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Quasi-Static Response
by

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The International Ship and Offshore Structures Congress (ISSC) is a forum for the exchange of information by experts undertaking and applying marine structural research.

The aim of the ISSC is to facilitate the evaluation and dissemination of results from recent investigations; to make recommendations for standard design procedures and criteria; to discuss research in progress and planned; to identify areas requiring further research, and to encourage international collaboration in furthering these aims. Structures of interest to the ISSC include ships and other marine structures used for transportation, exploration, and exploitation of resources in and under the oceans.

This three volume work presents the proceedings from the 16th International Ship and Offshore Structures Congress held in Southampton, UK from 20 – 25th August 2006.

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VOLUME 1

ISSC 2006

COMMITTEE II.1
QUASI-STATIC RESPONSE

COMMITTEE MANDATE

Concern for the quasi-static response of ship and offshore structures, as required for safety and serviceability assessments. Attention shall be given to uncertainty of calculation models for use in reliability methods, and to consider both exact and approximate methods for the determination of stresses appropriate for different acceptance criteria.

COMMITTEE MEMBERS

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KEYWORDS

Quasi-static response, strength assessment, ship structural analysis, semi-empirical approach, structural reliability, direct calculations, finite element modelling, fatigue, corrosion, ship structures, IACS Common Structural Rules, IMO Goal Based Standards, offshore structures.

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1. INTRODUCTION

A ship is a complex and complicated structure designed and built to withstand a variety of loads, namely; wave and wind loads which are ever changing, cargo loads as a result of ballast and full load operations and accidental loads due to such as collisions and groundings. Recently Finite Element Modelling (FEM) and Analysis (FEA) techniques have been developed to a level where these can be applied to analyse complex ship structures during the design process. Moreover, when design innovations are pursued, useful information can be obtained from direct load, response, and strength analyses. In such cases, it is essential to identify the relationship between the limit states and the corresponding loading conditions in a more precise manner. A comprehensive review of various strength assessment approaches was carried out by the previous ISSC Technical Committee II.1 (2003), where the focus was placed on the links of CAD/product model and FE model, advanced F.E. modelling, simplified load-response analysis procedure and also the aforementioned direct calculation procedure which requires the sophisticated links of hydrodynamic loading and FEA. Stress calculation at structural details and welds were reviewed along with the assessment of quality assurance of numerical calculations. In relation to the recently developed net scantling approaches, a probabilistic corrosion model was reviewed, in which the phenomena of generation and progress of corrosion was categorized by the following three processes; degradation of paint coatings, formation of pitting points and their growth into general corrosion. The buckling strength analyses and reliability-based analysis of structural responses were also reviewed.

The present committee report is organised in the following manner;

In Chapter 2, various strength assessment approaches for quasi-static response of ship and offshore structures are reviewed. These approaches include the traditional semi-empirical approach developed by the classification societies in their rules based on the vast service experience of existing structures, probabilistic approach, structural reliability approach and multi-scale and multi-physics approaches.

Chapter 3 forms a major part of this report where a comprehensive review of calculation procedures has been presented. First, the level of analysis in relation to design stages such as simplified analysis, direct calculations, reliability analyses, optimisation-based analyses (including reliability) have been discussed. Reference was also made to rule-based and rational-based designs. Secondly, recent works with regard to load modelling for the quasi-static response have been reviewed. Specifically, load modelling for rule based versus rational based design, loads extracted from towing tank trials, loads from sea-keeping and CFD codes, the effect of mass distribution have been reviewed. Uncertainties on the knowledge of loads have been discussed. Thirdly, a review of the structural modelling techniques has been presented. In finite element modelling, time spent versus expected results, uncertainties in FE modelling due to material, as built versus as designed, residual stresses, etc., adaptive methods, mesh criteria have been discussed. Finally, structural response assessment has been discussed in relation to new computational techniques, uncertainties in calculations and the development of naval-oriented post processing tools.

The structural responses of specific ship structures such as bulk carriers, tankers, Ro-Ro vessels, Inland Navigation vessels and LNG/CNC vessels are reviewed in Chapter 4. With regard to safety, structural problems of aged bulk carriers, accelerated phase-out of single hull tankers were discussed together with new rules and regulations introduced by IACS and IMO. In Chapter 5 offshore structures are reviewed. Owing to the small representation from the offshore field on the present committee, the review was limited to only FPSOs and VLFSs (Mega-float and MOBs).

No finite element benchmarking study has been carried out, even though this was the intention of the present committee members initially. However, some unforeseen problems in the membership of the present committee meant that finite element benchmarking study could not be carried out. Finally, Chapter 6 contains the conclusions and recommendations for future research.

2. STRENGTH ASSESSMENT APPROACHES

2.1 Semi-empirical Approach/Direct Calculations

Simplified analysis procedures for the quasi-static response calculations are of significant importance since they provide initial guidance during the early design stage but are also used to evaluate results obtained from more complex numerical calculations. For most vessels, the simplified analysis where rule loads are applied to a structural model is sufficient to cover the requirements from class and authorities. This is still the normal yard standard and as such an analysis step where error probability is relatively low. This step includes relatively simple calculation of strength (yield and buckling).

Direct calculations are usual for offshore structures where site specific wave data will be different for each site. For ships, this is less common as the rule loads are assumed to cover the loading in world wide trade. Lately more focus is placed on the safety of the vessels, especially vessels trading in harsh environments. It has thus become more of a norm to demand direct analyses for new designs and/or operation in harsh environments. Another aspect is that the classification society rules are based on vast service experience that has been accumulated by the classification societies on existing ships. Due to trends and demands in the current shipping market, new ship types such as high speed of vessels with catamaran, SWATH, trimaran and pentamaran configurations have been designed and built utilising lightweight materials where service experience is either very limited or do not exist at all. In such designs, direct calculations are the only reliable method of ensuring adequate safety of the vessel.

The load calculation procedures are of more importance when direct analyses are performed. Instead of a clearly defined set of loads, the loads have to be defined by the designer based on a set of assumptions. This requires more engineering decisions before the actual load can be calculated. The calculated loads may also have to be evaluated in order to ensure that they are according to expectations. This may be explained by linear hydrodynamic analyses to be used for fatigue calculations. The side shell will, if loads are not adjusted, experience a load range twice as high as intended as the load variation is between zero and the maximum pressure in the intermittent wet and dry area while the loads from the hydrodynamic program will show a negative pressure with the same size as the maximum pressure.

Direct calculation is normally an addition and not a substitute to simplified analysis as these normally will be required in addition to the direct analyses.

2.2 Reliability Approach

Reliability analysis is used to measure the probability of structural failure by considering both the loads acting on a vessel and the resistance (strength) of the structure in probabilistic terms rather than deterministically. Structural failure occurs when the load effect is larger than the resistance.

All uncertainties during the vessels lifetime from analyses to corrosion in trade need to be accounted for in the reliability analysis. This is normally not cost efficient for one single vessel and reliability analysis is therefore mainly used to establish target safety level. This means that it can be used to establish prescriptive criteria for rules that reflect target safety levels. In this way, a safety level can be met by the vessel designed according to the rules. Today's rules are generally not established in this way and it is difficult to know what safety level is included in the rules.

In reliability analysis of plates and hull girder, analytical formulae for strength predictions, can be conveniently employed. The methods such as first order reliability method (FORM), first order and second moment (FOSM) can be applied to this type of analysis since the limit state functions are explicitly expressed. Monte Carlo simulation has been integrated into progressive failure analysis for more accurate estimation of failure probability. For predicting the capacity of the plates using non-linear finite element methods, the limit state function is in implicit form which makes the FORM not suitable. In this case, the response surface method is considered to be more suitable.

The through life reliability of ships including the effects of corrosion and fatigue on the reliability of ultimate hull girder strength can be calculated by time dependent reliability analysis.

2.3 Multi-physics, Multi-scale Approaches

2.3.1 General

The accuracy of a structural strength assessment of a marine structure is heavily dependant on the accurate representation and application of realistic loads. By far, the most common practice for the evaluation of quasi-static response of the structure is to statically apply hydrodynamic loads which are determined separately from the seakeeping codes or CFD simulations, onto the Finite Element model. This is a two way process and slows considerably the execution of responses for large number of load cases.

Procedures to statically load the structure in a realistic way based on the loads determined from first principles approaches have been developed and adopted by several classification societies. For example, direct load transfer of hydrodynamic pressures and accelerations to a FE model to determine the whipping responses of a high speed vessel has been discussed by Pastoor *et al* (2002).

A similar work has been carried out by the Cooperative Research Ship (CRS), STRUC working group (http://www.crships.org/crs/WorkingGroups/Struct.html) in an effort to integrate software tools to generate load cases for FE analysis automatically for the fatigue and strength assessment of ships using the three dimensional panel method seakeeping code, PRECAL.

2.3.2 Compatibility between CAD/Product Models and FE Models

The mutual compatibility of structural analysis and naval architecture software packages is not satisfactory. Therefore, the scope for the improvement, acceleration and extension of design process can be obtained through great scale introduction of the 3-D ship product model. Full implementation of 3-D model starting from early stage of design and continued up to production stage is still not available. This puts restrictions on the implementation of high level design process and the electronic data exchange, although considerable progress has been made in this area.

In automotive and aircraft industries 3-D tools and comprehensive product models are already a standard. Shipbuilding has been left behind in this development. New 3-D tools have now reached to a level where they can be implemented in shipbuilding; especially the user interfaces have improved significantly enabling easy handling of the models.

The basic idea of a product model is that all the required information is stored in the same model: the information includes the general arrangement, detailed arrangements, ship systems, specifications, materials, schedules, planning, purchasing and simulations. 3-D ship model can also be transferred to other programs such as FEM, stability, and seakeeping and CFD programs. For example, STEP2 is an impressive attempt to unify and standardise the data exchanges based on a product model not only for the design, but for the whole life cycle as well. STEP2 is not yet mature, but the number of implementations is increasing. There are also other exchange standards such as XML 4, as an alternative to EXPRESS 5 as the physical file format for the transfer of product model data according to the STEP standard.

Although in theory the link between the 3-D product model and FE model can be done conceptually, different software packages are bundled with their own translators which are not necessarily compatible to other software. In addition, bi-directionality whereby changes to a 3-D product model can readily applied to an FE model and also changes to FE model feeding back to 3-D product model where the 3-D model can be used for detail design, can not be achieved with certainty. Therefore, transition from the Structural Model to the Detail Model is done today in a more or less sequential way.

Mutze *et al* (2005) discussed in a paper the transition phase between the structural design and the detail design focusing specifically on the support for a working procedure, where the detail design can be started well before the completion of the structural design and where these two design processes may exist concurrently over a significant time period. The method is based upon using a single Product Information Model (PIM) where the same information may be accessed both from a structural and a detail aspect simultaneously. The implementation of support for such process overlapping, concurrent structural and detail design in Tribon Basic Design was demonstrated.

2.3.3 Links between FEA and CFD

In the past, obtaining all of the simulation capabilities needed for complex and demanding modeling scenarios frequently meant combining several different software packages. Some commercially available FE Software packages such as Ansys Multiphysics (www.ansys.com/products/multiphysics.asp) provide coupled physics tool combining structural, thermal, CFD, acoustic and electromagnetic simulation capabilities into a single software product.

Such multiphysics tools integrate the power of direct (matrix) and sequential (load vector) coupling to combine the appropriate "physical fields" required for accurate, reliable simulation results. In this way, complex fluid-structural interactions can easily be simulated by incorporating a complete range of powerful iterative, direct and eigenvalue matrix solvers.

Fluid-structure interaction can be used wind and wave loading on ship and offshore structures. For example, the advanced ANSYS Fluid-structure interaction solution uses the multi-field solver to provide a true bi-directional fluid-structure interaction capability for time transient or steady state analysis with moving / deforming geometry by coupling the structural analysis tool with the computational fluid dynamics solver (CFX). It is understood that similar multi-physics solution is also available with the FEM tool (Abacus) and the CFD tool (Fluent).

In a multi-physics solution procedure, the structural part of the analysis is carried out using an appropriate structural analysis tool and the fluid part using a full CFD capability solver. The multi-physics solver technology allows the structural and fluid solutions to run simultaneously on the same or different machines. It should theoretically be possible to use more than one computer to reduce the time required for the fluid portion of the simulation or communicate with other computers across networks.

In the context of ship structural design, the predictive capability of CFD is needed to address complex interaction between a ship's boundary layer, non-linear free surface and the propulsion. The solution of near field flow is a key parameter to problems such as unsteady propeller loads, cavitation and propeller induced hull vibrations.

2.3.4 Adaptive Meshing

One of the main concerns in a finite element analysis is the adequacy and dependence of the results to the mesh discretisation. Advance Finite Element programmes provide automatic mesh generation and error estimating techniques and adapt the mesh creation (adaptive meshing) according to the stress distribution. The usual continuity assumption used in displacement based finite element formulations results in continuous displacement field but a discontinuous stress field. To obtain a better stress presentation, averaging of nodal stresses is usually performed and presented. The error estimating techniques use the difference between the averaged and non-averaged stresses to calculate the energy error for the element. If the errors for all elements are equal, it is deemed that the mesh is adequate. Otherwise, the adaptive mesh refined is carried out based on the even distribution of energy errors.

It is argued that meshes created by adaptive techniques produce better results than those generated by the experienced structural engineers. In adaptive meshing, mesh discretisation errors can be minimised and the final mesh quality and the solution can be obtained almost independently from the initial mesh chosen by the engineer.

In previous committee of II.1 of ISSC (2003), a benchmarking study on adaptive meshing was carried out. The structure investigated was part of a girder system of an aluminium superstructure deck. Contrary to the above statement that the solution using adaptive meshing can be obtained almost independently from the initial mesh, the study showed that the results were not independent of the user or meshing procedure. Although the study yielded that the mesh quality obtained by adaptive meshing is better than the quality of uniform mesh with the same number of elements, it required considerably long time and effort to arrive at the results. Therefore, it was argued that the mesh generated with an experienced engineer could provide results as accurate as or better than those obtained with the use of adaptive meshing but with much less time effort.

3. CALCULATION PROCEDURES

3.1 Level of Analysis Related to Design Stages

Different design stages demand different analyses approaches. The requirement of analysis method is mainly a cost/effort evaluation. The correctness of the analyses is compared to the required safety level at the given design stage. At the early stages of a project, the required analysis accuracy is less important and simplified analyses may be used while at later stages the different requirements from yard, owner, classification societies and authorities need to be included. The requirements will then typically depend on vessel type, knowledge of design, safety and inspection requirements.

3.1.1 Simplified Analysis / First Principles

For most vessels, the simplified analysis where rule based loads are applied to a structural model is the normal yard practice for the quasi-static response calculations, typically for yielding and buckling checks. However, more and more direct calculation procedures based on first principles are employed in determining quasi-static response of ship and offshore structures.

The main load component for buckling of deck and bottom structures is axial compression due to hull girder bending. However, the structure is generally exposed to bi-axial loading of axial compression and lateral pressure or multi-axial loading including in-plane transverse bending as well as axial and lateral pressure loads. It has been normal to evaluate the buckling strength by use of analytical formulas for uni or bi-axial loading. Recent research focussed on the more sophisticated methods for calculating the ultimate strength of stiffened panels under multi-axial loading. The introduction of the PULS program (new Joint Tanker Project) allows for more advanced buckling calculations. This is a semi-analytical computerized buckling code for assessing buckling and ultimate strength limits of stiffened panels subjected to the simultaneous action of in-plane loads in combination with lateral pressure. It is founded on advanced mathematical models and is accepted by several classification societies.

Many researchers have recently studied various limit states of the hull girder. Paik and Frieze (2004) presented the aims and scope of ISO code 18072 on the principles composed of four types of limit states, namely serviceability limit state (SLS), ultimate limit state (ULS), fatigue limit state (FLS) and accidental limit state (ALS) are considered in the standards. On the ultimate limit state (ULS) of the hull girder in the intact condition, in the damaged condition caused by collision or grounding and in the corroded condition, simplified analysis methods were proposed. Paik (2004a) described an ultimate limit state (ULS) based procedure for design and strength assessment of ship hulls under vertical bending moment. Yao *et al* (2004) introduced a method to calculate the shear stress distribution and warping deformation in a hull girder cross-section subjected to shear force.

In aging ships, corrosion and fatigue cracks are the two most important factors affecting structural safety and integrity. The structural failure of aging hulls in rough weather is thought to be the possible cause for several bulk carrier and tanker losses. Paik *et al* (2003a) studied the effect of time-variant corrosion wastage, which was developed on the basis of the available corrosion measurements for existing large bulk carrier structures, on the ultimate hull girder strength as well as the section moduli. The criteria for repair and maintenance of heavily corroded structural members so as to keep the ultimate longitudinal strength at an acceptable level were discussed. Hu *et al* (2004) and Hu and Cui (2004) proposed a methodology to assess the time-variant ultimate strength of ship hull girder under the degradations of corrosion and fatigue. The effects of fatigue cracks on the tensile and compressive residual ultimate strength of stiffened panels and unstiffened plates were analysed by a finite element method (FEM). Based on FE analysis results, some empirical formulae were provided for effective calculation of the compressive or tensile ultimate strength of cracked or intact unstiffened plates or stiffened panels.

Harada and Fujikubo (2002) derived simple formulae for estimation of ultimate strength of continuous plate with cut-out under thrust. Firstly, estimated formulae of elastic buckling strength have been derived based on the results of buckling eigen-value calculations by finite element method. Secondly, new plastic correction formula considering the yielding effect around cut-out for estimation of buckling strength has been introduced. Continuous stiffened plates under combined thrust and lateral pressure have three collapse modes, which are stiffener-induced failure caused by stiffener yielding, plate-induced failure by local plate collapse and hinge-induced failure by the formation of plastic hinges predominantly in bending. Yanagihara *et al* (2002) developed a simplified method to estimate the ultimate strength of the stiffened plates based on the collapse behaviour observed by finite element method. Yanagihara *et al* (2003) extended the method so as to consider the lateral pressure on stiffener side as well as on plate side. Since the lateral pressure on stiffener side causes compression at the stiffener top at the mid-span, the so-called stiffener-induced failure takes place until it changes to the hinge-induced failure mode under a high lateral pressure. Furthermore, Harada *et al* (2004) extended the application of the formulae to biaxial thrust condition based on a series of elastoplastic large deflection FE analyses.

Maeno *et al* (2003) performed a series of elastoplastic large deflection analyses to investigate buckling/plastic collapse behaviour of the bilge circle part subjected to uni-axial thrust. Based on the calculated results, simple formulas for the ultimate strength analyses of hull girder by Smith's method were derived to simulate buckling /plastic collapse behaviour of the bilge shell.

Simplified analyses for the strength assessment of passenger ships in a design stage have also been proposed. Heggelund and Moan (2002) proposed a prismatic beam theory for the calculation of a 60 m catamaran under longitudinal bending and torsion. The theory was modified to account for the effect of wide flanges and significant window openings typical for a catamaran hull and the results were compared with those obtained from a global finite-element model. Naar *et al* (2004) described a coupled beam method, which estimates elastic response in the longitudinal bending of a passenger ship with a large multi-deck superstructure. Naar *et al* (2004) based their theory on the assumption that each deck in the superstructure and also the main hull can be considered as a thin-walled beam. These beams are coupled to adjacent beams with springs modelling vertical and shear stiffness. The shear effect in the side and deck structures was included with options for large openings. As a result, the method allows for the calculation of the normal stresses and vertical deflections in the arbitrary location of the hull girder. Average longitudinal displacements of deck structures and shear stresses in the side structures can be estimated as well. Simplified structures were analysed in order to validate the coupled beam method against the three-dimensional finite element method.

3.1.2 Direct Calculations

Direct calculations are becoming more easily obtainable with the advances in modelling techniques, new calculation tools and computing power. In addition, results obtained from direct calculation procedures are easily accepted by the Classification societies. Various direct engineering approaches have been studied by many researchers.

Lindemark *et al* (2004) described the thinking behind Det Norske Veritas (DNV) ship hull analysis procedures from the 1950'ies and onwards. The focus was on the latest development in computer based design analyses, from hydrodynamic analysis through structural analysis, to strength and acceptance criteria. The current DNV fatigue analysis procedures were illustrated with examples from standard size (138 000 - 140 000 m^3) membrane type LNG carriers, spherical type carriers and a CNG carrier.

Østvold *et al* (2004) investigated the progressive collapse of a bulk carrier in the alternate hold loading condition using nonlinear finite element analysis. The magnitude of the cargo and sea pressure loads have been varied relative to the design loads to observe the influence of local load variations on the ultimate moment capacity and the progressive collapse behaviour. Also, the authors focused on a strategy for ultimate hull girder strength analysis of ship structures exposed to a combination of global bending moment and local loads from sea and cargo.

A series of elastoplastic large deflection FEM analyses on hatch covers of bulk carriers subjected to lateral load are performed by Yao *et al* (2003). Two hatch covers were selected for the folding type and the side-sliding type cover, which are designed in accordance with the old ICLL rule and new IACS rule, respectively. Calculated collapse strengths were compared with individual design loads, and a strength assessment was performed. On the basis of collapse behaviour observed in FEM analyses, a simple method was proposed to evaluate the collapse strength of a hatch cover subjected to lateral load.

Meinken and Schluter (2002) demonstrated the usefulness of Finite Element direct calculations for modern inland vessels (push barges). These are open-top, double-hull ships with unusually large length-to-beam and length-to-height ratios, shallow draught and an extremely long cargo hold. Therefore, they have low bending and torsional rigidity. Moreover, the state of the ship structure changes appreciably in course of service due to minor collisions, groundings in shallow water, corrosion and fatigue. Such imperfections reduce the stability and strength of the structure. The safety against collapse decreases.

Samuelides and Servis (2002) investigated the structural response of clam-type bow doors of Ro/Ro vessels under slamming loading conditions. The structural analysis was performed with the finite element code MSC/NASTRAN. The loading conditions were determined on the basis of towing tank tests, numerical calculation and regulations of classification societies.

Kaila *et al* (2004) applied a direct analysis procedure for guaranteeing the safety of a total of 10 sea-transports of complete spar hulls or hull sections. Spectral approach with hydrodynamic and detailed structural FEA models was used for the strength and fatigue analyses for the voyage route wave loads. Boh *et al* (2004) presented a numerical study using finite element analysis to investigate the response of stainless steel profiled blast barriers as an integral part of offshore topsides subjected to hydrocarbon explosions. The static capacity and the dynamic response of the barriers were established up to the maximum capacity level and into the post peak or buckling response regime.

3.1.3 Reliability Analyses

Reliability assessment for ship and offshore structures has caught many researchers attention. As mentioned in Chapter 2.3, the reliability analyses of ships and offshore structures are usually approached by First Order Reliability Methods (FORMs). Lua and Hess (2003) developed a hybrid approach based on the combination of the Monte Carlo simulation (MCS) technique and the first-order reliability method (FORM) to quantify the small probability of failure of a hull girder under longitudinal bending. The ultimate strength (ULTSTR) bending solver, developed by the U.S. Navy, was integrated with the hybrid probabilistic analysis framework. Rajasankar *et al* (2003) reported the overall importance and methodical use of reliability-based techniques to maintain the structural integrity of joints of offshore structures by using both Monte Carlo simulation technique and FORM.

Kmiecik and Soares (2002) proposed a method to determine the cumulative probability distribution function of the strength of compressed plates using a response surface approach. The distribution function was constructed by applying a first-order reliability method to calculate the probability of failure successively at different levels of loading. The limit state function was a response surface, which resulted from fitting a series to the results of a non-linear finite-element code. The approach has been applied to plates of different slenderness and boundary conditions and the results were compared with Monte Carlo simulations.

The service life of a ship has been extended in recent years due to better knowledge of wave loads and better quality control of materials as well as better manufacturing skills in ship production. The evaluation on the effects of corrosion and fatigue on reliability of an aged ship has become a very important task. Melchers (2003) demonstrated that those structures tend to deteriorate with time, the reliability assessment must take the time-dependent reduction of material strength properties R (t) and its time varying uncertainties into consideration by representing them as a probability density function. The study indicated that a fundamental approach to corrosion modelling is required and better-quality models to represent adequately the deterioration mechanism of corrosion are also needed. Qin and Cui (2002) developed a time-dependent reliability analysis to assess the ultimate strength of ship hull girders under corrosive environment. In their studies, a new non-linear corrosion model is proposed and whole corrosion process of the model was described in three stages: no corrosion, corrosion accelerating and corrosion decelerating. Hu *et al* (2004) used the linear model and the above non-linear corrosion model to investigate the time-variant ultimate strength of a double hull tanker girders under the degradations of corrosion and fatigue. A procedure to determine the maximum allowable corrosion thickness was also proposed.

Shama *et al* (2002a) demonstrated the effects of the corrosion rate and coating life mean values on the reliability and the reliability index of double hull tanker plates. They suggested that each ship owner or operator must record a fully detailed description of the ship's conditions, operational characteristics, maintenance, repair, scantling conditions and hull deterioration from the first day of service until the last day of service. Shama *et al* (2002b) manifested the impact of recoating and renewal of corroded double hull tanker plates on their reliability. The effects of the recoating process and plate renewal on the plate reliability (conditional and total reliability) were presented for a plate element under different loads.

Akpan *et al* (2002) developed an approach for reliability assessment of the ultimate strength of a ship hull structure in the presence of corrosion. The second order reliability method (SORM) was used to calculate instantaneous reliability of the primary hull structure. Sun and Bai (2003) presented a methodology for the time-variant reliability assessment of FPSO hull girders subjected to degradations due to corrosion and fatigue. The time-variant reliability and the parametric analysis are quantified. The COV of ultimate strength of hull girders was suggested for simple FORM.

Lassen and Sørensen (2002a) presented the necessary crack growth statistics and suggested stochastic models for a reliability analysis of the fatigue fracture of welded steel plate joints. The reliability levels were derived from extensive testing with fillet-welded joints for which the entire crack growth history has been measured, not only the final fatigue life. The aim was to provide data for the variables used in a MCS and to develop a Markov chain for fast reliability calculation, especially when predicting the most likely influence of numerous future inspections. Lassen and Sørensen (2002b) suggested a probabilistic damage tolerance supplement to the design S–N curves for welded joints.

Cole *et al* (2003) examined whether the classification society rules are applicable to the fatigue performance of a shallow–water platform subjected to wave climates of the North West Shelf of Australia. The results showed that the probability of fatigue failure was approximately three orders of magnitude less than the probability of storm overload failure. They suggested that the inspection effort on offshore platforms may be better directed toward higher-risk threats such as accidental damage and corrosion.

Folsø *et al* (2002) demonstrated a simple reliability-based framework in order to calibrate a new set of fatigue design guidelines which consider two different approaches for the assessment of loads, stresses and local stress raising effects, and partial safety factors must be given for any combination of these approaches.

Horte *et al* (2004) presented the use of Formal Safety Assessment methodology for the development of a risk based formulation for bottom slamming pressure on ship structures. The motivation of the study was to investigate the applicability of FSA methodology in development of standards for ship structures. A test set including 10 ships of lengths between 180m and 320m has been subjected to this analysis. A probabilistic model for the slamming pressure was formulated based on the relative motion and relative velocity between the ship bottom and the wave elevation. Both a standard direct analysis procedure and a prescriptive rule type formulation have been calibrated to structural reliability analyses' results at the cost optimum target reliability level from a cost-benefit analysis.

The survivability and reliability of damaged ships after collision and grounding was studied by Fang and Das (2004). Based on the Monte Carlo simulation technique, the failure probability of a damaged ship varies with different damage types, damage position, damage extent and sea conditions. Their analysis also indicated that the risk (failure probability) caused by grounding is far less than those caused by collision. This may be attributed to the fact that the residual ultimate strength of ship hull girder after grounding reduces more slowly than that caused by collision.

Reliability based analyses of offshore structures have been carried out by various researches; Ramsamooj and Shugar (2002) studied fatigue life of the connectors of a US Mobile Offshore Base (MOB), Fujikubo *et al* (2003a and 2003b) reported on the structural safety analysis of VLSF surrounded by a breakwater, Katsura et al (2003), etc. A reliability-based structural design of ship-type FPSO units was considered by Sun and Soares (2003b). In their study, different levels of design criteria based on LRFD format were investigated for FPSO structural design. The annual reliability indices for primary, secondary and tertiary failure modes were presented as a function of environmental severity factor. The service life extension of FPSO hull structures was investigated by Moan *et al* (2004) based on reliability analysis. Deterioration due to combined fatigue cracking, corrosion wastage of structural components and the interaction behaviour between fatigue and corrosion were investigated and the updated reliability level of a FPSO was evaluated based on the detection of fatigue cracks and thickness measurement before and after the vessel has changed its location and sea environment.

Reliability methods can also be used for optimization of design solutions. The probability of a failure as function of time can be estimated and combined with the associated failure cost and the risk cost can be determined. The total expected lifetime cost for the different alternative design solutions could then be estimated and compared. An example of this is the target value for the fatigue life factor related to safety level of a floating production vessel.

3.1.4 Optimization-based Analyses

Despite advances in computing capabilities in terms of capacity and speed, huge computational time is still required for the structural optimization of ships and offshore structures by using existing detailed analysis techniques. A variety of calculation techniques have been investigated by researchers (Yasuzawa, 2003 and Nakada and Suzuki, 2004, Kitamura et al, 2002) to find efficient and accurate techniques. Nakada and Suzuki (2004) proposed an efficient optimization procedure in order to find the optimal form of a semi-submersible type megafloat. An objective function based on a concept of a risk was used which unifies the structural weight and requirements of strength and functionality of the Megafloat such as a motion or an elastic response. To reduce the calculation time, they developed and used a simplified analysis model with sufficient precision and short calculation time which consisted of the equation of motion of a rectangular plate.

Klanac and Kujala (2004) presented an approach to reach an optimal design of different steel sandwich applications in ships. Kitamura *et al* (2002) discussed the use of Neural Networks as an alternative method to Finite Element method for structural analysis. As for almost all methods, Neural Network method has several weaknesses in its algorithm along with its advantages. The authors tried to back up these weaknesses by adding Lead Factor on the Neural Network system to lead the network to raise the precision of the analysis. The solution obtained by Transfer Matrix Method is used as lead factor and applied to a container ship.

3.2 Loads Modelling

Loads modelling can be conveniently divided into three parts; Load calculation procedures, Load calculation and Load application. Each part may be equally important. Many different approaches exist and especially the load definition is under continuous development. Since loads acting on ship and offshore structures fall within the scope of Technical Committee I.2, only application of loads to quasi-static response analysis is relevant and discussed here. This is discussed in connection with three major methods for load calculations. The following main methods of load definition are used:

- Rule loads (and closed form loads)
- Loads determined from hydrodynamic analyses (seakeeping codes and CFD)
- Loads obtained from measurements using scale models in towing tanks and model basins, and also full scale trials

The obvious advantage with rule loads is that they are easy to calculate and use. Classification societies have analysis programs where rule loads are automatically calculated and applied to either a structural model or more simplified analysis models. The major disadvantages are that the load uncertainty is relatively large both with regard to load level, load distribution and load correlation. The loads have also been a part of the total structural assessment "package" such that the required scantlings are reasonable but each component (such as the loading) may not necessarily be the best estimate. Example of difference between rule loads and direct calculations is shown in Figure 1.

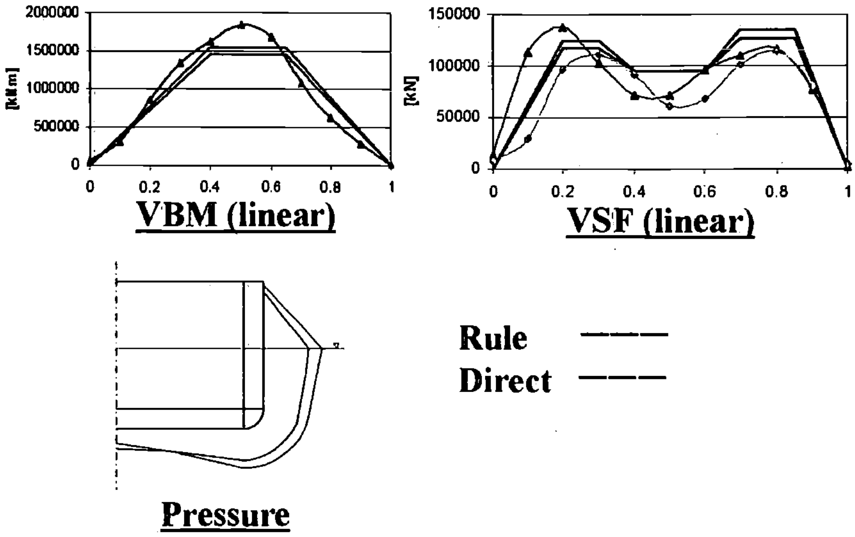

Figure 1 : Example of difference between rule loads and direct calculations.

Load application is relatively easy for rule loads. This simplicity does however lead to some problems. Correlation or phasing between loads is difficult to account for and combination of different loads acting on the vessel may therefore be difficult.

Even for fatigue loads where it is relatively easy to calculate statistical correlation between each load component, the total correlation of loads for one position is difficult as the rule loads are to cover a wide band of vessels. The correlation will also differ for different weather conditions, wave headings, spreading parameters, etc. This is difficult to build correctly into a set of rule loads.

Tools for fast estimation of loads and motions of ships are presented by Jensen *et al* (2004). These calculations are typically based on the same type of information as used in Rule calculations, but results can be post processed in the same way as for hydrodynamic analyses and different wave environments can therefore be evaluated.

3.2.1 Rule-based vs. Rational-based design

Though various design loads used in the strength assessment of ship structures were introduced by classification societies, most of them were determined as the simplified standard loads. Ship motion and wave load analyses are important to assist in the design of advanced vessels, both for the assessment of the structural integrity as well as the seakeeping performance. Accordingly, the rational-based design loads which pay attention to both sea state and wave-induced load response of ship structures have been currently proposed by many researchers.

Terai *et al* (2001) proposed a new fatigue design method based on storm model in the North Pacific using crack growth analysis. In order to develop the storm model for ocean route, many data are required such as wave scatter diagram, the number of storms, duration of storm and relative angle in storms. Then, Terai *et al* (2002) proposed a procedure to develop storm model in any ocean route which have only wave scatter diagram by referring to the results of crack growth simulation. Furthermore, Terai *et al* (2003) investigated the validity of the proposed procedure for the North Pacific Ocean and the Indian Ocean. Kawabe and Morikawa (2004) developed a new storm loading simulation model which is consistent with a long-term wave frequency table. Applying the storm loading model to calculate a ship structural response in the ocean, both the long-term distribution of the wave-induced response for extreme load and the time history of response for fatigue assessment of structure can be obtained directly.

Jensen and Mansour (2002) developed a semi-analytical approach to derive frequency response functions and standard deviations for the wave-induced bending moment amidships for mono-hull ships. The results are given as closed-form expressions and the required input information for the procedure is restricted to the principal dimensions: length, breadth, draught, block coefficient and bow flare coefficient, speed and heading, and the sea state parameters H_S and T_Z. Extreme value predictions were performed based on a user-defined operational profile and takes into account non-linearities due to bow flare using a semi-empirical closed-form expression for the skewness. The effect of whipping was included by assuming that whipping and wave-induced responses are conditionally independent given H_S. In the same way, Jensen (2004) provided a rational and efficient procedure able to predict the design wave-induced motions, accelerations and loads with sufficient engineering accuracy in the conceptual design phase and in risk assessment. Baarholm and Jensen (2004) applied the method to determine the long-term extremes by considering only a few short-term sea states. Long-term extreme values were estimated using a set of sea states that have a certain probability of occurrence, known as the contour line approach. Not only the effect of whipping by assuming that the whipping and wave-induced responses are independent, but also that of correlation of the long-term extreme value was studied.

Wang and Moan (2004) studied the statistics of nonlinear wave-induced bending moment in ship hull girders in a short-term period. Systematic probabilistic analysis was performed directly on wave load time histories for different ship types under various sea state and ship speed conditions. The order statistics concept and peak-over-threshold method were used for estimation of the extreme wave loads. The generalized gamma, generalized Pareto, and Weibull distributions were evaluated and compared with respect to the shape parameters, goodness of fit of the models to the wave load data, and statistical uncertainty in the extreme estimates.

Wu and Hermundstad (2002) presented and applied a nonlinear time-domain formulation for ship motions and wave loads and a nonlinear long-term statistics method to a container ship. The calculated long-term vertical sagging and hogging moments amidships were comparable to those given by DNV rules. They suggested that their approach can be used as a way of more accurately evaluating extreme wave loads and other nonlinear responses in ship design.

Shigemi and Zhu (2003) proposed the design sea states that closely resemble the actual sea states which are considered as the most severe for hull structures of tankers. Furthermore, the practical estimation methods of the design sea states, the design regular waves and the design loads such as ship motions, accelerations, hull girder bending moments and hydrodynamic pressures were proposed. Zhu and Shigemi (2003) applied the same method to the primary structural members of bulk carriers (see also Shigemi and Zhu, 2004). Comparisons between the results obtained by the structural analysis of a hold model applying the proposed design loads and long-term values of stresses by the most advanced direct structural analyses for different loading conditions were made. Iijima *et al* (2004a) discussed a practical method for torsional strength assessment of container ship structures. In order to estimate the torsional response characteristics as accurately as possible, three-dimensional Rankine source method, after being validated by tank tests, was employed for estimation of wave loads on a container ship, and FE analyses were conducted on the entire-ship model under the estimated loads. Then, a dominant regular wave condition under which the torsional response of the container ship becomes maximum was specified.

A paper by Bhattacharya *et al* (2005) outlined, as an essential input to reliability analysis, the development of a physically based probabilistic model of transverse watertight bulkheads (WTB) loads. Poisson arrival was assumed for damage events, and the maximum life-time load effect envelope on the WTB in damaged condition was derived. Simple phenomenological expressions of load components were used to underline the cause and extent of randomness in WTB loads. A response surface type approach was suggested for determining ship-specific model parameters.

Pastoor and Tveitnes (2003) conducted linear and nonlinear calculations for a modern navy frigate and compared the results with model tests. They presented a procedure to account for voluntary heading and speed changes in order to establish the joint probability of heading, speed and sea state. By using this in a proper statistical assessment procedure design loads for structural analysis can be determined.

3.2.2 *Loads extracted from towing tank trials*

Even though model tests are expensive and reanalysis are time consuming, many hydrodynamic loads can not be calculated accurately from hydrodynamic programs and the designer has to resort to model tests for the determination of realistic loads. Examples for such loads are

- Roll motions
- Non-linear sagging/hogging
- Green sea loads
- Sloshing
- Slamming
- Whipping and springing

Even though model tests may be the best tool for calculation of some hydrodynamic loads, procedures are not straight forward.

In the case of calculation of design loads, it is important to be able to measure the necessary data. Different from a hydrodynamic program, it requires much extra work to read additional pressures or section loads. The amount of results that are needed for design loads may be difficult (expensive) to extract from a model test. It may also be expensive to perform model test for a sufficient number of realisations to ensure that the design load actually is captured. It is therefore normally necessary with some kind of screening analysis in order to limit the number of model tests.

Calculation of sloshing pressures may serve as one example of the challenges with model testing. Vessel motions are input to the model tests while pressures pulses are output. Even with identical motion input, statistical results differ significantly. This illustrates the fact that results from model tests should also be treated with care. In addition to the procedures for finding correct waves (which are the same as explained for hydrodynamic analysis) model uncertainties regarding model laws, model stiffness, sensor uncertainties, creation of correct waves, etc. will influence the results.

To develop a practical prediction method for green water, slamming or sloshing load, tank trials are frequently utilized because of their uncertainties. Ogawa *et al* (2002a) conducted a series of model tests in waves to measure the green water loads that act on deck due to deck wetness using the model of general cargo ship. In order to assess the experimental results quantitatively, maximum value and probability density function of green water loads were estimated by the developed methods. Moreover, Ogawa (2003) conducted model tests using a tanker and a cargo ship on a domestic Japanese voyage. Vassalos *et al* (2003) proposed and implemented a methodology for estimating probabilities of deck wetness and impact loads due to green seas as a function of key design and operational parameters. Fonseca and Soares (2004) presented the results of an experimental and theoretical investigation of green water effects on the bow of a containership. The results from the model tests in regular waves, including motions, relative motions, heights of water on the deck, pressures and forces, were compared with numerical results from a time domain seakeeping code. Faltinsen *et al* (2003) applied a two-dimensional fully nonlinear wave tank to the experiments of green water and bottom slamming on a restrained VLFS with shallow draft.

Ogawa *et al* (2002b) carried out model tests in order to develop a practical estimation method of impact pressure on the bow flare. It is found that impact pressures have relation to ship motion and the wave height has much effect on the impact pressure. Hermundstad *et al* (2004) conducted model tests of a car carrier in regular head and bow quartering waves of various heights, in order to validate ship motion theories and a 2D numerical slamming calculation method. Calculated pressures agreed quite well with the experiments, especially for the most severe slamming events.

Comprehensive tank tests using a post-Panamax container ship model were conducted to examine the nonlinear characteristics of the torsional moments in regular waves of different wave heights and reported by Iijima *et al* (2004b) and Miyake *et al* (2004a and 2004b). The design loads for container ships were finally proposed by correcting the shape of distribution of the proposed design loads to consider the effect of nonlinearity in extreme waves based on the tank test results.

Tveitnes *et al* (2004) presented the recent model tests performed by DNV to determine sloshing impact loads in membrane type LNG carriers. The results have been applied in development of simplified load formulas taking into account the effect of varying filling level, wave heading, forward speed and wave height and also the variation with the size of subjected area. Sames *et al* (2002) conducted sloshing tests using a rectangular tank with a baffle at 60% filling level and a cylindrical tank at 50% filling level, in order to validate an existing finite volume computational method which can simulate fluid motions in partially filled tanks. Predicted time traces of pressures and forces compared favourably with measurements. Arai and Cheng (2004) described a treatment of the boundary conditions necessary to carry out an accurate and stable numerical computation of sloshing impact pressure exerted on the ceiling of a ship's liquid cargo or ballast water tank. A series of model experiments were conducted using rectangular and chamfered model tanks in order to verify the method. The numerical method was then applied to examine bulk carriers' ballast tank sloshing that may occur during ballast water exchange on the high seas. Rognebakke and Faltinsen (2003) investigated the coupled effect between ship motions and sloshing. Two-dimensional experiments of a hull section containing tanks filled with different levels of water excited in sway by regular waves have been conducted.

Moe *et al* (2005) reported full scale measurements of the wave induced hull girder vibrations and their effect to the fatigue life of an Ore Carrier trading in the North Atlantic. Immediately after entering into service the vessel experienced substantial vibration induced fatigue cracking, which initiated the need for full scale measurements. Wave and vibration stress records from strain sensors located in the midship deck region were supplemented by wave radar and wind records. Based on the measurements, the vibration stress response and associated vibration induced fatigue damage was determined for varying wind and wave forces and relative headings.

The paper reports that the highest level of the vibration stress occurs for wave and wind headings within 30° off the ship's course. The highest vibration level was observed in ballast condition. For similar conditions, the vibration level appears to be roughly halved in full load condition compared to ballast condition. The ore carrier was strengthened which increased the springing frequency by 10%. The corresponding effect of the stress levels and fatigue damage was investigated. The fatigue effects due to wave stresses and wave induced vibration stresses were considered and analysed separately. This shows the additional fatigue damage by wave induced vibration to be of similar order of magnitude as the wave damage. It was also found that Sea states with 5m significant wave height contribute most to the fatigue damage in both ballast and cargo condition.

It is claimed by the authors' of the paper, which the same view is shared by the reviewer, that the study represents the most extensive and thorough full scale measurements in relation to the fatigue contribution from global fatigue induced vibrations. It is also significant work in terms of documenting an increase of springing frequency of 10% based on full scale measurements as a result of structural strengthening.

3.2.3 Loads from sea-keeping codes

Hydrodynamic (seakeeping) programs are often utilised to determine loads. Although seakeeping codes have reached to a certain maturity, there are a number of input parameters such as loading condition, sea state, wave spreading, wave heading, forward speed, etc. which may influence the results more than the correctness of the hydrodynamic program itself. The load calculation procedure is therefore of major importance and should not be missed out in seeking for more correct hydrodynamic loads. An overview of methods that can be used to calculate design sea states is given by Pastoor *et al* (2003).

Loads from hydrodynamic analyses may be divided in many groups with different levels of accuracy and ability to capture different hydrodynamic effects. The following are the most important effects covered by hydrodynamic analysis programs:

- Motions
- Section loads
- Pressure distributions
- Forward speed effects
  - Planing
  - Added resistance
  - Frequency of encounter
- Impact pressures
  - Slamming
  - Sloshing
- Parametric roll
- Water on deck/green sea loads
- Finite depth effects
  - Forward speed calm sea problem (squat)
  - Influence on dynamic behaviour
- Second order wave loads

Some of these effects are very complicated to solve and it is therefore difficult for one program to capture all effects. Due to the complexity, of the different load effects and how to combine them, model tests play an important role in the validation of hydrodynamic programs. A program may solve specific load effects correctly, but this does not guarantee that the effect on integrated loads as motions and section loads are improved compared to a program without this load effect. This is due to the fact that the total loading consist of numerous effects that all must act together in order to get the correct resulting load.

For linear programs, validation towards other well verified programs may be performed. For non-linear programs this may be difficult and validations towards model test are more important. This is performed for many programs; examples are Hermundstad *et al* (2004) and Pastoor *et al* (2004a).

Another important aspect is the load application. This may vary from application of the actual calculated load (e.g. Vertical Bending Moment), to direct load transfer of all load components from the hydrodynamic program. If some load components are left out, the effect of these components should be known such that important load effects are not omitted.

Load application is not only a question about combination and level but also about timing. Application of, for instance slamming loads, as a quasi static load may lead to misleading answers as the time information of the slamming load is of vital importance. Short impulses that may depend on the dynamic behaviour of the vessel should not be treated as quasi static but rather as dynamic. The shape and rise-time are important parameters that may have larger impact on the response than the actual load level.

The following review provides an insight to recent work carried out in the area of seakeeping and CFD code development in order to determine the loads for strength (quasi-static response) assessment.

Seakeeping codes are indispensable especially in designing high-speed crafts and special ships such as trimarans or pentamarans. Boote *et al* (2004) presented a procedure for the evaluation of longitudinal design loads of a trimaran-type fast ferry. As the HSC code, which is used for the concept design, do not make reference specifically to trimaran-type vessels, a direct calculation of design loads has been performed by a long term analysis based on a seakeeping panel code.

Wu and Moan (2004) applied the established theory and procedure (Wu and Hermundstad, 2002) to a high speed trans-Atlantic pentamaran containership. Nonlinear time-domain simulations of ship motions and wave loads were carried out in different sea states. Short-term probabilities of exceedance were estimated by fitting the generalized gamma density functions to the histograms of the peaks and troughs extracted from the simulated nonlinear responses. Long-term probabilities of exceedance were obtained using the short-term results and served as statistical information on the load side in a reliability-based design approach.

Pastoor *et al* (2002) discussed the DNV rule requirements for direct analysis of High Speed Light Craft (HSLC), with emphasis on the hydrodynamic calculations. The practical application of nonlinear analyses according to these rules was described. For classification of other ships than HSLC the classification notation CSA-2 (Computational Ship Analysis) is applicable when direct analyses are applied. A summary of this class notation was given and a general strategy for nonlinear hydrodynamic assessments was presented. The nonlinear design hydrodynamic loads are based on a 20 years return period and a scatter diagram approach. It is a rational assessment procedure with different levels of complexity but without endless nonlinear calculations. Special features in the assessment scheme are the possibility to include slamming in the hydrodynamic analyses, apply direct load transfer of hydrodynamic pressures and accelerations to a FE model and conduct whipping analyses by using the slamming events as excitation sources. Special attention is paid to reduce the amount of nonlinear simulations by rational determination of critical sea states and by using advanced response conditioning techniques to replace random irregular simulations. Pastoor *et al* (2003) presented calculation procedures to determine extreme responses of ocean-going structures using nonlinear time domain simulations.

Dietz *et al* (2004) illustrated a new approach using Most Likely Response Waves (MLRW) to estimate the entire non-linear extreme response value distribution for a selected operational profile. The numerical results were performed for a Panamax containership using the non-linear time domain seakeeping code. Dietz (2004) studied, in his thesis, the application of conditional waves as critical wave episodes to predict extreme loads on marine structures.

Parunov *et al* (2004) described the calculation of design vertical wave bending moments for unconventional new generation oil product tankers that are characterized by low length-to-beam ratio. The linear strip theory was employed for the calculation of transfer functions, while standard IACS procedure was used for long-term prediction of extreme values. Teigen and Naess (2004) highlighted the problem of accurate assessment of second order wave loads on floating structures, and the consequences for the extreme response of structures subjected to stochastic loading. Particular emphasis was placed on the mesh size requirements and the numerical convergence.

3.2.4 Mass Distribution

Mass distribution may be important input to the analysis. The importance is defined by the type of analysis. For calculation of still water loads, the mass distribution is of vital importance, while for hydrodynamic pressure calculations it is of no significant importance as long as the global mass properties are correct.

For direct analyses where loads are directly transferred from the hydrodynamic analysis to the structural model it is important that the mass distributions are correct and consistent. On the other hand, if loads are applied manually to the structural model, mass distribution may be replaced by other loads and the importance therefore depends on the method of analysis.

3.2.5 Uncertainties on Load Knowledge

Uncertainties associated with an engineering problem and its physical representation in an analysis has various sources. These may be grouped as according to DNV Classification Note 30.6 into:

- *Measurement Uncertainty*
  Caused by imperfect instruments and sample disturbance when observing a quantity. It is usually quantified by the manufacturer but may also be evaluated from laboratory or full scale tests.
- *Physical Uncertainty*
  Also known as inherent or intrinsic uncertainty is a natural randomness of a quantity such as variability in current, uncertainty in yield stress etc
- *Statistical Uncertainty*
  Due to a limited amount of information such as a limited number of observations which causes uncertainty in the estimation of statistical parameters.
- *Model Uncertainty*
  Uncertainty due to imperfections and idealizations made in the applied physical and probabilistic models, and reflects a general confidence in the applied model to

describe "real life". It may further account for unknown effects of other variables and their interaction which are not included in the model.

For a ship, this may typically be uncertainties in:

- Wave climate (wave height, wave period, wave spreading, wave heading, etc.)
- Operational profile (load condition, speed, routing)
- Load analysis uncertainties (programs ability to calculate the effect correctly)
- Unusual loads such as shallow water effects (e.g. squat), accidental loads due to collision, grounding, explosion, etc.

Different aspects will be of importance for the uncertainty for the items above. In addition, the load calculation procedure, which is the interpretation of how to calculate and use different loads, is an important part that should be included in the uncertainty.

Vidic-Perunovic and Jensen (2003) studied the shallow water effect on the vertical wave-induced loads acting on the hull by a modified linear frequency domain deep water strip theory. The trends in motion and load responses with water depth were discussed for two particular ships. Vidic-Perunovic and Jensen (2004) analysed the wave-induced high-frequency bending moment response of ships, denoted springing. The aim was to predict measured severe springing responses in a large bulk carrier. It has been shown that the most important springing contribution is due to the resultant second order excitation in multidirectional sea. The incident pressure field from the second order bidirectional wave field was derived, including the non-linear cross-coupling terms between the two wave systems (e.g. wind driven waves and swell). Theoretical predictions of standard deviation of wave- and springing induced stresses amidships were compared with full-scale measurements for a bulk carrier.

Gu *et al* (2003) presented a large ocean going ship with significant springing responses, which have made a large contribution to the fatigue cracking for certain structural details. Four different theories for predicting ship responses and associated computer programs for predictions of springing were described. These theories represent four different approaches with various characteristics, e.g. linear, second-order, nonlinear, frequency-domain, time-domain, two-dimensional and three-dimensional, in calculating hydrodynamic loads and vibrations. The numerical programs, WASIM (DNV), SOST (DTU), SINO (CSSRC) and VERES (Marintek), have been well validated for ordinary ship responses. Assumptions regarding how the different programs are suited in the present calculations were provided and sensitivity studies were carried out. A selected number of full-scale measurements with various sea states and headings used for comparison between numerical results and the measurements were made with reference to simulated and measured high frequency (2-node vibration) and low frequency (wave induced) stresses.

Olsen *et al* (2004) presented about 20,000 observations of wave heights taken on board vessels sailing in the North Atlantic. The data covers year 2002 and 2003 and stem from a variety of ship types. From the analysis of the data some conclusions are reached about the effect of weather routing.

3.3 Structural Modelling

The necessity of finite element (FE) modelling technique has gradually increased not only by a dramatic decrease in the computational time in accordance with the advancement of the computer technology, but also by improving the pre- and post-processing in FE analyses.

Element modelling is an important aspect of Finite Element modelling and analysis. Considerable research efforts have been devoted to developing simple, robust, generalised and efficient element models. It is common practice to use conventional shell elements such as 4-noded quad-shell elements or 8-noded shell elements with both translational and rotational freedom for quasi-static response of ships. In recent years, the rotation free shell element models have been developed where the curvatures over an element are approximated in terms of deflection of the nodes in adjacent patch of elements. This method offers advantages in non-linear analysis.

In a FE analysis, model generation still accounts for quite a considerable portion of the total effort. Moreover, the accuracy of the FE results is influenced by the appropriateness of the model. As a means of speeding up the process of model generating, functions such as automatic element division, etc. have been incorporated to analysis tools. As discussed in Section 2.3.4 adaptive meshing may play an important role in reducing the effort in mesh generation as well as improving the approximation behaviour of FEM.

Another important aspect is the interconnectivity between the coarse global models and the detailed local models. Local detailed zoom models are needed for detailed stress analysis (for example, fatigue analysis). In some cases, several local zooming is required for accuracy to determine stresses (hot spot stress). Sophisticated commercial FE packages allow automated detailed local mesh generation and the transfer of boundary conditions obtained from global model to the local models.

3.3.1 Uncertainties on FE Modelling

Uncertainties on FE modelling in relation to materials used, as built versus as designed, residual stresses, and local corrosion are reviewed and discussed.

Rigo *et al* (2003) presented the results of an extensive sensitivity analysis carried out by the Committee III.1 "Ultimate Strength" of ISSC 2003 in the framework of a benchmark on the ultimate strength of aluminium stiffened panels. The target of this benchmark was to present reliable finite element models to study the behaviour of axially compressed stiffened aluminium panels (including extruded profiles). Main objectives were to compare codes/models and to perform quantitative sensitivity analysis of the ultimate strength of a welded aluminium panel on various parameters (typically the heat-affected zone). Furthermore, Rigo *et al* (2004) focused their discussion on the main outcomes provided by the ISSC benchmark study (Rigo *et al*, 2003).

Garbatov *et al* (2002) analysed the influence of corrosion on the stress concentration factors of typical ship structural details. While traditionally constant stress concentration factors were adopted, it was proposed to use time-varying stress concentration factors, which result from the progress of corrosion in the structure. Linear and nonlinear models of the effects of corrosion wastage on the plate thickness reduction were considered and stress concentration factors and fatigue damage were calculated as a function of time. The study concluded that the stress concentration factors have a nonlinear dependency with the time and this leads to a significant difference of the fatigue damage of structural components subjected to corrosion as compared with the traditional predictions.

Paik *et al* (2003b and 2003c) developed a mathematical model for predicting uniform or pit corrosion wastage of bulk carrier structures as a function of time. Corrosion measurements for existing bulk carriers, single- and double-hull tankers, and FSOs and FPSOs of various ages were collected and the statistical characteristics (mean, variance, distribution) of measured corrosion data were quantified in terms of ship age. The results and insights developed from this work should be useful for predicting the depth of uniform or pit corrosion in ship structures. A measured data set of corrosion for seawater ballast tank structures of bulk carriers and oil tankers was collected by Paik (2004b), and their corrosion characteristics were quantified by the statistical analysis in terms of ship age. Mathematical models for predicting time-variant corrosion wastage of the corresponding structures and relevant values for corrosion margin were suggested.

Gardiner and Melchers (2003) considered the physical processes of corrosion that occur in bulk carriers. Three main types of corrosive environments have been identified within a bulk carrier, namely, immersion in seawater, exposure to an enclosed atmosphere, and exposure to porous media. Fundamental variables influencing corrosion in each environment of the cargo hold region, ballast tanks and void spaces were identified. These serve to identify operational parameters that affect bulk carrier corrosion. Dunbar *et al* (2004) described an investigation on the effects of local corrosion applied to plates and stiffened panels typically found in ship structures. Finite element investigations of initial buckling, ultimate collapse and post-ultimate responses were presented and described through the use of load-shortening collapse curves. Geometric imperfections and residual stresses were included in the model and results were compared with analytical calculations and the available experimental measurements. This improved knowledge of the structural integrity of a damaged ship structure can be used to develop more efficient maintenance practices.

Nakai *et al* (2004a) investigated the pitting corrosion observed on hold frames in way of cargo holds of bulk carriers which exclusively carry coal and iron ore. A series of tensile tests has been conducted to investigate the effect of pitting corrosion on tensile strength of members. It was pointed out that the tensile strength decreases gradually and the total elongation decreases drastically with the increase of the thickness loss due to pitting corrosion. Also, a series of compressive buckling tests has been performed to examine the influence of pitting corrosion on buckling behaviour of members showing the compressive buckling strength of pitted members is smaller than or equal to that of members with uniform thickness loss in terms of average thickness loss. Moreover, Nakai *et al* (2004b) carried out a series of 4- and 3-point bend tests on structural models which consist of web, shell and face plates. The effect of web plate pitting on the lateral-distortional buckling strength in the 4-point bend tests was found to be small but the ultimate strength decreases with increase in the degree of pitting intensity. The ultimate strength in the 3-point bend tests was found to be decreasing with increase in the degree of pitting intensity.

Zou *et al* (2003) investigated ship structural vibration and underwater radiation noise using the coupled finite element/boundary element method. The finite element method (FEM) was employed to analyse modes and vibration responses of an entire ship for different kinds of excitations in consideration of fluid–structure interaction. The boundary element method (BEM) was used to analyse the underwater radiation noise. Hoffmann *et al* (2004) analysed the phenomenon of flow induced vibrations of structures and subsequent noise generation, which is based on numerical simulation approaches. Using empirical formula for power spectrum density and applying computational fluid dynamics (CFD) for defining necessary parameters a special finite element (FEM) formulation was used to predict the effects of noise generation in turbulent boundary layers.

3.3.2 *Advanced Finite Element Modelling*

One of the main difficulties presented by the classical FEM is the lack of flexibility to realise the refinement of a given zone from a large global model in order to analyse details. In the last decade, a number of improved numerical methods have been developed to tackle this difficulty. Particular examples to these methods can be given as the diffuse and meshless methods, the volumic correction multiscale approaches, the Partition of Unity Method, the GFEM, the XFEM, the micro- macro scale approach (or FETI method).

Suzuki *et al* (2002a) proposed a numerical simulation method for analyzing Mindlin-Reissner-shell structure using GFEM (Generalized FEM). GFEM can be considered as the generalization of FEM by making the node displacement not constant value but the function. The formulation of GFEM applied to Mindlin-Reissner shell element was shown, and coordinate transformation for GFEM was presented. Several examples confirmed the validity and accuracy of this method. It was shown that GFEM is effective against the distortion of the element shape compared with traditional FEM, especially in-place deformation. It was also shown that by changing the degree of polynomial locally, it is possible to control the accuracy locally. Suzuki *et al* (2002b) proposed a new global local iterative analysis method based on the overlaying mesh method. Pre-conditioned conjugate gradient algorithm block global local pre-conditioner and several other pre-conditioners were compared and it was shown that block global local pre-conditioner gives much better iteration convergence, and overall better performance even compared with the multi-frontal direct method. The algorithm was also used by iterative analysis using general purpose commercial code.

Nakasumi *et al* (2003) presented a mixed method of analyzing shell elements and solid elements using the overlaying mesh method. In the structural design of a ship's hull, the shell elements are used for the global model. However, the solid elements are necessary to analyze the stress concentration zones or the vicinity of a crack. In such cases, the models were analysed using zooming analysis, in which the results of a global model analysis were transferred to a local model analysis by imposing boundary conditions. The proposed mixed method is claimed to be more advantageous than zooming analysis in terms of the accuracy of the solution and the modelling flexibility. Some examples of a plate model with a cracked surface or with a projection are shown in order to demonstrate the effectiveness of the method. Nakasumi *et al* (2004) presented a new approach to crack propagation analysis for large-scale or complicated geometry structure. The approach utilises the connection of mesh superposition method and extended finite element method. In the former technique, two types of meshes were used and displacement was represented as the sum of them. And in the latter technique, discontinuity across the crack segment and singularity around the crack tips were represented in the approximation by enriching the nodal degrees. This technique does not require meshes to conform to the crack geometry which enables crack propagation procedure with no re-meshing process.

Kawamura and Sumi (2004) presented a development of a proto-type system for evaluation of corrosion damages by using the STEP (Standard for the Exchange of Product model data) technologies. A new concept for generation of analysis models for strength of aged ships from the database in the information system was proposed. Kawamura *et al* (2005) discussed a new strategy of fully automatic hexahedral mesh generation. In this strategy, the prerequisite for generating hexahedral is quadrilateral surface mesh. From the given surface mesh, combinatorial dual cycles (whisker sheet loops for whisker weaving algorithm) were generated to produce hexahedral mesh. Since generating good quality hexahedral mesh does not depend only on the quality of quadrilaterals of the surface mesh but also on the quality of the dual cycles generated from it, the method to remove self-intersections from dual cycles was proposed.

Driven by the growing oil exports from Russia, environmental impacts due to increased traffic, recent harsher ice conditions in Baltic Seas, there is an increasing demand for ice strengthened tankers. As a result, it has become very important to design ice strengthening side structures that are more producible while maintaining adequate safety and integrity. Wang and Wierniciki (2004) and Wang *et al* (2005) presented the methodology adopted by ABS to assess the ice strength of tanker vessels based on non-linear finite element modelling and analysis. The Guidance Notes on Nonlinear Finite Element Analysis of Side Structures Subject to Ice Loads were developed and presented. These Guidance Notes provide detailed instructions for structural modelling, material nonlinearity, ice loads, boundary conditions, and acceptance criteria. In addition, these Guidance Notes were applied to the evaluation of some design variations and designs for different ice classes.

3.3.3 Models for Detailed Analyses

In the context of fatigue strength assessment, some detailed analyses on ship structural members were performed. Several parameters affect the failure behaviour such as geometry and loading of the detail, throat thickness of the weld, axial misalignment and residual stresses. Doerk and Fricke (2004) performed fatigue tests and analytical computations with models considering the above mentioned effects. The analytical computations include structural hot-spot stresses and the propagation of cracks initiating from the root gap. Some tests showed unexpected results in comparison with the calculations. Beneficial residual stresses were identified to be the main reason for this, which have been validated by neutron strain scanning and thermo-mechanical analysis of the welding process. Such residual stresses are induced by the longitudinal weld shrinkage and restrained in-plane bending. From the investigations, a simplified procedure for the fatigue strength assessment of fillet welds around toes of brackets and stiffeners have been derived, including additional factors to account for residual stress effects.

Karamanos *et al* (2002) developed a methodology for the calculation of the maximum local stress, referred to as "hot-spot stress", in a multi-planar DT-joint, with particular emphasis on the effects of bending moments on the braces and the chord. Special attention was focused on the location where critical stress concentration occurs, as well as on the so-called "carry-over phenomenon" and its implications on the hot-spot stress value. Simplified design equations for fatigue design were proposed to determine SCF values due to bending in order to improve predictions with respect to existing design tools.

As part of a project to develop guidelines for reducing cracks in aluminium ship structures, Latorre *et al* (2002) performed experiments showing that the stress levels developed strongly depend on the welded connection details. This investigation summarizes the analysis of a common structural detail, one that results in a transversely loaded weldment and links to two sets of experimental test results. The first is the stress concentration observed at the intersection of the longitudinal and transverse members in a 1.5-m×3-m aluminium bottom panel tested under uniform pressure loading. The second is the reduction in fatigue life due to weld geometry variations between manually welded and machine-welded aluminium specimens. In order to clarify these two observations, the authors completed a detailed finite element analysis of a welded aluminium T-stiffener. The results showed a significant stress concentration in the weld toe area. This stress concentration was shown to be strongly dependent on the weld toe geometry.

Sumi *et al* (2004) investigated the characteristics of fatigue crack propagation and the remaining life assessment of ship structures by focusing attention on curved crack paths, the effects of weld, complicated stress distributions at three-dimensional structural joints, and structural redundancy. They developed an advanced numerical simulation system to predict realistic phenomena of fatigue crack propagation. The present method may offer an efficient simulation-based tool for the fatigue crack management of critical details.

Simonsen and Törnqvist (2004) presented a combined experimental–numerical procedure for development and calibration of macroscopic crack propagation criteria in large-scale shell structures. A novel experiment was set-up in which a mode-I crack can be driven 400 mm through a 20(+) mm thick plate under fully plastic and controlled conditions. The test specimen can be deformed either in combined in-plane bending and extension or in pure extension. Experimental results were described for 5 and 10 mm thick aluminium and steel plates. By performing an inverse finite-element analysis of the experimental results where the simulated crack growth is forced to correspond to the experimental observations, empirical criteria for ductile crack propagation emerge very clearly. Using the experiments with edge crack specimens (ECS) in combined in-plane bending and extension, crack propagation criteria were developed for steel and aluminium plates, mainly as curves showing the critical element deformation versus the shell element size. These derived crack propagation criteria were then validated against a separate set of experiments considering centre crack specimens (CCS) which have a different crack-tip constraint. The applicability of the often-used equivalent strain criterion was discussed versus a more rationally based criterion which takes into account the stress tri-axiality. A large-scale grounding experiment was also simulated showing very good agreement with measurements.

Various other modelling and analysis approaches have been considered by many. We will review some of these in sections 4 and 5 when we discuss ship and offshore structures.

3.4 Structural Response Assessment

As mentioned in chapter 3.1.2, structural response assessment of ship structures is carried out in accordance with direct calculations. Therefore, new computation techniques are introduced in order to develop more practical procedures in design stages. Then, studies about uncertainties in calculations are presented.

3.4.1 New Computation Techniques

Byklum *et al* (2004) derived a computational model for global buckling and post buckling analysis of stiffened panels. The loads considered were biaxial in-plane compression or tension, shear, and lateral pressure. Deflections were assumed in the form of trigonometric function series, and the principle of stationary potential energy was used for deriving the equilibrium equations. Lateral pressure was accounted for by taking the deflection as a combination of a clamped and a simply supported deflection mode. The global buckling model was based on Marguerre's nonlinear plate theory, by deriving a set of anisotropic stiffness coefficients to account for the plate stiffening. Local buckling was treated in a separate local model developed previously. The anisotropic stiffness coefficients used in the global model were derived from the local analysis. Together, the two models provide a tool for buckling assessment of stiffened panels. Implemented in the computer code PULS, developed at Det Norske Veritas, local and global stresses were combined in an incremental procedure. Ultimate limit state estimates for design were obtained by calculating the stresses at certain critical points, and using the onset of yielding due to membrane stress as the limiting criterion.

Paik *et al* (2004a) compared some useful ultimate limit state (ULS) methods adopted for the design of aerospace, marine and land-based aluminium structures. A common practice for aerospace, marine and civil engineering welded stiffened panel applications was discussed. Paik *et al* (2004b) measured some typical plate initial deflection shapes for merchant ship plating between stiffeners. The influence of such initial deflection shapes on the ultimate strength behaviour of steel plates subjected to biaxial compression as well as uni-axial thrust was then investigated applying nonlinear finite element analyses.

Fujikubo and Kaeding (2002) developed a new simplified model for collapse analysis of stiffened plates within the framework of the idealized structural unit method (ISUM), which was proposed by Ueda and Rashed (1984). Both local buckling of the plate panel and overall buckling of the stiffener could be analyzed by combining plate and beam-column elements of ISUM. The application of this method to a time-domain collapse analysis of a pontoon-type Very Large Floating Structure (VLFS) in regular waves was presented by Fujikubo *et al* (2003a and b). ISUM plate element was extended by Kaeding *et al* (2004) so that lateral loads could be directly applied to the plate element. Moreover, Fujikubo and Pei (2005) demonstrated the application of ISUM to analyze the progressive collapse behaviour of ship's hull girder in longitudinal bending.

The weight function method was originally derived for crack problems to calculate stress intensity factors for arbitrary loading conditions. Sumi *et al* (2005) extended to formulate the structural response analyses of two-dimensional elasticity, plate bending, and three dimensional plate structures by using a finite-element method. The solution procedure was based on the well-known Maxwell–Betti reciprocal theorem. The method is very useful for the analysis of structures subjected to a vast range of loading conditions, because structural responses can simply be calculated by the inner product of the universal weight function and load vectors. The validity and convergence characteristics of the present method were investigated by two dimensional elastic and plate bending problems, respectively. Finally, the method was applied to the calculation of the response amplitude operator (RAOs) of a stress component at a critical structural detail of a double-hull tanker.

Zhang, S. *et al* (2004) developed semi-analytical methods for analysis of plate crushing and ship bow damage in head-on collisions. Existing experimental and theoretical studies for crushing analysis of plated structures were reviewed and compared. Simple formulae for determining the crushing force, force-deformation curve and damage extent of a ship bow, expressed in terms of ship principal particulars, were derived for longitudinally stiffened oil tankers and bulk carriers with length of 150 metres and above. It is suggested that the approach developed can be used easily to determine the crushing resistance and damage extent of the ship bow when ship length and collision speed are known. The method can be used in probabilistic analysis of damage extents in ship collisions where a large number of calculations are generally required.

3.4.2 Uncertainties in Calculations

Structural experiments using scaled models are often conducted in order to verify the uncertainty in the finite element analyses, the validity of modelling and the accuracy of the calculation results. Sun and Soares (2003a) presented the results of an experimental investigation to determine the torsional ultimate strength of a ship-type hull girder with a large deck opening. Two models with the same dimensions and scantlings were designed to reflect the possible modes of failure under pure torque. A comparison between nonlinear finite element calculations and the experimental results for the two models was made.

Lehmann and Peschmann (2002) performed the large–scale collision experiment and its results were used to validate numerical calculations of the collision process. By means of the results obtained in respect of the breaking strains to be used in the calculations and other parameters, numerical calculations were performed of a double–skin structure with austenitic inside wall and/or austenitic shell and inside wall. It was shown that, with identical structure and identical mass of construction, the use of austenitic steel offers considerably greater resistance to collisions.

Kujala *et al* (2004) presented a summary of major design challenges and possible solutions about steel sandwich panels welded by laser. First, the behaviour of the all steel sandwich panels under bending loading was analysed. Analytical formulation were developed and verified by FE-analysis. Then the behaviour under local impact was analysed by FE-simulations, analytical formulations and extensive laboratory testing. Finally the important topic of the joining elements was investigated. The longitudinal joints form a crucial topic, especially when the deck experience high fatigue loading levels. Kozak (2004) presented a study on behaviour of laser welded T-joint under bending load. Results of measurements of strain field distribution were presented and example of numerical modelling was shown together with comparisons between the predicted and natural scale laboratory tests results.

Kuroiwa *et al* (2004) studied ultimate strength and collapse behaviour of bow structure by non-linear FEA. The effects of pressure acting area, dynamic loading and boundary condition were studied. The study concluded that duration of applied pressure does not affect structural response so much, when the bow structure is designed so that no significant plastic deformation occurs against the impact pressure. It was also demonstrated that both sides modelling is preferable in calculating structural response by FEA. From the results of the calculations and measurements of wave impact pressure on an actual ship, area where impact pressure acts was investigated. It was found that the area is localised and for design application it is appropriate to consider design wave impact pressure p_{des} over an equivalent area of 1/2 of A, where A is area supported by the subject primary member.

3.4.3 Need for Naval Oriented Post-processing

Although several commercially available FEM codes such as MAESTRO and FEM codes developed by classification societies – to a certain extent- are naval oriented FEM packages themselves, the need for dedicated naval oriented post processing tools of FEM calculations has been identified as one of the development areas in previous the ISSC Committee reports.

Ship Information Navigator (SIN) is a naval-oriented tool dedicated to finite elements computation models checking developed by Principia Marine, France (http://www.principia.fr). The tool can be used, before computation, to allow the structural engineer checking the model adequacy versus real structure and physical phenomenon to compute and it can be used, as a post-processor, to gain an easy and powerful access to usual results of a structural analysis and to avoid using general purpose post-processing tools that are usually complex to use.

The main features of SIN are

- Hierarchic representation of the structure in a usual way for designer,
- Splitting primary and secondary stiffeners,
- Display of stress values against rule criteria,
- Automatic computation of cell buckling criteria (with choice of Rule set),
- Ability to take corrosion into account,
- Frequencies "scan" function on one or more node components for forced responses,
- 2D view with automatic display of scales (frame number along X, longitudinal bulkhead position along Y and deck name along Z),
- Ability to create custom elements groups,
- Function to automate images creation.

3.5 Example Finite Element Comparative Study

The present committee was not able to perform a benchmark Finite Element study, even though a format and the usefulness of a benchmark FE study were discussed in the committee meetings. Nonetheless, the following comparative FE study (although specific example is on ultimate strength and therefore could be considered more relevant to Technical Committee III.1), provided by one of the Committee members, is considered to be of benefit to the readers.

A comparison of the ultimate bending moment of the ship calculated with two different methodologies has been developed in a thesis in Naval engineering at University of Trieste (Emolumento, 2005). The progressive collapse behaviour of a cruise ship's hull girder under longitudinal bending load in hogging condition has been analysed with the RINA's (Registro Italiano NAvale) software code 'RINACOLL' which was developed in order to perform an ultimate state analysis and to estimate the ductile collapse strength of a ship's hull girder. The main theoretical assumption is that the collapse results from a sequence of failure of local components rather than from an overall simultaneous instability of the complete cross section, see Lambiase *et al* (1997). This tool provides the results in terms of ultimate bending moment (both horizontal and vertical) and the curvature-moment history, imputing as loading condition a sequence of curvature points in a user fixed flexural plane. This allows one to address the collapse behaviour of the hull by concentrating on the collapse behaviour of the local components that make up the cross section, where such components are modelled as a single plate-stiffener combination. The method has been developed by considering only the vertical bending moment acting in the ship symmetry plane and does not allow for the effects of additional type of loading such as shear, torsion, or horizontal bending.

A first area requiring of further development concerns plate effectiveness, and in the future research works our principal aim will be to assess in a more precise manner the influence of initial distortion and of torsional stiffener plate rigidity upon the effective plate width to consider in evaluating the beam-column collapse. Another significant area of future development is the post-buckling behaviour that probably includes the greatest number of approximations in the present method. In fact, almost all the test cases performed and illustrated in this report have shown that the major approximation in the present method is in the unloading region (i.e. the post-collapse behaviour) and our next goal will be to develop simplified empirical relationships to treat this problem.

However the next step will be to extend the method to treat unsymmetrical ship sections and to account for the horizontal bending moment effects. Then we will implement the procedure to asses the effects of additional types of loading such as shear, torsion and warping. The comparison with FEM analyses, underlying that all these approximate procedures needs to be validated further. In fact, the finite elements calculation, developed only with a FEM model shows large difference in the ultimate bending moment, so sensitivity analysis to evaluate the effective influence of imposed boundary conditions, plate and stiffeners imperfection upon a realistic load shortening curve, are needed. Figure 2 gives a comparison of results between the two procedures and the Figure 3 shows the finite element model analysed with the non-linear commercial finite element code MSC.Marc 2005.

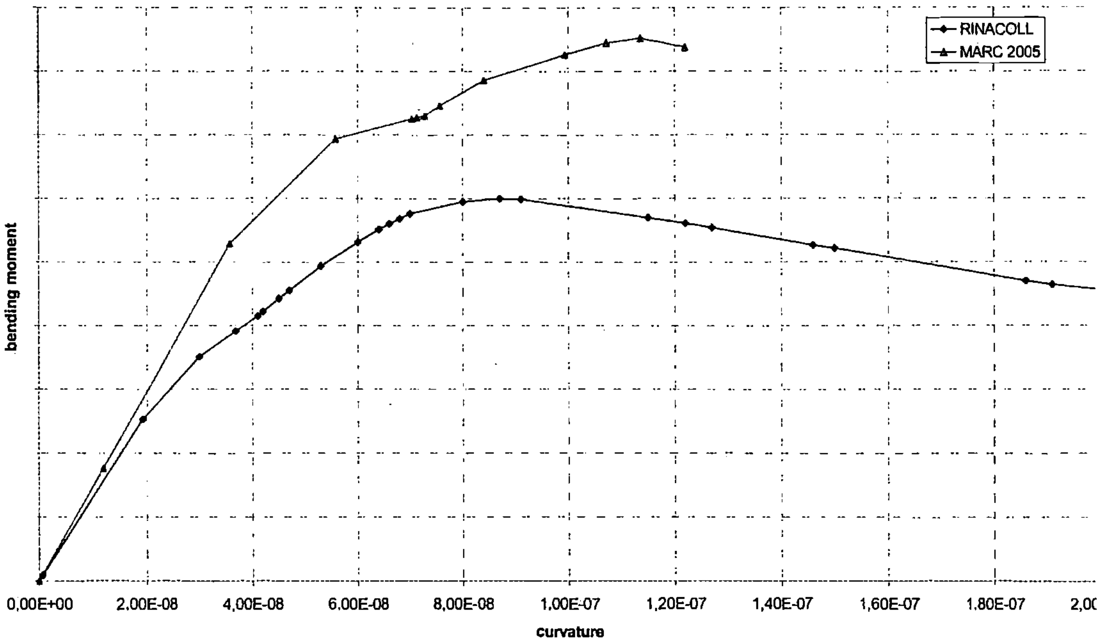

Figure 2 : comparison of the curvature-bending moment calculated with rinacoll and non-linear finite element analysis.

4. SHIP STRUCTURES

4.1 Ship Specificities

In this chapter, structural characteristics and relevant problems of the following vessel types have been addressed.

- Bulk Carriers,
- Tankers,
- Ro-Ro vessels,
- LNG/CNG vessels, and
- Inland Navigation vessels.

Also, developments of IACS Common Structural Rules and IMO Goal Based Standards have been reviewed and discussed in relation to quasi-static response assessment.

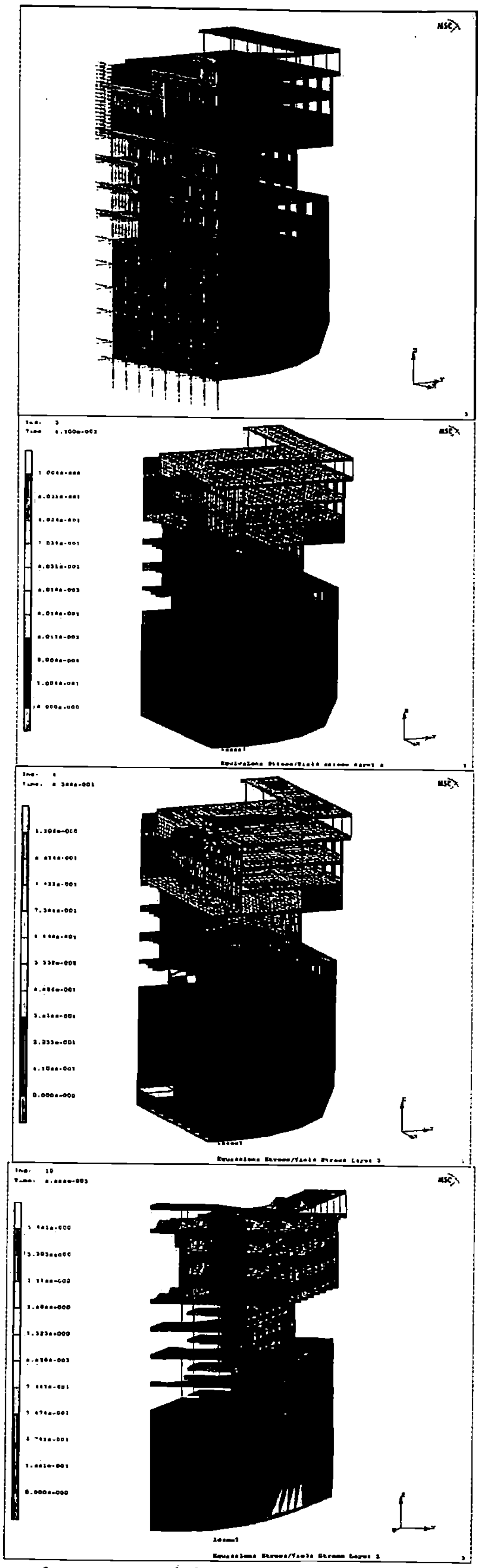

Figure 3 : Finite element model with the results at different load step.

4.1.1 Bulk Carriers

The safety of bulk carriers has been one of the principal items on the agenda of IMO and IACS since the early '90's. As a result, an increased regulatory safety regime was introduced through IMO and a more extensive survey regime by IACS with improved awareness of the implications of structural damage on hull integrity. The measures introduced by IACS for new and existing bulk carriers went some way to address the problems of bulk carrier strength inadequacies but the subsequent conclusions of the re-opened Formal Inquiry into the Derbyshire loss in November 2000 coupled with high profile losses of several capesize vessels in 2001 raised further concerns over the suitability of modern single skin bulk carriers for their intended trade. Servis *et al* (2003) presented a methodology for modelling hold No.1 of bulk carriers using finite elements in order to assess the structural integrity of these areas under the loads prescribed by IACS. Results from respective nonlinear analyses using IACS loads are also presented.

The increased hatch cover design strength together with watertight bulkhead strength criteria as well as increased double bottom strength and hull girder strength as a result of flooding are examples of such measures. Ergas *et al* (2004) stated that based on the recent research carried out at SSRC on bulk carrier safety, the most dominant loss scenario is that of the hatch covers' failure. The casualty data indicates that the capesize bulk carriers are more at risk for hatch cover failure than the smaller ships (IACS, 2001). Extensive research on the subject reinforced the conclusions from the casualty data by revealing that the existing requirements prescribed by ILLC66 and UR S21 (Rev.3) are not sufficient for the hatch covers fitted to capesize vessels (like M/V Derbyshire). They presented findings of a part of the on-going investigation regarding Panamax size bulk carriers.

In response to shortcomings of the bulk carriers' safety, IACS put in place a package of additional measures to enhance the robustness of the single skin designs (Nieuwenhuijs *et al,* 2005). These measures are based on

- Strengthening the side shell in order to avoid water ingress
- Avoiding progressive flooding of more than one hold
- Alerting the crew of a flooding occurrence at a very early stage.

More recently, IACS URS 25 was introduced in June 2002 following an IACS/industry discussion initiated on the loading conditions presented in the loading manual and for which the ship was approved in many cases did not give the owner the ability to use the full potential of his ship. Applying URS 25 results in a steel weight increase of 5-7%. It appears this increase in steel weight has been well accepted by the industry, owing to transparency of rule making process.

The focus on bulkers also led to a number of other changes, which were published as URS 21, 26, 27, 28, 31 and UISC 179-180, a unified interpretation of SOLAS chapter XII reg 12-13.

Scantling requirements for hatch covers for new ships have been increased by URS 21. SOLAS chapter XII reg 12-13 requires a water ingress alarm in all cargo holds for existing ships to alert the crew at the first instant of a possible flooding.

URS 26 deals with the strength of small hatches on the exposed fore deck and URS 27 deals with foredeck equipments and outfittings, in order to limit the risk of flooding of forward spaces. Both apply to both new and existing ships. URS 30, giving requirements for the closing devices of hatch covers 1 and 2. URS 28, requiring a forecastle on new ships, increases buoyancy in the forepart as well as protecting the first cargo hatch against green water.

The revision of the LL Convention, which entered into force at the 1st of January 2005, includes the introduction of an additional reserve of buoyancy at the fore end (Reg.39(5)). The additional reserve of buoyancy applies to ships assigned a type B freeboard. URS 31 was introduced to further limit side shell damage to existing ships. It gives renewal criteria for side frames, which when replaced must be brought up to the new ship standards of URS 12.

SOLAS II-I reg. 3.6, providing permanent means of access on new bulk carrier over 20,000 GT, will facilitate effective surveys. SOLAS chapter XII reg. 14 will ban, as from the 1st July 2006, alternate hold loading for bulk carriers of more than 10 years of age if they are not meeting the requirements for withstanding flooding of any one cargo hold.

In addition, IMO mandated the fitting of double side skins to bulk carriers of 150m in length or above at their 76th Marine Safety Committee (MSC) meeting in London in December 2002. This decision was taken with the argument of double side skin will enhance the inherent structural integrity of the vessel by offering protection to the side shell frames from corrosion and mechanical damage. However at MSC78 in early 2004, the decision on mandatory double side skin construction was revoked to leave the choice of Double Side Skin Bulk Carriers (DSSBCs) optional. This decision was taken based on the conclusions of the 'Comparative FSA Study on single and double side skin bulk carriers' submitted by Greece and carried out on their behalf by Strathclyde University.

A paper by Johnston and Harrison (2005) explains the background to the development of the current and ongoing bulk carrier safety legislation, discusses ongoing measures to improve bulk carrier safety along with possible future developments through the analysis of the fleet and new-build trends. Johnston and Harrison (2005) predicted the seaborne iron ore trade to grow by 4.4% p.a. to 2015 due to mainly growing Asian demand. Other dry bulk commodities were also forecast to increase although not as dramatically. This will also result in changes in the distribution of the different sub-segments making up the bulk carrier fleet. Table 1 gives the make up of the bulk carrier segments at the start of the century, the current fleet and future projection at 2015.

Table 1
DISTRIBUTION OF BULK CARRIER SEGMENTS (COMPILED FROM JOHNSTON AND HARRISON (2005))

	2000	2005	2015
Handysize	41%	35%	24%
Panamax	27%	31%	35%
Capesize	32%	34%	41%

Apart from the changes in the segment distributions, analysis of current build suggests that concentrations of size in each segment group are expected to occur. Based on this information, Johnston and Harrison (2005) predicted that concentration on capesize will be 170000-180000 DWT range, panamax size will not change being 75000 – 80000 DWT range and handymax ships will be concentrated on 50000-60000 DWT although 30000-40000 DWT handy size bulk carriers will also be popular.

They argued the advantages of double side skin will be easier hold cleaning and the potential for reduced port time compared with single hull, easy inspection and safer access to side structure and improved resistance against low energy collisions.

Some perceived disadvantages of double side skin bulk carriers are higher new-build price than single hull of same size, loss of hold cubic volume, heavier steel-weight, reduced dead-weight compared with single hull of same size, difficulty associated with corrosion protection and maintenance of double hull spaces (although the authors accepts this as a valid argument for the smaller ships, they do not agree that it necessarily holds true for capesize and panamax vessels) and possible a lower standard of ship survivability in case of hold flooding.

However, Johnston and Harrison (2005) argued that double hulls would go a long way to satisfy such concerns and in particular for coal and ore carrying panamax and capesize vessels (representing an increasingly larger proportion of the fleet) which are continually subjected to the rigours of heavy grab/unloading equipment damage.

IACS are currently addressing the classification issues with the development of common structural rules (CSR) for bulk carriers which apply to both single and double hull vessels in excess of 90m. Nieuwenhuijs *et al* (2005) discussed the main provisions of the classification requirements included in the Joint Bulker Project (JBP) Rules. The basic principles of the approval of the structural design, the sea-induced loads, the limit states criteria and the accepted calculation procedures were explained, establishing the link with the damage data and basic strength principles.

The main innovations of the JBP rules are

- Corrosion additions corresponding to 95% of measured corrosion losses after 25 years of service
- Ultimate limit state of the hull girder in intact and damaged conditions in order to minimise the risk of the ship breaking her back at sea
- Concept of a minimum safe domain of loading conditions imposed by classification
- Accidental limit state with flooding of each individual cargo hold and failure of one single side-shell stiffener
- Fatigue life analysis based on 25 years of navigation in North Atlantic environment.

With the publication and expected entry into force in 2006, JBP common rules are based on present day state of the art techniques and accumulated experience. It is argued that one clear set of rules and methods will stimulate shipyards and design offices to design fit for purpose, cost effective ships. Also, it will allow the future research and development efforts of the individual societies as well as the research efforts of the maritime industry as a whole to be implemented in one set of Rules. A more detailed description of the JBP rules is presented in Section 4.2.

Bryson (2005) discussed management of a bulk carrier structure in view of the Enhanced Survey Programme (ESP) and subsequent requirements of IACS. The paper provides vast practical experience of detection and repair of many defects common to bulk carriers and places a great emphasis on the importance of managing the structure of bulk carriers. Such management should commence as soon as the ship is delivered from the newbuilding shipyard. Bryson argues that the ESP and subsequent IACS measures provide an adequate framework to formally document the structural condition of the ship and states the importance of regular communication and discussion between the owner/manager, classification society and other interested parties.

As discussed previously, the increase in the dry bulk market have resulted an unprecedented increase in new bulk carrier orders by the shipowners reacting to the market conditions. Although, in general bulk carrier designs are considered to be proven designs, new designs are also emerging, as are shipyards with little or no experience in building bulk carriers. For this reason, a Bulk Carrier Newbuilding Specification Guide by BIMCO has been prepared and will be released to the Industry shortly. In spite of being prepared by people representing shipowners' perspective, the guide is striving to achieve a balance between what is reasonably required by the owner and what is to be considered reasonably expected from the shipyard. Main philosophy and the structure of the guide were explained in a paper by Mortensen (2005).

4.1.2 Tankers

Stricter international regulation enacted in the early 1990s and advances made in design and safe operation of tankers saw a significant improvement in the tanker industry safety record. According to The International Tanker Owners Pollution Federation, oil pollution from tankers for the period 1997-2003 was only 25% of the pollution for the period 1990-1996. The total number of reported tanker incidents with pollution for the period 1997-2003 was only 37% of the figure for the period 1990-1996, while at the same time the total oil trade has increased by 15%. However, two particular accidents; *Erika* in 1999 and *Prestige* in 2002 with their heavy oil cargoes causing extensive pollution on European shores, have had major political, social, economic and technical implications.

The EU became seriously concerned that the age limits for the operation of single hull tankers set in (EU) Regulation 417/2002 were not stringent enough and introduced a new set of more stringent timelines in Regulation 1726/2003 (amending the previous regulation) on 22 July 2003 (EC Regulation No 1726/2003). Subsequent to this development, Marine Environment Protection Committee of IMO amended MARPOL 73/78 by adopting– in line with EU Regulation- accelerated single hull tanker phase out and a new regulation on the carriage of heavy grades of oil in its 50th Session (IMO, 2003).

Under a revised regulation 13G of Annex I of MARPOL, the final phasing-out date for Category 1 tankers (pre-MARPOL tankers) is brought forward to 2005, from 2007 (IMO, 2003). The final phasing-out date for category 2 and 3 tankers (MARPOL tankers and smaller tankers) is brought forward to 2010, from 2015, although exceptions are being made to certain Category 2 and 3 tankers allowing these vessels to be operated beyond 2010 subject to certain conditions such as having carried out satisfactory Condition Assessment Scheme (CAS).

The Condition Assessment Scheme (CAS) was also made applicable to all single-hull tankers of 15 years, or older. Previously CAS was applicable to all Category 1 vessels continuing to trade after 2005 and all Category 2 vessels after 2010. A new MARPOL regulation 13H was introduced on the pollution prevention from oil tankers which bans the carriage of Heavy Grade Oil (HGO) in single-hull tankers.

Aksu *et al* (2004) proposed a risk-based methodology for design and operation of tankers and developed a framework and suitable tools for a methodological assessment of risk to be undertaken to provide a rational basis for making decisions pertaining the design, operation and regulation of oil tankers. Such support can be used to make more informed decisions, which will in turn contribute to reducing the likelihood and severity of future oil spills.

Lee *et al* (2004) discussed proactive, risk-based structural integrity management of VLCC's based on Formal Safety Assessment (FSA) methods and safety case principles. This paper proposes a strategy for developing a Structural Integrity Management (SIM) system applicable to hull structures based on FSA. A model embracing the life-cycle of the vessel was outlined, leading to the development of a ship specific hull safety case and how this can be achieved was demonstrated using readily available technologies and resources.

In 2002 American Bureau of Shipping (ABS), Det Norske Veritas (DNV) and Lloyd's Register (LR) initiated a major project to jointly develop a single set of Classification Rules for the hull structure of oil tankers. The objective of the project to develop common rules was to avoid possible competition on the minimum safety standards. The three classification societies have worked together to combine their expertise and experience and produced a common set of rules for oil tankers (Joint Tanker Project (JTP) Rules) with a length greater than or equal to 150m. The philosophy adopted by the project, key technical aspects and the relationship with IACS Unified Requirements and other initiatives within IACS and IMO were presented in a paper by Card *et al* (2004).

Although Joint Tanker Project started independently of IACS, all current and forthcoming Unified Requirements, relevant to the structural design of oil tankers, have been incorporated into the new Rules and JTP accepted as one of the two pilot projects in the development of IACS Common Structural rules along with the Joint Bulker Project. Cooperation between the two projects was necessary to maintain coherence across ship types at the outset.

One significant improvement in the new Rules is the definition of loads which were included in a general section of the Rules. By adopting this approach, the user of the new rules should be in no doubt about the origin of the loads or what the loads represent. The dynamic loads cover normal service loads, at 10^{-8} probability level, and more extreme hull girder loads for ultimate strength in the intact condition. Extreme loads on localised structure and accidental conditions, such as flooding, were not included although the modular approach that has been adopted lends itself to including other load cases, or introducing new information, at a later stage relatively easily. Rule design wave loads are based on the existing IACS Unified Requirements where possible or derived using the wave statistics of the North Atlantic sea area specified in IACS Recommendation 34. First principles hydrodynamic calculation methods were used to derive the design loads and an equal probability was assumed for all headings.

The JTP Rules contain formulations for ship motions accelerations, external and internal pressures and global vertical and horizontal wave bending moments and shear forces. Prescriptive Rule requirements and for finite element analysis the conditions for obtaining the most onerous structural response were established based on maximising primary load components for a 25 year return period. The simultaneously occurring secondary loads were accounted for by using load combination factors, which have been determined using the equivalent design wave approach. For fatigue assessment the loads were used to calculate the expected stress range history based on a suitable distribution function. A number of assumptions were made, such as a forward speed of 75% of the declared service speed. The reference load value used is at the 10^{-4} probability level of the Weibull long-term probability distribution.

A net thickness philosophy has been adopted for the JTP Rules, which provides a direct link between the thickness that is used for strength calculations during the design stage and the minimum steel thickness accepted during the operational life of the ship. The strength calculations performed during the design stage are based on net scantlings. Newbuilding gross scantling requirements were calculated by the addition of an allowance for the expected wastage during the design life of vessel to the required net scantlings determined in accordance with the Rule requirements.

Rauta (2004) reviewed the specific challenges for a double hull tanker structure in relation to coating and discussed sources for corrosion with reference to ballast and cargo tanks. Based on the evidence from the current fleet, the author stated that the operating conditions in the ballast and cargo tanks of the double hull tankers would accelerate both the initiation and the rate of corrosion and suggested that although there might be some coatings available in the market that would perform satisfactorily, and provide long term protection against corrosion, their reliability is, however, dependent on a strict control of the application, thickness of the coating and the ambient temperature. Research is, therefore, needed to manufacture coatings less dependent of the accuracy of the film thickness. New coatings should also keep their properties and flexibility at high temperatures at which double hull tankers operate.

Carlton (2004) addressed the primary aspects of the design and operation of tankers across the range of ship sizes based on Lloyd's Register's trials and service experience with double hull tankers. In particular, the paper discussed aspects of mechanical damage, structural fatigue and corrosion of the hull structure; the influence of the after body structural design on the propulsion machinery systems; shaft alignment; propulsion; vibration and manoeuvring.

Handy size double hull tankers have been around since the 70's for the transport of chemicals and oil products, while larger tankers with double hulls were generally introduced in the mid 90's. Double hull offshore loading shuttle tankers of Aframax size and above were introduced in the mid 80's. A paper by Hansen *et al* (2004) examined the experience gained from these early built double hull tankers. He concluded that the main experience from operating a number of such double hull shuttle tankers, built from the mid eighties until the present is that there seems to be a generally reasonable correlation between present fatigue life calculation methods and actual service experience. However the author suggested for further work in this area in order to enable owners to order ships with a relatively trouble free hull service life, and that it is possible to achieve a long and relatively trouble free corrosion protection in ballast tanks through a proper coating specification and supervision at the new building stage. This does not however in any way replace the owners and managers responsibility for proper and conscientious inspection and maintenance of the ship hull structure.

Magelsen (2004) presented an evaluation on the difference between single hull and double hull tankers in relation to conceptual design of double hull tankers, fatigue, both high cycle and low cycle, corrosion and corrosion protection, wastage margins in service and access to structure. Magelsen (2004) concluded that double hull tankers from a structural point of view will reduce the risk of pollution and increase the safety of tanks. However, this is based on the knowledge of the conceptual design/maintenance and willingness to do what is needed by the bodies involved in the ship operation.

With the accelerated single-hull tanker phase-out, ship owners face unscheduled demands on capital to replace these vessels. There is a serious question whether adequate shipyard capacity will be available to meet the demand in the short term. An alternative to meet IMO requirements is to rebuild a single-hull into a double-hull. This may significantly reduce the cost of replacement. In addition, there are many yards worldwide that can do the rebuild that would not be able to perform new construction. A paper by Hagner *et al* (2004) outlined a proven patented internal rebuild process already applied to five ship-sized oil barges (24,000 – 32,000 dwt). Discussion was made of the practical structural solutions and experience. The similar patent-pending process to rebuild single-hull tankers into double-hull tankers with internal double bottom and external double sides was discussed. For the selected method of tanker rebuild, the principal area of concern is potential speed loss. To solve this, extensive use has been made of Computational Fluid Dynamics (CFD) supported by model basin testing showing very good correlation of resistance and wave profiles between the two methodologies.

4.1.3 Ro-Ro Vessels

Applications of First Principle Methods in Ro-Ro ship design have been reviewed in general by Krüger and Stoye (2004). Although focused on hydrodynamic problems, this publication outlines the general development of Ro-Ro ships. If Ro-Ro Ships are benchmarked with Container Ships, it is obvious that the efficiency of container vessels has been boosted during the last ten years due to market demands. Compared to this development, Ro-Ro design seems to change gradually only. The authors conclude that there must be potential in increasing efficiency of Ro-Ro ships. Design wise, two simple measures have to be taken:

- Increasing cargo input of ships
- Increasing the speed of ships

For freight Ro-Ro, increasing cargo input brings the necessity to increase the number of decks above the freeboard deck, as the length and the breadth of typical vessels is restricted by operational requirements (harbour and lock restrictions). At present, a Ro-Ro 5-decker is under construction in Europe. As a consequence of the increased number of decks, deck girder heights have to be optimized (e.g. by means of finite element calculations) in order to reduce the overall height as much as possible for stability reasons. Deck girders, which span the entire width of the vessel without any additional support as well as high racking loads are the most challenging aspects in this optimization process.

In contrast to other ship types like e.g. container vessels, Ro-Ro ships are generally not critical with regard to longitudinal strength or hull girder torsion. This can be explained by the continuous decks and the closed cross sections of Ro-Ro ships. However, due to large openings in the side walls of hull and superstructure a detailed global analysis is strictly required to investigate the degree of effectiveness of the upper decks with regard to hull girder bending.

Very high wheel loads on vehicle decks are still a significant problem with specific relevance for RoRo-Vessels. Thus, research is focused on local design of cargo decks.

The use of sandwich panels has been investigated in the SAND.CORe project. Sandwich panels have been successfully used as an overlay for existing vehicle decks in order to reinstate and/or strengthen these decks. Overlay technique is an non-intrusive and cost-effective technology (see e.g. http://www.ie-sps.com). Based on the experience with repair solutions, the application of sandwich panels for new buildings has been investigated in the SAND.CORe project (http://www.sandcore.net). In general, a sandwich panel consist of two metal sheets with a relatively light-weight core either of the same material or of a plastic. A variety of products with different cores (Cellular, Honeycomb, Pyramidal, Plastic and Concrete cores) have been taken into account in that project. For one particular panel, Barkanov *et al* (2005) carried out a detailed optimization procedure for a wheel loaded vehicle deck. The optimisation problem has been formulated as a minimum weight design subject to stiffness and strength constraints. Klanac and Kujala (2004) carried out a case study for a hoistable car deck using sandwich. The study leads to the conclusion that sandwich panels, when supported by a girder system, are a significantly better solution than a traditional design (cost and weight savings).

Another way to optimize deck structures is the use of high tensile steel. Janssen (2004) outlines the design of a very fast ferry made of high tensile steel 690. Eylmann *et al* (2004) investigated the fatigue behaviour of car deck made of very high tensile steel. Fatigue tests and numerical calculations were performed to investigate the fatigue behaviour of a vehicle deck with trapezoidal stiffeners under wheel loads. The results confirm that the fatigue life is rather independent from the steel strength.

4.1.4 LNG/CNG Vessels

International energy trade, almost entirely in fossil fuels, will expand dramatically. Cross-border gas pipeline projects will multiply, and trade in LNG will surge, LNG shipping capacity will increase by at least some 50% between 2002 and 2005. The amount of proven gas reserves has risen year on year since 1980. Global reserves of natural gas recently surpassed oil reserves and gas is still being discovered in large quantities. By 2020 it is expected that the world consumption of gas will exceed that of oil (Bingham, 2003). Factors that will influence the number of LNG ships, operational requirements, size and different type of vessels for gas transportation are discussed next.

The problem facing the gas industry is not finding the gas, but getting that gas to the market. This can be done in several ways such as gas pipelines and liquefied natural gas (LNG). The pipeline compared with the LNG transportation is a cheaper option. However, the heightened awareness over security issues may slow this process as it would be difficult to control thousands of kilometers of pipelines and could boost the demand for LNG carriers. For a long time, the capability to design and build LNG ships was restricted to a few shipyards. However, the demand for LNG ships is now so great that there are yards all over the world gearing up to take a share of the LNG market. A report by Samsung Heavy Industries (2003) predicted that up to 120 LNG ships will be built in the next 10 years.

Traditionally LNG ships have been designed to operate on fixed routes between the same loading and discharge terminal. However, some of the recent new builds have been ordered on speculation in an effort to take advantage of the developing spot market. This makes it difficult to predict the sea states that the ship might encounter which may lead to significant design changes in relation to structural strength and fatigue. LNG vessels are typically designed to have a fatigue life of 40 years or more. Another point is that the size of LNG ships is gradually increasing. Current vessels have capacities around 138 - 145,000 m^3, but designs are now on the table for capacities of 165,000 and 250,000 m^3 and over (SAMSUNG H.I., 2003). Construction of such size of LNG vessels is considered to be within the bounds of shipyards capabilities; however, these designs are limited by the draught, length and air draught available at the loading and discharge ports. This means the development of new, wider, shallow draught hull forms that will necessitate some rethinking of the current designs.

Furthermore, a clear trend is seen towards loading and discharging of gas at offshore terminals, in particular in the US after the 9-11 event in a bid to reduce risk exposure and to minimise environmental impact. Due to the focus on terrorist threats it is becoming difficult to get permission to build new land based LNG receiving terminals in the US. The option is then to construct offshore discharge terminals where off-loading can take place far from densely populated areas and busy ports and estuaries posing a much reduced risk to the environment and the people at large. The gas can be either discharged as liquid LNG/LPG into a floating receiving barge or as gas from a regasification plant onboard the gas carrier via an offshore buoy or platform system to shore ready for distribution into the onshore gas grid. This will require:

- reliable ship to ship LNG transfer systems or
- on-board re-gasification before discharge as well as
- tank systems capable of operating with all tank fillings.

Floating installations, (FSRU – Floating Storage and Re-gasification Units) as well as floating production units (FLPSU –Floating LNG Production and Storage units), is an upcoming market that will depend on finding acceptable solutions for being able to operate without tank filling restrictions.

The LNG market asks for more operational flexibility to enable trading in more harsh environments and operation with partially filled tanks in order to serve new market segments and trades - LNG carriers offloading at offshore buoys (re gas vessels) and/or receiving terminals, milk runners, spot traders etc. There is a shift towards more cross-Atlantic trading and trading in colder climates as well as a significant increase in the size of LNG carriers.

Carriers designed for operation in harsher fatigue environments (North Atlantic), in Cold Climate (CC)/Arctic involving ice-traversing/breaking will be more common due to the opening up of the giant Russian gas field in the Barents Sea (Shtokman) and in the Yamal and Gydan peninsulas in the Kara Sea.

Sloshing in LNG tanks has gained increasing attention over the past period of time. This is mainly caused by developments in the LNG market, changes in the design and operation of LNG ships and an increasing interest in floating gas field exploitation. The issue of sloshing in partially filled tanks is relevant for spot trading and offshore loading/off loading of LNG ships as well as for FPSOs with LNG capacity. DNV has developed a step-by-step experimental procedure to determine sloshing loads for structural analysis of the insulation system and tank support structure which was discussed in papers by Pastoor *et al* (2004b) and Tveitnes *et al* (2004). Of key importance for a reliable evaluation is the step-by-step approach, putting emphasis on an accurate treatment of every step. This means careful modelling of operational and environmental conditions, accurate ship motion calculations, a well-defined procedure for identifying design sea states, a proper experimental set-up and an accurate treatment of the statistics involved in every step in order to determine reliable and realistic design sloshing pressures.

To study sloshing loads in partially filled LNG tanks irregular sloshing experiments have been conducted for head and beam seas for different filling levels and sea severities. A 1/20 scale model of a tank from a 138.000 m^3 membrane type LNG ship was used for the tests. Measurements have been conducted using pressure transducers and pressure transducers mounted in clusters. Pastoor *et al* (2004b) provided an overview of the tests with an analysis of the impact pressure statistics, the pressure pulses and the associated subjected area and discussed the effects of different filling levels, sea severity, ship speed and heading. The results are used to establish first draft sloshing load formulas intended for preliminary design and for the purpose of defining needs for rule development (Tveitnes *et al*, 2004).

Also, Zhao *et al* (2004) presented the results of experimental and theoretical studies that were carried out at MARINTEK for sloshing impact loads inside tanks of LNG ships. They also considered the slamming induced whipping loads and parametric rolling of large LNG ships. Theoretical study suggests that the probability of phenomenon of parametric rolling occurring is increased when the gas tanks are 70% to 90% full.

The LNG transportation requires installation of liquefaction equipment into a gas field which increases the production cost of the LNG. This is typically done at –163 °C and compression ration of 1:600. For certain fields the use of LNG as a means of transporting the gas makes the operation uneconomic. New proposals are being tabled by some ship owners to transport the gas as compressed natural gas (CNG) or as pressurized liquid natural gas (PLNG). CNG hull will carry cargo in gaseous state at –2 °C with a compression ratio 1:297 which are significantly lower than LNG values (The Naval Architect, July 2003). These methods of shipping reduce the cost of the supply chain by removing the need for expensive liquefaction trains.

A new type of ship (CNG) has been introduced – a combination of a crude oil tanker and a container ship. It has a large set of vertical pipes, designed according to enhanced pipeline design principles, for the transportation of compressed natural gas. The weight of these pipes is 50% of the weight required by conventional pressure vessel design codes, making possible a large storage volume. Ships have so far been designed to transport up to 33.5 MSm^3 gas on each voyage.

The present concept for compressed natural gas was introduced by Knutsen OAS Shipping and has been developed with assistance from Europipe GmBH and Det Norske Veritas. Stranded gas is by definition available gas that cannot be developed economically, either because the volumes are too small to justify LNG production, or because it is too far from the market or existing infrastructure to justify pipelines. The new system is a gas transportation solution that fills the gap between the pipeline and LNG concepts.
Economic evaluations show that the new Knutsen PNG® concept will be highly competitive as compared to pipelines and LNG transport for distances of up to 2,500–3,000 nautical miles. The advantage is less investment in infrastructure and greater flexibility. The potential market for CNG carriers is large as more than half of the world's known reserves are associated with stranded gas. Two papers by Valsgard *et al* (2004a) and also Valsgard (2004b) explained the key steps in the development process, summarizing the findings of the risk study, the containment design and the qualification testing as input to the development of the new DNV CNG rules that came into force by July 1st 2003.

4.1.5 Inland Navigation Vessels

The following text on Inland Navigation Vessels specifically refers to operations at river Rhine. However, this should not be seen as a restricted focus since much of the technical aspects discussed should be applicable to all inland navigation vessels operating in rivers all around the world.

The current main dimensions for inland navigation vessels (tankers and dry cargo) at the Rhine are: LxBxDxT = 110.0x11.45x3.65/5.30(dry cargo/tankers)x3.60 m, DWT = 3300 tonnes, 208 TEU or 10 tanks of 380 m^3 each. Because of the continuous increase in dimensions, ships with lengths of 135.0 m will appear soon, and breadth up to 13.50 m. The maximum dimensions of ships intended for restricted services are even much larger. Most ships for inland navigation are equipped with a push barge bow, and they regularly sail with 5 barges coupled to it.

The safety aspects of navigation on the river Rhine is regulated by the Central Committee for Navigation on the Rhine (CCNR), see www.ccr-zkr.org, which ensures a precise control of the enforcement of common rules and is a platform for communication between the riparian states with regard to all aspects of navigation. The concern of all member states about the safety of navigation and the environment is the outset of all regulations adopted by the CCNR. The Rhine Regulations are permanently adapted to the evolution of needs and technology. Their adoption as basic provisions on a European level is envisaged. If a ship conforms to the regulations, a so-called "ship's attest for the Rhine" (i.e. ship's certificate) is issued by the Inspection Commission of the CCNR member state.

The most important regulations of CCNR in view of our interest are:

- *The Inspection regulation for Rhine vessels*, which settles the requirements regarding stability, strength, equipment, manoeuvrability and stopping quality as well as machinery space, steering gear, manning, crew and safety in working spaces.
- *Provision concerning the carriage of Dangerous Goods on the Rhine (ADNR)*, which settles the technical and operational safety requirements for the licence and the operation of inland navigation vessels carrying on board dangerous goods.

Except of ships which carry hazardous cargoes, it is not required that inland navigation vessels are built under class. The Inspection regulation for Rhine vessels of the CCNR is applicable for dry cargo ships, which includes the construction aspects in principle. A uniform and complete set of requirements for the construction and strength of these ships are not published by CCNR. The practice of most national authorities is to seek a strength level which is more or less equivalent to that of the classification societies.

The ADNR provisions apply to all vessels intended to carry dangerous goods on the Rhine, in addition to the Inspection regulation for Rhine vessels. Apart from the requirements to limit the risk of accidental cargo outflow, the ADNR provisions require also that these ships are built under supervision of a recognized classification society.

To limit the risk of accidental cargo outflow, the current ADNR requirements set a limit of 380 m^3 for the size of cargo tanks in combination with a standard double skin of 1 m width or single skin with independent tanks. Due to the growth in main dimensions of inland navigation vessels, and from an operational point of view there is a growing interest in larger tank volumes. In view of the risks involved, the authorities were very reluctant to allow larger tanks or alternative constructions, but new international guidelines based upon the equivalent risk method are being developed now and will probably be published soon. The principle of equivalent risk is based upon Eqn. (1) :

$$R = p.E \tag{1}$$

with:

R	=	the risk,
p	=	the probability of tank rupture,
E	=	the effect of cargo outflow.

In case the effect of a calamity increases due to a larger tank volume it is required that the probability of the calamity is reduced inversely in order that the risk does not increase. The procedure for the equivalent risk method as adopted until now, is in global terms as follows, see Vredeveldt and Roeters (2004) and Vredeveldt *et al* (2004):

The probability of tank rupture and the effect of cargo outflow have to be calculated for both the conventional and the proposed new situation.
The effect, E, of a calamity can be quantified by the number of casualties due to the outflow of dangerous cargo. Based upon the assumption that the number of people involved is proportional with the affected area, this part of the evaluation requires an as good as possible prediction of the affected area for all possible combinations of cargo type and death causes.
When a collision takes place, the probability, p, of tank rupture is related to the probability that the amount of collision energy available on the river exceeds the energy-absorbing capacity of ship structure and tank until the moment of cargo outflow (crashworthiness) for a variety of collision scenarios as speed and bow shape of the colliding ship, striking location and striking angle.
For the effect, E, as well as for the probability, p, of tank rupture, the results of the worst scenarios have to be used when equating the equivalent risk.

A first approximation of the energy available in the worst scenario is based upon the assumption of a fully inelastic collision at right angles amidships, taking account of the influence of added mass effects. Tabri *et al* (2004) presented a thorough analysis of the external dynamics to find the influence of surrounding water, elastic bending of the hull girder of the struck ship, and sloshing of water in partially filled tanks upon the distribution of total energy available over the striking ship, the struck ship and net deformation energy in the struck ship in order to explain a remarkable disagreement between numerical predictions and test results, as initially investigated by Konter *et al* (2004).

The net deformation energy in the struck ship can be calculated from the force-penetration curve up to rupture of the tank wall when the bow of the colliding ship penetrates the struck ship. In view of computational efficiency, these quasi-static crashworthiness calculations are normally carried out with an explicit finite element formulation as given in Eqn. (2) Vredeveldt and Roeters (2004), Dimas and Soares (2004) and Wu *et al* (2004):

$$\ddot{x} = M^{-1}\left(F^n_{ext} - F^n_{\text{int}}\right) \tag{2}$$

where:

M	=	diagonal mass matrix,
F^n_{ext}	=	applied load vector at time t^n,
F^n_{int}	=	stress divergence or internal load vector at time t^n,
$\ddot{x}$	=	vector of nodal accelerations.

The analysis is highly nonlinear due to very large displacements, contact nonlinearity to avoid that material penetrates other material and material nonlinearity because of the extreme strains up to failure of the material, which requires correct material flow models including true stress strain, see e.g. Okazawa *et al* (2004) and Zhang *et al* (2004).

In order that the results of numerical simulations of the phenomena during collision are realistic, there is a lot of discussion in the literature about a number of aspects as: friction, strain rate effects of mechanical properties of material, element type and size, mesh and element type dependency of crack growth direction, the failure strain plus local necking, inclusive their dependency upon element size and type and finally the failure criteria for welds. See a.o. Lehmann and Peschmann (2002), Naar *et al* (2002), Konter *et al* (2004), Wu *et al* (2004), Okazawa *et al* (2004), Dimas and Soares (2004) and Zhang *et al* (2004) for these aspects. We will not discus these topics here, as they will probably be dealt with more in detail in the report of Committee V.1: "Collision and Grounding".

Recently, a number of studies on crashworthiness were published, see a.o.: Jastrzebski *et al* (2004) for results of numerical simulations to compare the crashworthiness of different structural arrangements, while Lehmann and Peschmann (2002), Naar *et al* (2002), Vredeveldt and Roeters (2004) and Wu *et al* (2004) published the results numerical simulations which were also verified with experimental results. Cho and Lee (2004) published an analytical method for early crashworthiness predictions of stiffened plates, which was verified by experimental results.

The bottom structures II and IV as considered in Naar *et al* (2002) were early variants of the Y-type structure designed by Ludolphy of Royal Schelde Research. In this structure the longitudinals were replaced by hat shaped or Y-type longitudinals, which gives a remarkable improvement of the crashworthiness. The basic idea of this design is to delay fracture of the outer (and inner) shell by provoking global collapse through avoiding hard spots. The Y-type longitudinals were designed in such a way that they showed a controlled collapse pattern, which enables the built up of membrane stresses in the outer (and inner) skin, resulting in an efficient energy absorbing structure, while the weight of the construction is almost the same as the conventional one. Side structures based upon this patented principle have been applied in two new push barges of Chemgas Shipping B.V. fitted with pressurized cargo tanks of 550 m^3. See also earlier mentioned reports by Vredeveldt and Roeters (2004) and Vredeveldt *et al* (2004) for acceptance of the increased tank volume. The principle of the Y-type structure and the design considerations for integrating it in the construction of the barge are explained by Graaf *et al* (2004).

The rules of Classification Societies for inland navigation vessels are in general still based upon the classical descriptive format with implicit safety margins. In case of new structural arrangements, i.e. modern crashworthy structures, strong increase in main dimensions, new ship concepts as very high net loads on the bottom structure of chemical tankers with pressurized cargo in integral tanks, extended sailing areas etc, this format is not suitable, because the basic principles are not explicitly formulated and the safety margins are unknown.

To overcome these problems, and in line with the change of the rules for seagoing ships during the last decades, the rules of Classification Societies for inland navigation vessels do also gradually commence to develop into a goal based format based upon first principles, including explicit formulation of: realistic loading cases and relevant failure methods to be considered and safety margins related to the risks involved. This format will also give much better opportunity to find optimal constructions.

As the draught of inland navigation vessels is strongly limited, especially in case of low water levels, it is worth to consider light constructions in order to increase the loading capacity. The application of innovative constructions as proposed in Figures 2 and 3 of Jastrzebski *et al* (2004), and new materials, see NN (2005), are interesting.

4.2 Classification Societies Common Rules Development

The most important development of Classification Rules has been the establishment of Common Structural Rules for Tankers and Bulk Carriers separately as two joint projects of different Class Societies. This development is described next.

The common Rules for Tankers and Bulk Carriers have been developed separately, each by a group of IACS Classification Societies. The IACS is the International Association of Classification Societies, formed by the ten of leading class societies. About 90% of the world's cargo carrying tonnage is covered by these ten societies and one associate. The aim of IACS is essentially to guaranty a unified level of safety. However, classification rules have been developed over the last decades by each classification society separately. In addition, Unified Requirements have been tarred by IACS members and transposed into the individual member's rules.

The aims of the Joint Tanker Project and the Joint Bulker projects are to develop a set of completely unified Rules and Procedures for the determination of the structural requirements for oil tankers and bulk carries respectively.

The intention of both projects is to combine experience and resources of several classification societies and to develop a single common standard. Furthermore competition between class societies with regard to structural requirements shall be eliminated.

It is expected by the societies that a greater transparency to the technical background of the Rules and the application of only one set of Rules will reduce the costs for the shipbuilding industry. A further main objective is that vessels meeting the new standard will be at least as safe and robust as would have been required by any of the existing Rules of the Class Societies. Finally they shall fully embrace the anticipated IMO requirements for goal based new construction standards.

IACS JTP Common Structural Rules

The principles of the development are described in a paper by Card *et al* (2004). The authors emphasize that current classification societies' rules have evolved over many years and have been mainly developed on an empirical basis. As a consequence, the underlying theory and safety philosophy is not always transparent to the user. Thus, the new project is aimed at developing rules that are more easily understood and based on clearly identifiable scientific principles. By clearly stating the fundamental principles on which the new rules are based, it will be possible to relate all aspects of the structural requirements explicitly to the load and capacity models that are used in most modern design codes.

A framework was established that sets out the various elements of the development hierarchy. The objectives form the highest level. In the next step, a systematic review determines the elements that should be considered. The systematic review is carried out in a two step approach. Hazards affecting the structural integrity are identified for all phases of operation. The consequences are evaluated in terms of impact on live, property and the environment. Those hazards were identified that have to be controlled by the rules. The next stage is to evaluate the consequences of failure for each structural member resulting from these hazards. Furthermore, the basis for control through acceptance criteria and capacity models are determined. For each structural member the possible consequences of structural failure are identified and assessed with respect to life property and environment. Based on systematic review, the design principles are formulated. The whole concept follows closely the principles of the Formal Safety Assessment (FSA) adopted by the IMO. Card *et al* (2004) listed the primary benefits of developing and presenting the design principles in that way as follows:

- It gives a common platform for development of the specific requirements in the rules.
- It ensures consistency throughout the standard
- It provides transparency in terms of scope and method of development
- It simplifies the process of extending the structural requirements to cover other ship types or to provide the basis for consideration of ships with non-standard configurations (novel design).
- It provides the baseline from which to develop and refine the rules in a consistent and logical manner and hence leads to simplified rule maintenance.
- It permits identification of any gaps in the rules.

A key feature of the Common Rules is a clear and transparent definition of the loads. All other sections of the rules refer to the load definition section and define what kind of load has to be applied for a particular problem. This approach ensures that there is no doubt about the origin of the loads or what the loads represent.

The net thickness approach provides a direct link between the scantlings that are used for the strength calculations and the minimum thickness accepted during operation of the ship. Gross scantlings result from the addition of a wastage allowance that distinguishes between local and global corrosion wastage. This methodology takes the fact into account that the hull girder cross section does not corrode uniformly.

A 3-D finite element analysis of hull structure in the cargo region is mandatory. This analysis is aimed at verifying deformation, stress level and buckling safety of the main structural elements.

A fatigue analysis of all structural details that are known from experience to be vulnerable to fatigue damages has to be carried out. The fatigue assessment procedure follows the common methodology of an S-N curve approach using the linear cumulative damage model using a Weibull probability distribution based on long-term environmental data for 25 years service in the North-Atlantic Ocean.

Besides some prescriptive formulae to check the buckling safety of structural members, a numerical buckling code can be employed for the buckling check. This advanced buckling check is based on non-linear analysis technique and controls the ultimate capacity of plates and panels. It covers bi-axial compression, shear stress and lateral pressure.

The new rules will also offer a simplified hull girder ultimate limit state assessment in order to proof the capacity of the hull girder

It should be noted that the major portion of the rules consist of prescriptive requirements for global and local strength. As already mentioned, the intention of the involved classification societies is to provide by these prescriptive rules a ship structure that is at least as robust as would have been required by any of the other existing rules of ABS, DNV or LR. From the consequence assessment presented by the class societies, it can be seen that the scantlings are in many cases increased when using the common rules. In general, it is expected that the steel weight of tankers built according to the new rules is slightly higher than those of tankers built according to the existing rules.

IACS JBP Common Structural Rules

The Joint Bulker Project Rules are applicable to single side skin and double side skin bulk carriers of a length greater then 90m. All relevant requirements influencing the structural design including SOLAS, Load line and IACS have been incorporated. For the benefit of readers, a summary of key aspects of the JBP rules as discussed by Nieuwenhuijs *et al* (2005) will be provided in the following.

The principles the new JBP rules based on are

- When considering the structural safety of the ship the first thing to check is the structural continuity. No strength analyses can compensate for a lack of continuity in ship structures.
- There has to be adequate ultimate strength of the hull girder, ensuring sufficient robustness of the design against total collapse.
- The scantlings in areas of high stress and high corrosion have to be increased locally.
- The strength of primary members has to be verified. Presently this is done through FEM calculations, while the shear strengths of the floors and the girders of the double-bottom are checked according to simplified formulas. Minimum thicknesses of the primary members are also imposed, depending on the length of the vessel.
- For structural details, which experience and feedback in service have been shown to be crack-prone occurrence of cracks have to be prevented.
- The continuity and consistency with all the IACS and IMO changes need to be ensured.

The main provisions of the JBP rules are

Like the JTP Rules, the net scantling approach was adopted which sets to determine and verify the minimum hull scantlings that are to be maintained from the new building stage throughout the ship's design life to satisfy the structural strength requirements. It clearly separates the net thickness from the thickness added for corrosion that is likely to occur during the ship in operation phase. The corrosion addition was determined by the procedure published by ClassNK.

Wave loads for unrestricted service were determined based on navigation in the North Atlantic all the year round and a design life of 25 years, in accordance with the draft IMO Goal Based Standards.

The JBP rules use the equivalent wave concept which is well adapted to the loading of a finite element model of the ship. Design load cases are derived from results of the equivalent wave approach as

- For each equivalent wave (i.e. for each wave maximising a specific load parameter) the values of the other parameters induced by that wave are calculated.
- The value of each load parameter for the equivalent wave is expressed as a fraction of its long-term value, so that, for each wave, a combination is obtained in which the maximized parameter appeared with a factor equal to 1.0 and the other with lower combination values.
- Each combination identifies a load case.
- Analysing the load cases so obtained for all the ships considered, it is possible to identify some recurrences in the combinations between the load parameters. Finally, the design load cases are identified.

Four limit states, namely serviceability limit state, ultimate limit state, fatigue limit state and accidental limit state were considered.

The serviceability limit state includes:

- local damage which may reduce the working life of the structure or affect the efficiency or appearance of structural members;
- unacceptable deformations, which affect the efficient use and appearance of structural members or the functioning of equipment.

The ultimate limit state, which corresponds to the maximum load-carrying capacity, or in some cases, the maximum applicable strain or deformation, includes:

- attainment of the maximum resistance capacity of sections, members or connections by rupture or excessive deformations;
- instability of the whole structure or part of it.

The fatigue limit state relates to the possibility of failure due to cyclic loads.

The accidental limit state in flooded condition includes:

- the maximum load-carrying capacity of the hull girder
- the maximum load-carrying capacity of double bottom structure
- the maximum load-carrying capacity of bulkhead structure

IACS carried out ramification studies to investigate how JBP CSR will influence the scantlings. The findings of these studies were

- JBP CSR requires a slight increase in steel weight in general.

- The steel weight increase of a UR S25 compliant ship is relatively small; 2.7 to 3.7% and for non UR S25 compliant ship is 6% on average, depending on the ship size/shipyard/class, etc.
- For ships L<150m the steel weight increase is around 3%
- The weight increments arise both from skin plates and transverse members.
- The weight increments come mainly from local scantling check, followed by direct strength analysis and then hull girder ultimate strength check. The contribution from fatigue strength analysis is almost negligible.

Paik and Frieze (2004) in a paper read at the SNAME Annual Meeting discussed the general requirements for limit state assessment of ship structures. The paper makes references to IACS developments and for this reason, a review of the paper was provided by a committee member whom has been involved in IACS developments.

As well noted in the paper, ship structures are left behind in terms of structural design and strength assessment procedure, while all other types of structures such as aerospace, land-based and offshore structures are going ahead.

For design and strength assessment of ship structures, allowable (working) stress based approach (ASD) and buckling strength checks adjusted by plasticity correction are still being used, while design and strength assessment of all other types of structures are based on limit state approach. Fortunately, the IACS realized this and it is implemented in the IACS common structural rules. Recent advancements and achievements in technologies for limit state design and assessment of ship structures (JTP and JBP Rules) are indeed great and so fast, as those of other types of structures.

In the last decades, much progress has been made on structural assessment of both offshore and ship structures which led to enhanced design procedures, code of practice (e.g. API RP 2A-LRFD for fixed offshore structures) and class rules (for merchant ships). The paper provides a good insight on the basis of a recent ISO initiative on merchant ship structures and, in doing that, illustrates similarities and differences with respect to the offshore structure practice. The work presented by the authors is very interesting and would deserve a series of comments. However, this discussion is limited to few, mainly philosophical, aspects which are found in need of clarification. In this discussion reference is sometimes made to IACS Common Structural Rules (CSR).

Contrary to what is stated in the introduction, the partial safety factor (which the authors call, based on offshore fixed platform practice, LRFD) approach is used by several IACS Member societies: to date at least 3 societies have a full "LRFD" approach in their structural rules.

Moreover, the paper could give the impression that IACS Members' structural rules are:

- not considering different limit states (introduction): for several years already ULS, FLS and even SLS (serviceability limit states) are covered in the rules of all IACS Members
- not based on structural risk assessment (pages 3 to 5 of the paper): depending on the consequences of structural failure class rule requirements are formulated either implicitly or explicitly with different safety factors.

A thorough structural risk assessment has been the first step in the development of IACS' common structural rules, as explained above. Transferring offshore structural safety principles to ships is not a straightforward task as the paper seems to suggest. As an example, the readers' attention is drawn to two philosophical aspects:

a) Structure Risk Classification

The paper suggests (page 5) that since for ships "…evacuation is not planned in expectation of encountering a design event" they are high consequence installations equivalent to (Table 3) a "..platform which is continuously occupied by persons…and from which personnel evacuation prior to the design environmental event is either not intended or impractical".

This conclusion seems rather simplistic; e.g. the ship is not permanently moored like a fixed platform and can move away from storms and personnel on board is trained for evacuation, the crew according to ISM/STCW conventions requirements, passengers according to SOLAS evacuation design and operational requirements;

b) Return Period for Analysis

The paper states (page 7) that speed reduction in heavy seas, which results in a wave load reduction, should not be considered because we should not "..rely on crew intervention to effectively be part of its structural safety management process…". While not necessarily disagreeing with this principle, the fact is that engines for ship propulsion are designed to develop their maximum output in calm or moderate seas at full speed, while the maximum achievable engine output and ship speed are significantly reduced in heavy seas (say 10m significant wave height).

In the conclusions (page 12) the authors state, "… the shipbuilding, shipping and shipping insurance industries have experienced considerable difficulties because they do not have standardized guidelines for the limit state assessment of ship structures". This statement gives the wrong impression that ship safety is just a matter of design while we all know that proper maintenance and responsible operations are at least as important as a good design: the ship's in service survey requirements (including structural re-assessment) which are part of class rules are not to be forgotten. Nevertheless it is agreed that structural design is to be properly checked. All IACS member societies have guidelines or additional rules for limit state assessment.

To provide a corresponding set of limit-state guidelines for ship structures, an ISO Working Group under TC 8/SC 8 has been established in order to provide in a formal framework a set of general limit-state requirements. The first deliverable of the working group will be the series of International Standard ISO 18072 to constitute a common basis covering the aspects which address the limit state assessments of ship structures. (DRAFT ISO/DIS 18072-1 "Ships and marine technology – Ship structures- Part 1: General requirements for their limit state assessment"). It uses the limit state approach rather than the allowable (working) stress approach since it is now well recognized that the former is a more rational basis than the latter for determining true safety margins of structures including land-based structures, offshore structures and ships. The ability to correctly determine the safety margin is a key to the ability to design a safe, yet economical structure.

Traditional design methods and standards have been based largely on working stress concepts. The standards used by Classification Societies, shipbuilders, and others have evolved over many years, and incorporate analytical methods as well as experience gained from ships in service. The more modern limit state approach explicitly addresses the concept of safety margin, and therefore might be considered as more accurate measure of safety, although results may differ in some areas compared to the working stress approach. Both approaches will provide safe and reliable structures if used appropriately. However, neither will guarantee freedom from failures or structural problems. A rigorous program of inspection, maintenance, and repair during construction and periodically thereafter, and operational guidelines, supplement the design criteria and assumptions to provide an acceptable level of structural safety throughout the ship's service life.

The series of International Standard ISO 18072 is intended to serve as a basis for defining a consistent and realistic level of safety margin for ship structures. An ability to more rationally assess the true margin of safety will also lead to improvements in related regulations and design requirements as well. Through its application the intention is to achieve levels of structural integrity appropriate for manned and unmanned ship structures, whatever the nature or combination of the materials is used.

The ISO 18072-1, actually circulated in draft for comment and approval, addresses general requirements for the standardization of the strength assessment of ship structures based on four types of limit states, namely, serviceability limit state (SLS), ultimate limit state (ULS), fatigue limit state (FLS) and accidental limit state (ALS), while the other parts of ISO 18072 series will address specific requirements for the different types of limit states. The assessments in accordance with these limit states necessarily require definitions of loading, analysis, materials and construction standards. In-service inspections are prescribed as appropriate in each part of ISO 18072 series.

It is clear that a strength assessment is closely related to structural design. However, the initial determination of structural dimensions and scantlings are not included in the series of ISO 18072, it being presumed that procedures and guidelines for the same are in detail provided elsewhere, such as in the relevant rules and regulations of classification societies or regulatory bodies' requirements.

4.2.1 Further Development of Structural Design Systems of Classification Societies

Recent developments of structural analysis tools by several major classification societies have been reviewed and presented in the following section.

ABS

ABS constantly updates the ABS SafeHull programs to reflect the yearly changes to the Steel Vessels Rules for Tankers, Bulk carriers, Containership and FPSO. ABS developed the "Guide for Building and classing Membrane Tank LNG Vessels" in 2002 and released the SafeHull LNG version 1.0 in February 2003. ABS published the revised LNG Guide in 2004 and released SafeHull LNG version 1.1 to reflect the updated Guide.

ABS, DNV and LR formed the IACS Joint Tanker Project to develop the Common Structural Rules (CSR) for Double Hull Oil Tankers, which was first published in June 2004. The ABS CSR/Tankers software was released in April 2005. The CSR/Tanker rules 2nd draft was published in March 2005 and 3rd draft was published in October 2005. ABS is updating the software to reflect the final CSR/Tanker rules, which will be effective on April 1, 2006, and plan a release in early 2006. ABS is also developing application software for the CSR for Bulk Carrier originally developed by the IACS JBP team and plans a release in 2006.

LR

Lloyd's Register constantly updates the focused software systems LR provide to support the classification of ships. The main focus of the development has been on the software used to confirm compliance with the Rules and to implement the ShipRight SDA procedures, centring around the RulesCalc and ShipRight SDA software packages.

Software for calculating scantlings according to the Rules and Regulations for the Classification of Naval Ships has been added to the already successful RulesCalc and Special Service Craft (SSC) software. RulesCalc has been continuously updated to take into account the successive drafts of the Common Tanker Rules, and the SSC software has also recently been updated and will be made available soon.

The development of ShipRight SDA has focused on making FEM analysis more time efficient. The software's ability to handle cargo loading, boundary condition and post-processing calculations more efficiently have all been significantly improved, especially in relation to the Common Tanker Rules. The software is also being updated to take the new Common Bulk Carrier Rules into account.

LR has also developed interfaces to LR software from the primary ship design packages. Working interfaces exist for NAPA and Tribon, allowing designers to take snapshots at any time and to quickly transfer them to the software to rapidly assess compliance.

DNV

A number of activities have been performed over the last three years. Both the Machinery Calculation package, the Life Cycle system and Nauticus Construction were introduced in this period. Nauticus Hull has been enhanced continuously through the period, and during 2005 DNV put much effort in the development of software supporting the new Common Structural Rules agreed upon among the IACS members. DNV also developed the PULS buckling code and method which will be part of the new common rules for Tankers. (Information about this on the DNV web: www.dnv.com)

DNV has decided to develop also software for the new Common Rules for Bulk Carriers. The development has just started and DNV Software will deliver a first version in time before the new rules are effective, April 2006.

GL

The program Poseidon has been continuously adapted to the Rule changes (up to Edition 2005). Several new key features have been integrated into Poseidon. The geometry and topology description and input has been improved substantially. The graphical user interface as well as the import and facilities have been enhanced significantly. Particularly additional features were added for the 3 D geometry view. The connection to "GL Rules online" is base on hyperlink technology.

Further improvements among others are the consideration of hull girder torsion and corrugated bulkheads as well as a capacity check of each member of a cross section.

4.3 IMO Goal Based Standards

On the 79th session in 2004, the IMO's Maritime Safety Committee (MSC) agreed to work on goal-based standards. The intention was that IMO should play a larger role in determining the fundamental standards to which new ships are built. However, this does not mean that IMO will take over the detailed work of the classification societies, but rather that IMO intends to state what has to be achieved, leaving classification societies, ship designers and ship yards the freedom to choose the way and means to achieve the prescribed goals (IMO Homepage http://www.imo.org). A Working Group on goal-based new ship construction standards agreed on a five tier system for the further development of the basic principles. Its work plan includes the further development of the first three tiers:

Tier 1: Goals
Tier 2: Functional requirements
Tier 3: Verification of compliance criteria

It is upto the classification societies and other recognized organizations to develop the last two tiers:

Tier 4: Technical procedures and guidelines, classification rules and industry standards
Tier 5: Codes of practice and safety and quality systems for shipbuilding

Basic principles and goals for goal-based standards for new ship construction were agreed in principle by IMO's Maritime Safety Committee (MSC) at its 80th session in 2005. The results are summarised by IMO as follows:

- The MSC agreed in principle with the basic principles of goal-based standards and with the Tier 1 goals developed by the Working Group on Goal-based New Ship Construction Standards.
- The goals relevant to ship structures include design life, environmental conditions, structural safety, structural accessibility and quality of construction.

It is noted by the committee that the goals relevant to ship structures concentrate mainly on the design and construction and do not specifically include the aspects of ship operation, inspection, maintenance and repair throughout the life of the ship which are also very important contributors to safety of ships.

The agreed basic principles state that IMO goal-based standards are:

- broad, over-arching safety, environmental and/or security standards that ships are required to meet during their lifecycle
- the required level to be achieved by the requirements applied by class societies and other recognized organizations, administrations and IMO
- clear, demonstrable, verifiable, long standing, implementable and achievable, irrespective of ship design and technology; and
- specific enough in order not to be open to differing interpretations.

The Tier 1 goals are based on the premise that - for all new ships - "ships are to be designed and constructed for a specified design life and to be safe and environmentally-friendly, when properly operated and maintained under the specified operating and environmental conditions, in intact and specified damage conditions, throughout their life".

The Working Group also made progress on developing the Tier II functional requirements, agreeing that for new oil tankers and bulk carriers in unrestricted navigation (the ship is not subject to any geographical restrictions (i.e. any oceans, any seasons) except as limited by the ship's capability for operation in ice); the specified design life is not to be less than 25 years and they should be designed in accordance with North Atlantic environmental conditions and relevant long-term sea state scatter diagrams. Other functional requirements for these ship types were agreed by the Working Group, including those relating to structural strength, fatigue life, residual strength, and protection against corrosion and so on.

The MSC approved the work plan for future work on GBS and agreed to establish a Correspondence Group to develop draft Tier III criteria for the verification of compliance.

The work plan for future work includes; consideration of the probabilistic risk-based methodology in the framework of GBS; completion of Tier II - functional requirements; development of Tier III - verification of compliance criteria; implementation of GBS; incorporation of GBS into IMO instruments; development of a ship construction file and consideration of the need for the development of a ship inspection and maintenance file; and consideration of the need to review consistency and adequacy of scope across the tiers.

5. OFFSHORE STRUCTURES

5.1 Introduction

Structural characteristics and associated problems related to FPSOs and VLFS structures have been addressed. For VLFS structures two specific developments namely; Mega-float and MOB have been considered separately.

5.2 FPSOs

Lotsberg (2004a) presented a design procedure for fatigue assessment of welded pipe penetrations in plated structures. The procedure covers full penetrations welds, partial penetrations welds and fillet welds and is based on calculated stress concentration factors using finite element analyses for relevant geometries of penetrations through plated structures. Fatigue cracking from the weld toe and from the root of fillet welds was considered.

Physical mechanisms behind green water events on FPSO's (Floating Production Storage and Offshore loading) in severe storm waves were investigated by Stansberg and Kristiansen (2004). In particular, wave nonlinearities and crest amplification at the bow region in head seas were studied. From a case study including model tests analysis of an FPSO with a slender bow, it was found that the incident wave nonlinearity is important. Wave/hull interaction was also identified, partly as linear 3-D diffraction, partly as nonlinear bow flare effects, while a minor contribution comes from second-order wave-hull interaction in this case.

Bergan and Lotsberg (2004) presented an overview of a joint industry project, carried out in the period 1998 – 2003, addressing the problem of Fatigue Capacity of FPSOs. Spectral methods are becoming standard methodology for fatigue assessments of FPSOs. This methodology is well suited numerical methods in combination with finite element representation of the global structure and structural details for response analyses. A proper link between calculated stress and fatigue capacity is required in order to achieve a reliable design. The project has generated significant amounts of numerical data as well as laboratory fatigue test data of typical ship details to improve the basis for this. In a parallel study within the JIP the status of current design recommendations and relevant published data concerning the fatigue capacity of fillet welds were reviewed by Lotsberg (2003). In order to examine the validity of those recommendations and to supplement the fatigue test data base, a test matrix with 33 specimens was developed. This included 8 simple fillet welded cruciform joints that were subjected to axial loading and 25 fillet welded tubular specimens that were subjected to axial load and/or torsion for simulation of a combined stress condition in the fillet weld. The data obtained from these fatigue tests were presented and also compared with design guidance from various codes.

Lotsberg and Sigurdsson (2004) presented a derivation of a hot spot stress S-N curve to be used when the hot spot stress is derived from finite element analysis of plated structures. Lotsberg (2004b) discussed the Finite Element analyses performed for assessment of hot spot stress in the FPSO Fatigue Capacity JIP and recommended a methodology to perform fatigue assessment of plated structures based on Finite Element analysis combined with one hot spot S-N curve.

Five different specimens representing different typical welded connections in ship-shaped structures were fatigue tested by HHI in Korea. The test data from the five different specimens for one loading condition were transferred into one hot spot S-N diagram. It was observed that two of data series plotted rather high in the S-N diagram as compared with the other three test series. The reason for this was questioned. It was decided to test a few specimens at another test laboratory for verification of the test data. The same types of specimens were fabricated by HHI and shipped to Oslo and fatigue-tested in the laboratories of DNV. The results from this fatigue testing were presented by Kim and Lotsberg (2004) in addition to the original fatigue test data from HHI. Also, Lotsberg and Landet (2005) compared the fatigue test results with a hot spot S-N curve that was recommended for design of plated structures subjected to dynamic loading.

Storsul *et al* (2004a) investigated the calculated and measured stresses at weld connections between side longitudinals and transverse frames in ship shaped structures. This work was performed as part of the joint-industry project "FPSO-Fatigue Capacity". Five full scale test specimens of welded connections between side longitudinals and transverse frames were fatigue tested at the DNV laboratories in the first phase of the project. Also finite element analysis using shell elements were performed. It turned out that it was difficult to get good correspondence between the calculated stress and measured stress for specimen no 1 which is the most complex detail. In phase 2 of the project a more comprehensive analysis was performed using a finite element model with 20 node solid element. Storsul *et al* (2004b) performed a convergence analysis using different finite element models and stress evaluation techniques. The types of elements used are 4- and 8-noded shell elements and 20 node solid elements. The 4-node shell elements include additional degrees of freedom for improved in plane behaviour. Different combinations of element lengths and widths in the range 0.5t x 0.5t up to 4t x 4t were used. All models were analysed with 4 and 8 node shell elements. 20 node solid was used for three of the models only. The analysed results were compared with target hot spot stress values.

Profiled blast barriers are an integral part of offshore topsides where they are required to protect personnel and safety critical equipment against the effects of a possible hydrocarbon explosion. Limited studies on their response have been investigated, particularly at high overpressures. Boh *et al* (2004) carried out a numerical study using finite element analysis to investigate the response of stainless steel profiled barriers subjected to hydrocarbon explosions. By examining three profiles of varying depth (deep, intermediate and shallow) commonly used in offshore topside structures, the criteria governing their behaviour are highlighted. The static capacity and the dynamic response of the barriers were established up to the maximum capacity level and into the post peak or buckling response regime. The parameters that were found to have profound effects on the analyses include imperfections, boundary conditions and modelling assumptions. Through this study, recommendations and guidelines of using finite element analysis for the design or analysis of such explosion resistant barriers were given.

Offshore installations like FPSO's are designed to ensure a safe and economical operation during the intended service life of the installation. Deterioration processes, such as fatigue crack growth, take place from the very moment they are taken into use. Thus in order to ensure that the condition of the installations remains in compliance with the safety requirements throughout their operational life a certain amount of inspections, condition monitoring and maintenance is required. Probabilistic methods have been used to develop a basis for an in-service inspection programme for FPSOs hull structures with respect to fatigue cracks, see Sigurdsson *et al* (2004). Reliability methods have been found efficient for planning in-service inspection for fatigue cracks, accounting for both the detection accuracy and the sizing accuracy for observed cracks. The time to first inspection and the interval between the inspections based on a specified required safety level could be evaluated.

Based on results from inspections for fatigue cracks, an updating of the estimated fatigue reliability can be carried out through conditional updating. For the S-N fatigue approach, the inspection results can not be used directly to update the estimated fatigue reliability, as no direct relationship between the crack size and the damage accumulator D in the S-N approach is available. A calibration of the S-N fatigue approach to the fracture mechanics (FM) fatigue approach is therefore required. The parameters in the FM analysis may be calibrated by fitting the probability of having a critical crack size as a function of time obtained from the FM approach to the results corresponding to failure obtained from the SN approach, applying e.g. least-squares fitting.

It should be noted that calibration of the FM approach to the SN approach is in general inconsistent, as the crack initiation period included in the S-N approach is not incorporated in the FM formulation. This may lead to non-conservative results in the reliability updating based on the outcome of inspections.

5.3 VLFS

As population and urban development expand in land-scarce countries with long coastlines, land reclamation and Ocean Space Utilisation or Sea Basing is an option to ease the pressure. A variety of concepts has been considered in the past in view of ocean space utilisation using floating structures, see: Suzuki (2005a) and Watanabe *et al* (2003 and 2004). Much research on VLFS's has been initiated in the past decade by two large national programs, see Moan (2004):

- The Mega-float program in Japan (TRAM: 1995-2000), initiated by the Ministry of Land, Infrastructure and Transportation. This program mainly concentrates on fixed pontoon type floating structures (Mega-float) in sheltered waters, see Suzuki, (2005a). A Mega-float consists of a floating structure, a mooring system, access and eventually breakwaters. Examples of applications are: a floating airport, an offshore container terminal, a sport facility, a floating emergency rescue base, etc. The greatest importance in the research was placed on the application as floating airport and runway with overall dimensions up approximately to LxBxDxT = 4770x2000x7x2m.

- A1000m long model of a Mega-Float Phase 2, which was provided for verification experiments on structural safety and functionality as an airport, was divided and utilized as a Mega-Float IT base. Since the effectiveness of Mega-Float was approved based on the results of these experiments, Japanese shipbuilders propsed the construction method of floating structure to the re-expansion project of Haneda

Airport. Though not a Mega-Float but a hybrid construction method (reclamation and pile) was adopted in 2004, verification experiments using prototype models of Mega-Float have been continued in order to make international standards (ISO:19904-1) because it has been recognized that Mega-Float was indispensable to worldwide future technology.

- Mobile Offshore Base Science and Technology Program in USA (1997-2000). The focus of this program, sponsored by the US Office of Naval Research, was a self-propelled, modular floating platform, suitable for harsh environment, which can be assembled into lengths up to 2 km to accommodate conventional take off and landing (CTOL) operations of long range cargo aircraft, see Palo (2005). It is planned to provide logistic support for US military operations in areas where fixed bases are not available. As the semi-submersible type floating structures are raised above the sea level using columns to minimize the effects of waves, they are suitable for deployment in high seas with large waves. As a consequence of these considerations, the Mobile Offshore Base (MOB) program concentrates on large structures, consisting of a number of serially aligned modules, which are mobile in individual mode.

Three distinct types of VLFS's are being researched at the moment, see Newman (2005) and Suzuki (2005a):

- Barge or pontoon-type structures. They are rather simple in concept, but suffer from relatively large wave loads. The maximum deflections tend to concentrate near the upwind edges.
- Large arrays of small buoyancy elements combined with a pontoon type platform, called a Semi-Submersible type Mega-float (SSMF). The main advantage of this concept is the reduced level of global wave loads, however the hydrodynamic analysis of these structures is complicated by the relatively large number of panels required to describe the geometry and wave interference phenomena between the elements. The wave loads are very sensitive to incident wave conditions (periods and angles).
- Arrays hinged structures. This has the advantage of reduced bending loads as compared to a single rigid hull of the same overall length. A configuration with semi-submersible type platforms (MOB-concept) results in much smaller motions and shear forces in way of the hinges than for a similar array of hinged rectangular barges. It is to be realised that the hinge constructions are very highly loaded, delicate and complicated constructions, especially in case they have to be detachable.

VLFS's have a number of distinct features:

- Their huge horizontal size, which makes the wavelengths of practical interest very small compared to the horizontal size.
- Their small bending rigidity, such that the hydroelastic response becomes more important than rigid body motions.
- The analysis of hydroelastic responses for VLFS's require huge computing capacities (memory and speed) in case conventional analysis methods are applied.

As the hydrodynamic behaviour of a VLFS is characterized by its hydroelastic response in waves, the structural stiffness is a governing parameter for their design. This implies that the relationship between structural stiffness and global elastic responses is generally complex: an increase in structural stiffness can lead to an increase in cross sectional forces and stresses.

It is concluded that, for all types of VLFS platforms, the Quasi-Static Structural Response in waves is directly coupled with the hydroelastic behaviour of the platform, which implies that the structural response in waves is a dynamic response in principle. This unconventional situation is the reason that we will discuss the structural response of VLFS's in waves in this report in combination with the hydro- and elasto-dynamic aspects as far as they are relevant in view of loads and stresses.

In practice, the design of Mega-floats can be divided into three basic stages, see Fujikubo (2005):

- During the first functional design stage a simple and fast method of hydroelastic response analysis is used to optimize the fundamental magnitude of cross sectional stiffness, and the corresponding basic design variables such as structural depth, primary members' arrangement and size.
- During the second stage a detailed design is performed for the actual configuration with variable planar form and/or structural depth, openings in bulkheads, variable water depth, breakwaters etc. Local stresses are calculated with zooming techniques. The size and arrangement of structural members are determined through the evaluation of strength and Serviceability Limit States (SLS).
- During the third stage the structural safety assessment for the system levels are performed.

The Analysis Methods of VLFS's can be grouped into some main types, see Newman (2005):

- Two-step approach, using simple analytic/numerical analysis methods, such as rectangular thin mats or arrays of cylinders, in the first step for the hydro-structural problem. These methods are suitable to gain understanding of asymptotic limits for extremely large structures, and for optimization in the design stage. In the second step, detailed 3-D elastostatic calculations have to be carried out, using first-step output as wave forces and cross sectional forces. This attempt to reduce the amount of computation by the application two not properly integrated steps is a strong demerit of this approach.

- Hong *et al* (2005) presented an overview of various hydroelastic analysis methods based upon thin plate representation with their merits and demerits and also compare the computational efficiency and accuracy by checking their capacity to satisfy zero shear force and bending moment along the edges of the platform:
  - Mode superposition method (MSM), which uses orthogonal function sets in longitudinal and transverse direction. Use of Chebyshev polynomials MSM II instead of free-free beam modes MSM I has advantages in quick convergence and enhancement of satisfying the free moment condition along the edges.
  - The BEM-FEM direct method uses Mindlin plate elements and BEM to establish the final equation for fluid-structure interaction.

- The Eigen-function Expansion Method (EEM) is numerically effective and accurate for the hydroelastic analysis in case of a mat-type structure in shallow water depth.

From their results of numerical analyses it was concluded that MSM with free-free beam mode functions cannot satisfy moment and shear free conditions at the edges. BEM-FEM direct method, EEM method and MSM II method generally show good results for bending stresses, while they show different behaviour in shear stresses. BEM-FEM shows unrealistically high shears stress along the edges, whereas shear stresses of MSM II converge as the mode and mesh numbers increase. EEM is superior.

Kim *et al* (2005) state that MSM and EEM are analytical methods which have some difficulties in the analysis of structures with irregular shapes. However, they are numerically very efficient. The BEM-FEM direct method requires much computing time and memory, but structures with arbitrary shapes and stiffness distribution can be readily analysed.

- A recently developed, one-step integrated fluid-structure interaction analysis method, see Seto *et al* (2002), Seto *et al* (2003), Seto (2004) and Seto *et al* (2005), based upon a hybrid finite-infinite element method with domain decomposition for the water waves and a conventional finite element representation for the construction. It is suited for stepped hull boundaries, stepped bottom depth, breakwaters and is capable of analyzing realistic models with a deck, a bottom, bulkheads etc. Substantial computational savings have been achieved because it uses modal approach and it generates a symmetric block banded matrix structure. Yet this method places heavy demands on the computer capacity, which means that the multi-step approaches for lager VLF's are still required.

- A combination of general-purpose packages for hydrodynamic diffraction analysis and for structural FEM representation. An important advantage of using general purpose software is that a wide variety of structural configurations can be analysed, and that they are available "off-the-shelf" with documentation and validation. The most significant disadvantage of this approach is the huge requirements in view of computing capacity.

Because of their evolutionary character, based upon a combination of engineering fundamentals, empirical information and historical precedent, it is stated by several authors as e.g. Palo (2005), Watanabe *et al* (2004), Suzuki (2005) and Fujikubo (2005), that Classification guides only rarely apply to the design of new, innovative structures, as it is not clear in advance which phenomena and failure modes will be dominant. This means that the structural design of VLFS's needs a first-principle approach that requires a performance rather than a descriptive format, and is to be based upon rational analysis methods to predict structural responses, as well as explicit design criteria incorporating operating conditions, strength and serviceability requirements, safety requirements, durability and cost effectiveness. The safety criteria are generally expressed by limit states, see Moan (2004). The criteria for Ultimate Limit State (ULS) and Fatigue Limit State (FLS) follow the same principles as established for ships and offshore structures, which are based upon first principles. The implicit safety level aimed at should be carefully considered in view of the potential consequence of failure. Accidental Collapse Limit State (ALS) requirements are intended to prevent progressive development of failure when subjected to accidental or abnormal load. The initial damage should correspond to events as ship impacts, fires etc.

Further to this overall picture on the analysis methods for VLFS's, the relevant aspects found in the literature in view of Quasi-Static Response will be discussed slightly more in detail under the following two separate sections: Mega-floats and MOB's.

5.3.1 Mega-float

Recently, structural behaviour of Mega-floats have been investigated by many researchers, see Takagi *et al* (2003); Murai *et al* (2003); Takaki *et al* (2003); Okada 2003. Inoue *et al* (2003) summarised the methods to calculate stresses in structural details of a Mega-float:

The one-step method uses a detailed structural model to perform the hydroelastic analysis, to arrive at a stress distribution which completely corresponds to the elastic motions. For the accuracy of the stress analysis it is desirable to apply this one-step method, however the degree of detailed modelling for the entire construction is limited because of its high demand on computing capabilities.

The two-step method uses a simple structural model in the first step to solve the hydroelastic responses and the stresses are calculated in the second step using more detailed structural models. Three different methods are possible for the second step: method 1 uses an entire structural model, which still requires huge computing capacity, and the other two methods are variants of the so called stress factor method. Both of them use local structural models: method 2 is used in case the stress is governed by a single load component (e.g. bending moment) and method 3 is applicable in case the stress in the detail is governed by concurrent multiple load components.

It is to be realised that the accuracy of the results from a two-step method is governed by the precision of the first-step analysis. For example, the changes in fluid dynamic forces at rigidity-varying parts are not reflected to the second-step results because fluid dynamic forces from the first-step are applied unchanged in the second step. It was concluded that Method 1 is the most reliable of all two-step methods, however it takes enormous computing time to calculate RAO's for all details in all wave condition with an extremely large model for the entire structure. Method 2 and 3 are efficient tools to calculate stresses in details of the construction.

Fujikubo (2004) also presents an overview of structural analysis methods plus limit state checks and relevant failure modes for the design of a Mega-float. With the one step method the local structural configurations are considered in global hydroelastic response analysis and the stresses of local structural members are directly obtained. Due to the huge size of a Mega-float this analysis method is not very efficient as it requires an extraordinary number of degrees of freedom. The two step method uses a hierarchical system of analysis; the hydroelastic interaction is solved in the first step using a simplified structural model based upon either an orthotropic plate, or a plane grillage or a sandwich grillage, each with their specific merits and demerits. In the second step, the cross sectional forces and external pressures are applied to more detailed quasi-static structural models using the stress factor method. A global collapse analysis of a VLFS using ISUM is discussed, and finally the structural safety assessment of a pontoon-type VLFS considering damage to the breakwater.

Oka *et al* (2003) applied the two step method in combination with the stress factor method for concurrent multiple load components, as proposed by Inoue et al (2003) and verified the results with full scale measurements on a 200x100 m scale floating structure. The estimated stress around a scallop at a transverse bulkhead shows very good agreement with the measured stress in a short term wave condition. Chen *at al* (2004) studied nonlinear sectional forces induced by the membrane forces for a very large floating plate with large deflections in a multidirectional irregular seaway, using the nonlinear von Karman plate equations. In the analysis linear incident waves are assumed and the nonlinearities in the response are solely due to the coupling between axial forces and bending moments. The extreme values of vertical displacements and bending moments were predicted for a period of 20 years using extreme value statistics taking into account the kurtosis of the response. The numerical results show that the membrane contribution both in terms of axial stresses and its effect on the bending stresses can be important.

Yasuzawa (2003) studied the optimum structural configuration and scantlings of primary structural components of a Mega-float with dimensions 4770x1650x7 m, in a stage where the principal dimensions as length, breadth, depth, dead and live loads have been decided upon in the functional design. The objective function contains structural weight and cost of structural material plus welding. The objective function is minimized using structural safety constraints based upon limit state stress levels and relevant safety factors. The limit states are initial yielding and elastic buckling of plates, girders and stiffeners. A fixed value was used for the safety factor, and stresses were evaluated with the beam theory. The maximum bending moments and shear-forces in longitudinal and transverse direction are based upon a formula which is based upon results from hydroelastic analyses with a 2-D model.

Ohta *et al* (2003) presented results of numerical analysis and experimental validation for additional structures at the weatherside in order to reduce hydroelastic response of super sized offshore Mega-floats where breakwaters are not feasible. An innovative solution is presented which reduces hydroelastic response and prevents enhancement of wave drifting forces.

In order to avoid breakwaters, Kim *et al* (2005) investigated the effect of stiffness distribution, hinge links, moon pools and structure shape on the hydroelastic response of Mega-floats. The BEM-FEM direct method of analysis was used in combination with the higher order boundary element method for the analysis of the fluid flow and the FEM with Mindlin plate elements for the structural mass and stiffness matrices. Hinge links were represented by the penalty technique to modify the equations. A 1000x500 m Mega-float at a draft of 2 m in water depth of 50 m is considered in the numerical analysis. Various positions of hinge links between pontoon and breakwater and different stiffness distributions are considered. A multiple hinged breakwater, a rounded hinged breakwater as well as configurations with longitudinal or transverse moonpools were considered to reduce the response. It is concluded that Mega-floats with two hinges and rounded breakwaters with one hinge are economically efficient up to a wave period of 13 sec because, without increased stiffness, they have response reduction performance comparable to that of uniformly stiffening.

Suzuki and Iijima (2003) presented the design optimization methodology for a 2000x330 m Semi-Sub type Mega-float (SSMF) intended for service as an airport. This unprecedented solution is supported on multiple columns and moored offshore at 70 m water depth or more. A step-by-step optimization method was used by selecting in each cycle the best model after comparing the response characteristics (vertical displacements, bending moments and drift forces) of the alternatives. Mooring is modelled by spring elements. Based upon the analysis results, it was decided to apply a staggered array of approximately 300 floaters of simple shape without footings or lower hulls. Finally it is concluded that, in view of the optimization process, further research is needed on nonlinear damping effects, drift forces and wind forces

Suzuki and Nakada (2005) present the results of an optimization study for a 2200x330 m SSMF for use in open sea, using an objective function based on structural weight and a penalty method for considering constraints conditions related to safety and functionality as motion and elastic response. For optimization the total number of columns and their positions were fixed. The deck was divided in forty regions, each having their own sizes of column-footings. The deck depth was also variable. From the optimization it appears that the deck depth must be minimized under constraint of allowable response, and the diameter of the columns is relatively small. The structural weight was finally reduced by about 12%.

Katsura *et al* (2003) dealt with the limit state and reliability analysis of Mega-floats, based on collapse behaviour analysis under the hydroelastic response in irregular waves. First, buckling and ultimate collapse strength of the deck, bulkhead and bottom panels, including lateral pressure effects, is calculated with AFOSM. Next, a simplified method is presented for collapse behaviour and reliability analysis under extreme sea loads with a combination of FEM and plastic node method and an estimation method for probabilistic loads considering the hydroelastic response in waves. Then, the dominant limit state modes of a 5000 m class Mega-float are obtained under combined bending, shear and lateral pressure loading. Finally, the results of the reliability level are presented including the effects of design parameters.

Fukuoka *et al* (2003) presented the procedures used to analyze the structural safety and functionality of a VLFS to be used as an airport and report on the analyses applied to the model of a prototype floating airport in Tokyo Bay. Design wave load conditions were determined by analyzing Tokyo Bay wave data and hydroelastic response analysis of a large floating airport model with a length of 4770m was carried out under such design wave conditions. Structural stresses under combined load conditions consisting of permanent loads, live loads and wave loads were evaluated and a structural safety assessment was made. Consequently, it was found that a floating airport is likely to be as adequate as an airport on land.

Namba *et al* (2004) presented a long term cumulative fatigue damage prediction method for the dolphins of a mega-float and verified it with at-sea experimental data on a pontoon model. The cumulative fatigue damage code prepares statistical data of loads on the mooring dolphin using simulations with the horizontal motion prediction code, and calculates short term fatigue damage based on F-N curves and predicts the long term fatigue damage with use of a long term wave scatter diagram. The estimated mooring forces and horizontal motions agree rather well with the experimental results.

5.3.2 MOB

Following relevant US-MOB-program accomplishments were reported by Palo (2005):

- The introduction of an accelerated "pre-corrected FFT" equation solver, which reduces the computing time of diffraction codes to analyse responses of these MOB structures in waves, using 100.000 panels, from days into minutes.
- A new universal load generator (ULG) in combination with a new higher order method to represent the surface and singularity density reduced the discretization errors and enabled an exact mapping of pressures from the hydrodynamic to the structural model with independent panelizations.
- Large scale laboratory tests were conducted on a model (1:60 scale) of 1, 2 or 4 elastically scaled semi submersibles (each 6 m long), connected by two stiff but elastic connectors, to obtain hydroelastic validation data. Unfortunately these data have not yet been analysed.
- Studies directed to large-scale wave specification, including a metocean database, a typhoon database and spatial coherence studies of ocean waves at scales up to 2 km.
- Initiation of the development of a MOB Classification Guide based on performance and reliability standards.
- A number of relevant remaining challenges were also reported:
- Complete a first draft of the MOB Classification Guide.
- More extensive exercising of hydroelastic and structural models in order to gain more insight in relative merits and pitfalls.
- Optimize the semi-submersible configuration in view of cargo operations, contribution of torquing response to forces in the connectors and air gap.

Ramsamooj and Shugar (2002) performed a linear elastic fracture mechanics reliability based design analysis of fatigue life for the connectors of the five sections 2 km long US MOB designed by Brown and Root. A performance function is defined in terms of the normal stress range, starter crack and material properties, which are random variables. The reliability analysis is performed for sea state 1-8 random loading. The reliability function is defined in terms of the mean life and the total uncertainty in the fatigue life.

Ikegami *et al* (2005) designed a new type of mechanical connecting device for a multi-connected system composed of small-scale floating bodies as an alternative for the usual united floating body. Calculations and model tests were performed to find the optimum value for the spring constant of the restricting mechanism to minimize the coupling-forces. Friction and wear tests were also executed to find suitable materials for oscillatory sliding parts in multi-degrees of freedom connecting mechanisms. The practical use of the mechanical connecting device was verified in a field test.

6. CONCLUSIONS AND RECOMMENDATIONS

The committee has reviewed recent works concerning the topics identified by the committee mandate. The review included various strength assessment approaches from the traditional semi-empirical approach developed by the classification societies in their rules based on the vast service experience of existing structures to probabilistic and structural reliability approaches for quasi-static response of ship and offshore structures. Reference was also made multi-scale and multi-physics approaches when analysing ship structures.

The compatibility of structural analysis and naval architecture software packages will improve accelerate the design process. This can be achieved through great scale introduction of the 3-D ship product model. The basic idea of a product model is that all the required information such as the general arrangement, detailed arrangements, ship systems, specifications, materials, schedules, planning, purchasing and simulations can be stored in the same model and this information can also be transferred to other programs such as FEM, stability, and seakeeping and CFD programs. Although in theory the link between the 3-D product model and FE model can be done conceptually, smooth transition between the two models especially bi-directionality can not be achieved with certainty. Some recent developments have been reviewed in this area whereby a single Product Information Model (PIM) with two views is created where the same information may be accessed both for the structural and production aspects simultaneously.

The level of analysis in relation to design stages such as simplified analysis, direct calculations, reliability analyses, optimisation-based analyses (including reliability) have been discussed. Recent works with regard to load modelling for the quasi-static response, specifically, load modelling for rule based versus rational based design, loads extracted from towing tank trials, loads from sea-keeping and CFD codes, have been reviewed.

Recent works on advance structural modelling and analysis techniques for evaluation of yielding, buckling fatigue and ultimate strength capacity of the structures have been discussed. Current research on the compressive buckling strength is focused on the determination of ultimate strength behaviour of unstiffened and stiffened plates under axial compression, lateral pressures and in plate bending. For the corrosion and fatigue assessment the review highlighted that current trends are to employ time dependant reliability methods.

Recent developments in relation to bulk carrier and tanker safety have been discussed. IACS have introduced a number of unified requirements in an effort to improve the structural safety of ageing bulk carriers which are thought to be effective. Furthermore, new IACS Common Structural Rules based on Joint Tanker Project (JTP) and Joint Bulker Project (JBP) developments shortly to be introduced are considered to be a step forward designing tankers and bulk carriers. New Common Structural Rules adopt the limit state approach which explicitly addresses the concept of safety margin, and therefore might be considered as more accurate measure of safety. It is noted that the JTP and JBP common structural rules have been developed separately although interaction between the two groups of classification societies was present. As such, differences are observed in load and structural modelling, and criteria for fatigue and buckling/ultimate strength between the two common structural rules. A quick and thorough harmonization of both Rules in view of assessment methods and criteria is strictly recommended. Also, it is stressed that a rigorous program of inspection, maintenance, and repair during construction and periodically thereafter, and operational guidelines should supplement the design criteria to provide an acceptable level of structural safety throughout the ship's service life.

A review on the IMO's new development of Goal Based Standards (GBSs) was conducted. Although, the 5 tier approach adopted by IMO is yet to be developed to a great deal, it appears that classification societies will still play an important role in the structural adequacy of the designs. The full development of IMO GBSs will take some time but it is interesting to note that the emphasis was placed by IACS on the compliance with IMO GBSs when developing the common structural rules. Also, it is noted by the committee that the goals relevant to ship structures in IMO GBSs appear to concentrate mainly on the design and construction, and do not specifically include the aspects of ship operation, inspection, maintenance and repair throughout the life of the ship. These, along with design and construction, are integral part of the safety of ships and should be considered in the goals explicitly.

A comprehensive review of Ro-Ro vessels, Inland Navigation vessels and LNG/CNC vessels in relation to quasi-static response evaluation has been provided.

The review of FPSOs has revealed that an extensive recent research has been concentrated on the determination of fatigue characteristics of welded joints. Finite Element modelling techniques using advanced shell and solid elements have been considered to determine hot spot stresses. Fatigue tests were carried out on specimens that were subjected to axial load and/or torsion for simulation of a combined stress condition in the fillet weld and results were used to validate a hot spot S-N curve recommended to be used for design of plated structures subjected to dynamic loading when the hot spot stress is derived from finite element analysis of plated structures. The review highlighted the acceptance and widened use of spectral methods for fatigue assessments of FPSOs.

For VLFS platforms, the Quasi-Static Structural Response in waves is directly coupled with the hydroelastic behaviour of the platform. This unconventional situation is the reason that the structural response of VLFS's in waves are considered (also discussed in this committee report) in combination with the hydro- and elasto-dynamic aspects. Structural evaluation is often carried out based on advanced direct methods and reliability principles owing to the lack of service experience and novelty of designs.

Future recommendations for topics which could be reviewed in future Committee work are:

- Interconnectivity and model exchange bi-directionally between 3-D product models and FE models
- Advance methods for mesh generation of FE models,
- Advance methods to account for corrosion and fatigue in assessing structural strength,
- Reliability based inspection and maintenance, and life-cycle design concept,
- Impact of IACS Common Structural Rules and IMO Goal Based Standards on ship structural design,
- Structural aspects of specialised ships,
- Structural aspects of offshore structures,
- A Finite Element benchmarking study to ascertain uncertainties and errors in transferring boundary conditions from global models to detailed local models.

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