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18$^{\text{th}}$ INTERNATIONAL SHIP AND
OFFSHORE STRUCTURES CONGRESS

09-13 SEPTEMBER 2012
ROSTOCK, GERMANY

VOLUME 3

COMMITTEE V.7

IMPULSIVE 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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1 DISCUSSION

1.1 Official Discussion by Odd M. Faltinsen

1.1.1 Introduction

The committee has given a broad review on the subject and I agree with many of their statements. A more specialised but challenging problem which is not mentioned in the report is launching of free-fall lifeboats from offshore platforms which has created attention in Norway due to the economic consequences of operational limits. Safe launching must be possible in as high sea states as possible. The concern is slamming loads as well as acceptable accelerations for the passengers. The design constraints of the lifeboat are, for instance, sufficient volume for the passengers, small weight and good propulsion.

The committee's introductory description of the effect of impulsive pressure on ship structural response is an important message which historically has not always been realised. One must not focus on the impact pressures when the high pressures have a short duration relative to structural natural periods of modes that give dominant contributions to large structural stresses. A good illustration of this fact is the theoretical analysis of vertical drop tests of horizontal aluminium and steel plates on waves and calm water reported by Faltinsen (1997) that was compared with the experiments by Aarsnes (1994) (see also Faltinsen *et al.* 1997). The bending stiffness of the plates was Froude scaled in the model tests to give representative values of the lowest natural structural frequency. For a given drop velocity the maximum pressure showed very large variations for different tests with varying wave conditions including calm water. The maximum pressure varied from below 10 to nearly 80 bar for the largest tested drop velocity of about 6 m/s and was probably influenced by the presence of air cavities and acoustic waves. If the size of the pressure gauges had been even smaller, even higher pressures may have been measured. The maximum stresses were not sensitive at all for the different impact scenarios for a given impact velocity, i.e. there is poor correlation between maximum pressure and maximum stress. The reason is that the main contribution to high stresses comes from oscillations with the natural frequency of the lowest structural mode and the fact that the time duration of the large impact pressures is very short relative to the highest natural structural period. The fluid dynamic details of the pressure loading are insignificant for the maximum structural stresses. The theoretical model is very simple. At the end of the initial slamming phase the sum of the impacting velocity and a space-averaged elastic vibration velocity of the structure is zero. This, together with the fact that the initial deformations of the plate are zero, provides initial conditions for the free elastic vibrations of the plate. The maximum structural stresses occur during this free vibration phase. The time dependence of the generalised coordinate of the lowest mode after the initial impact phase can be described as a free vibration of a mass-spring system of a plate which is fully wetted on the lower side. The mass term is the sum of a generalised structural mass and added mass term. The spring term is due to the bending stiffness. One does not need to know the slamming pressure in the theoretical analysis of structural stresses. The important parameter is the impact velocity. The stresses have according to the theory a linear dependence on the impact velocity. The latter tendency is experimentally confirmed. The case illustrates the need for close cooperation between structural mechanics and fluid dynamics.

When considering global response due to slamming, it should be noticed that both

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the water entry and exit phase may matter. The water entry and exit phases are associated with increasing and decreasing wetted surface, respectively.

1.1.2 Local Slamming

General

Section 2.1 mentions the importance of the relative impact angle which means that the roll angle can be an important parameter. The latter fact implies that more attention should be given to oblique sea. Structural damage in oblique sea due to bow-flare slamming has been reported by Yamamoto *et al.* (1985). Large-amplitude rolling was an important contributing factor.

Fundamental Hull-Water Impact

Section 2.2 deals with fundamental hull-water impact. 2D flow assumptions are typically made. The fact that experimental errors exist is often ignored when numerical calculations are compared with experiments. Both bias and precision errors may matter. Investigation of precision errors requires repetition of tests. Bias errors can, for instance, be due to 3D flow in experiments that were intended to be two-dimensional. Other possible bias errors are mentioned later in this section. One procedure is to use endplates to achieve 2D flow. The latter fact implies that the size of the end plates should be investigated. I have seen tests with obviously too small end plates. Another technique is to measure on a midsection of a 3D structure with constant cross-section. The length-to-“beam” ratio may become too small at the end of the drop for the 2D assumption to be true. Here the “beam” refers to the breadth of the instantaneous water plane area (Zhao et al. 1996). Zhao *et al.* pointed out an inconsistency in measured vertical force and pressures for the bow flare section referred to in Figure 1 in the committee report. This indicates measurement errors and has relevance for the comparative study between different numerical methods with the experimental pressure at one position that is presented in Figure 1 in the committee report. The boundary element method used by Zhao *et al.* (1996) agreed very well with measured force while it over predicted the pressure. Since theoretical results for slamming are normally for constant water entry speed, it is important during the tests to have as constant water entry velocity as possible in order to minimise the effect of the acceleration dependent force.

There exists a broad variety of CFD methods. Some methods use approximate free-surface capturing methods such as the volume-of-fluid, level set and color-function methods. Verification and validation are basic requirements. Verification involves benchmark testing, convergence studies and satisfaction of global conservation of mass, momentum and energy. A good example on benchmark testing is comparison with the similarity solution results presented by Zhao and Faltinsen (1993) for water entry of upright and rigid 2D semi-infinite wedges. The water entry velocity is constant, gravity and air flow are neglected and potential flow of an incompressible liquid without surface tension is assumed. The fact that inviscid liquid is assumed is an unimportant error. Anyway, it is easy to set the viscosity coefficient equal to zero and neglect turbulence in the input to a CFD code solving the Navier-Stokes equations. I can refer to two examples were a benchmark test as that was done. Two master students independently used two different commercial CFD codes. Each student used only one of the computer codes. Both of the CFD codes were based on the finite-volume method to solve the governing equations and the volume-of-fluid method to capture the free surface. Since human errors due to the user happen, I will not mention the names of the commercial computer codes. In one case good predictions were obtained

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for very low deadrise angle while the other student obtained good results only for deadrise angles larger than 45 degrees. A small deadrise angle is challenging for a CFD code. The same is true for a boundary-element code with correct free-surface conditions. The rapid change of the flow at the spray roots requires locally small cells/elements or many particles depending on which numerical method is used. The committee report presents in Figure 1 a comparison of pressure between different numerical methods and experiments for impact of the bow flare section mentioned above. The case is relatively simple and does not prove the applicability of the methods to more challenging cases with small local deadrise angles such as during the initial water entry of a bulbous section. One of the SPH calculations presented in Figure 1 show large pressure oscillations which often happen with particle methods. Marrone *et al.* (2011) have modified the original SPH method where the undesired effect of spatial and temporal pressure variations is minimized. I would have appreciated that convergence tests of the numerical code were discussed in connection with Figure 1 in the committee report. It is relevant in this context to mention comparative seakeeping tests of the S-175 ship that I was involved in as a member of previous ITTC seakeeping committees. The experiments done by different organisations showed non-negligible variations. Calculations done with the same strip theory showed also non-negligible variations. Comparative tests of slamming pressures for difficult cases should be encouraged. The experiments and the use of a given method should involve different organisations. This is the type of work that can be organised by ISSC and ITTC.

A challenging problem during water entry is ventilation which may cause non-viscous flow separation from curved body surfaces. An example is during water entry of bulbous sections. Rolling and transverse velocity of ships combined with water entry can also cause flow separation. Sun and Faltinsen (2009) studied numerically the free water entry of a rigid bow-flare ship section with strongly nonlinear free-surface effects. The effects of the roll angle on the forces and pressure distributions on the ship section were investigated by a boundary element method with exact free-surface conditions within potential flow theory without surface tension. The non-viscous flow separation model is described in detail by Sun and Faltinsen (2006) (see also Sun, 2007) and involves detecting pressures smaller than the atmospheric pressure on the body surface next to the free surface. Sun and Faltinsen (2009) found, for the ship section studied, the vertical forces did not change much with the roll angle when the roll angle was small, whereas the horizontal force clearly increased with increasing roll angle. As the roll angle becomes larger, there will be a stronger impact on the flare surface, which can cause very high localised pressure in the flare area; the latter effect may cause hydroelastic effects. Non-viscous flow separation from the section bottom can occur for large roll angles, which was demonstrated numerically by an example. Flow separation significantly influences the pressure at the section bottom while the free-surface elevation and pressure distribution on the windward side are not apparently affected. Comparisons between the calculations and the model test results by Aarsnes (1996) are affected by experimental bias errors, induced, for instance, by the oscillatory motions of the rig and the upward force effects of the elastic ropes. 3D flow effects may not have been important in the tests.

Hydroelastic Interaction

It is good to see the many reported hydroelastic studies involving different materials. I would have appreciated more discussion on when hydroelasticity matters for local response and for which structural members it has primary importance, i.e. similar to

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Faltinsen (1999) who studied the relative importance of hydroelasticity for an elastic steel hull with wedge-shaped cross-sections penetrating an initially calm water surface. Stiffened plating between two rigid transverse frames was examined. A hydrodynamic strip theory with a Wagner-type method in combination with orthotropic plate theory was used and the focus was on stresses in the second longitudinal stiffener from the keel. It means that the studied problem cannot be analysed as a 2D problem. The stresses in the longitudinal stiffeners are more important to study than the stresses in the plating. Non-dimensional parameters were used to show when hydroelasticity matters. The importance of hydroelasticity for the local slamming induced maximum stresses increased with decreasing deadrise angle β and increasing impact velocity V. The bending stiffness but not the structural mass is an important parameter. Using realistic structural dimensions and relative impact velocities for ships implies that hydroelasticity may have to be considered for local slamming for deadrise angles less than about 10 degrees.

Sun and Faltinsen (2006) have also studied the water impact of an elastic cylindrical shell by coupling a boundary element method for the water flow and a modal analysis for the structural responses. It was shown that the initial water impact, the flow separation from body surface and the ventilation near the free surface can affect the structural responses at a later time of the water impact.

Wave Impact

Section 2.4 deals with impact loads on both the columns and the underside of large offshore platforms. I would add to the description on the use of a numerical wave tank with a CFD code that dispersion errors in the incident waves may happen when a CFD code with a free-surface capturing method is used. The latter difficulty is dealt with by using small cells in the free-surface zone. The committee refers to numerical calculations that include viscous effects. Viscous effects are normally considered secondary in impact problems. However, if propagating waves hit the vertical front of a horizontal deck, the flow will separate from the front edge when the water subsequently moves downwards from the front. A viscous code is beneficial then.

An air cavity may be formed during wetdeck slamming such as in Abrahamsen's (2011) (see also Abrahamsen and Faltinsen, 2012) tank-roof impact studies. High-speed compressible air flow matters in a small time period prior to the closure of the air cavity and is difficult to numerically solve. There is a singular tendency in the numerical velocity and pressure predictions at closure. The closure problem has similarities with the "water hammer" problem. The impact causes inwards water jets to the cavity which are also challenging to handle.

Wetdeck slamming on catamarans and offshore platforms are similar problems. Wetdeck slamming has also similarities with slamming on a nearly flat overhang at the transom of a container vessel. Both local and global effects should be considered. An example on the importance of both water entry and exit phases for global effect of wetdeck slamming was illustrated by Ge *et al.* (2005) for a high-speed catamaran by means of experiments and simplified theoretical analysis involving frequency-domain strip theory without hull interaction. The magnitude of the negative forces during the water exit phase can be as large as the maximum force during the water entry phase. Since the Wagner method does not apply during water exit, a von Karman method was used. Using the Wagner method partly during the water entry phase had a small influence on the global response. The fine details of slamming occurs on a very small time scale relative to the time scale of global response and are therefore not

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important for global response. The nonlinear Froude-Kriloff and hydrostatic forces did also contribute. Both the water entry and exit forces must be considered for properly studying the global response. The latter fact can easily be illustrated for heave and pitch response where the duration of the deck wetting is smaller than one quarter of the natural heave and pitch periods. The force impulse determines the response and only considering the water entry phase would obviously lead to highly conservative response.

The global analysis by Ge *et al.* (2005) does not consider the fact that local hydroelasticity may have an important effect on the local slamming induced stresses when the angle between the impacting free surface and the body surface is small. Since the time scale of the local response problem is much smaller than the time scale of the global response problem, the local response problem would require a separate analysis.

Helmers *et al.* (2012) recently developed an efficient Monte Carlo simulation approach to perform the stochastic analysis of slamming loading on marine structures in irregular seas, while a simple Wagner method was used to evaluate the impact force. The probability distributions of the maximum impact forces were addressed. It was found that the deadrise angle, up-crossing level, flow separation from the knuckle, vertical motions and roll motions can influence the maximum impact force at the high probability level.

After the section mentioning the model test performed by Baarholm (2009) and the consecutive CFD computation by Kendon *et al.* (2010), the following can be added:

Vestbøstad (2009) also performed CFD computations comparing with this model test, using the CIP method following Hu and Kashiwagi (2004). The focus of this work was to obtain as accurate wave kinematics as possible for the incoming wave. A numerical wave tank was therefore used to generate the waves. However, only regular waves were used in both experiments and simulations. This is also the case for the work performed by Iwanowski *et al.* (2010), and is common practice for this type of studies performed by the offshore industry. However, recent model tests (see Scharnke *et al.*, 2012) show that the forces obtained using regular waves differ from loads obtained using extreme wave crests generated from irregular waves. This is a major challenge for the CFD methods, as only deterministic, regular waves are usually generated. 5^{th} order wave kinematics are often used as input at the inflow boundary in such simulations. The wave kinematics beneath a steep irregular wave may differ substantially from 5^{th} order Stokes kinematics, leading to increased loads.

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

The limitations of CFD methods due to the required CPU time are clearly illustrated in the committee report. Recent examples on coupled CFD and structural analysis of whipping and springing of ships are provided by El Moctar *et al.* (2011) and Oberhagemann and el Moctar (2012).The 2D generalised Wagner method presented by Zhao *et al.* (1996) has been popular to use as a time-efficient numerical tool in combination with a ship response analysis. The 2D generalised Wagner method is able to handle sufficiently accurate larger local angles between the impacting free surface and the body surface than the Wagner method. It is worthwhile to mention some of its limitations. It requires that the instantaneous breadth of the water plane increases with time, i.e. the complete water entry of a bulbous section cannot be considered. The latter fact implies that fictitious body shapes are introduced in practice. The assumption

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of 2D flow is an important limitation for some bow-shapes. The 3D generalised Wagner method was presented by Faltinsen and Chezhian (2005). However, it is not clear in general how to apply the 3D method to a ship in waves. Further, the forward speed effect on slamming has to be incorporated. A quasi-steady approach of forward speed effects on slamming has been reported, i.e. the steady wave elevation at different instantaneous submergences was accounted for. The error in neglecting dynamic effects on slamming due to the forward speed needs to be studied. We should ideally solve the slamming problem as a fully integrated part of the ship response without doing a separate slamming analysis. A fully integrated analysis was done by Sun and Faltinsen (2011) for a planning vessel by using a 2D+t theory based on potential flow with a 2D boundary element method in head sea. Fully nonlinear 2D cross-sectional flow problems were solved and the flow separation from chine line can be simulated. The predicted heave and pitch motions were compared with experiments and the agreement was good. Nonlinear effects were shown to be more important when the incident wave encounter frequency is close to the heave and pitch resonance frequencies. Large vertical vessel accelerations occurred as a consequence slamming. The 3D flow effect near the transom stern, which is neglected in a 2D+t theory, shows non-negligible influence on the predicted bow acceleration near the resonance wavelength. A 2D+t theory is also relevant for semi-displacement vessels but not for the vertical response of displacement vessels.

Further studies are needed to incorporate slamming as a fully integrated part of the calculation of wave-induced ship response in a time-efficient way and such that e.g. 3D flow and forward speed effects are correctly accounted for. It is appropriate to assume potential flow of incompressible water in such an analysis. However, using state-of-the-art nonlinear boundary element methods is presently too time-consuming. We are now working on developing a more time-efficient potential flow solver which we have called the Harmonic Polynomial Cell (HPC) method. It implies that the water domain is divided into cells. In each cell a set of polynomials that satisfy Laplace equation is used. Exact nonlinear free-surface conditions are satisfied. The method has been shown to be very time efficient and accurate for idealised problems (Shao and Faltinsen, 2012 a). However, there is some way to go before we can prove the efficiency and accuracy in concurrent modelling of waves, ship motions, slamming loads and structural responses.

1.1.3 Global Slamming

In section 3 on global slamming it is stated: "In recent years, the research on nonlinear wave load calculations 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." First of all, what are the references to these studies? Further, I would appreciate more precise definition of terms used. Is the framework for the investigations an approximate theory, e.g. is one referring to so-called blended methods? Does second-order theory mean that it is only the incident waves that are described by second order theory or is some approximate methods used to account for the second order effect of the ship? It is relevant to refer to a somewhat different case examined by Shao and Faltinsen (2012 b) that does not involve slamming but illustrates the importance of nonlinear free-surface effects. Second-order springing excitation was studied. It was demonstrated by a complete second-order theory accounting for wave-body interaction

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that the second order potential gave clearly the dominant contribution. A so-called blended method does not account for this fact. Generalising such a method to include higher order than second-order hydrodynamic effects would be impractical and I can therefore not make a firm statement about a scenario with combined whipping and springing.

1.1.4 Sloshing

General

Faltinsen and Timokha (2009) describe the many different hydrodynamic impact scenarios that may happen in a tank as a function of the filling ratio. Shallow liquid cases and high filling ratios may involve flip-through or gas cavities.

I agree with the committee's statements about the many fluid dynamic parameters that may matter in analysing slamming induced structural response due to sloshing. By fluid is meant gas and liquid. Thermodynamic effects may also matter for LNG and NG. Further, hydroelasticity is of concern. Sloshing-induced slamming in LNG tanks is for me the most challenging slamming case. I agree with the committee that CFD has limitations which reflect the fact that model tests are the basis in design. However, model tests are also limited due to the fact that all fluid dynamic and thermodynamic parameters that may be important are not considered. Further, the tank model is normally assumed rigid. It is challenging to properly model the structural properties of a membrane tank in model scale. The time scale of a fluid dynamic phenomenon such as acoustic effects relative to natural periods of structural modes contributing to large structural stresses is important in judging if a particular fluid dynamic effect matters. If a fluid dynamic effect occurs on a time scale much shorter than important structural natural periods, the details of the fluid dynamic effect do not matter. An idea about important structural natural periods can be obtained from the numerical studies by Graczyk (2008) who examined slamming load effects on a part of the Mark III containment system. The hydrodynamic part of the analysis was strongly simplified while the structural modelling was complete. Typical main dimensions of the tank could be a length of $43\,m$, a breadth of $37\,m$ and a height of $27\,m$. Because the corners complicate the analysis and structural details were not available, the studied segment of the containment system was not adjacent to corners. The lateral dimensions of the panel were. This corresponds to an assumed span of girders and stiffeners in two perpendicular directions. The thickness of the segment was approximately $300\,mm$. The resin ropes, the steel plate and two layers of plywood with a layer of foam in between were included. These components are the most important in a dynamic analysis.

The lowest modes are governed by the steel-plating response. The bending response of the plywood next to the resin ropes matters from about $300\,Hz$ dependent on how the added mass was estimated. Because the steel bending causes tension/compression of the plywood, there is also important plywood response associated with the lowest mode.

A slamming case is analysed numerically in terms of response spectra. An average slamming pressure of 10 bar acting on the considered segment was assumed. The time duration of the loading was $3\,ms$. The effect of added mass was included in a very simplified way. The maximum response values were of significance for the evaluation of the structural strength. Four different locations were studied. It is not only the lowest modes, governed by the steel response, that matter. There is a significant influence from modes with a range of natural frequencies from about 100 to $500\,Hz$.

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An important effect of these higher modes is compression of the foam and local bending of the plywood plate adjacent to the resin ropes. The effect of liquid compressibility is believed to matter for frequencies of the order of $1000\,Hz$ and higher if the influence of bubbles in the liquid is neglected. A mixture of gas and liquid can significantly lower the speed of sound and thereby increase the time scale of acoustic effects (Faltinsen and Timokha, 2009). Even though the committee refers to a publication by me saying that the change of the speed of sound due mixture and gas are likely to be of secondary importance, I must confirm that I am uncertain about my statement.

If the ratios between the impact duration and important natural periods are small, the fine details of the hydrodynamics are not needed in describing what the maximum structural stresses will be. In the introduction we briefly described the analysis by Faltinsen (1997) when the ratio between the impact duration and the important natural period is small. The situation for the membrane structure considered by Graczyk (2008) is different. Significant response of the lower plywood occurs already during the slamming impact, i.e. before the free vibration phase. This is both due to the slamming duration and the higher natural frequency of the lowest important mode $(125 - 165\,Hz)$.

Model tests of slamming and sloshing are typically done with prescribed tank motion which may be found by calculations as a realisation of the ship motions in representative sea states. The calculations must account for the mutual interaction between ship motions and sloshing. The 2D numerical calculations and experiments by Rognebakke and Faltinsen (2003) with forced harmonic sway motion illustrate the mutual interaction between sloshing and wave-induced ship motions and the fact that nonlinear sloshing matters. The external flow can to a large degree be based on linear potential flow. However, nonlinear viscous roll damping must be accounted for. There are different linear potential flow methods such as a 3D method where the forward speed effect is only accounted for through the frequency of encounter. The accuracy of the latter 3D method is unknown to the author due to the fact that, for instance, the explicit forward-speed dependent terms considered in strip theories such as the Salvesen-Tuck-Faltinsen (STF) method are not included. How much the latter 3D method differs from the STF method when the STF method is an appropriate approximation needs to be investigated. An example of a more complete 3D potential flow theory involves solving the so-called Neumann-Kelvin problem in the frequency domain by using a Green function satisfying the radiation condition and the free-surface condition with explicit forward-speed dependence. There is no interaction between the local steady and unsteady flow. The complexity of the Green function and a line integral along the intersection between the mean free surface and the ship surface in the representation of the velocity potential makes the method numerically challenging. Rankine singularity methods are used when the interaction between the local steady and unsteady flow is accounted for. If an inertial coordinate system is used, the so-called m_j-terms in the body boundary conditions are numerically challenging and fundamentally wrong for sharp corners. The latter problem was avoided by Shao and Faltinsen (2012c) by using a body-fixed coordinate system. The sloshing effects ought to consider nonlinear effects which can cause 3D flow such as swirling, diagonal waves and chaos in prismatic tanks with length-to-breadth ratio around one (Faltinsen and Timokha, 2009). The latter can occur even though the forcing is along a tank wall. A linear theory will then only account for 2D flow. Tank roof impact may also affect the global sloshing induced forces and moments (Faltinsen and Timokha, 2009). Even though CFD is not recommended in general for sloshing-induced slamming, it

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may better describe the global effect of sloshing. However, the computational speed of CFD methods make it in practice unrealistic for long time simulations in a sea state. The nonlinear multimodal method (Faltinsen and Timokha, 2009) is a fast method which from a CPU point of view can realistically simulate the effect of a sea state. Assumptions are potential flow of an incompressible liquid without overturning waves. 3D effects can be considered. However, the method has not been developed to the stage where it can be used in engineering calculations. One drawback is the difficulties in handling shallow liquid cases with realistic tank excitation amplitudes. Then we are left in practice with linear sloshing theories which are fast and are commonly used. What errors are caused in slamming induced structural stresses by using calculations of tank excitations as a basis for model tests should be investigated. An issue is also the statistical analysis of the response.

Since sloshing-induced slamming causes filling restrictions in prismatic membrane tanks, a natural question to ask is if there are ways to reduce the load level. Swash bulkheads are a possibility from a hydrodynamic point of view. However, it seems impossible to use in membrane tanks. The IHI SPB self-supported prismatic type B tank with aluminum-alloy as material and used for LNG cargo is equipped with swash bulkheads. A swash bulkhead is typically placed in the middle of the tank perpendicular to the main flow direction. The opening area ratio of the swash bulkhead is a main parameter. If it is small, an important effect is the change of the highest natural sloshing period to a level where sloshing is less severe. The latter effect depends on the excitation level. Flow through the holes causes flow separation and thereby damping of resonant sloshing. It is illustrated by 2D calculations in Faltinsen and Timokha (2009) how the wave amplitude response depends on the sway excitation of a rectangular tank as a function of forcing frequency and solidity ratio. The solidity ratio is one minus the open area ratio. Comparisons between experiments and theory for non-shallow depths of rectangular tanks with nearly 2D flow and sway excitation are presented by Faltinsen *et al.* (2011a and b) for a wide range of solidity ratios and frequencies. Germanischer Lloyd states that the total area of perforation of swash bulkheads should not be less than 5% and should not exceed 10% of the total bulkhead area. The hydrodynamic studies mentioned above indicate that minimum wave response for realistic tank excitation occurs for higher open area ratios; let us say an open-area ratio in the order of 0.2. However, final conclusions from a hydrodynamic loading point of view require that realistic tank excitations are considered together with focus on sloshing-induced slamming.

Experimental observations in shallow water depth for sufficiently large harmonic excitations reveal impact events on the swash bulkheads caused by steep wave profiles hitting the bulkhead (Firoozkohi, personal communication, 2012). Most of these impact events are seen for large solid area ratios and frequencies clearly larger than the lowest natural frequency for the clean tank. In the absence of pressure measurements on the bulkhead, qualitative calculations using visual photographs and pressure impulse theory give pressure values comparable to slamming pressures that take place on vertical tank walls due to sloshing impacts. Direct pressure measurements and further theoretical analysis are needed to prove the qualitative calculations.

Model Tests

It says on line 4 in the 3rd paragraph on page 18 in the report that: "Authors conclude that the leakage is not the main cause of decay and that the heat transfer between air and water might be important." This is unclear and can be written: Authors

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conclude that air leakage was not present after the first period of oscillation and is hence not a source of the general decay in their experiments. Based on a simplified analytical model, it was found that the heat exchange between the air inside the air pocket and the surrounding water and tank wall contributed to the decay of the air pocket oscillations. In the same paragraph it can be stressed that air and water were used.

1.1.5 Green Water

I would like to add some supplementary material to the report. A systematic and comprehensive description of the green water-on-deck phenomena is provided by Faltinsen and Greco (2011) on the basis of experiments (directly performed or from other investigators) and of 2D numerical simulations based on a Boundary Element Method (BEM) and on a field method solution. The main water-shipping scenarios were identified as: dam-breaking (DB) type, where the shipped water propagates similarly as the flow generated after a dam breaking; plunging-wave (PW) type, where the water invades the deck in the form of a large scale plunging wave hitting the deck or superstructures; initial plunging plus dam breaking (PDB) type, where the water enters the deck in the form of a small scale plunging wave hitting the deck near the bow and then propagates as in a DB event; hammer fist (HF) type, where a rectangular-shaped liquid mass rises obliquely above the deck and then splashes violently against it. The PDB appeared as the most common scenario, PW and HF the less common but also potentially the most severe. All types of water shipping can lead to water impacts against obstacles on the deck. The PDB, PW and HF cause also impacts against the deck and lead to more or less pronounced air entrapment which can affect the resulting green-water loads. From the study, in general the numerical analysis of green-water occurrence and severity appears rather difficult due to the complex phenomena possibly involved and the intrinsic nonlinear behaviour.

The DB large-scale features can be simulated coupling a suitable seakeeping solver with a shallow-water approximation for the in-deck liquid evolution, as proved by the promising numerical and experimental studies by Greco and Lugni (2012) and Greco *et al.* (2012). The adopted solver combines a weakly nonlinear external solution for the wave–vessel interactions with a 2D in-deck shallow-water approximation, and a local analytical analysis of the bottom-slamming phenomenon. It can handle regular and irregular sea states and vessels at rest or with limited speed, expected in rough seas. The solver was compared with 3D model tests on a patrol ship at rest or small forward speed in head-sea regular waves. From the investigation the wave-body interactions can lead to slamming loads with different features depending on the location of the impact: on the hull bottom, the pressure evolution was typically characterised by a church-roof behaviour, with the first short peak due to the water impact against the structure and the second mild rise due to wave-reflection effects; on the ship deck, the pressure has a double-peak behaviour near the superstructure, with the first peak due to a water-wall impact and the second peak caused by water falling and impacting on underlying liquid, and a single-peak behaviour near the bow, due to the new liquid entering the ship deck; on the side hull, the pressure has a church-roof behaviour for mild conditions and a double-peak behaviour for severe conditions. Recently Greco and Lugni (2012) have used the same method and 3D experiments on a FPSO model to investigate the occurrence of parametric roll with water on deck. Numerically it is found that the green-water loads support the parametric roll excitation for the studied cases. As expected the instability develops after a transient phase where the roll motion is characterised by both the excitation (incident-wave) frequency and the

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roll natural frequency that eventually dominates the signal. As a result the water on deck is first periodic with the excitation period and then with the roll natural period, say T_{4n}, which is affected by the nonlinear wave-body interactions. For the examined cases, T_{4n} tends to reduce as the incident wavelength-to-ship-length decreases.

To handle general water-on-deck scenarios the shallow-water approximation is not suitable and numerical methods able to handle breaking and fragmentation phenomena are needed. On the other hand, the state-of-the-art solvers are not able yet to provide accurate results and reliable statistical investigations of the local and global green-water loads in the case of realistic geometries due to the demanding memory-space and CPU-time requirements. A compromise between capability, accuracy and efficiency could be represented by hybrid methods based on Domain-Decomposition (DD) strategies, where the problem solution is split in time and/or in space among different solvers. Each solver is chosen as the most efficient among those accurate and capable which are available. Recent attempts in this direction are represented by the 2D work of Colicchio *et al.* (2011) handling also air entrainment, and by the 3D investigation of Colicchio *et al.* (2010).

1.1.6 Underwater Explosions

Although underwater explosions have been studied over a century, a large part of the results have limited access. Many physical effects matter. The following additional references should be noted (Zong, personal communication, 2012). Zhang and Zong (2011) decomposed the motions of a ship subjected to underwater explosion into two parts: rigid-body motions and elastic deformations. The effects of rigid-body motions have consistently been neglected in the current literature based on the assumption that they are small. Zhang and Zong (2011) clarified that the effects of rigid-body motions are negligible if the ship under consideration is long, corresponding to longer than approximately $200\,m$ in their study. The effects of rigid-body motions are dominant for small ships, corresponding to about $60\,m$ in their study. Based on their theory and investigations, one can conclude that rigid-body motions reduce the amplitudes and vibration natural periods of the bending moments of the hull girder. This investigation is useful in design of mine-sweepers.

Zong *et al.* (2012) tried to establish an analytical method to consider the dynamic viscoplastic behaviour of a circular plate subjected to underwater shock. Although this is a classical problem, accurate prediction of plastic deformation in the centre of the plate is not easy, if we notice the fact that the earliest prediction in the World War One had an error over 100%, improved to the order of 30% a decade ago. Thanks to the introduction of a double-scale double-phase model which considers the effects of time-scales, local cavitation resulting from rapid plate motion, the prediction error has been reduced to within 10%.

Li *et al.* (2012) continued the work of developing a specialised boundary element method for simulating non-spherical bubble in the presence of a free surface. The trick lies in introduction of a vortex ring when the bubble experiences topological change at the stage of collapse. Numerical results show that the bubble collapse behaviour is more complicated than previously expected near the free surface, exhibiting different jetting formation patterns.

1.1.7 Damage to Structures

An accident involving wetdeck slamming happened 24 March 2010 with MS "Sollifjell" in Norway. A drawing of a longitudinal cut of the wetdeck is shown in Figure 1. The

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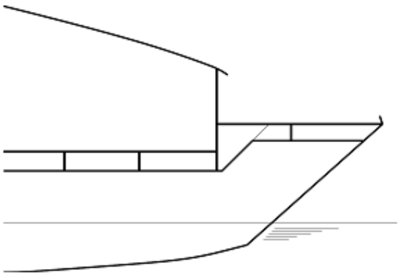

Figure 1: Illustration of the wetdeck of MS "Sollifjell" containing a 45° front panel

wetdeck is flat in the cross-sectional plane. The design of the front panel of the wetdeck was special. It had an 45° angle relative to the rest of the wetdeck. The consequence is that the forward speed can contribute significantly to the relative impact velocity on the front panel and thereby to high loading on the front panel. The loading on the front panel may have initiated the damage on the rest of the wetdeck.

Design procedures of wetdecks considering the slamming load effects have to be improved. The details of the vessel dynamics as well as the slamming load effects have to be accounted for. The wetdeck geometry (bow ramp angle, deck flatness etc.) and material ought to be reflected in the rules. Aarsnes and Hoff (1998) presented full scale experiments of wetdeck slamming on a 30 m long catamaran. The measured maximum strain corresponded to about half the yield stress. This occurred in head sea with significant wave height $H_{1/3} = 1.5\,m$ and ship speed 18 knots. The ship was allowed to operate up to $H_{1/3} = 3.5\,m$. The classification rules did not predict well that the ship had sufficient height of the wetdeck above sea level to avoid wetdeck slamming. It should be investigated if simple formulas for sufficient height of the wetdeck above sea level could be exchanged by direct simulations with state-of-the-art computational tools that properly predict the hydrodynamic effects on the trim angle which is an important parameter for wetdeck slamming on high-speed vessels.

1.1.8 Conclusions

General

I agree with most of what is written in the report. Most of my comments are supplementary. Some concluding remarks relative to my additional contributions are given below.

Local Slamming

Challenging benchmark tests are encouraged for numerical methods. A good example on benchmark testing is comparison with the similarity solution results presented by Zhao and Faltinsen (1993) for water entry of upright and rigid 2D semi-infinite rigid wedges at small deadrise angles.

Sloshing

Attention should be given to the accuracy of prescribed calculated tank motions used in model tests of sloshing-induced slamming.

Underwater Explosions

New numerical and analytical methods are urgently needed to clarify the mechanism and properly capture the physics behind an underwater explosion (Zong, personal communication, 2012).

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Rules

Rules for wetdeck slamming on ships should better reflect the physics.

1.1.9 References

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1.2 Floor and Written Discussions

1.2.1 Mirek L. Kaminski

First I would like to comment on the classification of the Sloshel project as the model test. It was a full scale test as it included a real containment system and a wave breaking impact having height of ten meters. Second I would like to know the committee opinion about the relationship between local pressure measurements and strains. In my opinion careful preparation of the experiment including the whole data acquisition system and pressure gauges results in a very good correlation. This has been proven in the Sloshel project (Kaminski *et al.* 2011).

1.2.2 Sergiy Baskakov

I thank committee for interesting report. I would like to add followings:

1. It is necessary to specify procedure of generalisation of results of simulation of a slamming on a real vessel. It demands shaping of corresponding similarity parameters.
2. Effects linked with behaviour of a vessel on a wave can be considered only in a complex. For example, lowering of punching shears can be reached having lowered speed. However, having diminished speed we expos a vessel to risk of a stopping by wave. From practical positions it means necessity of installation of minimum admissible speed at a course on a wave. It is especially actual taking into account tendencies of slowing of speed for fuel saving.

1.2.3 Shengming Zhang

Sloshing of LNG carriers is a repeated phenomenon. Some LNG carriers have experienced damages in the containment systems. Can the committee give comments on whether such damage is due to a single peak load or due to the repeated sloshing loads causing fatigue problems? Thanks.

1.2.4 Sharad Dhavalikar

In sloshing experiments or numerical simulations can we distinguish between sloshing pressure and impact pressure? If yes, how? Because classification societies give different formulations for sloshing pressure and impact pressure.

Can the experimental and numerical results be used/validated against rule values?

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1.2.5 Sören Ehlers

Concerning structural analysis and the definition of design pressures for LNG sloshing I would like to see the actual material stiffness and ultimate strength measurements of the containment systems to allow for the actual definition of the safety margin. Please comment!

1.2.6 References

Kaminski, M.L, Bogaert, H. and Brosset, L. (2011). Full and large scale wave impact tests for a better understanding of sloshing - Results of the sloshel project. *Proc.* 30^{th} *Int. Conf. on Ocean, Offshore and arctic Eng. (OMAE2011),* Rotterdam, The Netherlands.

2 REPLY BY THE COMMITTEE

2.1 Reply to Official Discussion

2.1.1 Introduction

First of all, the committee members would like to express our sincere thanks to the official discusser, Prof. Odd M. Faltinsen for his kind appraisal of our report and valuable and constructive comments not only on the introduction but also on the other contents of the reports. The committee will reply to each comment or discussion one by one.

The official discusser points that the report did not cover ‘launching of free-fall lifeboats from offshore platforms’. We agree that should have mentioned in the report. We are happy to hear that the official discusser agrees on the importance of the effects of impulsive pressure loadings on ship structural response which historically has not always been realised. He also mentions the necessity of close cooperation between structural mechanists and fluid dynamists for further progress in the area of impulsive pressure related.

2.1.2 Local Slamming

General

Regarding local slamming, the committee is satisfied with understanding that the official discusser agrees with the majority of the committee’s statements. The official discusser stresses the importance of proper verification of numerical methods including convergence studies and assessment of conservation of mass, momentum and energy. On the Local slamming the mechanics of the system explained by Prof. Faltinsen do make sense, in terms of pressure duration and relation to natural period and the problem being one of initial condition.

Fundamental Hull-Water Impact

The point Prof. Faltinsen makes on systematic computations, in terms of convergence is right, in general. Most of the time we rely on our experience to generate a refined enough mesh and hope it will be all right. However, the computing times involved make it difficult to follow a proper convergence analysis.

He is also right in pointing the example of the ITTC seakeeping committee study where same experiments and same numerical methods (at least on paper) produced differences. We must be aware of such possibilities, both in terms of experimental and numerical uncertainties.

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Hydroelastic Interaction

The official discusser comments that he would have appreciated more discussion on when hydroelasticity matters and for which structural members. It is the understanding of the committee that the official discusser primarily considers dynamic effects and the relation between load period and structure natural period when discussing hydroelastic effects. However, by definition hydroelastic effects are the effects of the response of a flexible structure on the fluid around it and the mutual coupling there between. The committee agrees that the peak pressure is a poor reference for determining the response, since the peak pressure is a sensitive measure. Instead it is the complete pressure distribution that matters.

Wave Impact

The official discusser refers to several studies which the committee, however, considers as relating to global slamming rather than to wave impact even though some mechanisms and aspects of course are in common for these two problem areas.

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

Prof. Faltinsen discusses planning hulls a lot in this subsection, which we did not consider at all. The point he made on Harmonic Polynomial Cell (HPC) is interesting, but probably more valid for loads or dynamic response in terms of nonlinear potential flow. The use of pressure gauges will provide a measure of hydrodynamic pressure. As such, these pressures are not that useful with respect to the design of local structure. A better way of determining design pressures is to utilise pressure panels where the panels are designed to respond at the same natural frequency as the actual ship structure. The committee is finally glad to understand that we share with the official discusser the view that the development of methods for concurrent modelling of waves, ship motions, slamming loads and structural responses is an important concern for future work.

2.1.3 Global Slamming

The committee should have paid more attention on precise definition of terms regarding global slamming in the report. As mentioned by the official discusser the paper presented by Shao and Faltinsen (2012b) would be very useful to understand the effects of the nonlinear free-surface and second-order hydrodynamic force on global slamming response.

2.1.4 Sloshing

General

As stated by the official discusser in the structural impact problems, together with the amplitude of the impulsive pressure the ratio of the impact duration to important natural periods can represent the physical phenomenon of the impacted structure. However, except unstiffened plates, it is difficult to analytically obtain natural periods of impacted structures. In that regards, the committee expresses thanks to Prof. Faltinsen for introducing Graczyk's paper (2008), in which the important natural periods of the cargo containment panel was estimated.

Model Tests

The committee also thanks to Prof. Faltinsen for his correction of the expressions regarding the decay of the air pocket oscillations.

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2.1.5 Green Water

The committee thanks Prof. Faltinsen for pointing out a few references that the committee missed. He describes a more fundamental study dividing the green water phenomenon in a number of different types. The main water-shipping scenarios were identified as: dam-breaking (DB) type, where the shipped water propagates similarly as the flow generated after a dam breaking; plunging-wave (PW) type, where the water invades the deck in the form of a large scale plunging wave hitting the deck or superstructures; initial plunging plus dam breaking (PDB) type, where the water enters the deck in the form of a small scale plunging wave hitting the deck near the bow and then propagates as in a DB event; hammer fist (HF) type, where a rectangular-shaped liquid mass rises obliquely above the deck and then splashes violently against it. Of course, the different types of green water might give rise to different extrapolations from model scale results to full scale.

We fully support the opinion of Prof. Faltinsen that state-of-the-art CFD solvers cannot yet be used for the statistical investigations, excessive CPU requirements and numerical stability are the key problems. Blended methods that split-up the problem and apply different solvers for each sub-problem might indeed be the solution for at least the next period.

2.1.6 Underwater Explosion

Referring the calculation results of Zhang and Zong (2011) Prof. Faltinsen states that the effects of rigid-body motions are negligible if the ship under consideration is long, corresponding to longer than approximately $200\,m$ in their study. The effects of rigid-body motions are dominant for small ships, corresponding to about $60\,m$ in their study. This investigation is useful in design of mine-sweepers. However, when the local rupture due to underwater explosion is considered, we believe the effects of rigid-body motion may be negligible. The committee thanks Prof. Faltinsen for introducing newly published references (Zong *et al.*, 2012 and Li *et al.*, 2012), which can be added to our report.

2.1.7 Damage to Structures

The committee thanks to the official discusser for providing another slamming accident happened 24^{th} March, 2010 with MS "Sollifjell" in Norway. The wetdeck of the catamaran was damaged due to high slamming pressure loading on its front panel which initiated the damage on the rest of the wetdeck. He also comments on full scale experiments of wetdeck slamming on a $30\,m$ long catamaran which was conducted in 1998. The committee would like to support his proposal to investigate the adequacy of the relevant classification rules for wetdeck height above sea level.

2.1.8 Conclusions

General

The committee is happy with the Prof. Faltinsen's appraisal of the report conclusions by agreeing with most of what is written in the report.

Local Slamming

Prof. Faltinsen has encouraged performing benchmark tests for various numerical methods and he also provided an example with which benchmark testing results can be compared. The committee should have conducted benchmark calculations. The committee seriously discussed the possibility of performing new benchmark tests with

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the test models reported by Mori (1977), which provides the measured pressure histories and permanent deflections of drop-tested aluminum alloy stiffened plate models. However, unfortunately, it was concluded by the committee not to perform for this time due to limited resources.

Mori, K. (1977). Response of bottom plate of high speed crafts under impulsive water pressure. *Jour. of the Society of Naval Architects of Japan*, 142, 297-305 (in Japanese).

Sloshing

Considering the structural design practice of LNG cargo containment systems where their model test results are utilised Prof. Faltinsen's comment on paying attention to the accuracy of prescribed calculated tank motions used in model tests is very timely and by which more reliable structural design of LNG containment systems can be achieved.

Underwater Explosions

The official discusser points out the urgent necessity of new numerical and analytical methods to clarify the mechanism and properly capture the physics behind an underwater explosion. Furthermore, practical design guidance should be provided for close proximity underwater explosions where the shock wave and bubble effects can be coupled.

Rules

The committee agrees with the official discusser requiring the betterment of the present rules regarding the wetdeck slamming on ships to reflect the physics.

2.2 Reply to Floor and Written Discussions

2.2.1 Mirek L. Kaminski

Prof. Kaminski is correct to classify the Sloshel project as a full scale test. The committee agrees on Prof. Kaminski's commenting that careful preparation of the experiment should provide very good correlated measurement results of local pressure histories and strain histories.

Second I would like to know the committee opinion about the relationship between local pressure measurements and strains. In my opinion careful preparation of the experiment including the whole data acquisition system and pressure gauges results in a very good correlation. This has been proven in the Sloshel project (Kaminski *et al.*, 2011).

2.2.2 Sergiy Baskakov

The committee thanks to Dr. Baskakov commenting on slamming from navigational view point. Unfortunately, no committee members have experiences of navigation and it is difficult for us to provide any practical guidance regarding how to practically avoid severe slamming damage in rough sea. However, it has been reported to experience several slamming impacts before changing the heading angle and reducing the ship speed. We believe that if any practical guidance of manoeuvring of ship is provided the number of repetition of slamming impacts causing severe structural damage in a single storm can be reduced.

2.2.3 Shengming Zhang

The committee fully agrees with Dr. Zhang saying that the sloshing of LNG carriers is a repeated phenomenon. Of course, repeated impacts due to sloshing might cause fatigue

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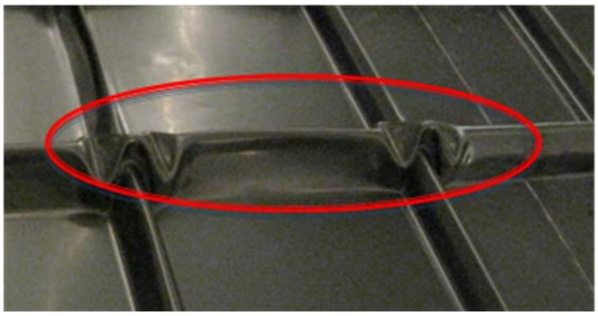

Figure 2: Damaged corrugation of LNG cargo containment due to sloshing

problems. However, more relevant cases can be accumulated plastic deformations due to repeated sloshing loadings as be seen in Figure 2. The figure shows the plastic deformation of the corrugation of an actual LNG containment probably due to repeated sloshing.

2.2.4 Sharad Dhavalikar

Mr. Dhavalikar is asking whether we can distinguish between sloshing pressure and impact pressure. It seems difficult to distinguish sloshing pressure and impact pressure, because sloshing is also an impact loading. The committee agrees on Mr. Dhavalikar's opinion saying that the present classification societies rules regarding the structural design of LNG cargo containment systems need to be more rational considering the nature of sloshing phenomenon.

2.2.5 Sören Ehlers

In replying to Prof. Ehlers the committee would like to categorise the sloshing of LNG cargo containments as a Serviceability Limit State problem rather than an Ultimate Limit State one. Of course, if the impact loadings due to sloshing are severe the structure can be collapsed. However, the reported damages of LNG cargo containment systems reported so far are very localised and not causing the collapse of the whole system.

We believe that in order to treat the sloshing impact of LNG cargo containment systems more rationally the design load needs to be defined not only the peak pressure but also its duration. Furthermore, the allowable extents of damage also need to be provided in the relevant classification society rules for the Serviceability Limit State analysis.