

18<sup>th</sup> INTERNATIONAL SHIP AND  
OFFSHORE STRUCTURES CONGRESS  
09-13 SEPTEMBER 2012  
ROSTOCK, GERMANY  
VOLUME 2



COMMITTEE V.7  
**IMPULSE PRESSURE LOADING AND  
RESPONSE ASSESSMENT**

**COMMITTEE MANDATE**

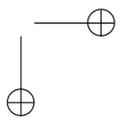
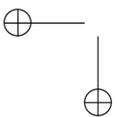
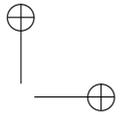
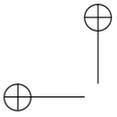
Concern for direct calculation procedures for evaluating impulsive pressure loadings, namely slamming, sloshing, green water and underwater explosion, and their structural response. The procedures shall be assessed by a comparison of tests, service experience along with the requirements of the rules for relevant classification societies. Recommendations for structural design guidance against impulsive pressure loadings shall be given.

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**KEYWORDS**

Slamming, sloshing, green water, underwater explosion, impulsive pressure, structural damage, classification society rules, natural period, peak pressure, impulse duration, equivalent static pressure



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## 1 INTRODUCTION

Recently assessments of impulsive pressure loading and response of ship and offshore structures have drawn more attentions of marine structural designers. In order to reflect the concerns regarding the pressure impact and structural response a new specialist committee was formed in the last ISSC. The committee report covered impulsive pressure loads and responses together, which were previously treated separate in various technical and specialist committees. The overall frame of this report is the same as that of the last ISSC report (Cho *et al.*, 2009).

The effect of impulsive pressure loading on ship structural response can be both global and local. Global impulsive loading makes whole ship structure vibrate while the local impulsive loading affects relatively small part of the structure at the fluid structure interface. The way in which the impulsive pressure loading will influence the structural response depends both on the amplitude of the pressure and on its evolution in space and time. In the analysis of the structural response, it is thus fundamental to consider both parameters, i.e. the pressure amplitude and space/time evolution, together with the structural response because the degree of interaction will depend both on the type of loading and on the structural characteristics. Indeed, the extreme pressure peaks (up to 50 or even 100 bars) do not necessarily means that the structure will encounter any damage because these pressure peaks are usually associated with very short duration in time and very small extent in space. That is why, when analysing impulsive pressure loading, one must always have structural response in mind. In addition to the importance of the spatial pressure distribution, one important parameter is the ratio in between the time scale of the loading relative to the structural natural periods contributing significantly to large structural stresses. When the loading occurs at the time scale of these periods, fluid-structure interactions must be considered which means that the fluid flow must be solved simultaneously with the dynamic structural response. All these comments are valid both for the global and local impulsive loading effects.

The committee reviewed many of recently published papers and reports related with impulsive pressure loadings and responses of marine structures. Comparisons of classification societies rules were also conducted and results were summarised in this report. Even though the progresses in predicting pressure impact loads and structural responses have advanced, the outcomes have not been reflected in the relevant classification societies rules. In hoping to improve those rules some recommendations are provided for structural design guidance.

## 2 LOCAL SLAMMING

### 2.1 General

With slamming is generally meant to be the impact between a structure and a body of fluid. Such impact creates rapid changes of fluid velocities and corresponding changes of hydrodynamic momentum. The related hydrodynamic loads increase with increasing rate of change of hydrodynamic momentum, which in turn increase with increasing relative velocity and decreasing relative angle between the body and the fluid. When the flat bottom in the fore part of a low speed ship is being lifted out of the water due to large relative ship motions, rather moderate relative velocities between the re-entering hull and the wave surface is needed for large slamming loads to develop. Higher ship speed implies larger relative motions and velocities, and here large slamming loads can develop despite the hull being flared or deadrised. Slamming might also occur when a

wave hits a stationary structure such as a platform deck or column. Slamming is characterized by large free-surface deformations together with spray jet formations in the intersection between the body and the water surface. The phenomenon is accompanied with related large pressure gradients, rapidly propagating peaked pressure distributions, complex flow separation and possibly air entrapment at small relative angles. For flexible structures the situation might be complicated further due to structure deformation related local changes of the relative velocity and geometry, and combined structural and hydrodynamic inertia effects. To this also adds the random nature of waves and ship motions. All in all this makes the prediction of slamming loads and related hull structural strength assessment a real challenge which still is far from fully mastered. Consequences of limitations in predictive capabilities in structural design might be structural damage or overly conservative and heavy structures. This chapter reviews research performed in the last three years in the area of local slamming, i.e. slamming loads and related fluid-structure interaction and responses for hull panels and other local structure. The chapter is divided into the four different problem areas: 1) *Fundamental hull-water impact*, involving studies of rigid simply shaped bodies impacting calm water and related hydrodynamic loads; 2) *Hydroelastic interaction*, involving studies of water impact of flexible structures and related hydrodynamic loads and structural responses; 3) *Wave impact*, involving waves impacting on stationary structures; and 4) *Concurrent modelling of waves, ship motions, slamming loads and structural responses*.

## 2.2 *Fundamental Hull-Water Impact*

Experiment is of course a very important source of knowledge, both for understanding the mechanisms involved and for gathering reference data for evaluation of theoretical models. However, due to the large complexities involved even in simplified fundamental hull-water impact situations, the experimental setup is far from trivial and only a few experimental series such as those by Aarsnes (1996) are available in the literature. Some new significant experimental work on fundamental hull-water impact has however been performed lately. Lewis *et al.* (2010) for example provide a comprehensive report on an experimental programme involving upright impact of a 25 degree dead-rise angle rigid wedge studying different wedge masses and drop heights. Pressures, vertical accelerations, position sensing and high speed camera images were obtained during the experiments. The comprehensive set of measurements, the detailed description of the experiments and equipment, and a detailed uncertainty analysis makes these data highly suitable for validation of predictions. Tveitnes *et al.* (2008) designed an experimental setup to enable near constant velocity impacts entries and exits with wedges with end plates. Forces, velocities, wetting factors, and derived added masses are presented and evaluated. The results are particularly valuable in simulation of planing in calm water based on the planing-immersing section analogy. Also Battley *et al.* (2009) carried out experimental investigations with near constant velocity panel-water impacts as further commented in the hydroelastic interaction section below. Huera-Huarte *et al.* (2011) designed a novel test rig in order to experimentally study high-speed panel-water impacts. Impact force and velocity are measured and high speed imaging is used. High velocity impacts up to 5 m/s were conducted at angles between 0.3 and 25 degrees with a practically rigid panel. Good correlation with the experiments by Tveitnes *et al.* (2008) and asymptotic theory are shown for impact angles larger than 5 degrees. Cushioning at smaller angles is demonstrated and discussed. De Backer *et al.* (2009) have performed experiments on water impact of different axisymmetric bodies. Wetting factors, pressures, impact velocities and ac-

celerations are presented. Measured pressures are compared with a three-dimensional asymptotic theory for axisymmetric rigid bodies which are found to significantly over-predicted the pressures. Possible reasons for the discrepancies between experiments and theory are discussed.

Not many studies considering analytical methods have been done lately. One of the few is by Yoon and Semenov (2009) presenting a semi-analytical method for modelling oblique wedge-water impact. The method is used to study the onset of flow separation from the wedge vertex as a function of wedge orientation and direction of impact velocity. Very good agreement with experimental data is demonstrated. Tassin *et al.* (2010) present a detailed review of several different analytical methods for the prediction of the hydrodynamic impact forces and pressure distributions acting on two-dimensional and axisymmetric bodies entering calm water. The studied methods reviewed include the original and a generalized Wagner method, the modified Logvinovitch method and the matched asymptotic expansion method. Results from the reviewed methods are compared with results from explicit finite elements arbitrary Lagrangian-Eulerian (ALE) simulations and experimental observations. The different methods are shown to agree well with small deadrise angles but differ significantly for larger angles.

Encouraged by the increasing computer power, fundamental hull-water impact has lately been studied using computationally intensive techniques including various RANS methods, Smooth Particle Hydrodynamics methods (SPH), Moving Particle Semi-implicit method (MPS), finite-element arbitrary Lagrangian-Eulerian methods (ALE), and Boundary Element Methods (BEM). Viviani *et al.* (2009) review a Smoothed Particle Hydrodynamics Method (SPH) that is under development and compare simulation results for drop tests with two-dimensional sections with corresponding results from a Reynolds-averaged Navier-Stokes solver (RANS) and experiments. Both numerical methods seem to be capable of capturing the physics of the slamming phenomenon, showing an overall satisfactory agreement with experimental results in terms of local pressure and total forces. Special considerations were made in the development of the SPH method to ensure its generality of application. However, it is concluded that further investigations are needed for example considering pressure instabilities and drift. Veen and Gourlay (2011) use a 2D Smoothed Particle Hydrodynamics method (SPH) to study slamming impacts of hull sections. Excellent agreement with experimental data is shown for a wedge shaped section regarding vertical velocity, force and pressure, and fairly good agreement for a flared hull section. The importance of proper modelling of the impact velocity profile is demonstrated and discussed. Khayyer and Gotoh (2010) highlight various challenges related to particle methods such as the Moving Particle Semi-implicit method (MPS) and the Smooth Particle Hydrodynamics method (SPH), for example regarding conservation of momentum and energy, interpolation completeness, non-physical pressure fluctuations, criteria for assessment of the free-surface, and provide references to a large number of efforts on improving these methods.

Fairlie-Clarke and Tveitnes (2008) use the finite volume of fluid method implemented in the CFD code Fluent 4 to study constant velocity wedge impacts on calm water. Pressures, forces, and free surface profiles are presented and possible modifications of the slamming momentum theory are discussed. Yang and Qiu (2010a, b) extend earlier developed Constrained Interpolation Profile methods (CIP) from 2D to 3D. In the CIP method the fluid-structure interaction is treated as a multiphase problem, which should make it suitable for modelling slamming problems with large free-surface deformations. The method is validated for a 3D wedge and a sphere showing good

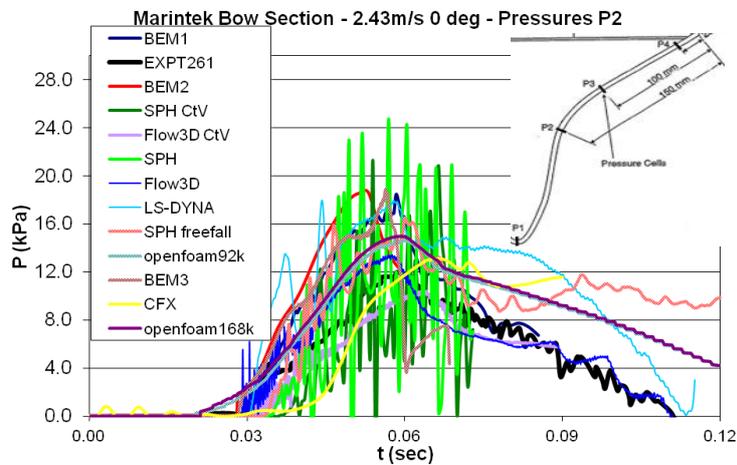


Figure 1: Predicted and measured pressures at point P2 of the bow section (Temarel, 2009)

agreement between simulations and experiments. Yang and Qiu (2010b) applied both 2D and 3D CIP methods on a 3D planing hull shape entering calm water with different roll and pitch angles. Slamming forces for the 2D method are generally larger than those by the 3D method. Experimental validation of the planing hull simulations are said to follow. Sun and Faltinsen (2009) studied two-dimensional water entry of a bow-flare ship section using an improved boundary element method where the fully nonlinear free surface conditions and exact body boundary conditions are satisfied and flow separation from knuckles is considered. Simulations are compared with previously published experimental results for upright as well as heeled sections. Fairly good agreement is found between simulations and experiments but the existence of experimental bias errors is obvious. Special effects related to the evolution of the free surfaces flow separation for heeled sections are demonstrated and discussed.

Brizzolara *et al.* (2008) provide extensive comparison between various numerical methods and experiments in the modelling of pressures and forces on a rigid bow section impacting a calm water surface. Both upright and heeled conditions are studied at various impact speeds. The numerical methods include three different Boundary Element Methods (simplified, i.e. not fully nonlinear), various commercial RANS software such as FLOW-3D, FLUENT (limited results), ANSYS-CFX (limited results), and LS-DYNA, OpenFOAM, and a Smoothed Particle Hydrodynamics (SPH) approach. There is reasonable overall agreement between predicted and measured pressures but the scatter is large as seen in Figure 1. The agreement is better for the lower impact speeds. All BEMs appear to overestimate the pressures. RANS type approaches FLOW-3D, as well as OpenFOAM and SPH appear to result in the best predictions, although they may suffer from large oscillation, especially the SPH. For the RANS methods, in general, the most stable results were obtained using free fall, rather than constant speed or simulating the velocity profile obtained in the experiments. The slamming forces show the same trends as the pressures. The complete set of calculations is reported by Temarel (2009).

### 2.3 Hydroelastic Interaction

The influence of hydroelasticity was investigated through analytical/numerical methods and a few experiments mainly, though not exclusively, focussing on V-type sections

prevalent in high speed craft. From these investigations it is apparent that the fluid-structure interactions involved are complex and that there is urgent need for more and systematic experiments for validating the numerical predictions.

Khabakhpasheva (2009) investigated the 2D coupled FSI problem of an elastic cylindrical shell penetrating at constant velocity in a thin layer of ideal fluid. Initially the shell is in contact with the liquid surface at a single point. The normal mode of approach is used for the coupled hydroelastic problem and the flow region comprises four subdomains with a solution obtained through matching. Results are presented for shells made of steel, aluminium and glass fibre plastic, for a range of thicknesses and impact velocities. Strain evolution with time, obtained at the bottom centre of the steel shell, show reasonably good agreement with numerical predictions in deep water and experimental results in shallow water. The study concludes that stress and deformation of the shell increases as the thickness of the liquid layer decreases. This study can be of practical interest, for example for bottom slamming of bulbous bows.

Mutsuda and Doi (2009) combined the Constrained Interpolation Profile (CIP) with the SPH method, the former for the fluid particles and the latter for the particles modelling the elastic structure. Examples are provided for a range of 2D impact problems, such as wedge with a range of deadrise angles, an elastic (aluminium) cylindrical shell, an elastic bow flared section impacting at 45 degrees and wave breaking on an elastic (steel) vertical wall. For the aluminium shell the strain variation with time at bottom centre is close to experimental measurements in deep water. The authors plan to improve their numerical model by accounting for air compressibility. Luo et al (2010) used the explicit FE code MS Dytran for the impact of stiffened panels. The code uses FE and finite volume methods to model structure and fluid, respectively, with an ALE algorithm for the fluid-structure coupling. Numerical results for one case of a stiffened steel panel fall within the scatter of experimental measurements of maximum pressure vs. maximum acceleration. Strain measurements were not available from these tests. The authors carried out a detailed numerical simulation for another steel stiffened panel, including various drop speeds and air cushion effects. These results show important differences between rigid and elastic impacts for pressure peak values and time histories. Their numerical results also show significant increase in peak pressures when the air cushion effect is neglected, but the predicted stress results do not increase as much. Oger *et al.* (2010) used the SPH method for fluid-structure coupling to simulate a range of impact problems, including 2D modelling of an elastic wedge (deadrise angle 10 degrees) impacting still water. Predicted pressures and deformations are compared with a semi-analytical solution showing good correlation, provided the tensile instability in the couple SPH method is removed using the artificial tensor procedure.

Maki *et al.* (2011) carried out 2D numerical investigations of an elastic wedge impact using one-way coupling, namely CFD (OpenFOAM) analysis of a rigid wedge and transfer of relevant information to a structural model which uses modal analysis for the wet wedge. The predicted deflections were compared to fully coupled theoretical and numerical models. The authors conclude that their method has poor time accuracy in the impact stage but shows good agreement for the maximum deflection, the latter indicating that the approximation used for the flexural added mass is acceptable. Stenius *et al.* (2011) analyse flexible panel-water impacts for a range of different panel properties, panel boundary conditions and impact scenarios using the explicit arbitrary Lagrange-Euler finite element method implemented in the code LS-DYNA and a simplified method combining beam and potential flow theories. Hydroelastic effects

are quantified by comparing with a rigid quasi-static solution where the hydrodynamic loading is modelled as unaffected by the structural deformation and the structural response is modelled as unaffected by structural inertia. The authors concluded that both hydroelastic inertia and kinematic effects can be important. Furthermore they emphasize the significance of impact scenario (or envelope) on the hydroelastic effects increasing or reducing pressures and panel response. Campbell *et al.* (2010) used a coupled FE-SPH approach to model the nonlinear FSI behaviour where the structure also experiences large nonlinear deformations. The explicit FE software DYNA3D was selected. The method is verified by simulating the dam break problem. It is subsequently applied to simulate the impact of a detailed helicopter sub-floor structure with water. The predictions are compared with drop test experiments. The acceleration presented shows reasonable qualitative agreement, due to differences between simulated and experimental conditions. However, the overall predicted deformation of the structure is claimed to be consistent with deformations observed in the experiment, such as joint failure and plastic deformation.

Battley *et al.* (2009) carried out experimental investigations on panels made of three different composite materials, one effectively rigid, for various impact speeds, deadrise angles and boundary conditions. The authors concluded that hydroelastic inertia effects have a significant influence on panel response. They also identify kinematic effects, such as large reduction in local deadrise angle at the chine, resulting in much higher peak pressures than for rigid panels. Kong *et al.* (2010) present experiments and numerical simulations of drop tests with a flexible section of a trimaran hull including side hulls, cross structure and internal structure. The numerical simulations are performed with the Autodyn FE solver using an Eulerian-Lagrangian method where the coupling between the fluid and the flexible structure is considered. Remarkably good correlation between measured and predicted peak pressures is presented. The validity of these observations is, however, somewhat difficult to judge, for example due to the limited information provided regarding pressure transducer diameters.

Qin and Batra (2009) use sandwich composite panel theory (including transverse shear and transverse normal deflection for the core and Kirchhoff plate theory for the skin) and 2D potential flow analysis, excluding separation effects. The majority of their calculations only partially account for the hydroelastic effects, excluding added inertia, having shown that such a model is adequate. Their study, however, only considers the initial phase of slamming until just before the water separates at the upper panel boundary. Das and Batra (2011) use explicit arbitrary Lagrange-Euler finite element method implemented in LS-DYNA to make detailed studies of slamming of sandwich panels including quantification of strain energy densities in core and laminates and effects of delamination. Another interesting application for sandwich panels is presented by den Besten and Huijsmans (2009). The structure is modelled using Euler beam theory for the skins and a linear orthotropic continuum for the core, with relevant compatibility conditions. The hydrodynamic impact force is modelled based on Wagner's method. The forced vibration response, subject to the impact load, is evaluated using modal summation. Damping is included using complex core moduli. The numerical results for a stiffened aluminium and a flat sandwich panel show that the bending stresses are larger for the former. There are no experimental measurements to compare the predictions.

#### 2.4 Wave Impact

The occurrence of wave impacts is a critical feature in the design and re-assessment of many offshore structures. With evidence of increasing storm severity and with

subsidence an important characteristics of some mature fields, the quantification of impact loads arising on both the columns and the underside of the lower deck of large offshore platform remains a difficult but important issue.

Roos *et al.* (2009, 2010) presented the experimental data arising from a physical model study of Gravity Based Structure subject to a severe sea state. They showed that far from being a highly localized effect, involving a thin sheet of water, the run-up associated with a steep wave can involve significant volumes of water, travelling at very high velocities, leading to occurrence of large impact pressure acting over substantial areas. They also showed that the largest loads frequently did not correspond to the tallest or steepest incident waves. They showed the importance of wave-structure and wave-wave interaction effects and the need to undertake long random wave tests in offshore engineering design. Baarholm (2009) performed a small scale model test campaign of wave impact on an idealized platform deck and clarified that the three-dimensional effects significantly reduced the wave-in-deck loads, in particular, for the water exit phase, the vertical force is almost halved due to three-dimensional effects. They showed that the Wagner based method with three-dimensional correction yields good results for the water entry phase, but it overestimates the water exit force and underestimates the duration of the wave-in-deck events. Kendon *et al.* (2010) compared the measured vertical load on the deck against simple potential theory and the result from CFD code STAR-CCM+. They concluded that for isolated impact events the simple potential flow based model is adequate for predicting the vertical loading on the deck. However, if there is a strong likelihood of steep wave grouping resulting in closely following wave-in-deck impact events, the aforementioned simple method may be non-conservative, and a CFD analysis or model test may be advisable to predict loading for such case.

Clauss *et al.* (2010) analysed stochastically the data from model tests with the Sleipner A GBS for estimating the impact pressure due to braking waves corresponding to an annual probability of  $10^{-4}$ . The procedure for calculating shock pressure due to breaking waves recommended by DNV was also applied. The two calculation approaches resulted in significantly different estimates for the characteristic  $10^{-4}$  probability impact pressure and the procedure recommended by DNV seemed to be strongly underestimating the impact pressure. They suggested that the different force sensor sizes had an influence on the resulting characteristic  $10^{-4}$  probability pressures. They concluded that the recommendation of DNV had to be altered to ensure a reliable prediction of the characteristic impact loads if the difference was still present by using the adequate force sensor.

Iwanowski *et al.* (2010) studied numerically a wave-in-deck load due to an extreme wave, acting on a jacket platform. Firstly, they calculated the fluid pressure acting on the platform using CFD code ComFLOW, in which VOF method was used to calculate the behaviour of fluid free-surface. Subsequently, the pressure was mapped automatically onto structural FEM shell elements and the structural response was calculated using LS-DYNA. Liang *et al.* (2010) calculated air gap response of a moored semi-submersible adopting a Navier-Stokes solver by VOF method. To confirm the accuracy of the numerical solver, the predetermined irregular wave train was simulated and verified against physical tank results. Xu *et al.* (2008a, b) studied the steep wave impact pressures and the structural dynamic response of floating production storage and FPSO bows using 1:80 scale segmented, instrumented models. They developed a time history simulation method, which makes use of a simple modification to linear random wave theory and a relatively simple slap force prediction based on

velocity times rate of change of added mass in order to calculate bow loading in random sea. Comparisons are made between experimental and calculated impacts and associated pressures. Simplified design rules for curved bows were proposed. Ten and Korobkin (2009b) used potential flow analysis for modelling steep wave impact on an elastic vertical wall. The fluid domain is compressible in the vicinity of the wall and incompressible elsewhere. The wall is modelled using Kirchhoff's plate theory. The equations of motion of the FSI system are in terms of the principal coordinates of the elastic plate and fluid loads. The method has been verified in terms of convergence analysis. It was also applied to two boxlike structures with different impacting wall thicknesses. A sensitivity analysis of modelling compressibility is also carried out.

### **2.5 Concurrent Modelling of Waves, Ship Motions, Slamming Loads and Structural Responses**

Since the pioneering work by von Karman (1929) and Wagner (1932) until present days the major research effort on local slamming has been on the idealised situation of a two-dimensional body impacting a calm water surface at constant speed or free-falling. However, in order to assess the slamming pressure and the related consequences for the hull structure in a design situation the slamming calculations must be combined with modelling of the ship motions in waves. As discussed in Hermundstad and Moan (2009) two main approaches can be distinguished, the "k-factor methods" and the "direct methods. In the "k-factor methods" the slamming loads are determined by scaling slamming coefficients (so-called k-factors), which have been pre-determined based on calculations or experiments, with a statistical measure of the square of the impact velocity, which typically is determined based on linear strip theory and linear response analysis (e.g. Ochi and Motter, 1973). The "direct methods" involve more thorough modelling of the ship motions in waves including the non-linear slamming mechanisms. Direct methods obviously have the potential to be significantly more accurate than the k-factor methods. Due to the high complexity of the slamming problem and the randomness of the waves direct methods however require significantly more computational effort. Kaspenberg and Thornhill (2010) for example reports that a 60 second CFD simulation (ANSYS CFX 11.0) of a captive model at forward speed in irregular waves took 7 days using 40 1.6 GHz processors. The development of direct methods that are feasible for design purposes will hence require special concerns to limit the computational effort. A few attempts of developing such approaches are reviewed in the following.

Lin *et al.* (2009) developed a nonlinear hybrid numerical method for predicting wet deck slamming of high-speed catamarans. In this method, the fluid domain is divided into an inner domain that encloses the ship and its nearby flow field and an outer domain that extends from the near- to the far-field flow. The flow in the inner domain is modelled with viscous flow theory while the flow in the outer domain is described with potential flow theory. An overlapped matching zone is employed to couple the two flow solutions. Simulations with a wave maker, a sphere impact on a flat water surface, and the wet deck slamming of a high speed catamaran are demonstrated but quantitative evaluation is limited.

Hermundstad and Moan (2009) use a non-linear strip method to simulate ship motions and determine slamming loads based on the simplified 2D boundary element method in Zhao *et al.* (1996). To speed up the calculations a pre-calculation and scaling approach is used and slamming forces are only calculated for wave encounters for which slamming conditions have been detected with a simpler method. Simulated

pressure time series are compared with measurements from two different experiments with 2D sections impacting calm water and from two different model experiments with ships in waves. The agreement is reasonable but the pressure magnitudes differ considerably in several cases. Evaluation based on statistical measures would be a good complement. Kaspenberg and Thornhill (2010) determine slamming loads based on momentum theory with particular concern for slamming related pile-up and pile-up due to the static bow wave. Similarly as in approaches for simulation of planing craft in waves (e.g. Garne and Rosén, 2003) spacial derivatives of added masses are pre-calculated and then scaled with the momentary position and velocity of the ship in a seaway. Hereby the computational effort can be limited making long term simulation of slamming loads and derivation of statistical properties for design purposes feasible. The idea is that this simplified method should be tuned with more advanced CFD calculations for improved accuracy and then integrated in a ship motion simulation scheme. The method is compared with experiments and CFD calculations for a captive model in a seaway showing reasonable agreement.

### 3 GLOBAL SLAMMING

#### 3.1 General

With the increasing demand of large-scale and speed in shipping industry, the wave impact of large container ship, cruiser and multi-hull boat is becoming more and more important. Study on wave impact is mainly to make right Class Rules which can guide structural design of ships according to reasonable and reliable impact loads, thus, we need a practical direct calculation method about impact response.

The first construction on wave impact was by von Karman (1929). Now, people have achieved fruitful results on the impact problem of two-dimensional structures, reliable results were given in numerical method (e.g. Zhao and Faltinsen, 1993, Zhao *et al.*, 1996) and laboratory experiments (e.g. Chuang, 1967, 1970). Reliable results have not been obtained for 3D hull impact in numerical method (Xu, 2010); Many researchers had conducted ship model test, but the scale effect must be considered, and the impact responses of hull in model test need to be validated by the result of in-service experiments.

Sailing ship's wave impacts are complex and dynamic physical phenomenon, it is a very difficult task to establish a comprehensive physical model and mathematical model. This model should include geometric nonlinear, wave-surface nonlinear, nonlinear motion and 3D effects. It is not practical that all of the nonlinear and 3D effects are included in the model. We can predict the impact response of ships by establishing a simple model which takes part of nonlinear and 3D-effects into considerations, then continue to carry out the improvement and revision.

A methodology for investigation of this challenging phenomenon is drawn up and a mathematical model is worked out. It includes the definition of ship geometry, mass parameters, structure stiffness, and combines ship hydrostatics, hydrodynamics, wave load, ship motion and vibrations. The modal superposition method is employed. Based on the presented theory, a computer program is developed and applied for hydroelastic analysis of a large container ship (Senjanovic *et al.*, 2009).

In general, the global slamming response needs to be combined with the simultaneously obtained global and local steady state load effects, in terms of extreme values for ultimate limit state checks and cyclic load histories for fatigue design checks. Vessel speed and possible heavy weather avoidance are also important factors and the

operational profile should be properly defined when determining design load effects. Moreover, it was noted that even if slamming loads initially induce large sagging loads, they would also imply large hogging loads due to the transient dynamic character of the response (Moan *et al.*, 2006). This is important since the hogging condition may be the governing design condition, e. g. for container vessels.

The need to augment existing design rules with a rigorous means to identify design wave conditions is discussed by Kim and Troesch (2010). Rather than using Monte Carlo methods for determining the effects of combined wave plus slam induced whipping loads, a design load generator analysis process is used. Basically with this approach, the phase distributions that lead to the  $m^{\text{th}}$  maxima at a prescribed time are determined. From there, an ensemble of short time series that will return target extreme events at a present time is created. The analyst can then use these time series ensembles to predict lifetime maximum loads at prescribed target extreme values.

### 3.2 Laboratory Experiments

For laboratory experiments, a scaled ship model is needed which directly brings the scale effect, methods to extrapolate the results of models to full scale are not yet developed (Hirdaris and Temarel, 2009), but in-service experiments are much more expensive. The experimental program consists of tests in both regular and irregular head waves, and the measured quantities included wave elevation, vertical motions and hull pressures (Tiao, 2011).

Slam events experienced by high-speed catamarans in irregular waves were characterized through experiments using a hydroelastic segmented model. The model was designed to represent the dynamic behavior of the full-scale 112 meter vessel and to allow the measurement of the slam load on the bow and wet deck (Thomas *et al.*, 2011). In order to measure vertical moment, the ship model must use segmented model in the experiments. This also accords with the actual condition of ships. The real ship hull will vibrate in waves.

Hydroelastic segmented model tests have been undertaken in head-seas to investigate the parameters affecting the whipping vibratory response of high-speed catamaran vessels subject to slamming. The first longitudinal modal frequency measured on full-scale INCAT catamaran vessels is used as a basis for predicting the flexural response frequency of the hydroelastic segmented model (Lavroff *et al.*, 2010).

### 3.3 Hydroelastic Analysis

The classical approach to determine ship motions and wave loads is based on the assumption that the ship hull acts as a rigid body. The wave load is then imposed to the elastic 3D FEM model of ship structure in order to analyse global longitudinal and transverse strengths, as well as local strength with stress concentrations related to fatigue analysis. Large ships are relatively more flexible and their structural natural frequencies can fall into the range of the encounter frequencies in an ordinary sea spectrum. So, a reliable approach to determine ship motions and wave loads requires analysis of wave load and ship vibrations (springing and whipping) as a coupled hydroelastic problem (Senjanovic *et al.*, 2009). Ship motions and wave loads can be analysed by 3D nonlinear hydroelasticity theory which takes wave impact into consideration.

The study of hydroelasticity of ships first gained momentum in the late 1970s with the work of Bishop and Price, who established the 2D hydroelasticity theory of ships (Wu and Cui, 2009). Then the theory of hydroelasticity was extended to 3D for ships

with a forward speed in the middle of 1980s (Wu, 1984; Price and Wu, 1985; Bishop *et al.*, 1986).

In recent years, the research on nonlinear wave load calculation method has made some progress. Many methods have been introduced, including first-order theory, second-order theory and the body nonlinear theory. The nonlinear factors include the speed square of pressure expression, wet surface and free surface. Through a large number of studies it is shown that the dynamic nonlinearity is mainly due to the body nonlinearity together with the free surface nonlinearity.

A 3D nonlinear time domain simulation hydroelasticity analysis method of ship motions and wave loads is presented, taking body nonlinearity and hull impact into consideration. The hull girder is simplified as a Timoshenko Beam. Combined with the wet surface generation method, the velocity potential of flow field is solved by the source-sink distribution method. After all the wave forces acting on the hull girder are obtained, the forced vibration equation of hull girder is established. Then, the principal coordinates of each order vibration and the section loads of ship are obtained (Li, 2009).

It is important to determine the impact force, the existing calculation methods include numerical method, laboratory experiment method, in-service experiment method and empirical formula method. The results of theoretical calculation can be checked with experiment values. The accuracy of numerical method for the 3D hull cannot be trusted.

The empirical formula method is based on the Wagner wedge impact theory, the Chuang cone impact theory, and experiments performed at the David Taylor Naval Ship Research and Development Center. Determination of the impact pressure is based on the hypothesis that the impact velocity is equal to the relative velocity normal to the impact surface of the moving body and the wave surface. The proposed method has been verified by several model tests in waves and by actual ship trials of the catamaran USNS Hayes (Stavovy and Chuang, 1976).

Calculation and prediction of ship slamming pressures in severe seas is difficult for the sea conditions and 3D characteristics of ship hull shape must be totally considered,

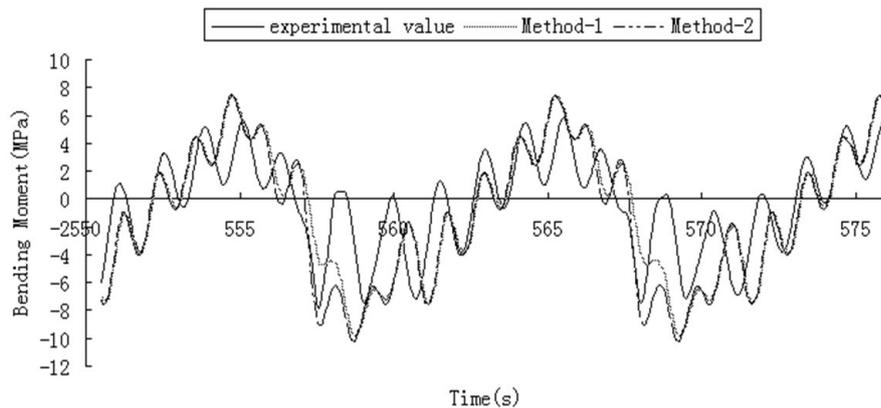


Figure 2: Experimental value and calculation values in different method of determine the impact force. Method-1 is empirical formula method. Method-2 is momentum method. Ship speed 9 knots ( $\lambda/L = 0.9$ ) in head waves, wave amplitude 8.75 meter.

the influence of ship motions such as heaving, pitching and rolling should be included. The slamming pressure coefficient is then a key factor to be determined (Wang *et al.*, 2010). The direct calculation of ship slamming pressure based on empirical formula is reasonable and reliable. The 3D effect of hull shape and wave surface and the influence of ship motions are considered. Impact force can be obtained by integrating the slamming pressure along hull wet surface.

Another calculation method assumes that impact force is related to the change rate of fluid momentum and buoyancy. If the transient added mass and transient area of subsidence of profile sections are known, then the impact force can be obtained. In Figure 2, there is an impact response calculation case of one Container Ship. The profile bending moment in experiment and theoretical calculation were compared. The impact force was calculated by different methods.

## 4 SLOSHING

### 4.1 General

This chapter is devoted to the evaluation of the dynamic structural response of the cargo containment system (CCS) inside the membrane type LNG tanks of different floating units (ships, FPSO's ...). Sloshing loads represent dominant part of the design loads. These sloshing design loads are relevant both for the ship hull structure and for the cargo containment system. As far as the hull structure is concerned the situation is slightly simpler and normally only global loads matter. Concerning the cargo containment system the situation is significantly more complex because CCS is directly exposed to the violent sloshing impact loading. There exist today two main types of CCS and they are shown in Figure 3. Both systems are owned by Gaztransport and Technigaz (GTT), and both systems are structurally very complex and involve different types of materials (plywood, perlite, invar, stainless steel, foam, glue,...) which are connected together and attached to the hull structure.

Because there are no numerical methods that can fully describe the sloshing induced slamming pressures, one has still to rely on experiments which means in practice model tests. The challenges are how to scale the model test results to full scale and properly account for the structural elastic reactions due to the fact that a rigid model is used in model scale. There are many contributing factors to scaling which have to be considered and one has to do certain approximations. Generally speaking, Froude scaling is expected to be a dominant effect. Correct ratio between the density of the gas and the liquid, the Euler number due to possible gas pocket effects, boiling (cavitation number) as well as hydroelastic effects have to be considered. An implication is that the effects of viscosity (Reynolds number), surface tension (Bond number) as well as the change of the speed sound due to a mixture of gas and liquid are likely to be of secondary importance (Faltinsen *et al.*, 2009).

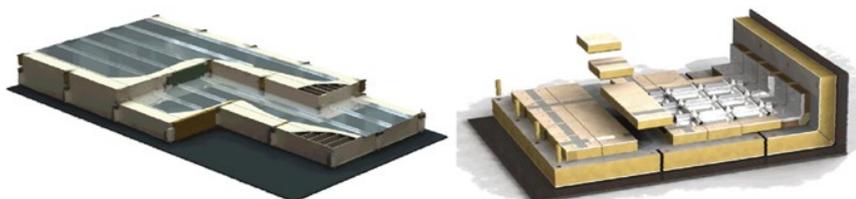


Figure 3: Two types of containment systems NO96 (left) and MarkIII (right).

The complex scaling issues are discussed, among others, by Yung *et al.* (2009) where attempt was made to propose a rational scaling procedure. The authors conclude that, despite the thermodynamic complexities along the NG/LNG phase boundary, dynamic similitude for sloshing is possible for geometrically similar models regardless of length scale provided that the Euler number, the Froude number and the Interaction index are the same. In particular, the Interaction index, which relates dynamic pressure communication between the ambient vapor and the sloshing liquid, provides a means to scale impact pressures for model tests with fluids readily available at convenient thermal conditions. The work of Yung *et al.* (2009) was a part of very extensive research done by Exxon Mobil in cooperation with GTT (Kuo *et al.*, 2009; He *et al.* 2009; Issa *et al.*, 2009; ...) with the final goal to produce a rational design methodology based on direct calculation approach. However, this very interesting methodology has not been applied in practice yet, which suggest that still many uncertainties exist.

Methodologies proposed by the Classification Societies for the practical design verification of the containment system are still essentially based on the so called comparative approach which relies on the use of the small scale model tests for reference and target ship. Within this comparative approach the small scale model tests on the reference ship, which doesn't experience any damage, are used to deduce the conservative pressure scaling factor and the same scaling factor is applied to the target ship. After that the resulting pressure loading at full scale is deduced and compared to the capacity of the containment system. The critical point in the analysis is obviously the scaling factor which does not have clear rational justification since it mixes all the different hydrodynamic phenomena into a single number.

Let us also mention that in addition to the evaluation of hydro-structure interactions during impacts, the direct calculation methodology for sloshing requires a very complex seakeeping analysis which has to be fully coupled with sloshing dynamics. This is obviously necessary in order to determine the representative design tank motions. Finally, a very complex statistical analysis is required both on seakeeping and sloshing impact sides in order to simulate the ship life.

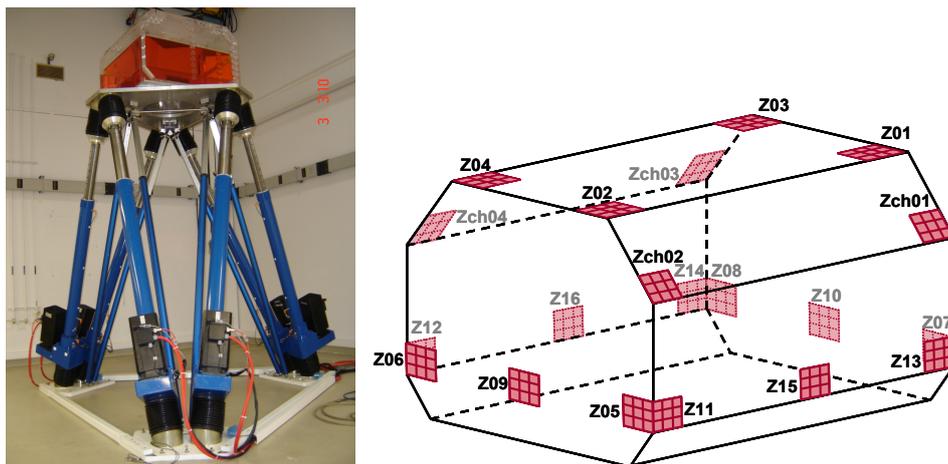


Figure 4: Hexapod system for sloshing model tests and typical pressure sensor locations

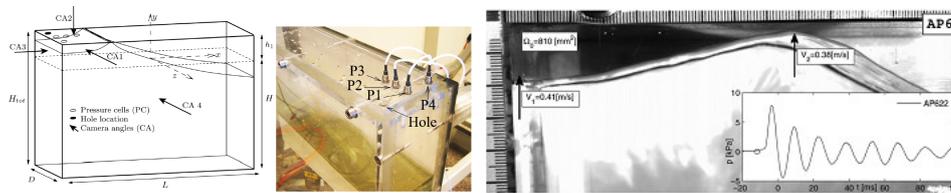


Figure 5: Model tests on impact involving the air pocket and typical pressure signal

#### 4.2 Model Tests

Several different types of model tests at different scales and with different objectives were proposed in the last few years. In particular, small scale sloshing model tests became nowadays rather classical and many important facilities exist all around the world and allow for testing the tank models at scale up to 1/25. The most typical sloshing model testing facilities are based on the use of hexapod (Figure 4) which showed to be very efficient in generating arbitrary time history of the tank motions.

As far as the overall sloshing behaviour is concerned the small scale model tests are very useful and give good qualitative impression of the violent fluid flow. At the same time the overall forces on the tank show good repeatability regardless of the model scale (Diebold *et al.*, 2011). This is because the overall sloshing behavior is mainly driven by the Froude scaling. When it comes to the measurements of pressure the situation is much more complicated; both regarding the repeatability and accuracy of the pressure measurements and, as already indicated, regarding the scaling of the measured pressure to the full scale. Different works on small scale model tests were published in the last few years (Kim *et al.*, 2009; Maillard *et al.*, 2009; Repalle *et al.*, 2010; ...).

In Abrahamsen *et al.* (2011) a dedicated model test to investigate the specific impact type on the roof of the rectangular tank was performed (Figure 5). The impact type is the one with the entrapped air pocket. The goal was to investigate the decay of the oscillations in the air pocket and possible sources of damping. Authors concluded that the leakage is not the main cause of decay and that heat transfer in between air and water might be important. Similar investigations were done by Lugni *et al.* (2010) where the breaking wave impact involving the air pocket entrapment was studied under different ullage pressures. One of the conclusions is that the influence of the ratio in between ullage and vapor pressure plays an important role and the decay of oscillations is much stronger in the vapor pressure regime. This suggests that the phase transition in between liquid and vapor phases plays an important role for damping the pressure oscillations.

This fact was also confirmed by Braeunig *et al.* (2010) where this phenomenon was investigated both experimentally (water and steam) and numerically. In Figure 6 the difference between the pressure signals with and without phase transition are obvious. All this illustrates again the difficulties related to the scaling of the model test results.

Very extensive experimental database of drop tests at small or full scale were produced at PNU by the team of Prof. Kwon (Chung *et al.*, 2007; Kim *et al.*, 2008; Oh *et al.*, 2009; Kwak *et al.*, 2010; Oh *et al.*, 2010). Very useful pressure measurements and high speed video of different impact types on NO96 and MarkIII geometries were produced. These types of measurements are essential for better orientation of the numerical developments and for their subsequent validation.

Driven by the difficulties related to the scaling, a very ambitious experimental project Sloskel (Figure 7) reported by Brosset *et al.* (2009) was initiated by GTT, Bureau Veritas, MARIN and Shell, and has been joined later by American Bureau of Shipping, Ecole Centrale Marseille, Chevron, ClassNK, Det Norske Veritas and Lloyd's Register. The originality of the experiments performed within Sloskel project lies in the fact that the real CCS was impacted by realistic wave impact conditions at full scale. The only, however not negligible drawback is that water under atmospheric conditions was used instead of LNG. Very extensive database of both loading (pressures, forces, ...) and the structural response of the CCS were collected both for NO96 and MarkIII CCS. Maximum measured pressures went up to 56 bars and still no significant damage of the CCS was observed. Thanks to the Sloskel experiments significant progress in understanding of the physics of the sloshing impacts was made.

The fundamental importance of the local flow characteristics prior to the impact was confirmed once again. This means that every detail flow aspect makes the direct assessment procedures very complex. This also means that the analysis of the small scale model tests without the corrugations (MarkIII) or raised edges (NO96) should be done with greatest care. Among other interesting results from the Sloskel full scale experiments, it is worthwhile to mention the detailed analysis of the fluid flow evolution during the different impact situations. One example of typical impact on MarkIII CCS is shown in Figure 8.

Following these investigations, Brosset *et al.* (2011) proposed the classification of the different impact phases into different elementary loading processes (ELP). In that respect 3 main ELP's were identified: (1) the actual impact (discontinuity of velocity), very localized and inducing acoustic pressure with the local velocity of sound of the aerated water; (2) the building of a jet along the wall from the impact area; (3) the compression of entrapped gas pockets or escaping gas jets. The idea behind this classification seems to be the decomposition of the arbitrary impact situations into different ELP's. Once each ELP properly assessed (still not clear how!) the final result will be the sum of the different ELP's in time. This work is still in progress and no final conclusions can be made yet.

Many other interesting issues (scaling - Bogaert *et al.*, 2010, deformation of the foam - Kaminski *et al.*, 2011, ...) were investigated within the Sloskel project and the analysis of the huge databases is still in progress.

At the same time, Sloskel project generated very important research activities which accompanied the full scale tests. Indeed, during the full scale experiments different difficulties were identified, one of the main being the lack of repeatability of the measurements for some important impact conditions. It was thus decided to investigate

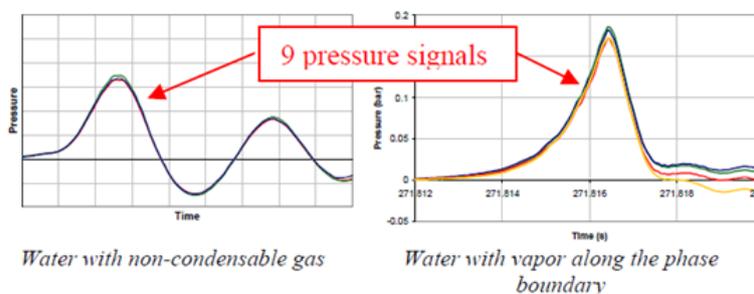


Figure 6: Air pocket pressure signature for different conditions



Figure 7: Quasi full scale impact experiments (Sloshel project)

this issue on a smaller scale and on a more simplified elastic structure. The MiniSlo project was organized and large scale model tests were performed in Ecole Centrale de Marseille. Measurements of the fluid flow (PIV) pressures and structural deflections were undertaken and very useful database for validation of the numerical codes was produced. Due to the well controlled laboratory conditions repeatability of the measurements was very good. One example of the measurements is shown in Figure 9. It is very likely that this kind of experiments will have larger importance in the future.

Parallel to the experimental work, important numerical activities were also performed within the Sloshel project (Oger *et al.*, 2009; Wang *et al.*, 2009; Braeunig *et al.*, 2009; Maguire *et al.*, 2009; Pillon *et al.*, 2009; Malenica *et al.*, 2009; Guilcher *et al.*, 2010; Dobashi *et al.*, 2010; Carden *et al.*, 2011; Wang *et al.*, 2011; Lee *et al.*, 2011; De Lauzon *et al.*, 2011). Different types of numerical methods were used (volume of fluids CFD, smooth particle hydrodynamics (SPH), semi analytical methods, ...) for both

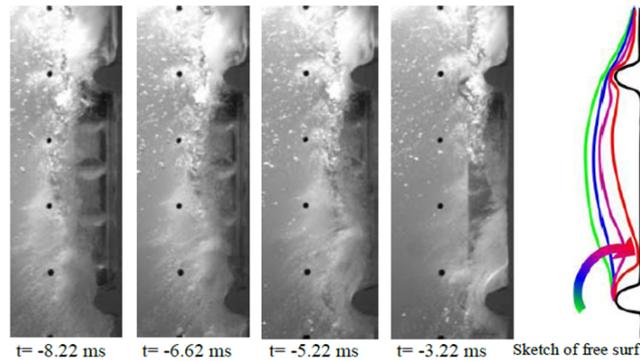


Figure 8: Different phases of the fluid flow during the impact on MarkIII CCS.

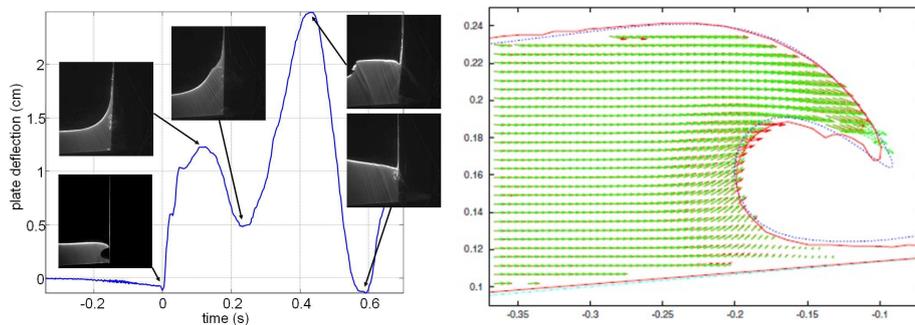


Figure 9: Large scale impact experiments (MiniSlo project)

rigid and hydroelastic types of hydro-structure interactions. In spite of all the efforts there still seems to be no fully efficient numerical method able to simulate this problem consistently.

Different other works on small/large scale model tests was done in the last few years (Kim *et al.*, 2009; Maillard *et al.*, 2009; Repalle *et al.*, 2010; Kim *et al.*, 2011) where different phenomena were investigated (pressure statistics, impact flow evolution, influence of density ratio, ...). One very important aspect of the model tests is the statistical properties of the pressure measurements. A large degree of uncertainties and scatter are usually observed (e.g. Fillon *et al.*, 2011). In this context, it is also important to mention that each pressure signal is not characterized by its maximum value only but the pressure should always be analyzed in combination with its time history (rise and decay time, oscillations, ...) and the surface which is affected. This introduces the additional non-trivial technical difficulties into this already complex problem.

### 4.3 Numerical Simulations of Sloshing

Different numerical methods for sloshing are proposed in the literature (e.g. Godderidge *et al.*, 2009; Chen *et al.*, 2009; Wemmenhove *et al.*, 2009; Rudman *et al.*, 2009; Ma *et al.*, 2009). These methods are mainly based either on potential flow, Euler or full Navier Stokes assumptions. Different numerical approaches which are usually employed are: BEM – Boundary Element Method, CIP – Constrained Interpolation Profile method, FDM – Finite Difference Method, FEM – Finite Element Method, FVM – Finite Volume Method, LS – Level-Set method, MAC – Marker-and-Cell method, MPS – Moving Particle Semi-implicit method, SPH – Smoothed Particle Hydrodynamics method, VOF – Volume-of-Fluid method and others.

Within the numerical methods for modelling of sloshing it is also worthwhile to mention the nonlinear analytically-based multimodal method proposed by Faltinsen *et al.* (2009a, b). The advantage of the method is its semi-analytical character which allows for fast calculations and detailed separation of different driving phenomena for sloshing. However, even if this method gives good insight into the overall sloshing motions it cannot be applied to the analysis of sloshing impacts.

With respect to all the numerical work which has been done, it is fair to say that there is still no fully efficient numerical method to deal with the overall sloshing hydro-structure interactions in a consistent way. Indeed, it appears that from computational point of view, it is impossible to take all the different physical effects at the same time. This is not only because of the prohibitive CPU time requirements but also because of the complexity of the physical phenomena which are involved (violent free surface deformations, hydroelasticity, phase transition, compressibility, 3D effects, low temperature, ...). That is why the actual research is more oriented to a kind of hybrid approach where the problem is subdivided into global and local parts. Indeed, the global fluid flow during sloshing can be reasonably described by the classical CFD tools but the complete treatment of the complex impact situations at the same time, appears to be impossible today. With respect to this, CFD can be used to determine the local conditions before impact (essentially the relative geometry and the relative impact velocity distribution) and the dedicated models for local impact simulations can be used for evaluation of the CCS structural response.

This idea was first introduced by Korobkin and Malenica (2006) and the most recent advances were presented in Ten *et al.* (2011). For different impact types (steep wave impact, impact with air-pocket, aerated impact and their combinations) which were

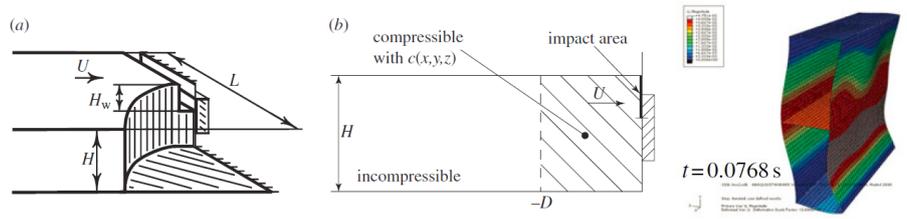


Figure 10: Example of simplified semi-analytical model for partially aerated impact type

identified for the low filling levels the semi-analytical (or semi-numerical) approach for fluid-structure interactions has been presented. Within this approach, the fluid flow is treated using the semi-analytical methods while the structural part is solved using the three-dimensional finite-element model. The choice of the simplified semi-analytical approach for the fluid flow was made in order to be able to have a full control of the flow characteristics, which allows for detailed investigations of the influence of different physical parameters. One example of the typical simplified impact situation is shown in Figure 10.

Different papers on the specific impact types were presented by the team of Prof. Korobkin (Khabakhpasheva *et al.*, 2009a,b; Malenica *et al.*, 2009; Ten *et al.*, 2009a,b; Khabakhpasheva, 2011). This work is ongoing and there is still lot of work to be done especially concerning the validation of different impact models.

The practical idea behind this global-local approach is to perform simplified parametric calculations for different impact configurations involving a small number of impact parameters (impact velocity, aeration, air-pocket volume, relative angle in between fluid and structure, ...) and check the structural resistance. Parallel to that the CFD (or alternatively small scale model tests) will give the most probable maximum value of the impact parameters. Both global and local results will then be combined in order to make the final check of the structural integrity of CCS. Similar ideas based on the exclusive use of CFD for both global and local flow is presented by Cho *et al.* (2008).

Finally let us also mention one important problem, which seems to not receive enough attention in the literature, and which concerns the numerical modelling of the CCS structure. As already indicated, CCS is a very complex structure composed of different materials connected together by special procedures and the representativeness of the classical finite element models should be considered more seriously. Even if some work on this issue has already been done (Isso *et al.*, 2009; Arswendy *et al.*, 2011a,b) this point requires more careful attention.

## 5 GREEN WATER

### 5.1 General

Ships and offshore structures are designed to withstand extreme sea states. This can be the extreme in the operational region for the offshore structure, or, for ships, usually the extreme in the North-Atlantic Ocean is chosen as the worst case scenario. Extreme sea states can lead to extreme events, one of these events is the exceedance of freeboard by the wave crest that results in a flow of water onto the deck and possibly an impact against a structure on the deck. Such an event is labelled “green water” and is the subject of research already for a good many years. Main reason for this research is the occurrence of damage on deck structures which are traditionally not designed for

these loads. For ships this damage is usually not critical, although a complete loss of the vessel can occur (Derbyshire accident), but for offshore structures like FPSO it can easily lead to oil leakage and loss of production time.

Interestingly, green water effects are also proposed for wave energy generation. Buchner and Jaouen (2009) describe model tests on a moored vessel where green water flows intendedly over the bow into a tank amidships. This tank drains via low water head turbines, thus generating an electrical current. The idea was presented in 2009, further work was published by Buchner, van der Schaaf and Hoefackers (2010). The green water aspect of this device is only a secondary power source, the main power comes from the anchor system that, via the motions at the bow, drives an on-board Power Take-Off system (PTO).

The review has been organized in three major categories, i.e. analysis by numerical methods, approximate method and experimental analysis.

### 5.2 Numerical Methods

Numerical methods are being used more and more to predict loads on deck and deck structures. Although good results are being obtained by different researchers using different methods, in the most cases the conditions are very artificial. Even today, it is not realistic to expect a good statistical distribution of green water loads in a realistic sea state. The problem is the excessive CPU requirement, but more important one is a long term simulation of a sea state in a numerical domain with proper wave evolution. Furthermore, it is not yet possible to obtain realistic results without reflection from the boundaries of the domain.

The most traditional method for extreme free surface deformations is the Volume of Fluid (VoF) method by Hirth and Nichols (1981). This method is still being used today, and similar methods like the Marker-density method by Lee *et al.* (2009) are being developed. The Marker-density method has, similar to VoF, problems in capturing the actual free surface; essentially the volume fraction of a cell is calculated. Calculations were carried out by Lee *et al.* using a very simplified wedge-type ship and a step-like water surface to generate the incoming wave. These results were qualitatively compared to the experiments by Greco *et al.* (2004) on a tanker model that was fixed in the basin; the pressure on deck was compared to the experiments by Pham and Varyani (2004) with the S-175 container ship. Since this is a different geometry and different impact conditions, no conclusions can be drawn from the apparent agreement.

Brodtkorb (2008) used the VoF method (ComFlow) to develop design rules for deck structures of jacket-type platforms. Forces on the deck appeared to be very spiky, for a problem of the VoF method that was reported before by Kleefsman *et al.* (2004). Brodtkorb used a low-pass filter on these forces before further analysis. Calculations for different geometries were carried out and compared with the API rules, a simplified design rule. The maximum horizontal load varied as function of the impact height and the geometry of the deck like external deck girders. The external deck girders incurred significantly higher loads than those given by the API method (Figure 11). The external deck girders appeared also to increase the vertical force on the deck. Brodtkorb *et al.* (2008) extended this work by including three slender pillars to model the jacket platform. They extracted velocities from the VoF calculations and used Morrison force coefficients to calculate the loads. Under deck structures were accounted for by applying geometry weight factors. Again the objective of the study was to develop an improved design load for impact loads on jacket-type offshore structures.

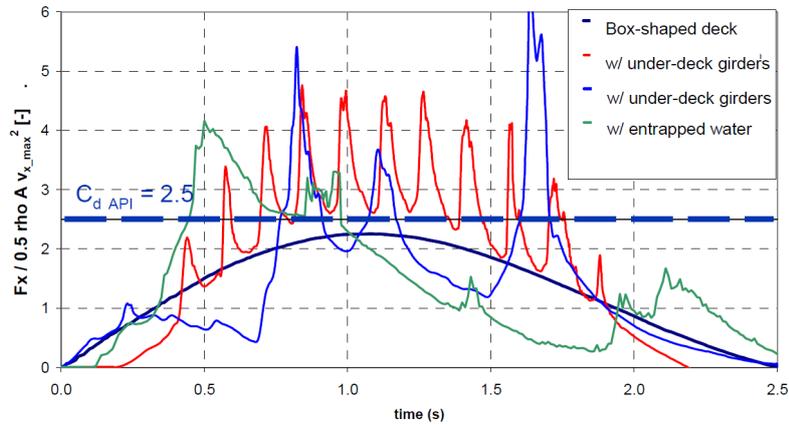


Figure 11: Horizontal force on a simplified deck structure with and without external girders. Results of CFD calculation compared to API method (Brodtkorb, 2008)

Schellin *et al.* (2009) studied the same problem using the combination of a VoF method and a FE analysis. The VoF method appeared to be quite advanced including a cavitation model for vapour bubbles that appear in low pressure regions and including an under-relaxation technique to avoid pressure peaks. Calculations were carried out on a coarse and fine mesh; the finer mesh showed a similar general flow behaviour, but the peaks of the horizontal forces were higher (Figure 12). These researchers

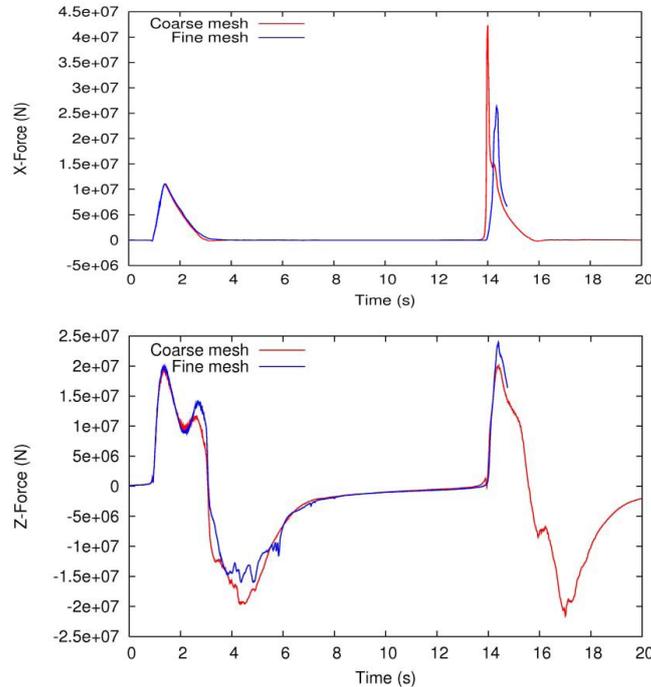


Figure 12: Effects of fineness of grid on horizontal (upper) and vertical (lower) forces on a platform for two successive wave impacts (Schellin *et al.*, 2009)

also recognized the importance of the local steepness of the wave crest, and that the velocity and consequently the loads are much higher if the wave overturns just before the impact. By using overlapping grids, one grid connected to the platform, the other lined up in the direction of the waves, they studied impacts in different wave directions. The results for the studied platform showed that impact forces were highest in head and following waves.

Liang *et al.* (2009) used the commercial solver FLUENT to model green water events and impact pressures on a moving 2D object in waves. For this 2D case they used  $2.0 \times 10^5$  cells. The results were compared to experiments carried out by Hu *et al.* (2006). The initial body motions agreed very well to the experimental values, stronger deviations occur after a few oscillations, possibly due to the effect of the water on deck. A comparison of local pressures is not shown.

Also Zhu *et al.* (2009) used the commercial code Fluent to calculate green water events, pressures on deck and pressures on a vertical wall of a moving body. The results were presented for a 2D case and compared those to the experiments by Greco *et al.* (2001) with very good results. They also presented results for a 3D FPSO and compared against the experiments by Buchner (2002). A case in regular waves was simulated using the provided motions of FPSO calculated with potential theory and imposing those in the RANSE method. The results for the pressure on deck were very good, the pressure on the vertical bulkhead compared less favourably to the experiments.

Lu *et al.* (2010) developed a VoF method for incompressible flow problems. The method uses an unstructured grid and solves the Navier-Stokes equations using an arbitrary Lagrangian-Euler (ALE) frame of reference. The method is demonstrated using a 2D example of a wave flume with waves overtopping a horizontal deck. Results of the wave elevation on various locations in the flume, and at the edge of the deck the velocities were compared well against experimental results published by Cox and Ortega (2002) with focused waves. Calculations of the pressure on deck for a 3D block with very low freeboard was compared well to the experiments by Yamasaki *et al.* (2005), but when with a vertical wall installed on the model the impulsive pressures on deck were less well predicted. Finally the case of a moving model of an FPSO was used. The motions were imposed on the numerical model. The numerical grid consisted of about  $5.0 \cdot 10^6$  elements; a simulation time of 45 s (model scale) took 29 hours on a 2-core processor. The results of pressures on deck and on the deckhouse showed a good correspondence to the experimental results by Liang *et al.* (2007).

Shibata and Koshizuka (2007) used a particle method to calculate the green water shipped on a fixed structure. Results were compared against the experiments by Tanizawa *et al.* (2004) on a FPSO. The numerical model was a simplified version of the physical model saving CPU time, and about  $3.3 \times 10^5$  particles were used in the calculation. The wave elevation at the bow agreed quite well to the experiments, but not the pressure on deck. It was concluded that the particles need to be smaller for a more accurate local pressure. The method was further developed and new calculations were presented by Shibata *et al.* (2009). In the calculations the numerical domain was minimized to save CPU time. The wave flume was limited to a length of about a half wave length in front of the vessel. Only the bow part of the vessel was modelled and the cross section of the wave flume was made triangular. The vessel motions were imposed using the results of the experiments; the walls were forced to move with the orbital velocities. By using symmetry on the centreline (the experiments were in head waves) they needed  $1.1 \sim 1.5 \cdot 10^6$  particles for the computational domain. The CPU time required was 2.5 ~ 4 days on a single core PC for a simulation time of 1.3 s. The

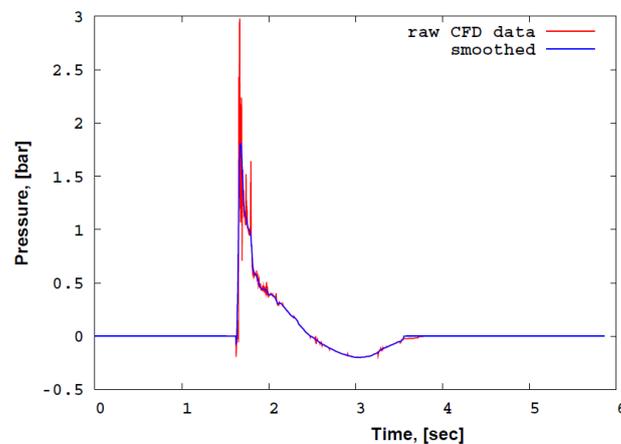


Figure 13: Spiky local pressure signal calculated by VoF method and smoothed curve, (Iwanowski, 2009)

general behaviour of the shipping phenomenon agreed very well to the experiments, but calculated pressures on deck showed very large numerical oscillations, although the values shown were averaged over 25 particles. The pressure impulse,  $\int p dt$ , showed a bit better agreement to the experiments although the differences were still 15 ~ 27% in comparison to the experiments.

Iwanowski *et al.* (2009) coupled a FE analysis to the results of the VoF calculation for the same problem of a wave impact against the deck of a jacket platform. They also used the ComFlow method, similar as used by Bordtkorb (2008) and Brodtkorb *et al.* (2008). Also Iwanowski *et al.* removed the pressure peaks by a filtering and smoothing procedure, Figure 13. The structural analysis was done using the commercial package LS-DYNA; the FE method was used only as a postprocessor to the hydrodynamic code. The results of this study were not verified against other results.

### 5.3 Approximate Methods

A very simple prediction method for bow flare slamming and green water loads on deck and on the superstructure was developed by Stansberg *et al.* (2009). The method uses the relative motions at the bow as computed by linear theory but enhanced with a non-linear corrections. Green water on deck is calculated by a simple formula for dam-breaking by Stoker (1957). Impact pressures are calculated with a simple formula using a slamming coefficient and the dynamic pressure. The method is intended to predict the maximum impact pressures in the early design stage; it is acknowledged that simplicity was achieved at the cost of accuracy. For more accurate predictions Stansberg advises to use CFD methods like a VoF method.

### 5.4 Experimental Methods

Experiments for green water events are still being carried out today. The objective of such experiments can either be to determine extreme loads or it can be for the validation of computer programs. Although it is realized that also scaled experiments violate scaling laws with respect to the effect of air entrapment, it is still today the best – if not the only – method to arrive at a statistical distribution of extreme loads. However, most experiments in the open literature are done on simplified models or on

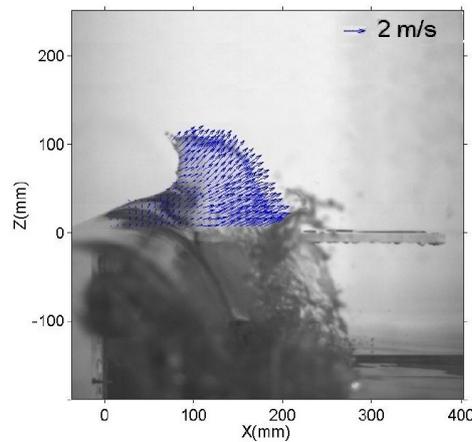


Figure 14: Flow velocities during an impact measured by Bubble Imaging Velocimetry (BIV) (Ariyaratne, 2009)

full blocked ships at zero speed (like a FPSO) using simplified wave conditions like regular waves or a focused wave to generate one single extreme event.

Rather fundamental experiments were carried out by Ryu *et al.* (2007). The experiment was carried out in a wave flume where a focused wave overtopped a fixed structure. The velocities in the fluid were measured using Bubble Imaging Velocimetry (BIV) as developed by Ryu *et al.* (2005). This technique is comparable to PIV, but instead of introducing particles in the flow the velocity of air bubbles is measured. The measurement plane is not illuminated by a laser sheet, this would lead to avoid scattering, but illuminated from the opposing side as the cameras. This method creates sufficient contrast to allow tracking of the bubbles. The results of the experiments appeared to correlate surprisingly well to the analytical dam break model by Ritter (1892) if or the initial water depth or the front velocity of the analytical model is properly tuned.

The objective of the experiments carried out by Ariyaratne *et al.* (2009) was to serve as validation material for numerical codes. They used a simplified wedge-shaped model of an FPSO, rigidly connected to the bottom of the basin. An extreme event was created using a wave focusing technique, flow velocities during the impact were measured in great detail using BIV, Figure 14. The instrumentation is described in detail, but, since the incoming wave is not presented in the paper, the results cannot be used by other researchers. Essentially the same results are again published in Chang *et al.* (2011); in this case also the measurement of the void fraction in the flow by a Fiber Optic Reflectometer (FOR) is mentioned; the void fraction is used to correct the pressure.

Experiments carried out by Tanizawa (2004) were used by Shibata, Koshizuka and Tanizawa (2009) for the validation of a particle method. The experiments were carried out with a towed model of a VLCC in regular waves; the pressure on deck was measured with 5 pressure gauges.

Also the work presented by Lee *et al.* (2010) is intended as validation material for numerical codes. They carried out systematic experiments on a barge type FPSO. They used a model, which was fixed in the basin, with a vertical blunt bow, an inclined blunt bow and a rounded bow to measure in detail the pressures on deck. The wave conditions used in the experiments were not realistic sea states, but regular

were. The intention was to have as simple as possible inflow conditions to facilitate CFD validation studies. A second advantage of using regular waves is, that – after the transient period – this constitutes essentially repeat tests. This allowed Lee *et al.* to carry out an uncertainty analysis.

Model tests on an FPSO in shallow water in wind, waves and current were mentioned by Guo *et al.* (2010). They used these data for validation of their CFD calculations, but since details of the experiments were not given, these results cannot be used by other researchers.

## 6 UNDERWATER EXPLOSIONS

### 6.1 General

Underwater explosions can cause significant damage to structures such as ship hulls. Considerable effort has been spent on understanding the physics behind these explosions so that precautions can be made to avoid critical damage. Many underwater explosion (UNDEX) studies were done with numerical simulation in addition to the experiments.

### 6.2 Numerical Procedure for Evaluating Deformation and Rupture under Explosion

There are three ways in which information may be exchanged between the fluid and structural solvers, as shown in Figure 15. The first is to transfer only pressure load at the structural interface from CFD solver to FE solver for structure. This one-way coupling is used when loading from the fluid domain is desired but the response of the structure has little influence on the load calculation. This procedure is useful for estimating the loads on a rigid body.

The second option transfers the fluid loading to the FEA solver and structural node velocities are transferred back to CFD solver. This option may be used for small deformation scenarios where the structural displacement has little influence on the fluid domain but the velocity of the structure changes the resulting pressure loading and by the response of the structure. This procedure may be used for estimating the cavitation of water. Cavitation effects play an important role in the UNDEX loading of

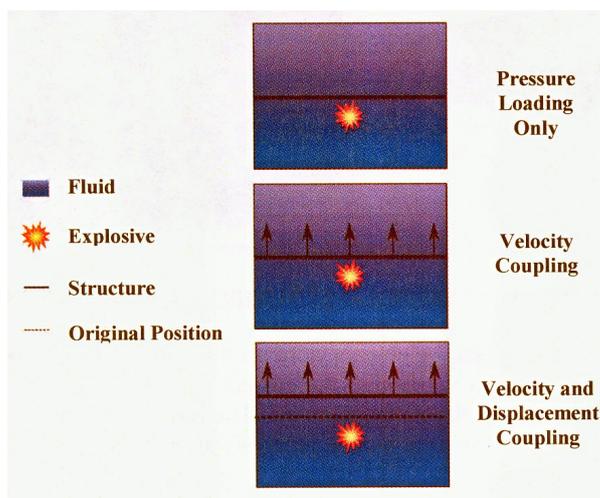


Figure 15: Three kinds of FSI coupling procedure

a structure. For far-field UNDEX, the structural loading is affected by the formation of local and bulk cavitation regions, and the pressure pulses resulting from the closure of the cavitation regions. A common approach to numerically modelling cavitation in far-field underwater explosions is Cavitating Acoustic Finite Elements (CAFE) and more recently Cavitating Acoustic Spectral Elements (CASE). Treatment of cavitation in this manner causes spurious pressure oscillations which must be treated by a numerical damping scheme. The third loading option is the same as the second option with the addition of the structure position being updated in the fluid domain. This option may be used for large deformation problems, where the structure moves over a large region of the fluid.

Using the DYSMAS code Wardlaw (2009) investigated computationally the detonation of a submerged charge beneath the plate suspended over a water surface. Simulations were conducted for a range of plate stand-offs and charge depths and validated against laboratory scale experiments. The results showed that the loading is dominated by water ejected upwards by the detonation for the case of a submerged charge and a plate suspended above the water. And, the shock produces pressures much larger than those associated with a plume strike for the case of either the plate or charge being on the surface. Aanhold *et al.* (2009) simulated a heavy underwater shock trial on the floating cylinder by three dimensional calculation. The calculations were done using the so-called Simplified Interaction Tool (SIT), an approximate interaction method developed by TNO as an add-on to LS-DYNA. The SIT is a very efficient tool for estimating the underwater shock response of complex 3D models of surface ships, because the water around the ship is not modelled by means of finite elements. Only added mass effects are considered in FEA. The results showed a good agreement of vertical motions with experimental results.

Lee *et al.* (2009) investigated the underwater explosive loading and failure of thin steel plates for close-proximity charges. The shock and bubble jet loading was measured, and a distinction was made between failure caused by shock alone, and failure caused by the cumulative loading from the shock and impinging bubble jet. They showed that the failure standoff limit increases as the plate thickness decreases. For 350WT steel the failure standoff limit increases as compared to A1008 mild steel because of smaller failure strain. These trends are correctly reproduced by a simple FEA model, but the standoff limit does not show good agreement.

Riley *et al.* (2009) conducted the experiments on rigidly-clamped circular and square air-backed steel plates, in which underwater explosive charges were placed at varying standoffs including contact. They performed the FE analyses with LS-DYNA using two different failure criteria based on a combination of normalized transverse shear stress and direct strain. They concluded that the LIC failure criterion predicts the onset of failure in a more realistic manner than the QIC.

$$LIC = |\varepsilon_e / \varepsilon_{rup}| + |\tau_e / \tau_{dult}| \quad (1)$$

were  $\varepsilon_e$  is the true element membrane strain,  $\varepsilon_{rup}$  is the true rupture strain,  $\tau_e$  is the maximum of the through thickness shear stresses in the element, and  $\tau_{dult}$  is the dynamic ultimate shear strength.

Riley *et al.* (2010, 2011) performed an extensive numerical modelling study using the Eulerian computational fluid dynamics (CFD) code Chinook, in standalone mode and coupled with the Lagrangian solver LS-DYNA, to investigate the prediction accuracy of the loading on rigid plates and displacement of flexible target plates subjected

to close proximity underwater explosion events. For the rigid targets, qualitatively Chinook was found to accurately reproduce the general trends in the experimental measurements. Quantitative gaps still remain in the load levels predicted. A major issue with Chinook is the lack of a material interface tracker which would allow for the distinction between the gas bubble and the surrounding water. For the flexible targets, the numerical simulation displacement time histories were compared to experimentally measured responses. They showed that Chinook impulse predictions were closer to the experimental results for the shock loading than the bubble collapses. They also showed that the three-dimensional models with a coarser fluid mesh give better agreement with experiments than more finely meshed two-dimensional models.

Dunbar *et al.* (2010) also investigated numerically to simulate a series of underwater explosions with the intent of estimating the critical standoff range at which the onset of rupture occurs by using CFD code Chinook and FE solver LS-DYNA. They showed that both the peak structural displacement and maximum bubble radius compare well with the experimental and empirical based solutions. And the peak shock pressures were improved by mapping from a detailed 2D model to a 3D model. However, this improvement did not significantly change the overall displacement, indicating that the response is possibly impulse dominated.

Stojko *et al.* (2010, 2011) examined the LS-DYNA/USA Fluid Structure Interaction (FSI) acoustic underwater shock methods, namely the Doubly Asymptotic Approximation (DAA), Cavitating Acoustic Finite Element (CAFE), and Cavitating Acoustic Spectral Element (CASE). A number of verification problems have been analysed and were compared with 'exact' solutions. The general strengths, limitations and suitability of the three methods were discussed. They also compared the calculation result of the bubble pressure, frequency, and radius with experimental results. For the bubble frequency, and radius and pressure trend versus depth the calculation results showed a good agreement with experiments, but did not show the quantitative matching of pressure.

Helte *et al.* (2011) performed small scale experiments to investigate the behavior of a flexible circular plate subjected to a close proximity underwater explosion. The most prominent effects are shock loading, target induced cavitation, loading from cavitation closure and bubble collapse. They also performed the calculation using the in-house 2D multi-material arbitrary Lagrangian-Eulerian hydro code GRALE2D. The performance and sensitivity of the parameters in the fluid-structure coupling, such as a penalty based method, and the cavitation modelling, a simple cut-off model, were of particular interest. Good agreement between experiments and simulations was obtained. But, the bubble collapse times in the simulations were too short in all cases. This could be an indication that the bubble energy in the simulation was wrong. However, the predicted response of the target from the bubble collapse was higher than the measured, contradicting the hypothesis of too low bubble energy.

Klenow *et al.* (2010) focused on investigating the severity of bubble oscillations on the structural response and a possible improvement to CAFE, based on the original Boris and Book Flux-Corrected Transport algorithm on structured meshes, to limit oscillations without the energy loss associated with the current damping schemes. By comparing CAFE, CASE, and the FE-FCT algorithm in the two-degree of freedom mass-spring oscillator problem, they showed the FE-FCT algorithm, which uses linear finite elements on structured meshes, used with residual diffusion and a one-sided flux limiter, is effective in reducing the larger oscillations associated with the CASE method while maintaining the increased accuracy.

Xie *et al.* (2008) developed further MGFM (Modified ghost fluid method) in order to increase the quality of results when simulating a close-in explosion in a deformable filled cylinder. Initial MGFM method was not very robust for this type of simulation because the FSI (Fluid-structure interaction) technique in this method didn't perform well under cavitation reload and solid tension wave i.e, the convergence was very slow and negative interface pressure appeared during the simulations. They proposed to solve the FSI explicitly rather than implicitly to avoid convergence problems and rewrote equations at the FSI zone without using tension stresses inside the solid in order to avoid negative pressures. Shin *et al.* (2011) investigated the applicability of numerical calculation using LS-DYNA ALE code for estimating shockwave motion of gas bubble generated by high explosive. They confirmed that the shockwave pressure was underestimated when the large number of element is not used. For the size of bubble and the time of expansion, the calculation results showed good correlation to the empirical formula. They also investigated the effect of ship speed on the dynamic response of high speed Mono-hull, catamaran, and trimaran in underwater explosion. They showed the possibility of calculation for hull rupture under explosion.

For the structural integrity assessment of pipelines subjected to underwater explosions, Monti *et al.* (2011) proposed an engineering approach, taking into account of loading due to the shock wave and gas bubble pulsation. Analytical and numerical approaches using ABAQUS/Explicit concerning the assessment of the structural response of the pipeline were presented, and criteria for Serviceability and Accidental Limit States were proposed.

### **6.3 Application of Composite Structure for Reducing Damage**

Recently, there has been an increased interest in the application of composite structures in the marine industry to take advantage their high stiffness to weight and strength to weight ratios, and high impact/shock resistance characteristics.

Dunbar *et al.* (2009) investigated the polymer coating effect of plate on the deformation under explosive loading. To examine this numerically, they adopted the FSI approach using Chinook, Martec's CFD solver, with LS-DYNA, FE solver. Solid elements are desired for simulations where the through-thickness properties and resolution of layered materials, like the polymer coating plate, are required. But, this FSI approach was implemented for only structural shell elements. Then, for coupling to fluid domain, the shell elements with a null material are paved on the solid elements. Using this procedure for modelling, they investigated the effect of the polymer coating on the deformation under explosive loading and confirmed that the maximum plastic strain was reduced by as much as 45 % for the thin plate model investigated by adding the polymer coating to the plate.

Xie *et al.* (2009) showed a 2D numerical case study for the transient analysis of an air-backed three-layered sandwich beam with clamped ends subject to a close-in underwater explosion, and the results were compared with a similar case with a rigid structure. They showed that structural deformation and transfer of energy lead to a reduced pressure shock and the initial shock is mostly resisted by the bottom steel face, and later followed by compression (plastic yielding) of the soft foam core. The energy absorption and dissipation provided by the soft core layer helped to protect the rear steel face, which showed negligible deflections and stresses that are one to two orders of magnitude lower than the front steel face.

Liu *et al.* (2010) investigated the influence of interfacial bonding on the transient response of sandwich plates subject to underwater explosions. They found that un-

bonded sandwich plates receive lower impact energy, and are able to dissipate more energy through plastic deformation of the foam core than perfectly bonded plates. Consequently, interfacial de-bonding leads to lower net energy transfer from the explosion to the target structure although it also increases the structural deformation due to stiffness reduction. Parametric studies showed that the advantage (diminishing of net energy transfer) is more significant than the disadvantage (magnification of the interface deflection). Thus, interfacial de-bonding through active/passive mechanisms may be beneficial for blast-resistant designs.

#### **6.4 Mounting of Equipments**

In naval ships, some methods or devices are acquired both to cut off the transmission of vibration from shipboard machineries and to protect them from external shock loading. One of the approaches is to install the passive mountings between machinery and a flexible supporting structure. More advanced performance has become necessary recently so far as at high frequencies in order to retain the stealth function of certain types of naval vessels.

Czban *et al.* (2009) compared the shock test severity of the Mil-S-901 lightweight machine with the drop tests outlined by the newly proposed ANSI National Standard for equipment in a Rugged Shock Environment. The resilient mounting system in the drop test series (ANSI) bottomed out, while it did not during the Mil-S-901 tests. It is concluded that while the drop test shock environment may not be representative of underwater explosions.

Moon *et al.* (2010) developed a new hybrid mount for shipboard machinery installed on naval ships. The mount is combined with a rubber mount and piezo-stack actuators. The rubber mount is one of the most popular and effective passive mounts to have been applied to various vibration systems to date. The piezo-stack actuator is featured by a fast response time, small displacement and low power consumption. Through a series of experimental tests conducted in accordance with MIL-M-17185A (SHIPS), MIL-M-17508F(SH), and MIL-S-901D which are US military specifications related to the performance requirements of the mount, it has been confirmed that the hybrid mount shows more effective performance for use in naval ships.

### **7 DAMAGE TO STRUCTURES**

#### **7.1 General**

Impulsive pressure loading induces different kind of damage on floating structures. Great pressure impulses may cause local plastic deformation on the loaded region but may also cause global damages in the midship section of a ship structure. Intermediate pressure pulses which occur several times may gradually cause large deformations or cause low cycle fatigue damages. Low pressure pulses with a high number of cycles may cause fatigue damages in structural details.

Generally the different types of loading may cause different kind of damages. In this chapter, the relevant literature regarding the permanent deflection as well as fatigue damages caused by impulsive pressure loadings has been reviewed. The chapter is divided in section corresponding to the loading types discussed in recent literature.

#### **7.2 Slamming and Whipping**

In January 2007 the Post-Panamax container vessel MSC Napoli was severely damaged in the English Channel. The vessel encountered a severe storm that overloaded the

structure resulting in the collapse of the hull girder just aft of the forward engine room bulkhead. It was concluded by DNV that the vessel did not have the necessary buckling strength margin. It also was stated that whipping could have contributed to the dynamic loading. Many Researchers concentrated on this item trying to find relationships between whipping and damages on ships. One result from the last ISSC-V7 committee work in 2009 was that the contribution from vibratory response doubles the fatigue damage induced by wave-frequency loads for bulk and container carriers.

Miao and Temarel (2009) analyzed the influence of whipping-induced loads on the structural strength of a container ship focusing on the investigation carried out on the failure of the MSC Napoli. Based on two-dimensional symmetric hydroelasticity analysis and relevant structural, hydrostatic and operational data, calculations were carried out in head regular and long-crested irregular waves. The investigation showed that whipping, due to bottom slamming, is only important for severe seas. The investigation also showed that the keel stresses, in way of the engine room, can be as large as the keel stresses at amidships. Storhaug (2009) published measurements from a 4400 *TEU* vessel similar to MSC Napoli in full scale and model tests. These measurements showed that whipping can increase the dynamic loading in similar sea states as MSC Napoli encountered. The measurements also illustrate that it is difficult to state exactly the amount of whipping in a specific sea state.

Experimental model investigations carried out by DNV, BV, HHI, CeSOS and Marintek for a 13000 *TEU* Container Vessel were presented by Storhaug *et al.* (2010a). In a similar project DNV, HHI, CeSOS and Marintek investigated the effect of springing and whipping on a 8600 *TEU* Container Vessel (Storhaug *et al.*, 2010b). The results show that wave induced vibrations can be of considerable magnitude relative to the conventional wave fatigue damage for the different trades. For the East Asia to Europe trade a fraction of 65 % of the total fatigue damage was related to wave induced vibrations. In this regard, whipping was considered far more important than springing. Dessi and Ciappi (2010) experimentally investigated the relation of slamming excitation and whipping response on a fast ferry sailing up to 40 knots at full scale and a cruise ship.

However, laboratory tests may not fully reproduce the critical conditions that may occur in reality (Gaidai *et al.*, 2010), e.g. model tests are mainly carried out in head seas. Measurements on real vessels in operation in harsh weather provide unique insight into the phenomena involved in the structural response to impulsive pressure loading. Mathisen *et al.* (2009) analyzed measurements from hull-monitoring systems on bulk carriers and container vessels to investigate the effects of wave-induced vibrations on fatigue damage. The results show a significant contribution to the total stress from the vibratory component under the harshest conditions that were available. The relative magnitude of the vibration stresses indicates that hull girder vibrations may need to be taken into account in the prediction of the extreme stresses in container ships.

Heggelund *et al.* (2010) presented the assessment of data measured on an LNG carrier during a period of about twelve months. It was found that the vessel has been in operation less than half the time during the actual period. The fatigue rate is found to be lower than predicted by component stochastic fatigue analysis and that the fatigue life is expected to be longer than the design life. Further, the contribution from vibration is found to be large (30 – 50 % of the total damage). The highest fatigue damage is obtained in rough seas and in the full load condition. It is found that most fatigue damage is accumulated in head or following seas.

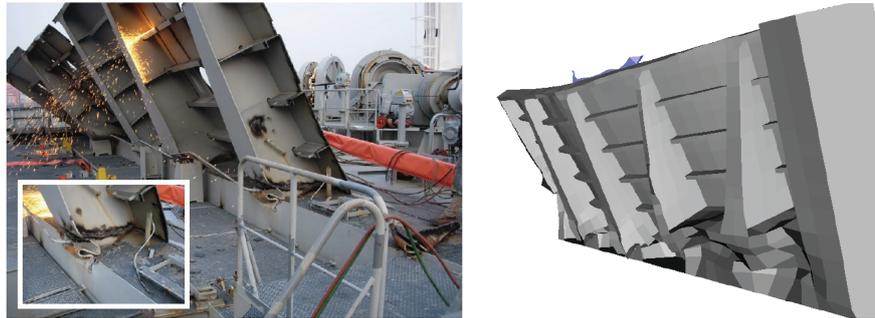


Figure 16: Comparison of actual collapsed breakwater (left) with numerically predicted one (right) (Heo *et al.*, 2010)

### 7.3 Green Water

The structural damages due to green water are mainly related to large deformations of local structures. Adegeest *et al.* (2009) studied the causes for severe breakwater damage of a Container Vessel crossing the North Atlantic in heavy weather. The particular interest was to identify possible measures to avoid failures in the future. The analysis involved linear and nonlinear sea keeping theory and a green water load calculation by adopting a 2D slamming theory developed for wedges. In general, good accordance with rules was found concerning calculated water pressures. Furthermore, the FEM calculations confirmed the experienced failure of the breakwater when subjected to the calculated pressures. Several studies of breakwater constructions and possible configurations were carried out.

Heo *et al.* (2010) proposed new design formulae that may be used to evaluate the structural performance of breakwaters installed on container vessels under green water impact loads. A series of numerical analyses for green water impact loads inducing post-buckling and breakwater collapse have been carried out. A verification study of the numerical results was performed using the actual collapse incidents of breakwaters on container carriers (Figure 16).

### 7.4 Underwater Explosion

Underwater explosion damage to steel panels has been studied extensively in the past. Recently interest on in-port vessels has prompted detailed research into structural damage from close-proximity underwater charges. Lee *et al.* (2009) investigated the detailed damage mechanisms caused by explosions of close-proximity underwater charges to thin target plates. The main loading on the plate was due the shock. However, because the standoff distances were less than twice the maximum bubble radius, a strong interaction between the detonation product bubble and the target plate caused a rapid water jet to impinge on the plate and cause additional loading and damage. As a result, four main regimes of loading and damage were identified: a) holing/petaling due to shock loading, b) edge tearing due to shock loading only, c) edge tearing due to the cumulative loading from shock and bubble collapse, and d) large deformation due to shock and bubble collapse loading.

In their study Lee *et al.* (2009) also performed finite-element analysis to investigate the detailed response and failure of the plates. Finite-element analysis showed good agreement with the experimental dynamic displacement due to shock loading. Plate slippage at the clamped boundary was found to influence the results significantly.

Riley *et al.* (2009) investigated the transition between the first failure mode (holing and petaling) and second of these failure modes (complete or partial edge tearing due to shock only). At less than 0.1 times the bubble radius holing, edge failure due to shock, and large plastic displacements without rupture were all observed in plate specimens. Explicit finite-element analysis with LS-DYNA was used to investigate the detailed response and failure of the plates. In the FE simulations the influence of different approaches including shell and solid elements for the plate, different failure criteria based on a normal strain, shear strain, or a combination of normalized transverse shear stress and direct strain. Finite-element analysis shows good agreement with the failure mode as well as with the post test deformations.

Yiannakopoulos *et al.* (2009) presented results from an exploratory study of the penetration of an aluminium target plate by a close-in underwater explosion. Two identical target plates were subjected to different levels of explosive load such that one was perforated whilst the other suffered only plastic deformation. High speed imaging and measurements of underwater pressure for these two events were used to probe the conditions leading to plate fracture. The data was compared with results from a LS-DYNA3D FE model to investigate the potential of current material models to capture this behaviour.

## 8 COMPARISON OF CLASSIFICATION SOCIETIES RULES

### 8.1 General

Traditionally, Classification Societies have made the safe requirement for the impulsive response based on a state of the art theory and many experiences. However, different procedures based for the requirement have been developed according to the damage data due to the impulsive loads which each Classification Society has collected from its classed ships. Recently, IACS (International Association of Classification Societies) has implemented CSR (Common Structure Rules) for Tankers and Bulk carriers since the 1st April in 2006. Therefore, tankers and bulk carriers classed to an IACS member constructed with the same scantlings due to the impulsive loads.

In order to investigate the different requirements from Classification Societies Rules for impulsive response like slamming loads, comparative calculations have been performed for a container ship.

The principle particulars of the container vessel are given as follows;

- Ship Type: 4,600 *TEU*
- LBP: 240.5 *m*
- Breadth (Mld.): 37.50 *m*
- Draft (Scantling; Mld.) : 13.0 *m*
- Block Coefficient: 0.646
- Design Speed: 21.4 knots

### 8.2 Plate Thickness and Stiffener Section Modulus Required by Bottom Slamming Pressure

The required plate thickness and stiffener section modulus due to the bottom slamming at the following draft condition, which is assumed to be one of the worst loading conditions vulnerable to the bottom slamming for the container ship, have been calculated according to four different Classification Societies requirement.

- Draft at A.P.: 8.967 *m*
- Draft at F.P.: 4.517 *m*

The calculation results are presented in Figures 17 and 18.

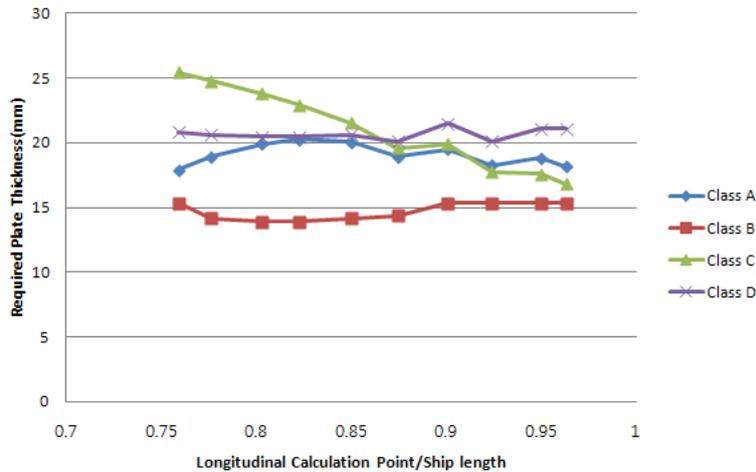


Figure 17: Required thickness of the bottom plates at centre line by the bottom slamming pressure

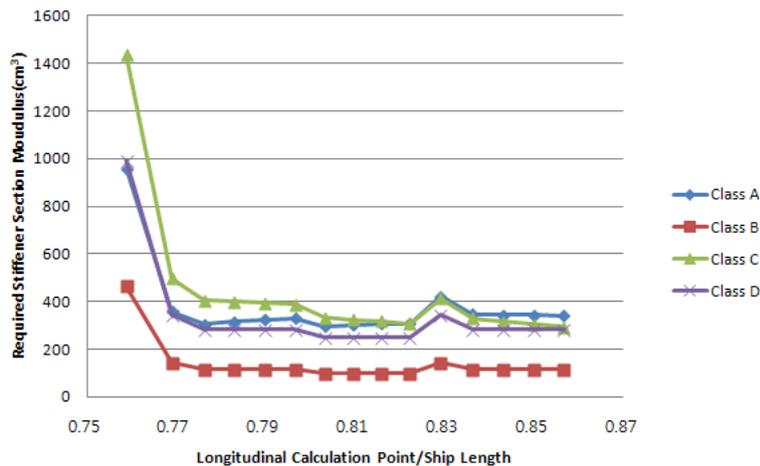


Figure 18: Required section modulus of the stiffeners at centre line by the bottom slamming pressure

### 8.3 Plate Thickness and Stiffener Section Modulus Required by Bow Flare Slamming Pressure

The required plate thickness and stiffener section modulus due to the bow slamming at a section of longitudinal position/ship length = 0.9 with the scantling draft (13 m) have been calculated according to three or four different Classification Societies requirements. The calculation results are plotted in Figures 19 and 20.

## 9 RECOMMENDATIONS FOR STRUCTURAL DESIGN GUIDANCE

### 9.1 General

The extreme difficulties related to the proper modelling of impulsive pressure loadings and the associated structural responses clearly appear throughout all the chapters in

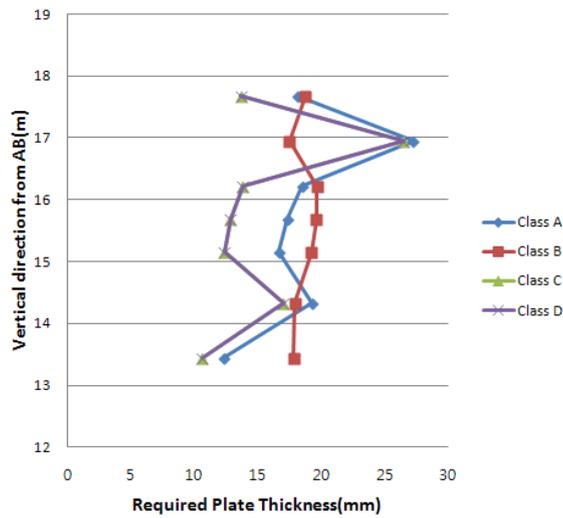


Figure 19: Required thickness of the shell plates at a section of longitudinal position/ship length = 0.9 by the bow flare slamming pressure

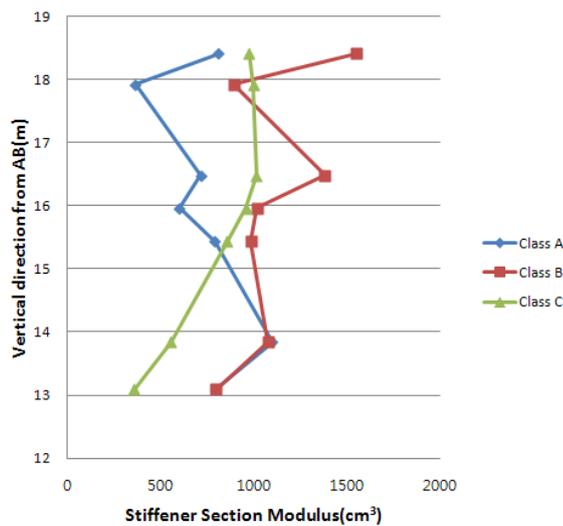


Figure 20: Required section modulus of the stiffeners at a section of longitudinal position/ship length = 0.9 by the bow flare slamming pressure

this report. This is probably one of the most difficult aspects of the hydro structure interactions in ship design. Indeed a very complex hydrodynamic flow needs to be coupled with the evaluation of the structural response. Whether this coupling should be weak or strong mainly depends on the ratio of the impulse duration relative to the natural period of the impacted structure.

In an attempt to improve the quality of the marine structural design against impulsive pressure loadings, some recommendations are provided herein based upon the reviews and investigations performed by the committee.

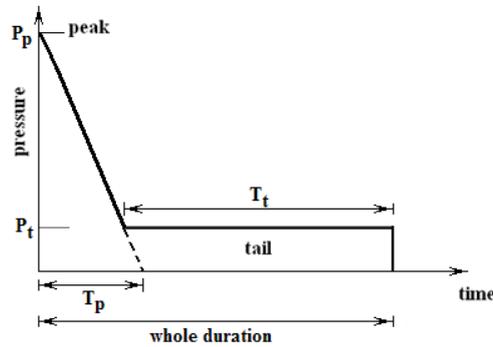


Figure 21: Idealised impulsive pressure history (Cho *et al.*, 2011)

### 9.2 Impulse Shape of Local Slamming Load for Design

For practical impact response and residual deformation analyses of local slamming loads it seems desirable to simplify the impulse shape. Some of the recently investigated results are summarised below.

*Effects of tail part;* When the peak duration,  $T_p$  is shorter than a half of the natural period ( $T_n$ ) of a impacted plate, the effect of the tail part on the extents of damage can be 8.2% at most. However, when the peak duration,  $T_p$  is the twice of  $T_n$ , the extents of damage can be a constant value regardless of the tail part duration. Therefore, the effects of tail part on the extent of damage can be negligible because it is known that the actual duration of the peak part of impulse due to slamming can be greater than the natural period of the impacted plate.

*Effects of peak part shapes;* For triangular impulses, if peak duration is shorter than a half of  $T_n$ , the damage extents are almost the same. However, when peak duration is longer than  $T_n$ , the monotonically decreasing impulse shows greater residual deformation than the other types of triangular impulse. When the impulse duration,  $T_p$  is shorter than  $T_n$  the isosceles type impulse gives the greatest deflections. However, when  $T_p$  is longer than  $T_n$ , the monotonically decreasing impulse yields the greatest deflections. According to published studies, it can be concluded that the rising time

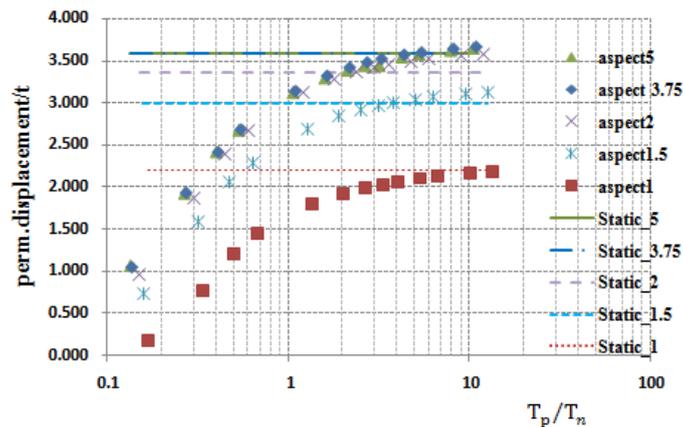


Figure 22: Effects of aspect ratio of unstiffened plates subjected to monotonically decreasing triangular impulse (Cho *et al.*, 2011)

of impulsive pressure loadings due to slamming can be neglected from the structural design view point.

Therefore, from a structural design view point, the impulsive pressure loadings induced by local slamming can be approximated by monotonically decreasing triangular impulses.

### ***9.3 Effect of Aspect Ratio of Impacted Plates on the Damage Extent***

As be seen in Figure 22, the extents of damage are increased according to the aspect ratio values. However, when the aspect ratios are greater than 2.0 the predicted damage extents are nearly identical regardless of aspect ratio values. In the figure, the extents of damage due to the static pressure are also depicted. When the aspect ratio is 1.0 the dynamic responses approach to that of static. However, when the aspect ratios are greater than 1.5 the converged extents of damage are greater than those of static.

### ***9.4 Global Slamming***

In the structural design of a slim high-speed ship, the local slamming loads and the springing effects of ship hull girder should be properly considered. Furthermore, slamming may induce whipping moment and the effects of which on the fatigue strength of the structure should be considered, especially of the bottom structures and the hatch corners. For the ships such as container ship and destroyer etc., the angle of the bow flare should be optimized to reduce the flare slamming. For ships with large openings, the torsion vibration effect induced by the slamming when the ship sailing in oblique wave should be studied.

### ***9.5 Sloshing***

The evaluation of the structural response of the CCS and the associated ship-structure in the LNG tanks is an extremely complex problem and the actual state of the art does not allow for rational direct calculation numerical approach. For that reason one has still to rely on experiments which means in practice model tests. The challenges are how to scale the model test results to full scale and properly account for the structural elastic reactions due to the fact that a rigid model is used in model scale. There are many contributing factors to scaling which have to be considered and one has to do important approximations. The small scale model tests are used in the context of the so called comparative approach where the scaling issues are hidden within the semi empirical considerations. Formally, the classification societies also accept validated direct numerical approaches. However, it still seems not to be a good candidate to perform these calculations, in spite of significant advances in numerical modelling which were achieved in the last few years.

### ***9.6 Green water***

Recent studies show that a considerable effort is being spent on applying CFD codes to the problem of green water and wave impacts on the superstructure. The main focus is on the zero-speed head seas case before sufficient confidence is built to approach the problem of a ship at speed in quartering waves. There is not yet a clear preference for any particular method, good results are also obtained with commercial codes. It seems very well possible to determine the general behaviour of the flow over the deck and also the pressure on the horizontal deck is well predicted by different researchers. This is not the case for the pressure on a vertical bulkhead. It is however not generally realized that such an impact is a rather chaotic event were small details of even air inclusions

can have a large effect. Consequently there are large spatial variations of the pressure and results can only be compared in a statistical manner. Another consequence is, that a twophase simulation modelling both water and air seems to be required for these types of impacts. The importance of turbulence of the green water problem is not fully investigated and studies using different turbulence models are welcomed.

### **9.7 Effects of Multiple Impacts**

As mentioned in the last ISSC report (Cho, *et al.*, 2009) the plastic deformation of shell plates as a consequence of multiple impulsive pressure loadings may be significant. According to numerical and experimental investigation results the effects of the repetition of the impulsive pressure cannot be neglected in the structural design against impulsive pressure loading.

One of the open questions is which material model, especially the strain hardening model, is most suitable for modelling the deflections due to multiple impact loadings. While for a single impact it is quite irrelevant if kinematic or isotropic hardening is used as basis, for multiple loadings these hardening models follow different hysteretic curves resulting in a different permanent deflection.

### **9.8 Classification Societies Rules**

Recently various investigations and research have been conducted to improve the accuracy of predictions and efficiency and stability of related calculations in the area of the impulsive loading including slamming. According to the state-of-the-art technology, innovations of the relevant classification society rules are progressing.

## **10 CONCLUSIONS**

### **10.1 Local Slamming**

Model or full-scale tests are still the most reliable approach in obtaining the pressure distribution and force on temporal and spatial scales, especially in disturbed water. Analytical approaches have been developed to a high degree of accuracy when predicting the impulsive slamming pressures in calm water for most dead-rise angles of the body with simple profiles.

Numerical simulations of slamming pressures have been, to a great extent, developed with acceptable accuracy and efficiency. Commercial or in-house software based on the CFD technique have attracted more attention in recent years and is an encouraging prospect. Due to the complexity of the slamming phenomenon, practical methods to obtain rational design pressures, forces and structural dynamic responses for a new design is still required.

### **10.2 Global Slamming**

Due to the 3D characteristics of the bow flare, the direct adoption of any 2D methods will induce some error. This is of particular concern for ship sections with a relative roll angle during the impact. The 3D character of the bow and bulb of container ships is particularly challenging to model.

While FE methods provide excellent tools for modelling the structural behaviour, the main challenge in estimating global slamming response is the calculation of the slamming force, especially in oblique seas due to the effects of rolling motion. However, the full FE models of complex ship structures are still quite computationally demanding and combined use of simple models and refined models in a hierarchical approach is useful.

The high frequency fatigue damage due to whipping can be significantly reduced by including the steady wave for the relevant vessel, implying better correlation with the experimental results. Therefore, more work needs to be done to improve the high frequency stress modelling. This includes amongst others, identifying and quantifying the sources of damping of the vibration as well as verification of the excitation sources of high frequency response.

### 10.3 *Sloshing*

Correct numerical modelling of hydro-structure interactions during the sloshing impacts inside the LNG tanks is still beyond the state of the art and there is still no rational direct calculation procedure to be used for design verification of the CCS. It is however important to mention that the different research projects which were undertaken during the last years have brought much more light into the physics of the sloshing impacts and important progress was made in the modelling of sloshing impacts both experimentally and numerically.

The full scale measurements and monitoring of the real LNG ships would be extremely helpful for better understanding of the way how the CCS is “suffering” in reality. Indeed, with respect to all the difficulties discussed above, it appears clearly that more feedback from experience is necessary in order to get more confidence into the existing design procedures. How to perform these full scale measurements is another complex question.

In any case, the actual situation is that, for the design verification of CCS, we still rely on the so called comparative approach. It is however important to mention that, in spite of all the imperfections of the comparative approach, the overall safety record of LNG floating units is excellent and only few incidents were experienced (Gavory *et al.*, 2009).

### 10.4 *Green Water*

In general, a good CFD calculation includes a verification study. Such studies where different densities of the grid are being used, different time steps and convergence levels are tested are very labour and time intensive. Presently these studies are carried out for stationary problems; of course the effort required for the stationary problem is much larger, but the work is necessary to demonstrate that the numerical schematization of the problem has converged. Only one of the reviewed papers included results for two grids.

Also experimental studies suffer from the rather chaotic event of a wave impact against a vertical wall. In order to get information on the accuracy of the experiments, repeat tests are required. In the ideal world, a comparison of a numerical result to results from experiments should include confidence intervals for both data based on the numerical verification study and the repeat tests in the experiments.

There appears to be a surprising lack of interest for the statistical distribution of extreme pressures or loads in the period covered by this review. Using a design wave technique for the ultimate (impulsive) load presumes knowledge about the critical parameters for wave impacts; this is as yet unproven. It is however clear that a long-term distribution cannot be predicted by CFD methods, for the next years we have to rely on experimental techniques.

### 10.5 *Underwater Explosions*

Traditionally, underwater explosions have been treated separately as shock wave problems and gas bubble ones due to the big differences of their time scales. However, for

close proximity underwater explosions the shock wave and bubble effect can be coupled. Even with today's powerful computational techniques it is not possible to obtain meaningful numerical results. Practical design-oriented procedures, therefore, need to be developed for more advanced structural design especially of naval vessels.

### 10.6 *Damage to Structures*

Various structural damages due to impulsive pressure loadings have recently been reported and reviewed herein. Some of the damages can be categorised as the accidental limit state but some can be the serviceability limit state. Design loads specified in relevant rules and regulations need to be reevaluated and the adequacy of the design processes assuming equivalent static pressures have to be reassessed based on the fail safe design concept.

### 10.7 *Comparison of Classification Societies Rules*

In order to investigate the requirements of several Classification Societies rules for the slamming pressure acting on the hull structure, comparative calculations have been performed for a 4,600 teu class container carrier. The required plate thicknesses and stiffener section modulus due to the bottom slamming pressure and the bow flare slamming pressure acting on the hull structure of the container ship are compared in accordance with the several Classification Societies rules. A little difference among the classification societies can be found in the requirements by the slamming pressure. The difference seems to be due to different damage data by the slamming loads which each Classification Society has collected from its classed ships.

### 10.8 *Recommendations for Structural Design Guidance*

Based upon the recent progresses regarding the predictions of impulsive pressure loadings and structural responses reviewed in this report, recommendations for structural design guidance are provided. However, for the betterment of the marine structural design against impulsive pressure loads collaborations between related organisations including classification societies are required.

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