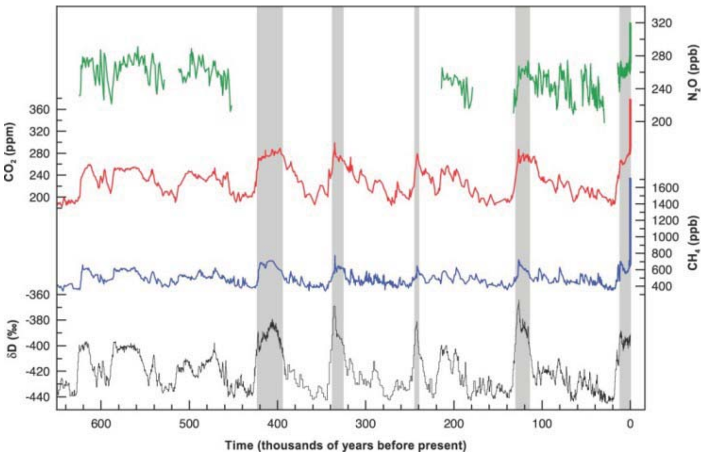

Figure 1: Green House Gases (GHG) change over the last 650,000 years (Intergovernmental Panel on Climate Change (IPCC) 4th Assessment (AR4) Report)

Modern western science is good at calculating the stresses for a given loading. In this project the main contributions are within that category. The uncertainty from the simplified method of the beam theory level may be estimated as ε_2=0.2~0.5; modern FEM analysis can reduce this uncertainty to ε_2=0.03 ~0.1.

The typical damage process for a ship may be described as follows. As the ship is put into service, the fatigue damage and corrosion damage will gradually accumulate and to a certain degree, a crack occurs and then the crack propagates. The strength of the ship will decrease as the crack propagates and the corrosion wastage increases. When the residual ultimate strength is lower than the instantaneous external loading, ship collapse occurs. Theoretically speaking, the fatigue damage process for a given loading history and the corrosion damage process for a given sea environment can be investigated through experiments, but the current capability to predict the fatigue crack growth is very limited. The uncertainty for the damage process from an unknown loading history is even larger. Let us assume this uncertainty is of the order of ε_3=0.8.

The total uncertainty for ensuring a designed ship of adequate safety can be estimated by the following formula:

$$\varepsilon = \sqrt{\varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_3^2} \tag{1}$$

If we keep ε_1=1.0 and ε_3=0.8, then the effect of reducing ε_2 on ε can be shown in Table 1. From this table one can see that the effect of reducing ε_2 on ε is very small after the beam theory accuracy. Therefore, from a systematic point of view, if our real purpose is to ensure the safety of a ship, the most urgent tasks should be the reduction of uncertainties in ε_1 and ε_3 rather than further reduction of ε_2.

Table 1: Effect of the stress calculation uncertainty on the uncertainty of safety assurance of a ship

ε_2	0.5	0.3	0.2	0.1	0.05	0.00
ε	1.375	1.315	1.296	1.285	1.282	1.281

The effective way of reducing the uncertainty in ε_1 is the environmental protection mentioned in this paper but little effort has been devoted to that. In terms of reducing ε_3, linear cumulative fatigue damage theory does not have the potential, while fatigue crack propagation theory does. This has been discussed in Ref. [1].

The purpose of this criticism is to allow us to reconsider the role of modern science since, from a philosophical point of view, modern science may not be as powerful as we have thought. Development of medical science can never be sufficient to solve all the health problems of human beings, neither is natural science sufficient to solve the "health" problems of engineering structures. The overall guidance of human behavior plays a more important role in ensuring the health of human beings and even engineering structures.

Reference

CUI, Wei-Cheng, Wang Fang and Huang Xiaoping (2011). A Unified Fatigue Life Prediction (UFLP) Method for Marine Structures, Presented in the workshop at DTU to honor Professor Preben Terndrup Pedersen's 70th birthday, Oct. 29,2010 and published in Marine Structures, Vol.24, No.2, 153-181.

Chen-Far Hung, Visitor

This paper presented the results from the MARSTRUCT project during a period of 6 years, in which 33 research groups from universities, research institutions, classification societies, and shipyards have cooperated. The project includes methods, tools, and experiments for following subjects:

- loads and load effects assessment;
- structural strength and performance, including aspects such as ultimate strength, fatigue, and crashworthiness;
- design and optimization of ship structures;
- reliability, safety, and environmental protection of ships.

I would like to express my deep appreciation to the authors for providing the highly valuable information and the plentiful, interesting results. I understand that the paper gives only a brief and limited description of the project, so some questions and comments are given below:

4. The ship grounding and collision simulations involve highly geometric and material nonlinear problems. In the impact analysis by non-linear FEA, the mesh size, distribution of mesh, and failure model of material are very sensitive to results, and the paper has shown these effects on the analysis results. Is there some common guide to account for the mesh sensitivity? The effect of model of contact surface and material model in the same case also play significant roles, especially in composite structures. Can the authors provide some information about those effects?

5. During the collision the kinetic energy of both colliding vessels will be redistributed, and a portion of the kinetic energy will be transferred to damaged structures of both vessels. In the early stage of collision, or when the kinetic energy change of both vessels is still relatively small, the damage to the structure of both vessels could be approximated by quasi-static analysis. When the kinetic energy of each vessel has changed significantly, can the motion of both vessels affect the damage results of the impact analysis? Are there some discussions on the effects of impact on the safety of onboard equipment (e.g. the main engine or auxiliary machines)?

6. The test result of the ultimate bending moment of the box girder showed that the residual stresses are very important in this type of experiment. The initial residual stresses depend on detailed design and manufacturing process. The experiment of the ultimate strength of the corroded stiffened box girder also showed highly interesting results. The two experiments provide a clear illustration of the extreme conditions beyond design limitations, and also valuable information for risk evaluation. Are there further results that can suggest guidelines for quality control of fabrication and the management of maintenance?

7. Optimization of the ship production process is a very complex problem with a large number of factors such as: huge volume of data, material flow, job flow, working space, layout of fabrication facilities, the labor quality, as well as the types and amount of products. They must all be taken into consideration, and some of these parameters are not easy to define as reasonable design variables (continuous or discrete). For some problems, an improved solution can be found, but it is difficult to find the final optimum solution. The solutions also depend on the production simulation and the search algorithm. The research results shown in the paper demonstrated that the ship production process can be optimized successfully with a reasonable production simulation; however, it is not easy to classify the difficulties of the solution level of the research cases.

8. The results of an optimization problem depend on its definition and search algorithm. In the section 'Benchmark on structural optimization of mid ship section of a fast ferry', the design variables, modeling, analysis subjects and constraint conditions, optimization tools, and the found results between five code cases were compared. The type of variable variation (continuous or discrete), constraints onvariables, and analysis modeling are different in the five cases; the solutions should also be different among the five cases. The results in the report show that the five codes can find an improved design successfully; the relative performance between each code is not suitable for comparison. Perhaps for the benchmark study purpose, the objective function was simplified as minimum weight. If the objective function is defined as cost including material cost, building cost, and maintenance cost, and the discrete variables related to market material list are used, then the solutions may be more practical.

Professor Jeom Kee Paik, Fellow

This paper reviews some important results recently obtained by a number of research groups in Europe in the area of Marine Structures, and could be useful to better understand the technical challenges and issues to be resolved. It provides a state-of-the-art review representing recent advances and future trends, although the review is limited to the literature authored by European experts.

Some critical comments are provided below as suggestions to improve the quality of the paper.

Section 2.1 Comparison of numerical and experimental slamming impact pressures. Figure 2 shows some examples of pressure predictions and comparison with experimental measurements. However, the results are very scattered, and the differences between the methods are very large. It seems that the methods applied are not successful in predicting slamming impact pressures. The profile of slamming impact pressures in terms of pressure versus time history can be characterized by four parameters, namely rise time until peak pressure, peak pressure, decay pattern after reaching peak pressure, and duration time. It is advised to clarify it more clearly in this regard. The paper mentions that RANS-based methods produce the closest agreement with experimental investigations. Is this a general conclusion?

Section 2.2 Simulation of the behavior of double bottoms under grounding actions. In this type of accident, cutting and crushing are dominant failure modes rather than buckling and plastic collapse. In terms of numerical computations, it is extremely important to define the rupture/fracture criteria, which will significantly affect failure mode and subsequently energy consumption patterns. It is recognized that the fracture criteria in nonlinear FEA depends on the mesh size, among other factors.

Section 2.2.2 Benchmark study. Figure 9 shows mesh models in the vicinity of the impact zone on the girder, using DYNA and ABAQUS programs. It is considered that the mesh model is too coarse to accurately simulate the grounding response. Also, I wonder why the test models of bottom structures used flat bar stiffeners rather than angle or T-bars, which are more realistic. In Figure 10, both vertical and horizontal forces show a similar trend with time in terms of comparing 'fully stiffened model' and 'only plating stiffened model'. Again, the definition of rupture/fracture criteria is unclear. Considering that there are many uncertainties in the simulation models, it is premature to make any definite conclusions based on these limited results.

Section 2.3 Load effects induced by abnormal waves. Is the body plan of the FPSO shown in Figure 12 new-built or converted? The trend of the simulations obtained by Fonseca et al. (2007) in terms of VBM versus L_{pp} is opposite to the rules.

Section 3.1 Benchmark study on the use of simplified structural codes to predict the ultimate strength of a damaged ship hull. For a damaged ship hull, the principal axis of the cross-section is rotated compared to the principal axis of the intact ship. However, as far as the hull girder collapse is concerned, the ultimate hull strength under vertical bending moment should be calculated with the horizontal axis, which is the neutral axis of the damaged ship hull parallel to the water line, and must be positioned in the right angle to the centre of earth. A damaged ship may be heeled due to water ingress or outflow of cargo, but even in this situation, the hull girder collapse strength should be evaluated with regard to the horizontal axis of the hull cross-section, parallel to the water line. The effect of residual stresses is usually significant in the ultimate strength of welded structures. However, it is said that welding residual stresses can be released due to the bending actions of ship hulls. One disadvantage of using the Smith method to analyze progressive collapse behavior of ship hulls is that stiffened panels must be modeled by beam-column elements with attached plating having effective width. This method can produce many computational errors when the stiffened panels fail by different collapse modes (e.g., tripping, stiffener web buckling, overall collapse) from beam-column type collapse. Also, when the initial imperfections together with combined loads are involved, it is not straightforward to define the effect width properly. It is observed in the paper that the ultimate bending moment has a higher variability in predicting sagging ultimate moment rather than hogging ultimate moment. Why? The discusser thinks that this may also be partly due to the disadvantage of using the Smith method. The paper mentions that the simplified methods may not be used for damaged ships. However, as long as the assumption that damaged members or parts are removed in the computations is accepted, the simplified methods will give reasonable computations.

Section 3.2 Benchmark study on the analysis of fatigue in joints. I wonder what the effects of thick plates and higher strength steel (e.g., YP40, YP47) in terms of crack initiation and propagation in the plate thickness direction would be. The studies in the papers utilized thin-shell elements considering the plate thickness effect.

Section 3.3 Benchmark study on collision resistance simulations of ship structures. As discussed in Section 2.2, the definition of fracture criteria in nonlinear FEA significantly affects the nonlinear structural consequences after collision. It is unclear how to deal with this problem.

Section 4.1 Test on mild steel box girders subject to pure bending moment. A photo showing a side view of the test set up together with a schematic plan would be helpful to better understand the test set up. The effect of initial imperfections in the form of residual stress and initial distortions is significant, particularly in small scale tests applied in the paper. Welding residual stresses are generated by equilibrium between a tensile residual stress block in the heat-affected zone and a compressive residual stress block in the middle of plate. If tensile residual stresses disappear due to load cycles, then the compressive residual stresses will also disappear. Besides, as discussed in Section 3.1, the effect of welding residual stresses may not be considered in terms of ultimate bending moments if cycles of bending actions are considered.

Section 4.2.1 Experimental set up of corrosion deterioration. It is unclear what the real yield stress of test material was, and what the test temperature was. What is the effect of temperature on the corrosion rate? The test results show that the corrosion distribution is non-uniform, and several places are exposed to very large corrosion damage. What is the reason for considering that the test structure is relatively small and the corrosion environment is almost uniform?

Section 4.2.2 Experimental set up of ultimate strength test. Regarding the moment-curvature relationship (Saad-Eldeen et al., 2011c), the linear range will be followed by geometric nonlinearity rather than by material nonlinearity, because the test model has very thin plates and subsequently elastic buckling must occur earlier. Also, it is important to realize that mechanical properties of steel are not changed regardless of corrosion damage. The unloading path in the ultimate bending moment regime is due to loss of redundancy, causing instability of the structure, which is typical behavior in collapsed structures.

Section 4.3 Fatigue tests. It is unclear what the new results compared to the existing database are.

Section 5. Methods and tools for structural design and optimization. The design process can be classified into three groups, namely, concept design, preliminary design, and detail design. What is the main focus of this section? In terms of reducing structural weight in association with green shipping, ultimate strength-based structural optimization is required.

Section 5.1 Benchmark on simulation and optimization of the ship production process. In addition to those described in the paper, it is rather important to develop a scheme for managing quality assurance and quality control in terms of fabrications and others.

Section 5.2 Benchmark study on global optimization of a fast ferry. What is the design criterion? Is it ultimate limit states? By structural optimization, what structural weight reduction was achieved compared to the traditional rule-based design methods?

Section 5.3 Benchmark study on structural optimization of the midship section of a fast ferry. It is considered that the mathematical algorithms for structural optimization must be similar, but the main differences are due to the ultimate strength criteria. In other words, the ultimate strength calculation modules in the process of structural optimization will be a key element to obtain accurate design results.

Section 6 Tools for structural reliability analysis of marine structures. The collision location can also be in the lower part of a struck ship. The accuracy of risk calculations is primarily dependent on selection of probable accident scenarios. It is unclear how to select such scenarios.

Section 6.1 Risk based maintenance of deteriorated ship structures accounting for historical data. It is not realistic to dry-dock for repair and maintenance, but on-site repair should be applied as necessary.

Section 6.2 Structural safety of damaged ships. It is required to distinguish three types of grounding, namely, grounding with forward speed, stranding, and squatting. The first type of grounding causes raking damage including transverse frame failure. Therefore, the one-sliced model of ship hulls between two adjacent transverse frames may be applied for the ultimate bending moment calculations.

Dr. Neil Pegg, Visitor

Thank you for giving me the opportunity to review this impressive volume of work, much of which I was not aware of. I am sure the audience will also find this summary of several years of work by several authors enlightening. Certainly much of this work is complementary to other efforts outside of the European Union and hopefully will lead to further collaboration and advancement of specific areas of technology.

Computer power is now making it possible to use computational fluid dynamics for practical applications, and the discussion on the use of various CFD codes for predicting slamming pressures is very timely. Indeed, there is similar work underway in other international research organizations.

The subject of guidelines for using FEA for specific problems such as collision and grounding is also very important to the marine industry. The challenge of having failure criteria dependent on element size is one that we have also recently come across in some similar work. It would be interesting to know more about why a fairly large difference of 15-30% was reported between ABAQUS and LS-DYNA results. Under "Methods and Tools for Strength Assessment", the paper refers to a "best practice document on finite element modeling" but does not give a reference, which would be valuable.

The benchmark study on simplified methods for ultimate strength echoes earlier work done in ISSC. I believe the captions are reversed on the hogging and sagging curves. The conclusion that the approximate methods agreed well with each other may be somewhat optimistic as the hogging results seem to vary by about 40%. Further discussion on the reasons for differences between the methods would be interesting.

The experimental program on the effects of corrosion on box girder ultimate strength is well described. The term "global efficiency" is referred to but not defined.

I found the discussion on optimization of the ship production process particularly interesting and timely as Canada is just embarking on a program to build about 50 major Navy and Coast Guard ships. Further work in this area would be of interest to Canadian and worldwide ship yards. It is good to see that there is considerable work continuing in structural reliability, which has been a difficult topic to bring to practical use in ship design and maintenance.

While this is a paper covering an enormous body of work which will be of interest to many readers, there are a couple of shortcomings which could be easily improved. Bringing work together from such a large number of authors is a challenge, and the paper has many errors in figure numbers. It could also be enhanced by more discussion on lessons learned and direction for future work in the various areas covered. There is also little discussion of one of the stated goals of the project on improving collaboration between researchers across Europe. What practices were put in place to encourage this, and were they successful?

The international community will benefit by being made aware of this body of work, and hopefully additional publications will further expand on what has been presented here.

Professor Y. Sumi, Visitor

The authors are to be congratulated for the very comprehensive presentation of the work, whose results are obtained in the MARSTRUCT project by a large number of European research groups. Having read this very interesting and informative paper, the discusser would like to ask two questions which are related to abnormal waves and corrosion effects, respectively.

In Chapter 2, the authors describe the load effects induced by abnormal waves (section 2.3). Although the highly non-linear aspects of analysis methods of the wave-induced load (such as slamming and whipping) are common to FPSOs and ships, the probability of occurrence of abnormal waves may significantly differ for sailing ships and moored offshore structures. How do the authors consider these differences, including the human factors in navigation in structural design? The authors are kindly requested to comment on this issue.

The authors describe the solution procedures in relation to the structural behavior after accidental events such as grounding (section 2.2) and collision (section 3.3), where uncertainties related to the failure criteria under multi-axial stress states and the representation of hardening in the plastic range under varying strain rates are considered. Then a question may arise as to how one should estimate the effect of corrosion with regard to the deformability and energy absorption of grounded or collided structures. Having learned the corrosion-dependent ultimate strength assessment of aged box girders presented in paper (Chapter 4), the discusser would like to have the authors' view point on this problem. In our experience, we observe considerable decrease of deformability and energy absorption of corroded plates, while the strength reduction is still moderate [see Ref.1].

Reference

AHMMAD, Md. Mobesher and Sumi, Y. (2010), Strength and deformability of corroded steel plates under quasi-static tensile load, Journal of Marine Science and Technology, 15-1, pp.1-15.

Ge (George) Wang, Member

First of all, I would like to express my appreciation to the authors for an excellent summary of MARSTRUCT, the EU Network of Excellence in Marine Structures.

I heard about MARSTRUCT from Professor Guedes Soares a couple of years ago when he visited us in Houston. Since then, I have been following the many studies of MARSTRUCT, and have enjoyed participation in several conferences that are part of this initiative.

This initiative is great in that it promotes cooperation among the leading research groups in Europe. MARSTRUCT has been impressive for the scale of cooperation, the volume of research work, and the values of produced research papers and reports.

Today, I feel it an honor to be given the opportunity of discussing this paper.

1. As we all know, the ship structural designs have been modernized during the 1990's and 2000's. The basis of ship structural design is rationalized. This revolution is reflected in the IACS Common Structural Rules for tankers and bulk carriers. The marine R&D community should feel very proud of this. These newly adopted class rules are formulated based on loads and strength evaluations that are built upon the achievements of long-term research and development. Without the results of extensive R&D, it would not have been possible for ship design rules to be rationalized.

   While rules have proceeded to a stage of unification, we are still facing technical challenges. One question that is being asked is – how can we refine our rules to achieve the best representation of the problems they are meant to solve. The methods for assessing strength and fatigue are established. The uncertainties of these methods are, however, not yet fully understood, though the rules are devised to be on the conservative side in general.

   MARSTRUCT is to be commended for conducting benchmark studies on predicting ultimate hull girder strength and fatigue strength of structural joints. Comparative studies like this will help us understand better the inherit uncertainties in various analysis methods and the uncertainties associated with the problems these methods are intended to deal with. I am sure that many of these results have been reviewed when classification societies develop and refine the design rules.

2. Another trend is that we are more and more required to think about the through-life value of our ships. This calls for considerations of not only initial construction and design but also the integrity of structures when a ship ages. It is equally important to note that MARSTRUCT has looked into this issue via programs for "modeling strength degradation phenomena and inspections used for reliability assessment based on maintenance planning" and "current practices and recent advances in condition assessment of aged ships". With the design rules are increasingly modernized, I expect to see more and more research efforts on life cycle management.

3. In addition to the traditional topics of loads and strength, MARSTRUCT also takes on the themes of risk and reliability analysis. I am glad to see their applications to damage, life cycle management – these areas are really where risk and reliability approach can find best values.

Overall, the initiative of MARSTRUCT is great. It has produced a tremendous volume of valuable technical papers that have contributed to the technology advances. To work collaboratively with so many great universities is in itself a success.

Congratulations to Professor Guedes Soares for leading MARSTRUCT. My thanks also go to all the coauthors, most are my personal friends, for making MARSTRUCT a success, and introducing this program to SNAME.

Authors' Response

The authors would like to thank the discussers for the time taken to comment on the paper and for the useful input and thoughtful questions, which will be answered to each of the discussers separately.

Professor Cui has looked at the global activity reported in the paper and has discussed aspects related to the way research is done in eastern and western countries and also discussed important aspects about how the directions of research should be decided in order to address the problems that contribute the most to the uncertainty of the safety predictions in ship operation.

It appears that Professor Cui has considered that this paper reflects the nature of all research done in Europe and that it corresponds to a plan to make the industry safer, and thus a clarification is required about the nature of research and its funding in Europe.

With the creation of the European Union (EU), the research funding which was until then of national origin started having two components, the National one and the European Union one. The emphasis of the EU funding has changed with time, typically with 5 year Framework programs, the 7th of which is now finishing. Although the EU funding also contemplates basic research in several fundamental disciplines, the major part of it goes to more applied type of research. An important feature is that it aims at promoting European cohesion and European dimension of research and thus it requires that funding should be sought by consortia of partners of several countries of different natures; combining universities, research institutes, and companies of different natures; and also contemplating small and medium size companies in some cases.

The natural evolution was that the National support for research has concentrated more on scientific issues of more fundamental nature, often done by only one research group or more recently by 2 or occasionally 3 groups. So, more fundamental research that often needs a long time to develop has tended to be funded nationally in complement to the EU research funding. So the European research cannot be thought as being only the EU funded one.

Some EU programs deal with more scientific type of problems such as environment and climate, while other are of more industrial flavor such as surface transportation and manufacturing. These later projects are product or result driven projects often led by the industry that will be using the results of the research.

An exception to this general approach was the present project that was a research network instead of a collaborative project and was dominated by research groups from Universities, having also research centers and Classification Societies, as opposed to the collaborative projects in which Universities cannot dominate and a balance needs to exist between different types of institutions.

So, while in a collaborative project the developments aim to reach one predefined objective, in the present project the main aims were to improve the cooperation among the research groups, leading to a better knowledge of their strengths and weaknesses, through a program of joint research and exchange of personnel. This has dictated the type of research that was possible to be done in the project: it was necessary to identify topics in which several research groups were currently working and to define a short term plan for their cooperation around that topic. The work done in this project was thus very much driven by the research topics that were already on-going at the research groups and were relatively mature. This also led to give more emphasis to benchmark studies which allowed inter-comparison between the methods developed at the different groups providing more solid basis for the work in those areas.

Professor Cui then goes on to justify that the largest uncertainties are in the descriptions of environment and of the induced loads, suggesting that more work should be concentrated on load modeling than on analysis of structures. We agree that the largest uncertainties are in the assessment of the loads on the structures and this is the reason why one of the 6 work packages in the project was in the estimation of the load effects. Furthermore the effect of climate changes was present in some considerations and some work was done in assessing the uncertainties in the present wave databases as a support for future predictions.

Significant efforts were devoted to methods of structural analysis and design, not because they are the more uncertain ones but because the objective of this project was to address structural analysis and design.

Professor Hung touched on various questions of different topics, which are responded in the same sequence.

1. The simulations for ship grounding and collision simulation depend on element type and size, material mode and rupture criterion. From the studies related to grounding resistance it was found that a rupture criterion based on Mises strain depending on element size and an element size of approximately 50 mm, i.e. length over thickness of element equal 2 to 3, are appropriate for the analysis. However, it is noted that not all deformation modes may be treated using a "universal" rupture criterion and applying the same guidelines regarding the selection of element size. Generally speaking there are no common guidelines for mesh sensitivity in the impact analysis which are agreed upon or could be considered generally applicable. References 15-17 discuss this issue in detail and they are clearly referred to in this paper.

   Regarding the effect of model of contact surface and material model it can be observed that comparative ship collision or grounding simulations typically utilize a rigid indenter to ensure an equal deformation shape for each alternative, hence, the contact area only depends upon the stiffness of the struck structure. This approach, together with quasi-static simulations as presented in this paper, results in the characteristic structural response to indentation of the structure in question. If the contact surface (i.e. striking geometry) is modified, the scenario is changed and hence a straightforward comparison becomes impossible. Furthermore, our experience shows that this approach is very realistic since a typical deformation of, i.e. a bulbous bow, is fairly limited during a collision event (unless it is specifically designed to absorb energy) because of its significant internal stiffening system. As a result, a general force versus penetration curve is not influenced much by the minor deformations of a bulbous bow or hard ground, which is the common indenter choice. The choice of material model and the sensitivity to the collision resistance is also discussed by reference 15-17, therefore it is not included in this paper as well as the possible influence of composite structures. The latter are typically not utilized for merchant vessels, where accidental analysis concerning collision and grounding are however relevant since they account for 20% of the accidents.

2. Related with the second question, in previous FE investigations it has been observed that at least for collisions with the struck ship assumed stationary, the structural damage occurs at the early stage of the collision, before the transfer of kinetic energy from one vessel to the other. Professor Hung has also questioned if there are there some discussions on the effects of impact on the safety of on board equipment like the main engine or auxiliary machines. That is not the case as it is outside the scope of the current article (and project) since it focuses mainly on the questions of the structure.

3. After recognizing the importance of residual stresses Professor Hung asked for further results concerning the control of fabrication and maintenance aspects. Some work was done on numerical studies of thermo mechanical behavior during welding (not addressed in this paper due to space limitations) and also of risk based structural maintenance planning (see section 6.1) but residual stresses have not been studied in isolation.

4. As regards the process simulation, the benchmark performed in MARSTRUCT was intended to demonstrate the efficiency and accuracy of two commercial simulation tools to model the production process typical of the shipbuilding industry; for this reason a simple but significant test case was selected, able to include some of the most common difficulties in modeling the process but not excessively complicated due to the budget constraints of the research activity. The simulation model of the whole ship production process would certainly involve much more modeling effort and would be much more resource consuming but it would not add further complexity.

5. In the optimization study we fully agree that, from a theoretical point of view, the comparison among the different codes is not completely fair; nevertheless we contend that this situation is representative of what really happens in reality, where different designers have consolidated design tools and are not free to select the best-in-class tool for every specific application. From this perspective, a more complex objective function taking into account other kinds of costs would have made the benchmark virtually impossible, due to the fact that many commercial codes used do not allow for user-defined objective functions.

Professor Paik has provided several comments and an extensive list of questions.

1. Concerning the comparisons with impact pressures, it is important to note that this is not a paper on slamming per se and thus only limited space can be devoted to the discussions of the details. However, the behavior of the different methods used with respect to each of these characteristics can be seen in the examples given in the paper. The figures and the text clearly say that there are differences. That was the whole point of this investigation.

   The paper also clearly shows that, for example Openfoam and Flow3D provide the closest results to the experiments, even in the difficult to model cases of impact at an angle (asymmetric impact). This conclusion is based on the results of this investigation.

   Finally, it is accepted in the community that current numerical methods have deficiencies, depending on the assumptions used, in fully describing impact induced pressures; this is applicable to slamming and, in particular, sloshing, as included in the Report of Committee V.7 Impulse Pressure Loading and Response Assessment of ISSC 2012 (pp.367-431).

2. We generally agree with the statement in the second comment. This is discussed in the last paragraph of 2.2.1 and 3.3.

3. Concerning the benchmark study, a 25 mm and 50 mm element is appropriate in terms of length over thickness ratio, number of elements between stiffeners, convergence and CPU time. We agree that in order to draw "universal' conclusions, it is necessary to investigate various deformation modes. The rupture criterion is presented in the last paragraph of 2.2.1, where the rupture strain is defined versus element size.

   Concerning the choice of flat bar stiffeners rather than angle or T-bars in the test models of bottom structures, it appears that angle or T-bars may be used in the US, while HPs are common in Europe. However, flat bars are in fact able to perform well in collision or grounding simulations and thus their potential is shown in this study.

   With reference to Figure 10, we agree that the definition of rupture/fracture criteria is unclear, but since this is a comparative benchmark study and since the same criterion is used for all cases the comparison can be considered valid, but we agree that it is premature to make any definite conclusions based on these limited results.

4. The FPSO that have been used in the study of the effect of abnormal waves is a new built one to operate in the region of the Middle East. The study has indicated that the largest responses are for platform sizes that are close to the length of the abnormal wave, decreasing then for longer waves, although the rule requirements for minimum wave loads do not follow the same trend.

5. Concerning the benchmark study on the use of simplified structural codes to predict the ultimate strength of a damaged ship hull, Professor Paik commented that for a damaged ship hull the principal axis of the cross-section is rotated compared to the principal axis of the intact ship, which is true. However the change may be ignored if the area of damage is small compared to the total area of the cross section or the damage is close to the horizontal neutral

axis of the intact ship, which is the case presented in Figure 2 of the paper.

As concerns the horizontal axis of the hull cross-section, it is parallel to the water line only in the case where the angle of heel is equal to the rotation on the horizontal neutral axis. As they result from different phenomena normally they are different. One may understand that by considering a damage in the side shell above the water line where one has a rotation of the horizontal neutral axis but the ship stands in the upright position, or the opposite situation where the ship has a small damage below the water line that floods the lateral tank(s) resulting in large angles of heel and no change in the neutral axis. In both cases the horizontal neutral axis is not parallel to water line.

Concerning the robustness of Smith's method, it is true that it may give very different results depending on the formulation of the load shortening curves of beam-column elements with attached plating having effective width. It is possible, and there are some formulations available (Gordo and Guedes Soares, 1993), to incorporate the most common collapse modes and the effect of main governing parameters like residual stresses in the formulation of beam-column and effective width of plating. But it is not straightforward to include explicitly the mode and amplitude of imperfections or the consequences of combined loads on the load shortening curves, which may result in significant error in very particular combination. However Smith's method can be extended to deal approximately with some of those effects.

Professor Paik has then addressed the fact that the ultimate bending moment has a higher variability in predicting sagging ultimate moment rather than hogging ultimate moment. The explanation that we have to offer is the one that is already in the paper, which is that the differences between the applied procedures to evaluate response of stiffened plates are more significant for more thin plating and slender stiffeners rather than plating of moderate thickness and stocky stiffeners typical for the bottom structure. The variability on the prediction of the stocky stiffened plate's strength is lower than of the slender ones because the former have a collapse dominated by yielding rather than the latter dominated by instability of the associated plate or the stiffener or the column as a whole (Guedes Soares 1988).

Finally Professor Paik asks for a clarification concerning the applicability of simplified methods to deal with damaged hulls, caused by a misunderstanding of a statement in the paper. We do believe that, despite the scatter in results, approximate methods can give good results and this was the main conclusion of the benchmark study. However because the benchmark was based on comparisons among numerical methods and no experimental result was available, it was stated that one could not extract definite conclusions of the benchmark study, despite the results being consistent.

6. Concerning the fatigue benchmark in section 3.2, the question regarding the effects of thick plates and higher tensile steel obviously refer to the thickness step in the deck. Fatigue assessment approaches are usually based on the traditional S-N approach, i.e. the nominal stress approach or the structural stress approach. The latter is able to consider secondary bending stresses occurring at thickness steps which determines the fatigue performance. Detrimental plate thickness effects are usually accounted for by decreasing the fatigue strength of thick plates above approx. 25 mm accordingly. Concerning higher tensile steel, it is common understanding that the fatigue strength is not higher in high-strength steel joints than in mild steel joints.

7. The set-up for the tests of the corroded box girders mentioned in section 4.1 is shown in Figure 22. Limitations of space do not allow more details of the set up to be shown, which however can be consulted in the paper that addressed those experiments (Gordo and Guedes Soares, 2008).

   Some load cycles have been made in the experiment and they will help in reducing the level of the residual stresses, but, as indicated in the paper, it was not possible to remove all residual stresses with this procedure.

8. In the corrosion experiment of section 4.2.1 the two specimens in the form of box girders were tested in a real corrosive environment in direct contact with sea water. The dimensions of the specimens are 1400x800x600 mm The box girders are made of normal shipbuilding steel with yield stress and Young's modulus of 235 MPa and 206 GPa, respectively. The specimens were exposed to Baltic seawater and tested in hot water. The box girders were placed in large tanks and seawater was pumped into the tanks continuously. The temperature of sea water was increased and additionally oxygen depolarization sub process rate was increased by the agitation of seawater, both of which resulted in corrosion rate increase. Detailed information about the corrosion set up may be seen in Domzalicki, et al., (2009).

9. In the ultimate strength experiment of section 4.2.2 Professor Paik is right in mentioning that there are geometric non-linearities that need to be accounted for. However there is no experimental evidence that the material properties do not change with corrosion. In fact, Professor Sumi in his discussion of this paper mentions his results that detected changes in some material properties when performing tension tests. Vu, et al., (2009) conducted a direct tension test on steel wires after 60, 90 and 180 days of exposure to the aggressive solution and concluded that corrosion led to a marked loss of ultimate strain and then to brittle failure of corroded wires. A reduction in the elastic limit and the ultimate strength of corroded stressed wire was observed. Also, a significant reduction of about 25% in the apparent elastic modulus of steel wire was observed. So, while there are still too few tests of corroded material to allow definite conclusions, there is already some evidence

that some properties do change, and these tests have also pointed out in that direction, making it clear that it is important to perform more experimental work to clarify this issue.

10. The fatigue tests reported in section 4.3, on specimens shown in Figure 28, aimed at investigating the fatigue behavior of fillet welded joints where the loading acts parallel to the non-fused root faces and where both the weld toe and the weld root are prone to crack initiation. In contrast to previous tests on doubler plates and lap joints showing only one type of failure, these tests help to validate different fatigue assessment approaches covering both types of failure, i.e. the approaches should predict correctly the relevant failure location which depends on the geometry parameters and local stresses.

11. To clarify the scope of the work related with methods and tools for structural design and optimization discussed in section 5, it should be noted that it covers all kinds of design tools and the three examples mentioned in the paper actually belong to different design phases; we could consider the global optimization of a fast ferry an example of "concept/preliminary" design tool, the midship section optimization an example of "preliminary/detail" design tool and the process simulation a tool for the "detail" design.

    As far as ultimate strength based structural optimization is concerned, the issue is not specifically addressed in this group of activities focused on "tools", but it is dealt with in other sections.

12. Indeed the accuracy of risk calculations are primarily dependent on selection of probable accident scenarios. The complexity in the identification of the most probable accident scenario is due to the large set of interrelated uncertain quantities and alternatives involved. The location of the damage and the damage itself are uncertain quantities that affect the still-water and the wave induced bending moments that follow after the damage and the strength of the possible ruptured hull.

    The various elements that an effective characterization of a design scenario for a ship in damage conditions should include have been discussed by Teixeira and Guedes Soares (2010) and Rizzuto, et al. (2010). In particular Rizzuto, et al. (2010) have used a Bayesian Network (BN) model to analyze a specific incident corresponding to a grounding event occurring in the hull bottom at mid-length.

    The use of Bayesian networks to model accidental events such as collisions and groundings allows the identification of a particular combination of damage location, damage size, and damaged compartments that most likely causes a specified unwanted situation (e.g. the maximum still-water bending moment or the failure of the hull girder).

    Even though the specificity of the analysis developed by Rizzuto, et al. (2010) did not allow any firm conclusion on the selection of a design scenario for grounding events, the work intended to give a contribution from a procedural point of view for a better treatment of accidental situations in the formulation of design checks in accidental conditions. Therefore the question regarding the selection and definition of these accidental scenarios for design purposes is still open.

13. Finally we agree that it is required to distinguish three types of grounding, namely grounding with forward speed, stranding and squatting.

Dr. Pegg had some pertinent comments. He identified the reference to a document on "Recommended practices in finite element modeling". This document still has the status of a project report as it was found difficult to publish it in a Journal due to its character. It is now included in the additional reference list as Chirica et al. (2010).

Dr. Pegg mentioned that ISSC has made a benchmark study with simplified methods, but it was with intact hull girders, while the present one addressed damaged sections, despite a first validation study with intact hulls. He has a point when he noted that there is still a wide variability in the results of the simplified methods to predict ultimate hull strength. For details we would refer to the paper with the account of the study (Guedes Soares et al. 2008). However it should be noted that that for the same method it is to be expected a spread in results for different levels of residual stresses, initial imperfections and boundary conditions, which may be of similar nature. The methods compared had different capabilities with regards to their abilities to model these characteristics.

Dr. Pegg also asked about the lessons learned with respect to collaboration among researchers across Europe. Indeed this aspect has not been covered but it can be said that it has been a challenging task to promote this cooperation. The main difficulty is probably on the synchronization of the timing in the various organizations as it is necessary that the researchers that are likely to cooperate on one specific problem have available time almost simultaneously. In fact this has also been a difficulty in organizing the joint work to be done during the project as sometimes the interested organizations did not have manpower available when some studies were being performed. Clearly the project allowed a much closer knowledge of the capabilities and limitations of the teams involved and this is a positive result for future cooperation.

After the project the organizations continued association through a so-called Virtual Institute, which is nothing more than an association not legally binding but with the aims of keeping some form of cooperation and interchange of information.

Professor Sumi has touched on various specific topics, the first of which are the load effects induced by abnormal waves, touching on the difficult problem of assessing the probabilities of abnormal waves. The present state of knowledge is that there are not methods available to assess the probability of a structure meeting an abnormal wave, being it a floating platform or a seagoing ship. The present knowledge allows the understanding of some mechanisms that will lead to abnormal waves and in some conditions probabilistic assessments are also possible. Guedes Soares et al (2003) used general considerations to indicate that these waves may have an occurrence rate of the order of 10^{-7}, which should only be considered as indicative. Furthermore it is known that these waves are of a transient nature and thus even if they occur they tend to disappear very quickly. So even if the probability of occurrence of such waves would be of that order of magnitude, the other difficult question is to estimate the probability that a floating structure would meet them. This will continue an open question for future research.

Professor Sumi has mentioned another problem, the effect of corrosion on structural strength in grounding and collision. His observations that corroded plates have less deformability and energy absorption seems in line with recent experiments. In his case he noted that the strength in tension was not much changed. However, recent experiments and subsequent analysis of corroded box girders have shown a clear reduction in collapse strength, which is partially attributed to the reduction in plate thickness and partially to change of material properties (Saad-Eldeen et al 2011, 2012a,b,c), although more experimentation is required.

Dr. Wang has rightly started by pointing out the important developments made in the industry with the adoption of the IACS Common Structural rules. In fact it was an important step for the industry to have these rules available, which has two important features. On one hand it represents a common effort of several Class Societies, with the obvious advantage of common formulations. The other important aspect is the adoption of the ultimate limit state instead of the elastic section modulus as the design criteria for the hull girder as well as the inclusion of more direct calculation procedures for loads and ultimate strength, which are a clear result of much accumulated research work. In this respect the results of the EU project SHIPREL come to mind, in which many of those formulations were proposed (Guedes Soares et al. 1996).

MARSTRUCT has tried to make some benchmark studies related with the contents of the IACS Common Structural rules although it did not manage to be so extensive in the aspects verified as we would have liked.

As rightly pointed out, significant efforts have also been devoted to maintenance aspects, to limit the consequences of degradation.

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