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COMMITTEE I.2
LOADS

COMMITTEE MANDATE

Concern for environmental and operational loads from waves, wind, current, ice, slamming, sloshing, weight distribution and operational factors. Consideration shall be given to deterministic and statistical load predictions based on model experiments, full-scale measurements and theoretical methods. Uncertainties in load estimations shall be highlighted. The committee is encouraged to cooperate with the corresponding ITTC committee.

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KEYWORDS

Cables/risers, fatigue, green water, ice loads, multi-bodies, parametric roll, rogue waves, slamming, sloshing, uncertainty analysis, vortex induced vibrations, wave loads.

CONTENTS

1. INTRODUCTION

The content of this committee's report is informed by its mandate, the expertise of its membership. The subject areas undertaken by specialist task committees of ISSC 2015: Arctic Technology (V.6), Accidental Limit States (V.1), Offshore Renewable Energy (V.4), Natural Gas Storage and Transportation (V.2), Risers and Pipelines (V.8), do have an impact on the committee's mandate, hence content of this report. Although ice loads have been entirely omitted, the subject areas of sloshing and vortex-induced vibrations have been reviewed. In addition, making the best use of the committee's expertise there are sections for loads on ships following damage and floating offshore wind turbines.

The structure of this report follows along similar lines to that adopted in previous ISSC reports. Nevertheless, it should be noted that (i) the versatility of computational methods to model more than one phenomenon, e.g. sloshing and slamming, and (ii) the focus of investigations in dealing with as complete fluid-structure interaction modelling as possible, e.g. risers and moorings and vessels, results in many overlaps between the sections and subsections of this report. Evaluation of wave-induced loads for ships is in Sections 2 and 3, with the former dealing with fundamental computations methods, hydroelasticity and abnormal waves, and the latter on slamming, sloshing, green water, measurements and damaged ships. Evaluation of wave- and current-induced loads on offshore structures is in Sections 2 and 4, with the former focusing on generic computational methods and the latter on vortex-induced motions and vibrations, mooring systems and wave-in-deck loads. Specialist offshore topics of floating wind turbines and lifting operations are also in Section 4. Probabilistic methods, design waves and fatigue loads for ships are in Sections 5 and 6. Finally weather routing and uncertainties in loads and loading conditions are in Sections 3.6 and 7, respectively, with conclusive remarks in Section 8.

2. COMPUTATION OF WAVE-INDUCED LOADS

Thanks to dramatic advances of computer science and technology during recent years, the numerical wave tank has attracted great interest from researchers. Computational Fluid Dynamics (CFD) making use of the Reynolds Averaged Navier Stokes (RANS) equations, although computationally intensive, features significantly in the investigations. Nonlinear potential flow solutions continue to be developed and used. Most of the numerical investigations deal with two-dimensional (2D) problems due to constraints from computational resources and/or CPU time consumption associated with three-dimensional (3D) modelling. This is particularly so when dealing with fully nonlinear modelling and irregular waves.

2.1 Zero speed case

2.1.1 Body – wave interactions

The problem of wave-structure interactions has been of great interest in both offshore industry and academic research in ocean engineering for several decades. Due to the complexity of interactions between water waves and offshore or coastal structures, model tests are traditionally considered as the most reliable method to predict wave impacts on structures. Nonetheless, the cost and scale effects of model tests are considered as the major limitations in the initial study where large numbers of cases might be required for testing. Thanks to the great efforts made by the scientific community in the past few decades, numerical models are becoming increasingly accurate and reliable with high efficiency, and numerical simulations now are usually employed in the initial stage during the design of marine structures and provide validation results for model tests. More efficient and accurate numerical modes are under development both in industry and academia.

The accuracy of linear and second order potential flow models, dominantly utilized in the industry, remain acceptable in practical engineering, in most circumstances. However, nonlinear effects and fluid viscous effects may be significant in some particular situations such as wave trapping within an array of bodies, wave resonance in a gap between side by side vessels. To address the higher order nonlinear and viscous effects, various numerical models are recently developed to achieve better predictions of wave impacts.

The nonlinearity due to the free surface is believed to affect the hydrodynamic responses of, hence loads on, structures, particularly if wave trapping is induced around the structures at certain frequencies. To consider higher order (beyond second order) nonlinear effects, fully nonlinear potential flow (FNPF) models are considered as one of the effective methods in simulating wave-body interactions. Ducrozet et al. (2012a) presented a modified higher order spectral (HOS) nonlinear potential model with a controlled wavemaker. In the HOS method, free surface velocity potential is represented by finite number of spectral basis functions, individually satisfying Laplace's equation and periodicity. The key point in the modified model is wave generation by an additional potential which satisfies the no-flux condition on wavemaker and nonlinear free surface conditions. Validation cases of 2D irregular waves and 3D focused waves illustrate high accuracy with comparisons against experimental data. Meanwhile, a comparative study was presented by Ducrozet et al. (2012b) who compared the finite difference based FNPF solver OceanWave3D (Engsig-Karup et al., 2009) and the HOS model. Simulating the typical problem of highly nonlinear waves propagating on a finite bottom of constant depth, they found that the HOS model is more efficient than OceanWave3D, and the efficiency difference depends on required accuracy level and wave steepness. In order to improve the efficiency of this finite difference based model, Engsig-Karup et al. (2012) implemented a massively parallel and scalable algorithm utilizing modern graphics processing units (GPUs). The significant improvement of computational efficiency shows the promising utilizations of GPUs in the development of numerical models in the near future. Subsequently, applying the idea of splitting the total potential in the fluid domain into an incident and a scattered field, Ducrozet et al., 2014 described a nonlinear decomposition method for solving the wave-structure interaction problems by extending the solver OceanWave3D. Accordingly the actual water surface is separated into two components, i.e. an incident and a scattered wave field. The incident wave field (elevation, velocity, potential, etc.) can be prescribed explicitly, resulting in a new boundary value problem for only the scattered wave field. In particular, the scattered flow potential satisfies the Laplace equation in the fluid domain and the boundary conditions are in terms of the scattered field properties (unknown) and incident field properties (known). At each time step of simulation, only the unknown scattered wave field is solved, while the actual wave field is obtained by superposing the incident and scattered wave field. They showed that one, in principle, could choose any wave model as the incident part; the only limitation on the incident wave being the capability of the chosen wave model. In their simulations, they only employed a nonlinear regular wave model, i.e. the stream function model. However, it is possible to prescribe irregular or focused 2D and 3D wave fields. They validated the model by simulating the case of nonlinear reflection on a vertical wall, with comparisons against other numerical results and experiments. They also presented a study of wave shoaling on an uneven beach. Linear components of wave surfaces obtained from harmonic analysis agree well with linear theory results. In addition, the efficiency, accuracy and convergence properties of the model were studied to demonstrate the significant gains of application of the splitting technique.

Meanwhile, the boundary element method (BEM) remains one of the widely used approaches to solve FNPF model. Guerber et al. (2012) presented a 2D model with a freely or forced moving submerged horizontal cylinder and solved the boundary value problem by a higher order BEM. The model was simulated to represent the wave energy converters (WECs), and model accuracy was checked by verifying the conservation of both volume and energy during the time marching of simulation. They compared their nonlinear results against linear results in the cases of submerged heaving cylinders. The agreement with linear results is great when they used a very small amplitude cylinder motion, while discrepancies increase as the motion amplitude increases. Zhou et al. (2013) presented a similar higher order 3D BEM model where a surface piercing cylinder was forced to move in the fluid domain. By varying the amplitudes of the moving cylinder, the nonlinear effects were found to be stronger in the cases of cylinders with rotational motions than those with translational motions. Discrepancies between fully nonlinear, linear and second order simulation results were observed as expected while using large moving amplitudes. They compared their results with previously validated fully nonlinear model by Bai and Eatock Taylor (2006) and experimental data by Chaplin et al. (1999), obtaining good agreement.

To deal with structures with complex geometries, Abbasnia and Ghiasi (2014) developed a 2D FNPF model based on higher order BEM utilizing the non-uniform rational B-spline curve, which could precisely capture structure boundaries especially where large curvatures appear. They studied wave diffraction around single, dual and an array of cylinders and again the nonlinearities were clearly observed from the time history of free surface elevations. The comparisons of wave forces against previous numerical results and experiments were only carried out for the case of a single cylinder. Focusing on the higher order effects on wave responses due to nonlinear free surface conditions, Bai et al. (2014a) employed a 3D fully nonlinear numerical wave tank (NWT) based on FNPF theory to study wave interactions with an array of cylinders. A mixed Eulerien-Lagrangian (MEL) approach was applied to update water surface through free surface boundary conditions which are described in the Lagrangian form. Fast Fourier Transformation (FFT) was used to perform harmonic analysis of their fully nonlinear results. They numerically demonstrated the existence of both first and second order near-trapping phenomena associated with the cylinder array of a typical configuration experimentally and analytically studied. A third harmonic influence at the second order near-trapped mode was found to considerably contribute to the fully nonlinear responses. Harmonic analysis shows that their first order results agree well with both experimental and analytical results, and that in the case of second order trapped mode their second order components agree better with experiments than the analytical results by Malenica et al. (1999). The third harmonic components of their results were reported to be very large, which however cannot be captured in the second order analysis by Malenica et al. (1999). You and Faltinsen (2012) investigated the interaction between waves and submerged body using a 3D fully nonlinear BEM (HOBEM). An additional application is on the interaction between the waves and a moored ship and the strong nonlinearity of ship motions and hydrodynamic loads were discussed.

One of the challenges for solving FNPF model using BEM is the long computational time required. A conventional BEM needs a CPU operation in order of $O(N^2)$, where N is the number of unknowns on the boundaries of the computational domain. Targeted at improving the computational efficiency, Shao and Faltinsen (2014) recently developed a new 3D FNPF model based on harmonic polynomial cells. The computational domain is discretized by harmonic polynomials such that the velocity potential at each field point is interpolated by a set of harmonic polynomials. Assembling all the discretized unknowns will result in operating with a sparse matrix which can be solved by any efficient matrix solver. This recently developed FNPF solver was demonstrated to be more efficient than an existing Quadratic Boundary Element Method (QBEM) and a Fast Multipole Accelerated QBEM (FMA-QBEM) by studying the boundary value problem on a unit cube which has an analytical solution. To validate the model, the authors presented the free surface elevations in the study of 3D sloshing in a rectangular box, with comparisons against finite element (FE) method and experimental results. Excellent agreement was demonstrated. Capability of capturing the higher order effects was also demonstrated in a case of wave diffraction around a bottom-mounted cylinder where experimental results are available. Higher harmonic wave forces on the cylinder compare well with existing FNPF model while some discrepancies were observed with experimental data, especially for the second harmonic forces.

While nonlinear effects in principle can be considered in all the FNPF solvers, viscous effects, however, remain another challenge which cannot be accounted within the framework of potential flow theory. With the viscous effects considered, one needs to solve the classical Navier-Stokes (N-S) equation. Peng et al. (2013) extended a NWT model based on a continuous direct-forcing immersed boundary (IB) method with the combination of volume of fluid (VOF) method. They applied the developed model to investigate the interactions between water waves and inclined-moored submerged breakwaters. Viscous process in the flow field, such as flow separation and vortex generation, can be captured and reproduced. Comparisons of wave elevations, mooring line forces and displacements of the moored body with tests revealed a favorable agreement. A similar combined IB and VOF model based on finite difference method was presented by Zhang et al. (2014) who performed various validation studies including oscillating cylinder in fluid without a free surface, liquid sloshing in a tank, water exit and entry of a horizontal cylinder, and a solitary wave over a submerged rectangular obstacle. Excellent agreement with existing analytical, numerical and experimental results was demonstrated for all. With this model, they also investigated a submerged and a semi-submerged ellipse rotating in a tank respectively, and violent water splashing, fluid vortex and flow jets were well captured, although there are no comparisons against numerical and experimental data. However, the numerical models of Peng et al. (2013) and Zhang et al. (2014) are both in two dimensions. In modelling 3D wave-body interactions, Wang and Guedes Soares (2014) presented a FE model to solve 3D N-S equations based on the Arbitrary-Lagrangian-Eulerian (ALE) description, where the fluid is solved by using an Eulerian formulation while the structure is discretized by a Lagrangian approach. The interface between solid bodies and fluids is also captured utilizing the VOF method. They investigated the water impact on a buoy which was a representation of a WEC and maximum pressures were shown to occur at the moment the buoy touched the water surface. The authors investigated particularly the influence of fluid domain mesh density showing that it could generate significant influence on the results. For example three different mesh densities were used for the case of a hemisphere impacting on calm water surface, showing that the highest mesh density predictions agree better with experimental measurements. This indicates that a high mesh density is required to achieve a certain accuracy, leading to high computational efforts in the case of 3D modelling.

The open source CFD solver OpenFOAM was recently demonstrated by Higuera et al. (2013a), (2013b), (2014)) to well capture the local flow characteristics around coastal structures. Specified boundary conditions for realistic wave generation and active wave absorption were implemented to demonstrate the capability of modelling a various type of nonlinear waves. Both 2D and 3D studies were carried out, and with comparisons against experiments, the overall performance in terms of accuracy and computational time is encouraging. A similar OpenFOAM model with further extension on wave generation was presented by Chen et al. (2014), who illustrated the higher harmonic effects of wave run-up and loading on bodies as well as the higher harmonics of focused wave groups. To generate wave groups in the wave tank, they did not use a piston-like wave maker; instead the wave was generated via the flux into the computational domain through a vertical wall. The volume fraction and horizontal and vertical velocities at the wave inlet boundary faces were specified. They simulated wave impacts on a semi-submerged horizontal circular cylinder and a vertical circular cylinder. Wave elevations and wave forces were compared with tests where the agreement is good even for harmonic components up to 4th order. For a semi-submersible platform with shallow draft, it is important to estimate wave run-ups accurately in order to fulfil requirements of the positive air gap below the deck. Nam et al. (2013) presented a simulation method which solves the two-phase N-S equations using finite volume discretization with a VOF method. Under the shallow draft conditions, highly nonlinear wave run-ups were observed at the front side of the first column. Wave amplifications due to nearly trapped mode between two columns lead to high wave run-ups at the back side of the first column. Vertical suction forces dramatically increase with the draft. Present calculations under both draft conditions show fairly good agreement.

Wellens (2012) specifically developed a model named ComFLOW based on the N-S equations to simulate extreme waves. A finite volume discretization of Cartesian grids was adopted in this model and the free surface in ComFLOW was advected using an improved VOF algorithm. The extreme wave impacts on the offshore structures were investigated in detail and an attempt was taken to efficiently reduce the spurious reflection from boundaries as the domain size was limited due to CPU time cost. Östman et al. (2014) presented numerical simulations of green water events and wave impact on a FPSO. The simulations are performed at model scale and the results are compared against experimental model test results and show reasonable agreement. The commercial Star-CCM+ CFD software is used in the simulations. The studied phenomena involve strong nonlinear effects with large variation in peak values of the studied quantities. The variations were, however, found to be more pronounced in the CFD simulations than in the experiments. Ideally a large amount of green water impacts should be computed in order to be able to make a statistical comparison against model test results. Due to very long simulation time it is concluded that use of RANS CFD tools for design optimizations of vessels exposed to green water phenomena is, at present, not mature enough. However, it can be used to give valuable physical insight in terms of visualization and understanding of complex nonlinear green water events.

Other than grid-based models, the gridless Smoothed Particle Hydrodynamics (SPH) method can also handle complex local viscous effects. However the difficulty is the treatment of fluid-structure interface. Bouscasse et al. (2013) presented a weakly compressible SPH solver which imposed a no-slip boundary condition on the solid surface via a ghost-fluid technique. Specifically the solid domain boundary is modelled by a set of imaginary particles, referred to as ghost particles, and the fluid fields (velocity, pressure and internal energy) are extended on these ghost points through mirroring such that the global loads on solid boundaries are evaluated through the momentum exchange between fluid and ghost particles. They modeled a dolphin dropped into a water tank and an oscillating box in a water tank. Comparisons were made with experiments in the case of a wave group interacting with a freely floating box. The surface elevations, box motions in sway, heave and roll are close to the experimental results. This technique was demonstrated to be capable of modelling complex interfaces between fluids and bodies; yet their model is in two dimensions.

It is well known that a 3D CFD solver requires a large amount of computational effort for large scale modelling such as wave interaction with marine structures. Although more details can be captured than a potential flow solver, a full scale 3D CFD solver may not be a preferred choice considering CPU time. Consequently, the combination of a FNPF solver and a CFD solver could be a promising strategy in order both to achieve high efficiency and to capture detailed fluid viscous effects near the structures (Sriram et al., 2014). Kristiansen and Faltinsen (2012) presented a domain decomposition model based on finite volume method (FVM) which solves the outer domain by a potential flow solver and the inner domain by an in-house CFD solver. Their 2D model was developed mainly to investigate the flow separation in way of the barge bilge in the problem of gap resonance between two side-by-side barges and the free water surface was modelled by the linearized potential solver which revealed to significantly improve computational efficiency. The accuracy of the model was demonstrated by comparisons of gap surface elevation against tests. Meanwhile, Sriram et al. (2014) presented a more complex hybrid model which combines not a linear potential flow model but a FNPF solver and an N-S solver. Particularly their FNPF solver is based on FE method and the N-S solver is based on the Improved Meshless Local Petrov Galerkin method with Rankine source solution (IMLPG_R), which was previously presented by Sriram and Ma (2012). The concept of the combination is based on the fact that a FNPF solver is more efficient in modelling wave propagation while a CFD solver is more accurate in capturing local fluid viscous effects. Comparisons with experiments demonstrated a very accurate and detailed capture of wave breaking while improving the computational efficiency of the IMLPG_R based N-S solver. Again, their model is in two dimensions. Up-to-date, Paulsen et al. (2014) presented a 3D FNPF solver combined with an N-S/VOF solver where the FNPF solver is based on their existing code OceanWave3D and the N-S/VOF solver is OpenFOAM. The computational domain was decomposed into an outer domain governed by the FNPF solver and an inner domain described using the N-S/VOF solver. Numerical computations of wave loads on surface piercing circular cylinders were carried out for the situations of weakly nonlinear regular waves, phase-focused irregular waves, unidirectional irregular waves on a sloping bed and multidirectional irregular waves on a sloping bed. Comparisons against experimental tests of wave elevations and inline forces in all the cases demonstrate good agreements. The efficiency achieved utilizing Message Passing Interface based parallel computation illustrates the potential of further development and application of the combined model in three dimensions.

In general, potential flow model remains one of the dominated efficient solvers for numerical simulation of wave-body interactions. Further development of 3D FNPF solves is still valuable. Nonetheless, it could be promising to develop hybrid 3D models combining a potential flow and a CFD solver.

2.1.2 Body-wave-current interactions

The effect of body-wave-current interactions for permanent, fixed or floating structures is primarily an issue for predictions of air-gap and wave drift force calculations. By change of coordinate systems, the hydrodynamic problem is equivalent to the forward speed seakeeping problem for a ship, with added resistance and wave drift force being the equivalent force contributions. Within the last reviewing period there has been a renewed awareness of the important effect of current on the wave drift force due to several incidences of mooring failures where overload is considered to be the main cause (Kvitrud, 2014). The fact that drift forces can be considerably enhanced in a combined wave-current environment has been known since the mid-1980s. However, the mooring design industry does not seem to be sufficiently aware of this. A reason for this is that available mooring design tools do not properly account for this effect. The major effect of current for linear wave-body interactions is the relative motion between wave and structure which is relevant for air-gap predictions, in particular the wave run-up in front of vertical surfaces.

Monroy et al. (2012) studied the interaction effects of the steady flow past the floater on the wave diffraction-radiation potential. The steady flow is taken as the double body flow. The time-harmonic velocity potential is decomposed into a linear part and an interaction part taking into account the interaction of the linear potential with the local steady flow at the free surface. The main difference in this approach and earlier developments, e.g. Grue and Biberg (1993), is the use of a non-secular Green's function. Results include the effect of current on first order surface elevation on fixed cylinder and drift force on freely floating tanker, comparing with the simplified method by Aranha (1994) which has been adopted by the industry. Stansberg et al. (2013) presented a discussion on the significance of the wave-current-structure interaction on wave drift forces, slow-drift motions and mooring line forces for offshore structures. Observations from experiments on an FPSO and a semi-submersible show the important effect of current on the surge motion and mooring line tensions.

The second order diffraction and radiation problem for a floating body with small forward speed has been investigated by Shao and Faltinsen (2013). The main contribution of this work is a consistent and robust method to handle the numerical difficulties associated with higher order derivatives in both the free surface and body boundary conditions. This problem is due to the transfer of the body boundary condition from the mean body position to the instantaneous position, resulting in the, so called, m_j terms which do not exist and cannot be evaluated at sharp corners. The new method takes advantage of formulating the boundary values problem in a body-fixed coordinate system in the near field. Body motions then appear in the free surface condition. However, when using the body-fixed system no higher order derivatives appear. A time domain HOBEM based on cubic shape functions was used to solve the wave-current interactions for the case of a bottom mounted and a vertically truncated cylinder. Shao and Helmers (2014) further developed and verified this method by comparing with previous analytical studies.

2.1.3 Multibody interactions

Within the context of multibody interactions research focuses on the gap resonance effect and multibody offshore systems. With reference to the former the 2D method by Kristiansen and Faltinsen (2012), combining inner domain CFD and outer domain potential flow solutions, has already been discussed in Section 2.1.1. It has been shown by Hong et al. (2013a), using linear potential theory, that the gap resonance can appropriately be reduced by introducing an artificial damping (a wetted surface damping), in the body boundary condition of two ships floating side-by-side in waves. Their numerical results have been obtained using 9-node discontinuous HOBEM. They have shown that using an appropriate value of the wetted surface damping, the unrealistically large first order, as well as time-mean second order, numerical values due to the Helmholtz and higher mode resonances in the gap can be reduced without altering numerical results at non-resonant frequencies. The appropriate wetted surface damping can be obtained by comparing numerical and experimental results of wave elevation at the first gap resonance frequency. Comparison of the numerical and experimental values of the sway drift forces on a FPSO and a shuttle tanker suggests that the wetted surface damping parameter can be successfully used to predict the first order hydrodynamic coefficients as well as the time-mean drift forces of two bodies floating side-by-side in close proximity.

Bunnik (2014) presented a time domain potential flow method which simulates the behavior of multibody offshore systems with large horizontal relative motions in waves. When the relative motions exceed a certain threshold value a new linear diffraction calculation is carried out. The time domain simulation is then continued with a new set of hydrodynamic coefficients (added mass, damping, 1st and 2nd order wave forces). As a test case a berthing operation was simulated in which an LNG carrier was pushed sideward towards a LNG FPSO in waves of various headings. These simulations showed that, depending on the wave direction, the effect of the change in hydrodynamic interaction can be significant, resulting in a considerable change in the time needed to complete the berth. Although the results so far look logical and realistic, convergence of the results with respect to the amount of panels used and the threshold value for updating the coefficients need to be studied.

2.2 Forward speed case

The problem of wave-induced loads on ships with forward speed is one of the most demanding in ship hydrodynamics, especially when considering the excitation by moderate or large amplitude waves. In theoretical/numerical approaches, this requires the proper consideration of the forward speed effects on ship motions and loads and of a variety of nonlinearities related to the large amplitude ship motions and to ship's actual wetted surface, as well to the change of the free surface of the incoming waves and their interaction with the moving ship. Due to the complications of the above set problem, simplifications and *engineering* solutions are often adopted. This implies that the exact nonlinear seakeeping and large amplitude wave-induced loads problems may be still considered unsolved. A brief review of related theoretical and numerical methods is outlined in this section.

Greco and Lugni (2012) developed a 3D seakeeping numerical solver to handle occurrence and effects of water-on-deck and bottom slamming. It couples (A) the rigid ship motions with (B) the water flowing along the deck and (C) bottom slamming events. Problem A is studied with a 3D weakly nonlinear potential flow solver based on the weak-scatterer hypothesis. Problem B, and so local and global induced green water loads, are investigated by assuming shallow water conditions onto the deck. Problem C is examined through a Wagner type wedge impact analysis. For coupling between A and B, the external seakeeping problem furnishes the initial and boundary conditions to the in-deck solver in terms of water level and velocity along the deck profile; in return, the shallow water problem makes available to the seakeeping solver the green water loads to be introduced as additional loads into the rigid motion equations. For the coupling between A and C, the instantaneous ship configuration and its kinematic and dynamic conditions with respect to the incident waves fix the parameters for the local impact problem; in return, the slamming and water entry pressures are integrated on the vessel region of interest and introduced as additional loads into the rigid motion equations. The developed solver has been applied to the problems of a dam breaking inside a closed tank and to the wave-ship interaction problem with/without water-on-deck occurrence for validation. Obtained results are compared with experimental data. Subsequently, Greco et al. (2012) carried out experimental and numerical investigations on a patrol boat at rest or travelling in head regular and irregular waves. In these studies motion RAOs, relative motions and occurrence, features and loads of water-on-deck, bottom slamming and flare slamming events, as well as added resistance in waves, were investigated. The analysis is systematic covering a range of Froude numbers, wave length (λ) to ship length (L_{PP}) ratios and wave steepness values. The main parameters that affect the global and local quantities are identified and possible issues in terms of, for example, water-on-deck severity and structural consequences are determined. Different slamming behaviors were identified, depending on the spatial location of the impact on the vessel, namely single-peak, church-roof and double-peak behaviors. A bottom slamming criterion is assessed. The major discrepancies with the experiments are discussed, and the importance of viscous hull damping and flare impact for the most violent conditions is emphasized. Inclusion of these effects has improved the numerical solution.

Hanninen et al. (2012) studied an interface capturing VOF solution for a passenger ship advancing in steep ($kA = 0.24$, k: wave number, A: wave amplitude) and short waves ($\lambda/L_{PP} = 0.16$), with the focus on estimating quantitative uncertainties for the longitudinal distributions of the first-third harmonic wave loads in the bow region. The computations were performed with the commercial flow solver ISIS-CFD. The uncertainty distributions obtained reveal that even the uncertainty of the first harmonic wave load varies significantly along the bow region. It is shown that the largest local uncertainties of the first harmonic wave load relate to the differences in the local details of the propagating and deforming encountered waves along the hull. The authors also discussed the challenges that were encountered in the quantification of the uncertainties for this complex flow case. Hanninen et al. (2014) considered the capability of their interface capturing method to predict local ship wave loads in short and steep waves (kA = 0.24, λ/L_{PP} = 0.16) by comparing with experimental results. The computations were performed with an unstructured RANS solver that models free surface flows with a VOF method. It was shown qualitatively that the solution behavior of the computed results is reasonable, even though the results can depend on the location of the computational points within the surface area of a pressure sensor. The agreement between computed and measured results is good at all the 10 locations on the bow of the ship. The characteristics of the wave loads vary between the sensor locations. Impact-type as well as smoother behavior of the loading is captured well by the numerical method. The work by Kim et al. (2012a) on estimating the long term midships bending moments and Oberhagemann et al. (2012) on embedding time domain field methods in extreme value predictions are discussed in Section 5.2.

Greco et al. (2013) developed a 3D domain decomposition strategy to deal with violent wave-ship interactions involving water-on-deck and slamming occurrence. This couples a linear potential seakeeping solver, in the outer domain, and Lagrangian markers for the body motion, in the inner domain where slamming, water-on-deck and free surface fragmentation may occur, involving important flow nonlinearities. The field solver combines an approximated projection method with a level set technique for the free surface evolution. Main features of the weak and strong coupling algorithms are described with special focus on the boundary conditions for the inner solver. Two ways of estimating the nonlinear loads by the N-S method are investigated, on the basis of an extrapolation technique and an interpolation marching cubes algorithm, respectively. The domain decomposition is applied for the case of a patrol boat travelling in head regular waves and compared against water-on-deck experiments in terms of flow evolution, body motions and pressure on the hull. The solver was successfully verified by comparison against the linear potential flow solution in the case of incident waves with small steepness and validated against model tests in the case of steeper waves.

Rajendran et al. ((2013), (2014)) presented a time domain numerical method based on strip theory. They calculated the probability distributions of relative motions and bending moments of a cruise ship in a set of extreme seas. Their approach includes two levels of complexity. The simpler one combines linear radiation and diffraction forces with nonlinear Froude-Krylov forces, hydrostatic forces and shipping of green water at the bow. Cummins' Impulse Response Function (IRF) formulation is used to represent the radiation forces. The second approach is a generalization of the first and the effects of body nonlinearity are considered by a simplified method, namely the memory functions, infinite frequency added masses and the radiation restoring coefficients are evaluated at each time instant as functions of the instantaneous wetted surface. A similar procedure is used to calculate the diffraction forces. In their latter model, the first order Froude Krylov pressures are replaced with a second order model. The 2nd order Froude-Krylov pressures are integrated up to the exact wetted surface area for each time instant. The nonlinear radiation and diffraction effects on the responses are analyzed by comparing the fully nonlinear results with the numerical predictions assuming linear radiation and diffraction forces. The short term nonlinear responses are represented by empirical probability distributions, obtained from time domain simulations, and the quality of the predictions is assessed by comparing with model test data.

Seng and Juncher Jensen (2013) developed a new approach, which requires reduced computational effort for the estimation of the short term statistical properties of the hull girder responses, as predicted by a free surface CFD solver. The approach, known as the MCF (model corrector factor), is an efficient alternative to the polynomial based response surface approach to the structural reliability analysis. The concept is to apply a predictor (e.g. a strip theory) to determine the most probable response conditioned wave sequence and the associated statistical properties. Thereafter, the predictor is applied to improve the evaluation of the responses for only a few selected wave sequences. An algorithm is proposed to support the selection process. To illustrate the process of transferring statistical properties to the CFD results (i.e. the corrector), an application to a 9400 TEU post Panamax container vessel is given using a nonlinear time domain strip theory as the predictor. The discussion focuses on the usage and the implicit requirements of the MCF approach, especially when slamming induced responses are considered.

Finally, a series of research investigations referring to the seakeeping problem are also reviewed. Though without direct reference to loads, these methods contain important methodology developments or applications, and will allow the calculation of wave loads with some additional development work. Sun and Faltinsen (2012) studied the steady and unsteady hydrodynamic problems of a semi-displacement ship with round bilge at high forward speed with a numerical method based on 2D + t theory. The ship was forced to oscillate in heave in the unsteady problem. No incident waves were present. The non-viscous flow separation from the round bilge of the ship hull was simulated. The pressure on the hull surface was evaluated and the sectional hydrodynamic vertical forces were obtained. Good agreement was achieved between the present calculations and the experiments, although some discrepancies near the bow and stern were observed. The interaction between the local steady flow and unsteady flow are automatically included and the nonlinearities in both steady and unsteady flow were considered. Shao and Faltinsen (2012) presented an alternative formulation of the boundary value problem for linear seakeeping and added resistance analysis based on a body-fixed coordinate system which does not involve the, so called, m_j terms in the traditional formulation when an inertial coordinate system is applied. Numerical studies were carried out for a modified Wigley I hull, a Series 60 ship and the S175 container ship for moderate forward speeds where it is thought appropriate to use the double body flow as basis flow. Results for the forced heave and pitch oscillations, motion responses, and added resistance in head waves show good agreement with experiments and other numerical studies.

He and Kashiwagi (2014) developed a time domain HOBEM for the 3D forward speed radiation and diffraction problems. Extensive results, including the exciting forces, added mass and damping coefficients, wave profiles and wave patterns for blunt and slender Wigley hulls with forward speed, are presented to validate the efficiency of the proposed 3D time domain approach. Model tests of the radiation and diffraction problems in a towing tank were also carried out. Computed numerical results show good agreement with the corresponding experimental data and other numerical solutions.

Liu et al. (2014b) presented a 3D nonlinear time domain method for the prediction of ship responses in waves based on the IRF concept. In this method, the wave excitation is decomposed into Froude-Krylov, radiation and diffraction forces. Incident wave forces are calculated through direct integration of the corresponding pressures over the instantaneous wetted surface. The radiation forces are obtained using the added mass and damping coefficients calculated by a 3D frequency domain code and transformed into the time domain by application of the IRF concept. Diffraction forces are obtained in a similar manner. Solving the six coupled nonlinear integro-differential equations of motion by a time integration method, motions in the six degrees of freedom (DoF) of the ship are obtained in the time domain. The validation of this method was conducted through applications to the S-175, DTC and KVLCC2 hulls. Good agreement was observed between the results of the present method, other numerical codes and available experimental data, which confirm the capability of the developed numerical approach to deliver reliable predictions.

Guo et al. (2012a) predicted the added resistance and ship motion of the KVLCC2 hull in head waves using the ISIS-CFD flow solver. The numerical results are analyzed in terms of added resistance, ship motions and wake flow. Both free to heave and pitch and fixed models are studied to investigate the contribution to added resistance from ship motions at different wavelengths, and the results show that ship motion-induced added resistance is negligible when the wavelength $\lambda < 0.6\ L_{PP}$. Comparison with calculations based on strip theory and experimental results shows that RANS predicts the added resistance better in all wavelengths.

Simonsen et al. (2013) investigated the KCS container ship in calm water and regular head waves by means of experimental and CFD studies. The experimental study was conducted in FORCE Technology's towing tank in Denmark, and the CFD study was conducted using the URANS codes CFDSHIP-IOWA and Star-CCM+ as well as the potential theory code AEGIR. The wave conditions were chosen in order to study response in waves under resonance and maximum exciting conditions for three forward speeds. In the experiment, the heave and pitch motions and the resistance were measured together with wave elevation of the incoming wave. The results show that the ship responds strongly when the resonance and maximum exciting conditions are met. With respect to experimental uncertainty, the level for calm water is comparable to PMM uncertainties for manoeuvering testing while the level is higher in waves. Concerning the CFD results, the computation shows a very complex and time-varying flow pattern. Comparison with experimental data shows that the computed motions and resistance in calm water are in fair agreement with the measurement. In waves, the motions are still in fair agreement with measured data, but larger differences are observed for the resistance.

It has been expected that the correct forward speed hydrodynamic coefficients of a surface ship advancing in waves would be obtained if the 3D frequency domain forward-speed free surface Green's function (Brard, 1948) and the 3D forward speed Green's integral equation presented by Hong (2000) were jointly used. Hong et al. ((2013b), (2014)) showed that the line integral in the 3D forward speed Green's integral equation can properly be discretized using 8-node inner collocation 2^{nd} order BEM. Their numerical results were obtained using Brard's Green function expressed through complex exponential integrals (Guevel et al., 1979). Predictions of the heave damping coefficients for the Wigley hull models I, II and III show that the larger the water plane area is, namely Wigley II, the more significant the waterline integral effect is. In this case, the free surface condition represented by the line integral, can neither be linearized nor be split into steady and unsteady conditions. They compared the calculated hydrodynamic coefficients to the experimental results by Journée (1992). They reported that their 3D forward speed method including the exact line integral can successfully be used to obtain the forward speed hydrodynamic coefficients of surface ships whose Length/Breadth ratios are greater than 5 when the Froude number is not much greater than approximately 0.3.

2.3 Hydroelasticity Methods

Research continues in improvements to frequency domain methods, as well as 3D time domain methods, the latter, by and large, involving coupling between linear and nonlinear BEM and FE analysis. Coupling between RANS and FE solvers is investigated for slamming related problems, e.g. Piro and Maki (2013).

Das and Cheung (2012) presented a directly coupled hydroelastic approach in the frequency domain with a rigorous treatment of the vessel forward speed. The formulation adopts a translating coordinate system with the free surface boundary conditions accounting for the double-body flow around the vessel and the radiation condition taking into account the Doppler shift of the scattered waves. A BEM, based on the Rankine source formulation, describes the potential flow and the hydrodynamic pressure on the vessel. A FE model relates the vessel response to the hydrodynamic pressure through a kinematic and a dynamic boundary condition on the wetted hull surface. This direct coupling of the structural and hydrodynamic systems leads to an equation of motion in terms of the nodal displacement of the finite elements. The results are compared against predictions from a seakeeping model with forward speed and the modal superposition method at zero speed. A parametric study of a Wigley hull shows that forward speed introduces new resonance modes, which amplify the elastic and rigid body responses of the vessel in waves.

Kashiwagi and Hara (2012) presented a 3D analysis method for ship hydroelastic problems in the frequency domain, which combines the Rankine panel method for analyzing hydrodynamic responses and the mode superposition method with 3D FEM for representing the structural deformation. The Rankine panel method takes into account the forward speed and 3D effects in a rational way and also the effect of steady disturbance flow on the free surface boundary condition. The natural frequencies of the *dry* elastic modes and corresponding mode shapes are computed by a 3D FE method, and the amplitudes of these elastic modes are determined by solving the coupled equations of motion. Numerical results are presented for a 2m modified Wigley model travelling in regular head waves, verifying expected performance of the developed calculation method.

Based on beam theory, Miao et al. (2012) developed a methodology for antisymmetric dynamic behavior including, warping function as independent deformation and the influence of structural discontinuity for open-deck ships using a range of theoretical models. The methodology was applied to investigate the response of a container ship travelling in regular oblique waves. The predicted results, in terms of dry hull characteristics and wave-induced loads, are compared with predictions using 3D linear hydroelasticity analysis. It was stated that, although the predictions from the 2D antisymmetric analysis are dependent on the theoretical model adopted, reasonably good agreement was achieved between 2D and 3D hydroelastic predictions; thus justifying their use as a more computationally efficient alternative to 3D models.

Senjanović et al. (2012) presented an improved method of ship hydroelasticity analysis, based on the modal superposition method and including structural, hydrostatic and hydrodynamic models. A beam model is used for the structure comprising a reliable advanced thin-walled girder theory taking into account shear influence on torsion as well as the contribution of bulkheads and the engine room structure, as structural discontinuities affect the ship hull stiffness. Consistent restoring stiffness is included in the analysis via the hydrostatic model. Added mass and hydrodynamics are determined based on the linear radiation/diffraction theory. Also, the analysis of springing effect on the ship fatigue life is introduced using the combination of the improved hydroelastic model and 3D FE substructure model. It is shown that the improved beam hydroelastic model can be efficiently used in the assessment of stress concentrations of ship structural details. Applicability of the developed theory is shown for the global hydroelastic analysis of a 11400 TEU container ship, including stress concentration determination in the selected structural details.

Vidic-Perunovic (2012) presented a finite water depth nonlinear hydroelastic strip theory, based on relative motion, for calculation of a ship's wave-induced vertical bending moment (VBM) in the frequency domain and applied it to an analytical beam and a tanker. An increasing trend in the low frequency part of the VBM was noted with decreasing water depth. When the water depth equaled approximately four times the draught of the vessel, the load response shifted towards lower frequencies, and the peak was significantly affected. For the high-frequency response, the magnitude of the springing peak increases with decreasing water depth, primarily owing to an increase in the added mass of the ship and the wave excitation force. Based on the analysis of the tanker, it was stated that the ship's response in different sea states increases substantially when the water depth is less than approximately five times the draught, both in linear and nonlinear springing calculations, compared with the deep water calculation.

Based on the linear random vibration theory, Papaioannou et al. (2013) developed a framework for stochastic hydroelastic analysis of very large floating structures (VLFS) subjected to multidirectional irregular waves defined through a directional wave spectrum. The approach involves a discrete evaluation of the relevant transfer matrices through a numerical solution of the fluid–structure interaction (FSI) problem that combines BEM for the fluid potential and the FE method based on the Mindlin plate theory for the plate response. Spectra of responses are obtained as well as extreme responses, assuming a Gaussian input. The proposed method is applied to the stochastic analysis of a VLFS and the influence of the mean wave angle on the standard deviation and extreme values of response quantities is demonstrated. It is found that the hydroelastic behavior of VLFS is greatly affected when considering a directional wave spectrum.

Chapchap et al. (2012) investigated the linear 3D radiation problem of a stationary floating flexible structure undergoing forced oscillations in time domain. The method uses a MEL scheme on an unstructured mesh. The Eulerian phase of the MEL scheme is solved using a constant BEM, in which Rankine sources and dipoles are distributed over the boundaries (i.e. walls, free surface and body surface) of the whole domain. Neumann and Dirichlet boundary conditions are enforced. In the Lagrangian phase, the linear version of the kinematic and dynamic boundary conditions are explicitly integrated in time allowing, at the next iteration, Dirichlet boundary conditions to be imposed on the free surface and the evaluation of the time derivatives of the potential function. The unified symmetric, including both motions and distortions, radiation problem is formulated and applied to the Wigley hull, treated as a uniform Euler beam, undergoing forced rigid motions and distortions. Comparisons with 3D frequency domain hydroelasticity predictions indicate that the implemented numerical schemes are working reasonably well.

Kim and Kim (2012) presented numerical analysis of ship hydroelasticity based on a fully coupled approach of linear BEM and FE method. For the analysis of FSI problems, a partitioned method is applied. The fluid domain surrounding the flexible bodies is solved by a B-spline Rankine panel method and the structures are modelled using a 3D FE method. The two methods are fully coupled in time domain using an implicit iterative scheme. The computed natural frequencies and motion responses of a simple barge and a segmented barge are validated through comparisons with experimental and other numerical results. A large containership is also considered in order to investigate the accuracy of the method on real ship application. Based on the computational results, the pros and cons of the approach are discussed, showing a promising capability for complicated FSI problems. Kim et al. (2013c) applied this fully coupled 3D BEM-FE method approach to two real ships, namely 6,500 TEU and 10,000 TEU containerships. Kim et al. (2012b) dealt with the numerical springing analysis of containerships. Good agreement is observed in linear responses. However, nonlinear springing responses based on weakly nonlinear approach do not show good agreement with the experiments. In addition, fatigue damage is calculated using this numerical method.

Yang et al. (2013) investigated the FSI for slamming impact phenomena and dynamic structural response problem in containerships at an initial design stage using a direct analysis method. Slamming impact pressures and dynamic structural response are studied using a commercial CFD program (STAR-CCM+) and a structure analysis program (ABAQUS), respectively. These two programs are coupled using the co-simulation function of STAR-CCM+, called the one-way coupled scheme of FSI. Numerical simulations are carried out for bow bottom and stern slamming impact loads of a containership in extreme design wave conditions. Also, the one way coupled analysis has been applied to obtain the dynamic structural responses of local structures.

Lee et al. (2012a) investigated nonlinear wave actions and wave induced global loads acting on a large container ship. An analysis procedure was established to determine values of wave induced VBMs considering the effects due to whipping suitable for design application. The analysis for predicting structural capacities has been carried out by computing the ultimate longitudinal strength of the container ship. Furthermore the assessment of the safety against failure due to excessive maximum loads is accomplished in Ultimate Limit States.

Mirciu et al. (2012) investigated the hydroelastic responses of a large LPG carrier in irregular head waves, based on Longuet-Higgins model with second order interference waves spectra. The LPG carrier has a double hull structure with length over all 238.7 m, design speed 17 knots and two loading cases, namely full cargo and ballast. The numerical analysis was carried out using the in-house code DYN, which is based on the 2D linear frequency and nonlinear time domain hydroelasticity theories, the latter using implicit integration procedures for the equations of motion. The resulting numerical hydroelastic linear and nonlinear response include low frequency oscillations response and high frequency vibratory response, taking into account springing and whipping phenomena induced by bottom and side slamming forces. It was shown that the nonlinear hydroelastic analysis could predict the extreme wave induced loads on the LPG hull structure.

In order to achieve safe and reasonable design with reference to whipping response of ultra-large vessel, Kobayakawa et al. (2012) developed a hydroelastic response analysis system which can calculate the stresses, including hydroelastic responses, on actual ship structures. The details of the system were described and validation study of system in regular wave was carried out. It was concluded that the system can simulate ship motions, hydrodynamic pressures and VBMs in regular head wave conditions with sufficient accuracy.

Malenica and Derbanne (2012) discussed actual tools and methodologies used in the design of Ultra Large Container Ships (ULCS), especially for the hydroelastic phenomena of springing and whipping. It was concluded that the modeling of springing and whipping is still a challenge and that there is no fully satisfactory numerical tool capable of dealing with these issues consistently.

Based on 3Dhydroelasticity theory of ships previously developed, including the effect of fluid compressibility, Zou et al. (2012) further incorporated the hydroelastic and sonoelastic analysis methods with the Green's function of the Pekeris ocean hydro-acoustic waveguide model, to produce a 3D sonoelastic analysis method for ships in the ocean hydro-acoustic environment. The method was applied to predict the sound radiations of a floating elastic spherical shell excited by a concentrated force and a LNG ship excited by the propeller induced pulsating forces acting on the wetted bottom plate of the stern in a shallow sea environment. The influences of the free surface and the sea bed on the generalized hydrodynamic coefficients, the acoustic pressure distributions in space are illustrated and discussed.

2.4 Loads from abnormal waves

Research on abnormal waves and their consequences on marine structures continue on many fronts, mainly focusing in new techniques of experimental generation of abnormal waves, experimentation of abnormal wave-structure interactions and numerical modelling to assess the adequacy of the methods used in representing the abnormal wave and its interaction with marine structures.

Bennett et al. (2012a) investigated how best to generate accurate, repeatable and controllable unidirectional abnormal waves in an experimental test facility for the purpose of practically modelling the response of a travelling vessel to abnormal waves. Three techniques, based on linear superposition principles, for producing an abnormal wave from a sea spectrum were compared, namely NewWave, Constrained NewWave and Optimized Sea. Each technique was tested for multiple sea spectra. The experimentally generated waves were compared to both linear and second order wave theory, to assess the adequacy of the former as it is used in the numerical models for predicting ships response and it is important to ensure they replicate the abnormal wave record used during experiments. The advantages and disadvantages of each abnormal wave generation technique are summarized in the paper. Results showed that in order to allow the most realistic predictions of ship responses, inclusion of the response history of the vessel, hence the random sea surrounding the abnormal wave is required, i.e. embedding the abnormal wave in an irregular wave. Two of the techniques used allow this, namely Constrained NewWave and Optimized Sea. The latter is the preferred option for realistic predictions, as it offers more control over the abnormal wave shape and significant anomalies between the required wave and that generated in the tank were observed for the Constrained NewWave technique.

Onorato et al. (2013) used a breather solution based on the one-dimensional nonlinear Schrodinger equation to generate critical wave sequences containing abnormal waves in the tank of the Technical University of Berlin. A breather solution describes the modulation of a slightly perturbed wave and is considered as a suitable modelling tool for abnormal waves. The seakeeping tests were carried out using a 2.3m model of a chemical tanker. The investigators carried out measurements with and without the model showing that the presence of ship did not alter the measurements of the generated wave. They also obtained satisfactory agreement between theoretical location of freak wave and tank observations. The amidships VBM and water-on-deck were amongst the measurements of interest for this committee. To measure the former the model comprised of two segments connected with force transducers. A large VBM was measured during the impact of the abnormal wave, exceeding what the authors referred to as *early stage* design VMB, especially in the sagging condition by approximately 40%. Furthermore, the water gauge on deck measured a water column of 10m full-scale during the impact. Although there are traces of high frequency components in the VBM record shown in this paper, it is difficult to draw any conclusions with reference to their origin. Nevertheless, this work emphasizes that abnormal waves have a significant influence not only on global loads but local loads such as water on deck.

Bennett et al. (2013) investigated experimentally the influence of forward speed on the motions experienced by a frigate encountering an abnormal wave and the implications that such encounters may have for ship design. Long-crested abnormal waves were generated using the NewWave and Optimized Sea techniques, thus allowing the influence of vessel response history on ship motions to be investigated. Random irregular waves, not exhibiting abnormal wave characteristics, were also used as comparators. The height of the abnormal wave tested in was defined relative to the sea state using the abnormality index and relative to the encountering vessel using the length index developed during the course of this research. Motion measurements are compared to prediction using 2D linear strip theory, and 3D partly nonlinear seakeeping theory, both showing good overall agreement and the latter showing better agreement with increasing forward and wave height. The severity of motions experienced by the frigate in abnormal waves increases with forward speed, until the frigate appears to be tunneling through the abnormal wave. Response history is a dominant contributor to ship motions, particularly at higher speeds and it is, therefore, essential to include it. The unexpected nature of abnormal wave occurrence means that it is important to consider additional factors such as likely operating condition and ship speed at the time of encounter when considering implications for ship design.

Vasquez et al. (2013) carried out experimental and numerical investigations on a bulk carrier stationary and travelling (Fn = 0.1) in irregular head waves with embedded abnormal waves. Two abnormal waves were used based on existing records, e.g. the new year wave. A segmented model, with the segments connected by force transducers, was used for the experiments and heave and pitch motions and amidships VBM were recorded. The numerical predictions were obtained using a 2D rigid body time domain method, including nonlinear hydrostatic and incident wave contributions, whilst the radiation component is based on the mean wetted surface hydrodynamics in the frequency domain and accounted for through IRFs. In addition the effect of green water, but not that of slamming, is included. The authors noted that the nonlinear effects in the numerical predictions were small, attributed to the hull shape of the bulk carrier. The overall agreement between experimental measurements and numerical predictions is good for Fn = 0, but VBM is overestimated for Fn = 0.1, especially for the more extreme wave condition. The authors observed that for the bulk carrier tested the influence of green water on the global loads was not important. With reference to the effects of forward speed a maximum increase of 27% for the VBM was observed for the more extreme case, although it is difficult to draw conclusions as only one non-zero forward speed case was tested.

Bennett et al. (2012b) compared experimental measurements of rigid body motions and global wave-induced loads of a naval frigate in abnormal waves to predictions made using a 2D linear hydroelasticity method. Experiments are conducted using a segmented, flexible backbone model of a typical naval frigate constructed of four rigid segments attached to a uniform aluminum backbone. The model was designed to match the natural frequency of the 2-node vertical bending moment. VBMs were measured at midships and the aft and stern quarters. The 2D linear hydroelasticity model idealized the vessel as a non-uniform Timoshenko beam and slamming was included via the Ochi-Motter impact slamming model. Qualitative agreement is seen between experimental measurements and 2D linear hydroelasticity predictions of VBM in abnormal sea states. However, the numerical predictions in general overpredict the maximum VBMs experienced. It is thought that this may be due to no consideration being given to the nonlinear effects when evaluating steady state components and future work should consider this. Furthermore, the maximum VBM along the vessel occurs at the aft quarter in experiments and amidships in predictions.

Zhao and Hu (2012) carried out experimental and numerical investigations on a 2D box shaped body, with a superstructure for green water simulation, in abnormal waves, focused and combined with a regular wave. The aim of their investigation is to assess how the RANS CIP (Constrained Interpolation Profile) -based method performs with extreme waves, ignoring turbulence and surface tension effects. There is good agreement between numerical and experimental wave profiles. Motions in the vertical plane, heave and pitch, and pressure on deck were measured in the experiments, with the longitudinal displacement constrained. Good agreement between predicted motions and measurements is obtained for the focused wave, but the predictions are smaller than the measurements in the more realistic case of the combined wave. The method also underestimates the pressures on the deck, but the overall qualitative agreement between predictions and measurements is satisfactory, showing that the method in question is suitable in modelling highly nonlinear phenomena. Zhao et al. (2014d) continued these investigations by refining their 2D numerical model by incorporating a more accurate free surface capturing method based on VOF. They also allowed for the surge motion, both in the experiments and numerical investigations, comparing the influence of constraining this motion. Only the focused wave was used in this work. When the surge is constrained, the agreement between experimental and numerical predictions for the motions shows some improvement, especially for the pitch motion. In the case when the box is free to surge, there is underestimation of the pitch motion attributed by the authors to the increasing complexity of the flow. With reference to the pressure on deck, the improved free surface capturing results in small improvements in the predictions. Nevertheless, the pressure is underestimated, when surge is either constrained or not, by comparison to the experimental measurements. The authors also investigated the influence of grid density on their predictions using coarse, medium and fine grids. The effect of grid density is small on the motions with the coarse grid providing closer predictions to the measurements. The on-deck pressure predictions are influenced more by the grid density, with the middle grid showing the best overall agreement, still underestimating, and the fine grid having issues with the first pressure peak when surge is not constrained.

Hu et al. (2014) investigated the interactions between a freak wave and a beamlike structure using 2D numerical modelling, equivalent to assuming that the beamlike structure is infinitely long in the athwartships direction. Nevertheless, their investigations are of interest due to (i) coupling between a

RANS (VOF) solver and (linear) FE method, through iterating the fluid pressure field and velocity and deformation of the structure at each time step; (ii) the successful generation of a, long-crested, freak wave based on real measurements; and (iii) the use of different boundary conditions for the beam, including a rigid beam. There are no comparisons of the predictions with either experimental measurements or other numerical predictions. Their observation that the beam deformation affects the bottom impact pressure, in the sense of pressure reducing with increasing deformation, is of interest. They also observed that there were relatively small differences between *dry* and *wet* natural frequencies, probably due to the 2D simplification of their modelling approach.

With ship encounters with abnormal waves occurring more frequently, it is important to assess whether such encounters are causing ships to operate beyond the limits of the design rules. Bennett et al. (2014) experimentally assessed the global loads experienced by a typical naval frigate in a range of abnormal sea states generated using the Optimized Sea technique. Experiments are conducted using a segmented, flexible backbone model (Bennett et al., 2012b) operating at its service speed of 18 knots full scale, in head seas. Measured VBM values are compared to those obtained from the design rules for naval vessels (Lloyd's Register, Bureau Veritas and Det Norske Veritas), both with and without allowances for extreme wave events. The presence of an abnormal wave event in a sea state increases the maximum VBM the frigate experiences by up to 2.5 times compared to in an equivalent random sea. The severity of slams experienced by the ship increases significantly with 40-60% of slams having a forefoot emergence of greater than 25% the ship length. The authors recommend that, in order to have a sufficient safety margin, design rules that account for extreme waves should be used; however, there were still some cases where this did not appear sufficient and these require further investigation.

Likelihood of occurrence of abnormal waves in relation to recent climate changes is an extremely important subject area affecting the consideration of abnormal waves when evaluating design loads. Accordingly two fairly recent papers are singled out for inclusion in this report. Vanem et al. (2014) dealt with uncertainties in the climate modeling and the effects of abnormal waves on the wave bending moments of ships. This may significantly affect the safety level of existing and newly developed ships; thus, it is an important area of concern. The uncertainties in the modeling of both the climate changes and in the modeling of the wave statistics are significant and conclusions vague. Without claiming generality, when comparing historical with simulated data, surprisingly the statistical mean and up to the 90% statistical quintiles of the historical data of wave heights are higher than the simulated future data for some selected scenarios. Also, the standard deviations are larger for the future projections, whilst the statistical upper tails are longer. The interpretation of this behavior and the consequences/conclusions on the way ahead are very crucial. In a further paper by the same research team, Bitner-Gregersen et al. (2014) presented the impact of climate change and extreme waves on tanker design. The study indicates that observed and projected changes in wave climate will have large impact on tanker design practice. Necessary increase in partial safety factor(s) and/or revised specification of the characteristic wave bending moment need to be further investigated.

3. SHIP STRUCTURES– SPECIALIST TOPICS

3.1 Slamming and Whipping

Impulsive slamming loads and the consequent vibratory response, namely whipping, continue to be the focus of numerous investigations, as commercial fleets face increasingly rough seas due to climate change and tight schedules. The modeling of water impacts and the calculation of whipping response along with their statistical combination with wave loads remain crucial aspects in assessing ship structural strength.

Analysis of the water exit phase in slamming problems has been the focus of many investigations. Korobkin (2013) used a potential flow formulation for describing the loads acting on 2D and axisymmetric floating bodies that suddenly start moving upward at a constant acceleration. The unknown size of the wetted area is determined by the condition that the speed of the contact points is proportional to the local velocity of the flow. This condition provides a nonlinear Abel-type integral equation which is solved explicitly. Predicted hydrodynamic forces are compared with the CFD results for a rigid wedge of deadrise angle 10° and a circular cylinder which enters the water and then exits by Piro and Maki (2011) and Tassin et al. (2013). Piro and Maki ((2011), (2012)) investigated the 2D slamming problem focusing in particular on the exit phase of a rigid wedge of deadrise angle 10° which lifts at constant acceleration. Their numerical approach for the air-water flow exploits a finite volume solver from the OpenFOAM library and is applied to an ALE form of the N-S equations. This approach allows computing the solution on moving and deforming meshes whereas the free surface is captured with a VOF technique. Conditions of the impact are selected in such a way that the speed of the wedge becomes zero before the wedge is completely wetted. Piro and Maki (2011) compared the computed slamming force with Wagner and Von Karman predictions, which overestimated and underestimated the slamming peak, respectively, with respect to the CFD approach. On the other hand the exit force time series from the CFD simulations by

Piro and Maki (2012) compared well with the experimental force measured by Tveitnes et al. (2008). Furthermore, Piro and Maki (2013) coupled their CFD solver to a deformable structure, i.e. an elastic wedge, using a modal representation that was obtained from a FE modelling of the wedge with beam and plate elements. A linearized boundary condition is used on the common interface to eliminate mesh deformation. In the case of a rigid body experiencing constant acceleration, a satisfactory agreement is obtained during water entry with Wagner theory and, during water exit, with the von Karman model. In the general case, accounting also for wedge flexibility, the numerical method is validated by comparing the structural response with the theoretical results by Korobkin et al. (2006) for hydroelastic impact at constant velocity. The hydroelastic effects were found to be important for a wide range of loading conditions, depending on the imposed entry velocity variation, where the rigid quasi-static solution was shown to underpredict the maximum deflection or stress and the rigid dynamic solution may underpredict or overestimate them.

Tassin et al. ((2012a), (2013)) addressed the 3D problem by solving the 2D problem of a body with time-varying shape (2D + t approach). Each 2D problem was studied by using the modified Logvinovich model (MLM) during the entry stage and the von Karman model during the exit stage. This combined MLM-von Karman model was applied to the vertical water entry and exit of the wedge studied by Piro and Maki ((2011), (2013)). It was found that during the entry stage these two methods agree very well. The agreement during the exit stage is in general good; however, the CFD results by Piro and Maki predict a longer duration and a larger force peak of the exit phase than the von Karman method.

Renewed attention to the water impact problem was motivated also by the analysis of aircraft landing on the water surface (ditching problem) as one of the goals of the SMAES FP7 funded project, as reported by Iafrati et al. (2014) The experiments were performed in the new CNR-INSEAN facility that was designed for performing water impact tests at the full-scale ditching speeds up to 180 km/h. The instrumented elastic plates of the fuselage are attached to a nacelle which is pushed by a crossbow system along inclined rails ending in the tank water. This is the first facility of its kind ever built for this purpose. Accurate prediction of the negative forces in the rear part of the fuselage during its landing was shown to be important in terms of the aircraft motion and the bending stresses in the fuselage. The ditching problem was also studied by Hua et al. (2011). To simulate the fluid-solid interactions caused by low speed ditching, the authors proposed a 3D dynamical structural model of the full-scale airplane including the wing and the control surfaces but disregarding the plastic deformation during impact. The FE model was coupled to an ALE fluid field model, and the computational model was then solved within LS-DYNA nonlinear FE code. No comparisons were given with either experimental data or other numerical methods.

The exact prediction of the wetted area affected by slamming requires some additional assumptions in the approaches based on the solution of the Laplace equation and, in this respect, some authors pointed out a similarity between the local flow close to the separation point in the problem of water exit and the problem of oblique impact with separation, in particular in the cases where there is a relevant horizontal speed. Reinhard et al. (2012b) implemented three different criteria for the rear separation point in blunt body water impacts with large horizontal and freefall vertical speeds. It was shown that the choice of the separation condition significantly changes the contact point limiting the wetted part of the body, the applied loads and then the predicted motion of the body. Reinhard et al. (2012a) imposed Wagner's condition for the rear contact point to achieve a solution for the oblique hydroelastic impact of a plate into the water. It was shown that the bending stresses in the plate may exceed the yield stress but ventilation decreases the bending stresses compared with a non-ventilated plate. Reihnard et al. (2013) described in detail the fully coupled model developed for representing the elastic plate impact onto the free surface of an incompressible fluid. In this paper they assumed that the fluid is attached to the plate from the turnover region to the trailing edge, so that any suction fluid forces contribute to the dynamics of the plate. The structural equations are solved by modal superposition subjected to a hydrodynamic pressure field along the wetted part of the vibrating plate for which an explicit formula is provided. The authors highlighted that if one applies to the elastic plate the pressure determined from the problem of rigid plate impact, then the bending stresses are overestimated. It was confirmed that the shape of the free surface, the hydrodynamic pressure and the flow, are all sensitive to the plate vibrations.

Tassin et al. (2012b) developed a simplified method based on the displacement potential formulation and the BEM for modelling the impact pressure field on 3D bodies of different shapes. Particular attention is devoted to the analysis of the wetted surface and the predicted slamming force is compared with existing results and with a series of impact tests carried out with a hydraulic machine. The application of a desingularized variational numerical method to the vertical hydrodynamic impact problem of axisymmetric bodies is addressed within the so-called generalized von Karman model by Santos et al. (2012). The 3D body penetrating the free surface is represented at each time instant as a double body built on the wetted part alone of the entire body. The method does not account for the description of the free surface pile up, as in the von Karman theory, but added mass contribution to the slamming force can be accurately computed for any 3D axisymmetric shape and were compared with WAMIT in the case of a sphere and an oblate spheroid.

Water entry of sandwich panels was recently studied because of their potential higher efficacy in absorbing slamming impacts with respect to panels made of homogeneous materials. Xiao and Batra (2012) employed the BEM for computing the loads on several 2D rigid hull sections because previous computations using LS-DYNA software (Das and Batra, 2011) exhibited fluid penetration at the solid boundaries. The authors compared the slamming pressure predictions with analytical solutions, other BEM results and experiments for straight wedges with deadrise angles ranging between 4°and 45° and curved bow sections, obtaining a satisfactory agreement overall. Subsequently Xiao and Batra (2014) coupled this BEM code to the FE solver of a sandwich panel to study the delamination problem during water entry of an elastic wedge with deadrise angles equal to 5°, 10°, and 14°, respectively. The sandwich panel was modelled with a layerwise third order shear and normal deformable plate/shell theory. At each time step the velocity and acceleration of the body and its local deformations are updated according to the condition that the hydrodynamic pressure varies within a prescribed tolerance; otherwise iterations in solving the panel-fluid interface equations restart (two-way coupling). In particular, they found that the consideration of geometric nonlinearities, namely nonlinear terms in the strain-displacement relations, significantly increase the peak slamming pressure experienced by the panel. The presence of delamination, studied including the cohesive zone model into a third order shear and normal deformable plate/shell theory, reduces the pressure acting on the panel surface. Delamination affects then deformation values compared to the case where the structure behaves linearly. No comparisons are presented against experimental data or other numerical methods.

Abrahamsen and Faltinsen ((2012b), (2013)) considered the effect of air pocket entrapment in 2D slamming phenomena caused by a free surface wave impinging a rigid wall. The air pocket during compression due to slamming is represented as an underdamped mass-spring system. They also derived a new analytical formula for the oscillation frequency of the entrapped air pocket, showing good agreement with BEM and sloshing experiments (Abrahamsen and Faltinsen, 2011). It was shown that the Topliss et al. (1992) formula is not accurate for large air pockets close to the free surface. The differences between the boundary element solution and the analytical formula showed also that the results are sensitive to the assumed shape of the air pocket. Abrahamsen and Faltinsen (2013) improved the scaling theory proposed by Lundgren (1969) which involved only the pressure amplitude but not the rise time. The proposed approach is based on fitting experimental data relative to pressure time history (Abrahamsen and Faltinsen, 2011) with a simple mathematical model governed by two parameters, denoted as kinematic parameters.

Lv and Grenestedt (2013) studied the sensitivity of the response of a hull bottom to a moving slamming load. Several parameters such as bending stiffness or pressure travelling speed were used. Both the structure, modelled as a linear Euler-Bernoulli beam, and the slamming load, using piecewise constant representation, are simplified. This is a 2D one-way coupling model and these assumptions allowed the authors to calculate analytically the dynamic solution without any dependence of the load on the response. The authors pointed out the existence of slam load travelling speeds at which bending moments and deflections are significantly amplified. Kim and Paik (2013) developed a design formula for predicting permanent deflection of stiffened plates and grillages under impact pressure loads acting uniformly in space and constant in time, i.e. square wave, on the wetted side of the plate. The method is verified by a comparison with nonlinear FE methods of stiffened plate structures under impact loads. The calculated permanent deflection at the center of the plate was slightly overestimated with respect to ANSYS/LS-DYNA results. The largest difference, of the order of 10%, was reached in the case of small plate thicknesses. Though the hydrodynamic slamming load is extremely simplified, the conceived expressions allow inclusion of the slamming problem into the structural design process. To calculate the added mass of elastic wedges impacting on the water, the discrete vortex method was proposed by Fu and Qin (2014). The same geometrical approximation of Wagner's theory is used and the structure is represented by a modal decomposition. The numerical results relating to the added mass matrix in case of small deadrise angles are in good agreement with analytical ones for the rigid wedge or with numerical ones provided by Khabakhpasheva and Korobkin (2013) for the case with the deadrise angle set to 10°.

Analysis of more complex geometrical configurations has motivated further efforts in implementing sophisticated computational methods. Panciroli et al. ((2012), (2013)) experimentally and numerically analyzed the water slamming of elastic wedges made of composite panels. In both papers the 2D hydrodynamic load was computed using the SPH formulation available in LS-DYNA, accounting for hydroelastic effect due to two-way coupling with the FE solver. In the first paper (2012) attention is mainly devoted to assess the calculation of hydrodynamic loads using SPH through comparison with strain responses recorded in free fall impact tests for various panel thickness, deadrise angle and impact velocity values. Results are in acceptable agreement in the initial stage of the water entry in terms of maximum strains, but accuracy suffers when the wetted zone becomes more fragmented at the late impact stages. Panciroli et al. (2013) focus on capturing the hydroelastic effects on stresses in case of large flexibility of the wedge panels. First it is shown that the experimental vertical acceleration of the free falling body is dependent on the wedge configuration, which could be one of these in the impacting part: cantilever plates, simply supported plates and plates clamped on both sides. In the case of wedges with clamped panels, the solution obtained with the FE/SPH coupled model compared well with results available in the open literature in terms of normalized pressure. Subsequently, the sensitivity of the solution with respect to the ratio between the wetting time and the first natural period was analyzed and was found to affect significantly the peak pressures. The BEM based on velocity potential and fully nonlinear boundary conditions in the time domain was applied by Sun et al. (2015) to solve the problem of a 2D wedge entering waves with gravity effect. The gravity effect was found to be relevant for the pressure distribution as the impact time becomes comparable to the ratio of the entry speed to the gravity acceleration. At the same time, impacting a wavy surface results in differences to the pressure distribution on the wedge sides depending on the wave height and wavelength. Scolan and Korobkin ((2012), (2013)) developed a potential flow theory for an elliptic paraboloid entering vertically a liquid surface on which a regular wave propagates. The Wagner problem is posed in terms of the displacement potential for achieving an analytical solution. Comparisons with experiments and the MLM show good agreement in predicting the initial rise of the vertical force at the early impact stage. Moore et al. ((2012), (2013)) extended the Wagner theory for the normal impact of 3D rigid bodies that are nearly parallel to the water surface. They highlighted that the points at which the free surface turns over in the solution of the Wagner model for the oblique impact of a 2D body are directly related to the turnover points in the equivalent normal impact problem. This observation allowed the authors to discuss the limits of applicability of Wagner theory to 2D oblique impact problems. Thus, for a symmetric body profile, they found that free surface elevation can be considered symmetric after proper change of variables, but this property is not transferred to the leading order velocity potential or pressure. Wang and Guedes Soares (2013) studied the 2D water entry of a bow-flared section, previously used in drop tests by Aarsnes (1996), with different heel angles using an explicit FE code in order to assess the influence of heel on the slamming pressures and forces. The modeling technique of the FSI adopts the explicit FE code LS-DYNA based on a multi-material ALE formulation and a penalty coupling method. The computed vertical force agreed well with BEM predictions irrespective of the heel angle, even if a significantly lower peak value was found at the maximum heel angle of 28.3°. In general, experimental values were found to be equal or lower than the computed ones with important discrepancies for hell angles larger than 10°. Maximum values increased with increasing heel angle and vertical impact speed for all the approaches considered. Pressure time histories were also compared but relative trends showed less clear interpretations. Yang and Qiu (2012) computed slamming forces on 2D and 3D bodies by solving N-S equations with a CIP-based finite difference method. In the case of wedges the numerical predictions agreed well with BEM results and experiments in terms of the pressure coefficient. They also investigated the free fall of a catamaran segment and a finite length cylinder, for which experimental data in terms of penetration velocity and maximum depth are available, respectively. The agreement was acceptable in both cases. A 3D Cartesian cut cell free surface capturing method was developed by Hu et al. (2013) for water entry problems and applied to rigid wedges and the generic Bobber heave type wave energy device. A high resolution Riemann-based finite volume flow solver for the air-water fluid domain was also implemented and results were compared with available experimental data. Nguyen et al. (2014) studied the water impact of various 3D geometries, namely a hemisphere, two cones and a free falling wedge, with an implicit algorithm based on a dual-time pseudo-compressibility method. Flow fields of incompressible viscous fluids were solved using unsteady RANS equations. A second order VOF interface tracking algorithm was developed in a generalized curvilinear coordinate system to track the interface between the two phases in the computational domain. Sensitivity analysis with respect the spatial grid resolution and the time step was performed so as to assess the accuracy of the results. Free surface deformation, pressure coefficients, impact velocities and vertical accelerations during impact are compared with available experimental data and asymptotic theory, showing good agreement at a reasonable computational cost.

Several papers were devoted to including/coupling slamming load predictions into seakeeping codes. Greco and Lugni (2012) employed the Ochi criterion for identifying the presence of water slams in the time history of the ship motion provided by a 3D numerical solver. The predicted pressures were then compared with experiments in Greco et al. (2012). A more complex approach for violent FSI, combining a potential flow and a N-S solver within a domain decomposition strategy, was then proposed by Greco et al. (2013) for handling slamming and water-on-deck phenomena at an acceptable computational cost. All three papers are discussed in more detail in Section 2.2. A benchmark study performed by the ISSC 2012 Committee II.1 Dynamic Response was reported by Drummen and Holtmann (2014). Several approaches for calculating the slamming loads in head regular waves, namely BEM over 2D sections and RANS solvers provided by ANSYS-CFX, Star-CCM+ and Comet, were considered and their capability for predicting the induced VBM of a flexible structure was compared. The reference experimental data were provided from seakeeping tests of a scaled segmented model of a long ferry. The method that generally performed better in predicting bow forces and amidships VBM was based on a fully coupled FSI computation based on the Comet RANS solver for fluid dynamics and a Timoshenko beam for structural representation. This paper is discussed in more detail in Section 7.1. Tuitman et al. (2013) pointed out the need of using a nonlinear seakeeping model, including the slamming load computation, for improving the stress analysis when using realistic 3D FE models. Slamming, Froude-Krylov force and hydrostatic loads included nonlinearities, whilst the diffraction and radiation loads were kept linear to reduce the computational effort. This analysis, though disregarding hydroelastic coupling, appears to provide significant improvements in estimating the ultimate stress on structural details compared to linear 3D BEM. A generalized Wagner model was exploited by Kim and Kim (2012) for the evaluation of slamming loads within a FSI solver, also discussed in Section 2.3, coupling a 3D Rankine panel method with structural models of different complexity, namely Timoshenko-Vlasov beam model and a 3D shell-based FE representation. The generalized Wagner model required dividing the bow part of the hull into 2D strips for which slamming pressures are computed and then applied to the structural models of a 6600 TEU containership and the scaled segmented model of a 10000 TEU ULC. Comparison of the different approaches with experimental data from scaled model experiments showed the code's capability of describing the slamming induced response. A practical procedure for computing the long term distribution of combined wave and whipping bending moments of container ships was proposed by Corak et al. (2013), discussed in more detail in Section 7.1.

3.2 Sloshing

Sloshing is the motion of free liquid surface inside a container and of practical importance with regard to the safety of relevant transportation systems. So far, many researchers have devoted their efforts to studying liquid sloshing problems. Over the course of the reporting period, newly proposed analytical methods, designed experimental setups and developed numerical schemes have been applied to improve the understanding of the sloshing phenomena. Due to the growing LNG market, hence, increasing size of LNG ships and tanks, sloshing has become of increasing concern for designers. Large impact loads induced by sloshing on tank walls may lead to structural damage and also have effects on ship motions and loads.

3.2.1 Analytical methods

Based on their previous work, Faltinsen and Timokha (2012) derived a new Trefftz representation for the sloshing velocity potential for the liquid sloshing problem in a 2D circular tank. This solution included a modified Poisson integral depending on the fully continuous component of the strength functions and terms that are proportional to the jumps of the strength function at the tank top. This work provides an analytical presentation for the sloshing velocity potential that is applicable for higher tank fillings and has a clear mathematical and physical treatment for the linear and nonlinear cases. Numerical experiments with the present solution using different base functions were conducted. Agreement with others' published results is good, suggesting that this solution can approximate the natural sloshing modes accurately for both lower and higher tank filling levels.

Ikeda et al. (2012) studied nonlinear liquid sloshing in a 3D square tank subjected to oblique horizontal excitation with an improved model. In their theoretical analysis, besides the two predominant sloshing modes, five higher sloshing modes were considered by applying Galerkin's method to derive the modal equations of motion. Linear viscous terms were incorporated to consider the damping effects. Van der Pol's method was applied to determine the frequency response curves for sloshing. Experiments were conducted with various excitation frequencies and excitation angles. The quantitative agreement between the theoretical results and the experimental data confirms the validity of the theoretical analysis. Since damping effects were taken into account in their study the obtained frequency response curves, containing both stable and unstable steady state solutions, for amplitudes and phase angles can clearly explain the phenomena of nonlinear sloshing dynamics in real systems. In their study, it was also concluded that higher sloshing modes play a significant role in improving the accuracy of the frequency response curves.

To theoretically study sloshing phenomena in a 2D rectangular tank in shallow water, i.e. low filling conditions, Antuono et al. (2012) proposed a modal system starting with a set of Boussinesq-type equations with a linearized dispersive term. Based on a spatial Fourier decomposition and capable of representing a generic 2D motion of the tank, this system employs a spatial modulating term to include the exciting forces. This leads to a formulation that is consistent with the conservation of momentum and energy of the flow. Comparisons between experimental measurements and numerical simulations validate the capability of the proposed model. The authors also pointed out the validation of the proposed model confirms that depth-averaged equations can provide a good description of sloshing motions when the water depth is shallow and the waves are non-breaking.

Faltinsen and Timokha (2013) were the first to construct an analytical method of nonlinear sloshing in a spherical tank. Using analytically approximate natural sloshing modes and curvilinear spatial coordinates, (i) general fully nonlinear modal equations, (ii) weakly nonlinear modal equations and (iii) Moiseev-Narimanov modal system were derived, respectively, for the spherical shape. In their study, the three systems play different roles. The first one is of auxiliary character while the second can be considered as a basis for the third system. The latter was emphasized in this study to construct an asymptotic time-periodic solution and classify the steady state wave regimes appearing as stable and unstable planar waves and swirling for spherical tanks theoretically. The results were compared against experimental data and good agreement was achieved for the liquid depth to radius ratios between 0.2 to 1. Discrepancies were found for higher ratios (i.e. between 1 to 2) due to the secondary resonance. The formulae for a square-based tank developed by Faltinsen et al. (2003) were extended by Takahara and Kimura (2012) and Takahara et al. (2012), suggesting that the method for the square-based tanks might have uses for appropriate engineering applications.

3.2.2 Experimental investigations

Ji et al. (2012) studied the nonlinear sloshing experimentally with the aid of the time history of wave elevation at the sidewall, free surface profile captured by high speed camera and velocity vector flow field obtained by PIV technique. In this study, non-resonant sloshing under the deep water filling condition was considered in a harmonically oscillating (surge) rectangular tank with breadth of 60 mm, length of 300 mm and height of 180 mm. Based on the experiments, they found that four regimes of sloshing waves can be categorized: mild 2D wave, strongly nonlinear 2D wave with hydraulic jump-like motion, 3D wave with regular structure in the longitudinal direction, and 3D chaotic wave. In their study they focused on a comprehensive discussion on strongly nonlinear 2D wave and they concluded that this off-resonant sloshing problem can be characterized into a combination of three sloshing motions: (i). standing waves during run-down process similar with linear sloshing, (ii) hydraulic jump along the vertical wall during the run-up process and (iii) bore motion propagating from the sidewall to the interior fluid region resembling a dam break during stationary process. The authors presented time histories of wave elevations on the tank wall, wave profiles and velocity vectors at selected time instants to show the evolution. These can be used to validate relevant numerical models.

To measure the impact pressure with accuracy during the sloshing process excited by large sinusoidal sway motion, Pistani and Thiagarajan (2012) setup a sloshing experiment in a 2D rectangular tank. In their study, the artificial pressure spike acquired by the transducer when measuring in the two-phase environment was resolved by lowering the excitation voltage of the sensors. Details of the analysis of characteristics of the pressure traces during the impact of the fluid and their location in the tank were also discussed, for a 30% filling level only. In addition, they proposed a strategy for defining a threshold pressure based on the transducer location and sloshing impact time.

Kim et al. (2013f) introduced the sloshing experimental facility at the Seoul National University (SNU). Recently, SNU equipped a new experimental facility for sloshing model testing, and this paper summarizes recent research and experimentation carried out. In particular, this paper focuses on the experimental setup, post-processing of measured signal, and findings from recent sloshing experiments. Their findings, being useful to those engaged in experimentation, are summarized as follows:

- Integrated circuit piezoelectric (ICP) sensors are sensitive to the change of contact medium. Temperature difference between the sensor and contact medium (i.e. gas or liquid) must be minimized before sloshing experiment. Sensors of the same type, diameter and linearity can show different results. Therefore, the pressure sensors need to be carefully chosen and applied to sloshing experiment.
- The density ratio of liquid and gas should be carefully handled in sloshing experiment sand analysis. The present experiment showed generally higher sloshing impact pressure with the higher density ratio of gas and liquid applied. Thus, when sloshing model test is performed, the consideration of the density ratio of liquid (LNG) and gas (NG) which satisfies that of actual LNG cargo is recommended in model tank.
- The current pressure-visual synchronized system may provide some important correlation between impact pressure and instantaneous flow velocity. The current PIV system showed oscillatory velocity field during sloshing impact occurrence. This type of observation is helpful for the development of numerical simulation code and understanding the relationship between kinematics and dynamics during sloshing.
- Statistical properties of peak pressure are dependent on the size of the time window in sloshing experiments for both regular and irregular motion excitations. In the case of sloshing experiments at

SNU, regular excitation required about 500 cycles for reasonable convergence and about 50-hour motion excitations were suitable for irregular motion.

Zhao et al. (2014a) carried out scaled model tests for an FLNG section excited in roll by white noise waves. Comparison studies of the vessel motions using fresh water and equivalent steel ballast weights are conducted. The following conclusions are drawn from this experimental investigation: (i) the spectral peak of the roll motions shifts to a lower frequency due to the changed center of gravity and the moment of inertia for the reference filling conditions in the study; a spectral peak of the internal sloshing oscillations is observed at the corresponding excitation frequency; (ii) sloshing at the head and the following sides of the inner tank exhibits similar responses for the reference configuration in this study; (iii) prominent RAO peaks of the internal sloshing oscillation have be observed for the excitation frequencies that are equal to the natural frequencies of sloshing in different modes; (iv) a large RAO of the internal sloshing at some excitation frequencies does not necessarily correspond to a large RAO of the vessel motions. Only one filling condition was selected as the reference. Therefore, great care is required when extending this study's conclusions directly to cases of translational motions and other filling levels.

3.2.3 Numerical simulation

To model the air pocket impact during sloshing in a 2D rectangular tank, Abrahamsen and Faltinsen (2012a) used two numerical methods applied at different stages of the simulation. Before the wave touches the roof, a new numerical method called the boundary-element finite-difference method was developed to simulate the two-phase flows. The water domain was discretized by a BEM while the air flow was modelled by a finite-difference method. The interface is tracked in space, satisfying fully nonlinear boundary conditions and remains sharp during the simulation. After the wave touches the roof and the air pocket is entrapped, a MEL method is used. The air pocket is then modelled by a polytropic gas law, whilst the water flow is modelled by a potential flow theory. Comparison between numerical result and experimental data shows that this numerical model overestimates the peak pressure inside the air pocket by 17% which may be caused by errors in the initial air pocket volume or the 3D effects.

Godderidge et al. (2012b) developed a mathematical model using a phenomenological modelling approach based on the pendulum equation. The equations were numerically solved by a variable-order Adams-Bashforth-Moulton scheme. Damping characteristics were replicated using a first and third order model. The use of modified impact potential makes the model capable of simulating nonlinear sloshing with fluid impacts. Godderidge et al. (2012a) applied this model to evaluate its capability in simulating sloshing in a rectangular tank at critical filling levels. Good agreement with other CFD method showing that the *rapid method* is sufficiently accurate and suitable for the fast time assessment of sloshing.

Guo et al. (2012b) applied the newly developed finite volume particle (FVP) method based on the fully Lagrangian frame work to simulate the sloshing flow in a 3D circular tank. Four sloshing cases were studied numerically and experimentally. The first two cases are the typical sloshing for a single liquid phase and studied the influence of the circular wall geometry in a sensitivity analysis. The free surface behavior and hydrodynamic pressure are also reported. Sloshing motion and its time of occurrence were compared with experimental data and generally good agreement was observed, while the maximum wave height was overestimated by the present method due to the difference in the initial condition between simulation and experiment. The second two cases simulated the sloshing with solid bodies to preliminary verify the applicability of the FVP method. Good agreement against experiments indicates that the FVP method can be applied to simulate 3D sloshing waves. Recently, Li et al. (2014b) employed a numerical model based on Finite Volume method to simulate sloshing in a 2D rectangular tank with the tree-based adaptive algorithm. The VOF scheme was adopted to capture the free surface. A series of sloshing experiments under roll excitation with various excitation frequencies and filling levels were carried out, obtaining pressure measurements to validate the numerical model. During their experiments, they found that the 3D effect was more sensitive to the increase of the frequency than the filling levels. They also reported that in lower excitation frequencies cases, standing wave dominates whilst travelling waves are barely found. In all cases investigated the numerical predictions match the experimental data fairy well.

SPH is a popular mesh-free, Lagrangian particle method with attractive features in modelling free surface flows. Shao et al. (2012) used a re-normalization approach to approximate density and applied a corrective kernel gradient to achieve better accuracy with smooth pressure field. Their method is aimed at simulating incompressible liquid sloshing, using the artificial compressibility technique. They also incorporated the RANS model to consider the turbulence effects. A coupled dynamic solid boundary treatment (SBT) algorithm was proposed to improve the accuracy near the solid boundary. Three sloshing case excited considering horizontal and roll excitations, both without baffles, and horizontal excitations with baffles in a rectangular tank were simulated, for a range of filling levels. Good agreement between the present SPH model and the experimental measurements without baffles and other numerical predictions validates the effectiveness of this numerical model. Based on this SBT algorithm, Chen et al.

(2013b) proposed further improvements to the SPH model by applying a smaller acting distance of repulsive boundary particles. They also utilized Moving Least Squares method in the density re-initialization to obtain better pressure field. Based on the improved SBT, a new pressure measurement method on solid walls was also given, which took a pressure correction term into account. A series of experiments were carried out using a 2D square tank with 30% filling levels excited by sinusoidal roll motions with four different excitation frequencies. The numerical predictions matched the experimental data well and improved pressure results were observed with this numerical model showing less fluctuations. Recently, Gotoh et al. (2014) proposed two schemes to improve the incompressible SPH-based methods used in the simulation of 2D violent sloshing flows with a particular focus on sloshing induced impact pressure. They comprised a higher order Laplacian of Poisson Pressure Equation (PPE) and an Error Compensating Source of PPE to minimize the instantaneous and accumulative projection-based errors. According to the authors' discussion, there are two error sources in this scheme which are related to the instantaneous variation of particle density and the deviation of particle density from the theoretical constant at a certain time step respectively. Comparison of predictions with available experimental measurements for sloshing in a rectangular tank excited by sinusoidal sway and roll motions, 16% and 33% filling levels, respectively, showed excellent agreement emphasizing the enhancing effects of the proposed numerical model. In their study, the importance of dynamically adjusted coefficients of error minimizing terms in the source term of PPE was highlighted, which is shown to be superior relative to a scheme with constant coefficients.

3.2.4 Sloshing with internal suppressing structures

In recent studies, baffles are the most used devices to restrain the sloshing motions. Wu et al. (2012a) developed a 2D numerical model to study the viscous fluid sloshing in tanks with baffles. The sloshing motion is captured by the time independent finite difference scheme while to simulate the baffles, the fictitious cell approach is applied. With the help of the stretch technique of the grid system, the local phenomena of the flow motions around the baffle tip can be captured. An experimental investigation of liquid sloshing in a rectangular tank with baffles was carried out, for surge motion and filling levels of 50% and 25%. Good agreement between the wave elevation measurements and the numerical results indicate that their present numerical model can be applied to analyze the sloshing motion in 2D tanks with internal structures. Jung et al. (2012) investigated the effect of the vertical baffle height on liquid sloshing in a 3D rectangular tank, 70% filling level. The ANSYS FLUENT CFD code was applied solve the N-S equations and the VOF method is adopted to track the sloshing motion. In their study, it was found that the critical ratio of the baffle height to the initial liquid height is 0.3, beyond which the liquid cannot reach the roof of the tank. When the ratio is 0.9, minimized sloshing wave was obtained. When the ratio is larger than 1, the liquid could not go over the baffle and almost linear behavior was observed. To examine the effectiveness of various baffle arrangements and provide test data for the numerical validation, Akyildiz et al. (2013) designed an experimental setup to study the sloshing behavior with and without baffles in a cylindrical tank with various filling levels under sinusoidal roll motion. In their study, it was reported that ring baffle arrangements are very effective in reducing the sloshing loads. By contrast, Koh et al. (2013) developed a constrained floating baffle (CFB). An improved consistent particle method (CPM) which applies a combination of a zero-density-variation condition and a velocity-divergence-free condition was employed to simulate the sloshing in a 2D tank with CFB. Experiments, in surge excitation, were also conducted and good agreement with the numerical result validated the improved CPM. In addition, it was also found that the CFB was effective in suppressing sloshing motions.

Apart from baffles, perforated screens are also commonly used sloshing-suppressing devices. Molin and Remy (2013) conducted an extensive series of experiments to study the sloshing motion in a rectangular tank subjected to forced sway and rolling motions with a perforated screen, 53% filling level for both. In contrast to the experiments carried out by Faltinsen et al. (2011), they focused on measuring hydrodynamic loads by force sensors fitted to the test bench with constant open ratio of the screen and varied motion amplitudes. In their study, damping coefficients were found to be large over a wide frequency range. Thus, they concluded that Tuned Liquid Dampers need not be accurately tuned and can be effective over a wide range of excitation frequencies. Instead of vertical placed screens, Jin et al. (2014) performed experiments to test the effect of a horizontal perforated plate on liquid sloshing in a 2D 62.5% filled tank subjected to sway oscillations with various excitation frequencies and amplitudes. It was observed that the frequency, of the wave generated due to sloshing, was minimally influenced by the plates whilst the wave amplitude was significantly reduced. In addition, they concluded that the plates must be placed under and closer to the water surface from the bottom to offer better restraining effects.

3.2.5 *Sloshing and ship motions*

Wang et al. (2012) investigated the interaction phenomenon of sloshing motions and the global wave loads by seakeeping model tests of a self-propelled LNG ship with a liquid cargo tank, 30% filling level. It was noted that the existence of liquid in the tank affected the natural rolling period of the ship. The motion period of the liquid in the tank depends not only on the inner shape of the tank and the liquid filling level, but also on the wave heading angle and ship speed. Sloshing induced tri-axial total forces between the tank and the ship are different depending on wave length and travelling speed. The existence of liquid sloshing in cargo tank might reduce the global wave loads of LNG ships to some degree. Sloshing influence from more tanks on global responses of liquid cargo carrying ships in waves need further investigation by experimental and numerical methods.

Mitra et al. (2012) developed a fully coupled model of nonlinear sloshing and ship motion. The fully nonlinear sloshing motion was studied using a FE method, potential flow, and the nonlinear ship motion was simulated using a hybrid marine control system. Simulated roll motions were compared with existing results in waves. Fair agreement indicated that the proposed model was expected to be useful in evaluating the coupling effect. In their study, the coupling model also allowed for the effects of wind, wave and current. It was found that the wave height can have large effects on sloshing, whereas the current velocities caused fairly marginal effects on the ship motions.

Tsai et al. (2013) carried out a numerical seakeeping-sloshing coupling analysis for an 8,000 TEU container ship with some cargo holds partially ballasted, with sea water, to simulate a full load condition, to design draft, required in sea trials. This procedure is unusual compared to the conventional ballast condition in sea trials; the risk induced by resonance of ship motion and sloshing water in cargo holds has to be checked in the design stage. A frequency domain model is utilized in the hydrodynamic numerical code HydroSTAR considering high speed effect, and the analysis includes nonlinear seakeeping, linear sloshing and finally the calculation of the coupled equations of motion. The additional resonant frequencies, especially for the rolling motions, induced by the motion-sloshing coupling effect are clarified and their corresponding operational scatter diagrams, for heading direction change based on specific sea state, are provided. The structural strength of the ballasted cargo holds are to be assessed for those critical rolling motions through a fully consistent quasi-static method by a hydro-structure interaction numerical code HOMER, requiring hydro mesh and FE structure models. These results confirmed that the induced resonant frequency will occur with full load condition and full ship speed, especially for rolling motion, and may cause serious structural problems.

Recently, Zhao et al. (2014b) developed a 2D coupled model which brings together the nonlinear sloshing flows and linear ship motions, both based on potential theory, in time domain. Experiments were conducted to validate the numerical model. An FLNG section comprising an outer rectangular hull and an inner rectangular tank was used in this study. The filling level was 20% in the tank. The hull was freely floating in the wave tank subject to beam waves. It is similar to past experiments of a barge with a tank on top. Good agreement was achieved for all cases presented. Based on the verified model, the coupling between ship sway motion and internal sloshing was investigated. It was observed that the magnitude of the internal sloshing is nonlinear with the incident wave height, both the internal sloshing and the ship motion exhibited amplitude modulation phenomena and that the sloshing reduction effects on the global motions at the natural frequency are caused by the fact that sloshing force was π behind the wave force.

Kim et al. (2014) developed the multi-liquid moving particle semi-implicit (MPS) method. In particular, a robust self-buoyancy model and surface tension model were developed. They also have a new interface searching method for tracing interface particles in a reliable manner. The developed multi-liquid MPS method is validated by comparison with three liquid-sloshing experiments by Molin et al. (2012). The interfacial natural frequencies are simulated by a free decay test using the MPS program and the results are compared with linear potential theory. The simulated results agree well against both experimental and theoretical values. The authors observed that the interfacial elevations can significantly increase when the excitation frequency is close to the natural frequencies of the respective interfaces. Subsequently the verified multi-liquid MPS program is coupled to a vessel motion program in time domain. At each time step, the excitations induced by the inner multi-liquid-tank sloshing are fed into the vessel motion simulation and the resulting vessel motion is again fed back into the MPS module. For the case of multiple liquid layers, there exist more than one sloshing natural frequency; hence, the relevant physics can be much more complex compared to the single-liquid-tank case. From the numerical simulations, the authors noted that the wash tank operation in head wave condition is much more robust than that in beam wave condition. The vessel motions with the three-liquid cargo and the corresponding solid cargo were also compared, and it was observed that the wash tank with liquid cargo can also function as a beneficial anti-rolling device. Based on these comparisons it was concluded that the simple approximation using equivalent rigid cargo and ignoring coupling with liquid sloshing can be unreliable in the design stage. Since maximum vessel motions and maximum interface elevations can be checked directly, the developed vessel motion/multi-liquid-sloshing coupled program can be used as a reliable prediction tool for the safety and operability of a floating system with large multi-liquid tanks.

Paik et al. (2014) presented a new method for determining the design sloshing loads, peak pressure and impulse, for FLNG. They also showed an example to validate the method. Thirty scenarios were selected using the Latin hypercube sampling method and a series of numerical computations were undertaken on FLNG cargo containment systems. Based on the results obtained from the study, they conclude that their method is validated using applied examples; hence, feasible for application to FLNGs. The sloshing probability calculated in the study is based on a limited amount of motion data. Thus, if field measurement data were to be used with this method, the accuracy of the sloshing loads would be more reliable and robust.

3.3 Green water

As the wave breaks and overtops the structure, the flow becomes multi-phased and chaotic as a large aerated region is formed in the flow in the vicinity of the structure while water runs up on to the structure. Thus, the so called green water is generated, which may cause significant damage to facilities and equipment on the deck of the platform. In addition, green water can have strong impact on the stability of marine structures depending on the amount of inundation and global momentum transfer. Green water loads occur when an incoming wave significantly exceeds the free board and water rushes onto the deck. Thus, any increase in the frequency of occurrence and severity of hurricanes implies that structures in the ocean are at higher risk of exposure to extreme waves and green water loads.

Determination of green water loads can be categorized into three methods as approximate, numerical and experimental (ISSC, 2012a). Approximate methods are simple and fast but less accurate and can be used at early design stage. Numerical methods are suggested for more accuracy. Although in most numerical studies conditions are more artificial. The major problem with this approach is excessive computational time. Furthermore, it is not yet possible to obtain realistic results without reflection from the boundaries of the domain. 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 numerical methods. Although it is realized that 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.

Despite the difficulties associated with analytical research, work in this area continued. Masoud (2013) proposed theoretical calculation of 2D nonlinear wave loads on a horizontal deck of a coastal structure located in water of finite depth, based on the Green-Naghdi theory of water waves or Euler's equations. It appears that the girders do not have any influence on the vertical force, and only a small influence on the horizontal force. The effect of formation of air pockets between the girders, in a model of an elevated bridge deck, was studied by adding air pressure relief openings to the deck of the structure. It was found that the entrapment of air pockets increases the vertical uplift force significantly. Results were compared with available laboratory experiments and linear solutions showing a close agreement. This case can be applied to ships with zero forward speed, e.g. moored.

Experimentally, the results of Lee et al. (2012b) for three different FPSO bow shapes in regular head waves were analyzed and compared to each other. Based on these results, a database for CFD code validation was built, such as peak pressure, and some design considerations were proposed. The experiment also shows that pressure peaks were closely correlated with the incoming wave amplitude for each wave length, which can be interpreted as a quadratic relationship between the pressure and velocity of the flooded water on deck. Ariyarathne et al. (2012) examined impact pressure on the deck area of a 3D model structure in a laboratory and related the impact pressure to the measured velocity as well as the void fraction on the deck. Xiao et al. (2014) carried out an experimental study to investigate the wave run-up and green water along the broadside of the 300000 DWT FPSO with a tower yoke mooring system in shallow water, considering non-collinear environments and different water depths. The impact of the motions and the gap between floater and seabed on the relative wave elevations and wave run-up is examined in details. It is shown that the impact of the gap is evident on all the wave elevations along the broadside. Moreover, the impact of vertical motions on the wave elevations along the broadside is relatively small and almost negligible for a large FPSO exposed to extreme waves in shallow water. Buchner and van den Berg (2013) studied experimentally the nonlinear wave reflection along the side of ships which can lead to green water on deck for moored and sailing ships, with a simplified test setup of a thin plate at an angle to the wave direction. The observed processes with plunging and spilling breakers close to the plate made clear that linear or second order models will not be able to predict this behavior accurately. It was concluded that higher order methods, that could include wave breaking, or CFD are necessary for a prediction of these important effects. These model tests can be used as important validation material. The experimental and numerical investigations by Greco and Lugni (2012) and Greco et al. (2012), which combine seakeeping and green water analyses, have already been discussed in Section 2.2.

Lu et al. (2012) developed a numerical time domain simulation model with VOF technique to study the green water phenomena and its impact loading on structures. Numerical simulations of green water problems carried out in this study include: (i) green water overtopping a fixed 2D deck, (ii) green water impact on a fixed 3D body without or with a vertical wall on the deck and (iii) green water impact on the deck and deckhouse of a moving FPSO model. Numerical results are compared with experimental measurements for both the water height on the deck and the impact pressure on the front wall of the deckhouse for each case, and show fairly good agreement. Xu (2013) examined the case of an extreme plunging wave impinging onto a horizontal deck, simulated by the enhanced, incompressible, SPH method. A first order density smoothing procedure and a density diffusion term in the continuity equation were introduced to smooth the pressure field. A series of simulations were carried out to verify the stability and accuracy of the numerical model. These include a hydrostatic simulation, a bubble rise problem and a dam break simulation. The benchmark studies showed that the enhanced SPH model developed is able to capture details of complex wave-structure interactions including the flip-through phenomenon. The simulations clearly show how the bifurcation of the impinging crest front could lead to the formation of a strong jet (*tongue* in 3D) that eventually collapses onto the topside of the deck. The remaining portion propagates forward under the deck, leading to higher pressures on the underside of the deck. These results contribute to shedding more light on the dynamics of green water on the topside of a deck in extreme waves. Zhao et al. (2014e) aimed their investigation on assessing the influence of the DoF of a floating body on the maximum impact pressure due to green water on deck. In experiments the DoF can be adjusted by a heaving rod and a restrained spring connecting the carriage and the guide rail. Their numerical method combines a 2D CIP model and VOF-type tangent of hyperbola for interface capturing/slope weighting (THINC/SW) approach. Experimental water surface elevations, body motions and impact pressure were compared with the numerical results for different DoF cases, and the agreement is satisfactory. Green water on deck and impact on the deckhouse is generated by the impingement of a focused wave group on the floating structure. The results show that the peak impact pressure due to green water decreases rapidly with increasing DoF.

Kim et al. (2013d) introduced hybrid CFD method for modelling and simulation of green water load on deck. Their method involves a combined approach of linear seakeeping and nonlinear CFD analysis, both using 3D modelling of the hull. Two large containerships were considered for analysis, for a range of headings. Damage cases of container carrier in way of breakwater and main supporting members were studied. Relative bow motion is considered as the dominant load parameter (DLP). An equivalent design wave for this DLP is used for CFD simulations, modelled as 5th order Stokes wave. Analysis procedure for the direct calculations of design pressure on breakwaters using advanced CFD method is provided in this paper. Newly proposed coefficients for design pressure are compared with IACS UR S3 and found to be reasonable, though on the higher side.

Ruggeri et al. (2013) evaluated numerically green water events in a box-shaped FPSO structure in regular beam waves for a captive model. The potential flow method WAMIT was used for quick checks, whereas CFD software StarCCM+ was used for detailed flow study. 2D and 3D approaches were modelled in CFD. Free surface elevations amidships were compared with experimental results. It is concluded that the 2D approach can be used only for few relatively long waves, whereas for the entire wave range, 0.75 L_{PP} to 1.5 L_{PP} in this paper, the 3D approach is recommended.

Joga et al. (2014) extended application of CFD methodology to simulation of green water to find the rate of water ingress into open holds of a container vessel. Two CFD solvers, StarCCM+ and ANSYS-CFX, were used to model the full scale ship in waves and the effect of water ingress. Computations were carried out only for beam waves and zero forward speed. Various heading and speed combinations were not considered for comparison with experiments due to higher computational requirement. Significant differences between the water ingress predictions of the two solvers and the experimental results were observed, the latter extrapolated from model scale. STARCCM+ results underpredict the mass flow rate, though relatively close to experimental rates. On the other hand, the mass flow rate predicted by ANSYS CFX is much higher compared to the experiments. However, vessel motions computed using both solvers were in line with experimental results. It is concluded that the differences in water ingress predictions are mainly due to free surface capturing by the VOF method and much refined mesh requirement in the region of open holds of the vessel.

Pakozdi et al. (2014) investigated the viability of a simplified coupled method between a potential theory based green water engineering tool, Kinema3, and the commercial CFD tool Star-CCM+. Results from a case study application on a large FPSO are validated against model test data. The case study contains analyses of the FPSO in long-crested regular and irregular waves, both in fixed and moored conditions. Three different headings are included. The approach for modelling green water events uses a

Finite Volume VOF method with a complex velocity inlet boundary condition. Thus, the Kinema3 engineering tool is used to generate simplified spatio-temporal inlet conditions from the relative wave elevation and wave kinematics at the bulwark, based on linear potential theory combined with nonlinear random wave kinematics. The VOF method is then used to model the detailed flow on deck, including impact forces on deck structures; that is to say, that only the deck is modelled in STARCCM+. Kinema3 can also generate simplified estimates for the peak water height, velocity and impact force values, assuming an extended dam-break approach together with a simplified, local 2D deck layout. Comparisons with the Kinema3-STARCCM+ results show an overall fairly good agreement, although flow details on deck can, of course, not be expected to be modeled that well. Comparisons of both aforementioned sets of results to model test data show good agreement for the relative wave height, water height and impact force level, in regular and irregular waves. Detailed time histories, including force rise-time, from the coupled Kinema3-Star-CCM+ CFD simulation analysis are quite similar to the measured ones. The CPU time consumption for the coupled simulation is moderate, compared to what would have been for a full CFD simulation. Hence, the simplicity of the simulation setup, the quality of the results and the CPU time efficiency makes this method a viable candidate for industrial use.

Considering the new offshore frontiers for oil exploration and production, in particular the Santos Basin region, FPSOs will be exposed to more severe wave conditions. This scenario requires more careful analysis with reference to the green water phenomenon. The complex physics involved in the water-on-deck flow implies several uncertainties regarding green water load analysis. Carvalho and Rossi (2014) proposed a methodology, taking into account model tests, CFD simulations and analytical formulations, to estimate the green water loads considering the water elevation above deck measured from experiments or numerical tools. In order to accomplish this objective, CFD simulations with different solvers were run for a benchmark case, showing that it is a suitable approach for a global result in dam-break cases. The term global is used with reference to the pressure computed on block due to the dam break. Other results include wave elevation at various locations. The CFD codes used were: ANSYS CFX, ANSYS Fluent, StarCCM+, Edge CFD and Petrodem MPS. The exploratory CFD benchmark case results showed that this technique is appropriate for complex free surface flows. Comparisons were carried out with experimental measurements by Kleefsman (2005). Although a more comprehensive and systematic evaluation should be done with respect to the differences between experiments and simulations, the simulation results reproduced the most critical pressure time series with approximately 5% deviations. Furthermore, CFD simulations using ANSYS CFX were carried out to simulate green water events for a typical Santos basin FPSO, together with model tests. Using a combined approach with experiments, a special boundary condition was calibrated to reproduce critical green water events for beam sea condition. In this special boundary condition the inlet surface boundary condition was switched to an open boundary at a particular time. This was done so as to avoid water accumulation in the deck area. Such calibration of the model allows for a detailed flow analysis. Considering the promising results from the benchmark case, this strategy can be used effectively in determining green water loads. Based on a critical event, it was found that the classical dam-break approximation for green water analysis can be very useful for estimating loads on structures, even in complex cases where appendages, in this case the riser balcony, have a clear influence on the flow. In order to extend this formulation to an even wider range of situations, the correction for objects having a vertical gap with respect to the platform deck was verified against CFD simulations, showing good agreement and including a safe margin. The new formulation is then combined with the local water elevation measurements, resulting in a green water loads evaluation procedure. The load reduction of vane type protection barriers is addressed through CFD simulations and, after a parametric study, the effectiveness of each barrier configuration is estimated. For the most efficient protection arrangement, the final load was one third of the original load.

Schiller et al. (2014b) addressed a significant green water problem in the Santos Basin using Kinema3, which is a simplified, yet robust, prediction tool of green water and wave impact on FPSOs in steep nonlinear irregular waves. Given the multi-directional wave conditions in the Santos Basin, the authors expanded this tool’s capabilities to consider arbitrary wave directions. Their study case was the FPSO-BR model provided by Petrobras. Predictions were validated against results from model tests performed at Marintek. A good agreement between the Kinema3 green water predictions and the model test records, especially for head seas was observed. For quarter-beam and beam seas, a satisfactory agreement was obtained with an adjustment of the empirical factor e_f, which is a small non-linear contribution to the relative wave height that is related to the amplification of the wave elevation due to interactions with the vessel. For quarter-beam and beam seas, a lower e_f factor is necessary, which can be interpreted as wave dissipation processes. For beam seas, the low value of ef is also partially due to the larger importance of roll motion, which may have a mean value and a low frequency component in reality. A progressive decrease of ef with increasing heading angle was observed. The authors conclude that additional verifications with CFD tools and model tests are necessary in order to clarify the relationship between ef, wave heading and the nonlinear wave-structure interaction. The authors also showed that the application of Kinema3 to arbitrary wave directions was a successful step in tackling new challenges associated with the green water problem. One major challenge in the Santos Basin is the bi-directionality of sea states. Although wave impact from the largest waves, coming from S-SW, may be minimized by heading the vessel towards S-SW, the analysis demonstrated that the vessel may be subject to significant green water from E-SE beam seas. The authors showed that beam seas produced the largest green water problem with respect to occurrence, intensity and FPSO deck area affected by water impact.

3.4 Experimental and full scale measurements

In the last few decades, the investigation of complex FSI problems related to slamming phenomena has motivated not only the need for reliable simulation, but also more challenging objectives for experiments in model basins and for sea trials. In this section, therefore, recent research aimed at studying wave-induced high frequency response by means of experimental tests and full scale observation is discussed. Measurements related to sloshing and green water are reviewed in Sections 3.2 and 3.3, respectively.

Lavroff et al. (2013) carried out an extensive experimental investigation of wet-deck slamming in regular head waves using an elastically scaled model of a wave-piercer high speed catamaran. The segmented model consisted of three parts with the forward part comprising the forward demi-hulls and the center bow as a separate segment. The sophisticated design of the catamaran model allowed measuring the slamming vertical force acting on the center bow and the vertical bending moment along the demi-hulls in order to identify the critical conditions in the operational envelope of the vessel. Slamming occurred in a range of the encounter frequency that was found to be relatively larger in the case of the higher regular wave amplitudes and the induced loads were approximately proportional to the wave amplitude squared. The longitudinal position of the slam impact on the center bow showed a small but significant dependence on the wave height and frequency. Wu et al. (2012b) discussed the capability of representing the bending full scale behavior with segmented models made of rigid segments and flexible joints. Several aspects, such as the number of segments and the stiffness distribution, are considered for accomplishing the hydroelastic scaling of a 13000 TEU containership. The authors found that 3-joint segmented structural model provides a sufficiently accurate representation of the real ship, if the hydroelastic effects depend mainly on the first vertical 2-node flexible mode. These hydroelastic effects in the vertical bending moment appeared not to be sensitive to the stiffness distribution among the flexible joints in a 3-joint segmented model. Hence, the authors concluded that the same joint stiffness can be applied when adjusting the model to achieve the targeted natural frequency of the first flexible mode. Zhu and Moan ((2013), (2014)) focused on the wave-induced nonlinear effects which appear in VBM response of ULCS. Zhu and Moan (2013) focused on the explanation of the differences between sagging and hogging VBM extreme values. Amongst well known sources of asymmetry, like nonlinearities in the hydrodynamic forces and ship hull geometry, in particular, they considered the nonlinear contribution to the overall loading due to the pressure field acting on the bow which affects mainly the hogging VBM. Two container ships, 8600 TEU and 13000 TEU, were considered with segmented model tests in regular and irregular head waves. Regular waves allowed the authors to clarify the role of super harmonics in increasing or decreasing the hogging and sagging peaks. High, but rather unrealistic, speeds for such ships in rough seas had a significant impact on the VBM asymmetry through higher order harmonics and high frequency vibrations mainly more in sagging than hogging. Zhu and Moan (2014) investigated the effect of regular and irregular oblique waves on extreme values of VBM for the case of a 13000 TEU ULCS. The authors found that the extreme values for both sagging and hogging were higher in oblique waves than in head waves. In particular, the second harmonics of the amidships VBM affected the peaks in regular waves to an extent which showed to be dependent on the heading angle.

Dessi and Ciappi (2013) investigated the slamming occurrence for a ferry cruising at high speeds with an elastic segmented model tested in irregular long-crested waves. They observed that the tendency of the slams grouping into sequences made of two or more events (clustering phenomenon) violated the hypothesis of their statistical independence. Sequences of closely occurring impacts were found to produce higher or lower global responses depending on the phasing with ship-beam oscillation excited by the previous impact(s). The combination of high speeds and high sea states was found to play a relevant role in inducing the slam clustering. However, a direct correlation between each slamming event and the encountered wave height, or even between the slamming severity and the impact velocity, was not always present. Time separation of slams inside a sequence was approximately equal to the natural pitching period of the scaled ship. A new criterion based on the wavelet analysis of the amidships VBM was then introduced to identify the occurrence of a slamming event, apart from the usual distinction between bottom or bow-flare slamming events. A slightly different version using filtering and Hilbert transforms for the analysis of transients is also presented by Dessi (2014a). Jacobi et al. (2014) applied a similar criterion to the identification of slamming events during full scale trials on a wave-piercer high speed catamaran. This criterion is based on the definition of a stress rate threshold, first proposed by Thomas et al. (2003). The choice of the strain gauge location proved to be critical for the correct application of the proposed slamming criterion: the strain gauge located in the centrebow archway and mounted on a stiffener cut out at frame 64 was at the end selected, as it clearly presented vibrations uniquely associated to slamming. To avoid false positive slamming events, the analysis of the stress time history needs to be combined with a second criterion detecting the downwards decelerating bow motion. Using this criterion, the number of slams per hour with a certain intensity can be determined and their dependence on speed, wave height and heading analyzed. The influence of the ride control system in alleviating the slamming stresses was found to be more relevant at high speeds. The existence of an overall trend, with a weak association, between the relative vertical velocities and the stresses occurring after the slam impacts was noted. However, the association is so weak that it cannot be used as a primary indicator of slam occurrence and magnitude, similarly to the case of fast monuhulls as shown by Dessi and Ciappi (2013).

Andersen and Juncher Jensen (2014) investigated the effect of hydroelastic high frequency vibration on the extreme hogging wave bending recorded onboard a 9400 TEU container carrier. The stress measurements amidships were obtained using two long-base strain gauges mounted in the passageways, port and starboard sides, just below deck approximately amidships. The wave field close to the ship could be estimated with the onboard wave radar and the rigid body response was recorded from an inertial motion unit. They found that the 2-node mode is, by and large, responsible for the ship vibrations even in quartering seas, with no evident torsional contribution, and that the hydroelastic contributions may double the stress levels at some instants. Thus, their analysis brought to attention the possibility that predicted total wave hogging VBM, accounting also for whipping loads, may exceed slightly the design stress values for that ship in extreme but realistic sea states. The combination of steady state wave loading with loads associated to whipping and springing is also analyzed by Barhoumi and Storhaug (2013) in the case of 8600 TEU container vessel, equipped with a comprehensive onboard hull monitoring system with 20 strain sensors for global and local hull response and monitored for approximately 4 years. On the basis of the strain data collected at various ship sections, the authors found that the contribution of whipping to the reduction of fatigue life and to extreme loading is important in particular zones of the ship structure. Though fatigue appeared as a less relevant issue for the east Asia routes compared to the north Atlantic ones, the effect of voluntary speed reduction and routing on the structural loads continues to be significant for this type of vessels.

Iijima et al. (2014) carried out an experimental investigation on the post-ultimate strength collapse behavior of a ship's hull girder under whipping loads. The 1/100 scaled model comprises two rigid bodies, a connecting deck hinge and a sacrificial specimen amidships which bent under the relative rotation of the two segments. The mechanical properties of the model and, in particular, the ultimate bending strength follow the similarity law proposed by Wada et al. (2010). The tests were conducted keeping the model afloat on the water and the whipping loads were artificially reproduced by dropping an object onto the ship section. It was observed that the sacrificial specimen collapsed less when the whipping loads had a shorter duration, indicating that the collapse may not occur to a large extent under impact loads. An original experimental approach of 3D water impact at constant speed was presented by El Malki Alaoui et al. (2012). The hydrodynamic force acting on axisymmetric rigid bodies striking a horizontal liquid surface at constant vertical speed was investigated using a hydraulic shock machine, which allows carrying out impacts at high speeds with small deviations in the velocity. Comparisons between theoretical model, numerical results, also discussed by Tassin et al. (2012b), and available experimental measurements are reported in this paper showing an acceptable agreement.

Dessi (2014b) presented a technique based on a combination of proper orthogonal decomposition and spline approximation for reconstructing the unsteady distribution of sectional loads due to waves along a ship hull. To validate the proposed technique, the hydrodynamic lumped forces acting over hull segments were initially made available by calculating numerically the sectional loads and then spatially integrating these loads over the segment sections. The set of time-varying segment forces constituted the input data from which the original sectional load distribution was successfully reconstructed. The robustness of this technique was tested against the presence of noise in the input data. This approach was used by Dessi (2013a) for obtaining the experimental slamming load distribution in regular wave tests with a segmented hull. The time history of the forces acting on each segment was measured with load cells and the sectional slamming force at each time step was extracted on the hull sections subjected to water impacts. Thus, a greater detail in the spatial load distribution can be obtained from experiments with segmented models and structural ship design can benefit from reliable load data with improved resolution.

Several papers dealt with signal processing techniques for highlighting some features of the ship vibratory response. Kim et al. (2013e) proposed the use of the cross correlation between the wavelet transforms of the ship response and an ideal and tailored IRF to extract the whipping part of the response.

The authors successfully applied this technique to a realistic signal obtained from the WISH-Flex simulation code. The analysis of the ship vibratory response was also considered by Mariani and Dessi (2012) for identifying the wet operational modes in terms of shape, frequency and relative energy associated with each elastic mode, with proper orthogonal decomposition which does not require the measurement of the exciting force. They compared seakeeping tests of an elastically scaled model in head waves for different sea states, with/without slamming as the case may be, highlighting how energy is captured mainly by the 2-node vertical bending mode. Damping estimation of the experimental whipping mode using the random decrement technique (RDT) or the autocorrelation function (ACF) was considered in a successive paper by Dessi (2013b), using the same dataset used by Mariani and Dessi (2012). The damping values were found to be different depending on the particular signal processing technique, RDT or ACF, used and on the choice of some parameters within the same technique. The random decrement technique in combination with the wavelet transform was also applied by Kim and Park (2014) to data obtained from elastic model tests for damping identification of the wet bending modes. The authors explained the differences in modal damping estimation between still water conditions and forward speed in waves with the presence of viscous effects.

Ikeda and Judge (2014) carried out a series of tow tank experiments performed on a 1.2 m model hull in regular waves. Pressures on the bottom of the hull were measured on one side with traditional point-pressure sensors and on the other side with pressure mapping pads. The goal of this research is to study the fundamental physics of the water impact of high speed planning hulls and to measure the slamming loads and resulting motions of the craft upon reentry into the water after becoming partially airborne. A set of towed model experiments was conducted in calm water, regular waves and irregular waves to capture a sequence of individual impact events. The pressure signals from the pressure pads (providing both spatial and temporal resolution) and the point-pressure measurements (high temporal resolution) have been presented for individual slam events, allowing a deterministic approach to investigating high speed planing craft wave slamming.

3.5 Loads due to damage following collision/grounding

One area that has become of great concern to the design and operation of ships is that of accidental damage. Accidental damage to ships and, subsequent, flooding can occur in a number of ways, but generally damages due to collision and grounding are of primary concern, particularly for ships at high risk with respect to the loss of lives or pollution of the marine environment. Naturally, events of non-accidental structural failures leading to ship's loss are also of great concern for some ship types, e.g. the loss of containership MOL Comfort in June 2013. The aim of this section of the report is to focus on the load implications on the ship after the event, mainly on loads of hydrodynamic origin and not to replicate part of the work undertaken by Committee V.1 Accidental limit states.

The IACS Harmonized Common Structural Rules (CSR-H) (IACS, 2013) are aimed at checking the hull girder ultimate bending capacity in the damaged state for the seagoing condition to ensure that it satisfies the residual strength checking criteria. Accordingly the VBM, M_D, in hogging and sagging conditions, to be considered in the ultimate strength check of the hull girder in the damaged state is obtained as:

$$M_D = \gamma_{SD} M_{SW-D} + \gamma_{wD} M_{wv} \tag{1}$$

where $M_{SW\text{-}D}$ is the permissible still water bending moment, M_{wv} is the rule vertical wave bending moment (VWBM), $\gamma_{SD} = 1.1$ is the partial safety factor for the still water bending moment SWBM) in the damaged condition and $\gamma_{WD} = 0.67$ is the partial safety factor for the VWBM in the damaged condition. The general characteristics of global loads on damaged ships are apparent from the partial safety factors included in Eq.(1). The SWBM may increase with respect to permissible SWBM in intact condition, whilst the rule VWBM is considerably reduced. The most dangerous situation is the flooding of ballast compartments in the amidships region, causing increase of sagging SWBM in the vicinity of the damage. Downes et al. (2007) performed a case study on an Aframax tanker showing that in the full load condition 10% of the cases lead to an increase in sagging SWBM of 25% or more of the allowable SWBM. The literature review of increases of SWBM used in structural reliability assessments of damaged oil tankers is presented by Burić et al. (2012), where they found that SWBM in sagging may in some cases increase by a factor of two compared to the intact SWBM.

Differences between wave load effects employed for intact and damaged ships arise because of the effect of flooding on the calculation of hydrodynamic loads, as well as from different environmental conditions and exposure times to be taken into account. Downes et al. (2007) suggested two practical approaches for calculation of hydrodynamic loads on a damaged ship. The first is the added mass approach where the seawater which floods into the vessel is assumed to become part of the vessel's mass and moves with the vessel. For calculating the hydrodynamic forces, the damage opening is assumed to have negligible impact on the overall hydrodynamic properties of the hull. This approach should be accurate for damage extents which are small compared to the size of the tanks which are breached. The second approach is applicable for larger breaches, where the damaged tank and all of its mass are removed from the vessel, as well as its surface area from the hydrodynamic model. The hydrodynamic interaction between the waves and the structure of the opening needs to be modelled.

Reduced exposure time to environmental conditions after damage should be considered before the ships is taken to a safe location. Prestileo et al. (2013) modelled the damaged ship by the added mass approach with 24 hour of exposure to a sea with a heading of 210^{O} and a speed of 5 knots. Reduced exposure time is counteracted by the hypothesis that the damage has occurred because of adverse sea conditions, so the sea state envisaged after the accident is not a normal but a severe one. The truncated diagram was used by removing half of the complete scatter diagram characterized by lower wave height, less than 8.5 m, and keeping only the most severe sea states. The aforementioned choice of truncation and exposure time yield results in terms of average extreme VWBMs which are approximately 80% of the corresponding value for the intact ship in her entire life.

Lee et al. (2012c) applied a computational tool based on a 2D linear method to predict the hydrodynamic loads for a damaged warship. They obtained larger VWBM for damaged condition, compared to the intact ship. The global dynamic wave-induced loads calculated using 2D linear method are also compared to measurements. In head and stern quartering waves, the differences between the computations and measurements of global dynamic wave-induced load response amplitudes are reasonable. In general, however, linear strip theory overestimates measurements for both intact and damaged ship conditions.

Stettler and Thomas (2012) presented a detailed flooding and structural engineering study to accurately model, simulate and evaluate the progressive flooding, sinking and structural failure of the historic Titanic following her collision with icebergs. Detailed computer flooding analysis models were developed, and novel techniques for dynamic flooding simulation using the commercial software GHSTM were developed and implemented. The resulting loads of these detailed flooding simulations were applied to structural FE models using MAESTROTM for conducting detailed stress and hull failure analyses. The technical documentation of the developed computer models, including sources of information, assumptions, conventions and methods, as well as the technical discussion of simulation results and the *lessons learned* are applicable to similar marine forensic analyses.

Spanos and Papanikolaou (2012) investigated the time dependence of survivability/floatability and stability of ROPAX vessels, when sustaining side collision damage in beam irregular waves using a 3D and 6 DoF nonlinear time domain simulation method for ship's motions and flooding, where the flood water mass is time-varying and oscillating in a coupled way with the ship motions. Conducted research confirms that ROPAX ships characteristically capsize fast, when sustaining damage leading to capsizing. A probabilistic analysis of the survival time after collision damage reveals that even for the most generic damage conditions assumed, the survival time in the case of capsizing remains short, which is characteristic of this type of ship design, exposing the typically large undivided deck to flooding in higher waves.

Dankowski and Krüger (2013) presented a progressive flooding method in still water which is based on the calculated flux between the compartments using a modified Bernoulli equation. Large and partly flooded openings are taken into account as well as optional air compression and flooding through completely filled rooms. The method uses a typical damage opening based on the generated damage cubes by a Monte Carlo simulation to perform a direct progressive flooding assessment for each critical intermediate case. The combination of flooding calculations with a Monte Carlo method extends the classical damage stability calculations to the time domain, which allows a more accurate estimation of the overall safety level of a ship to withstand damage. Furthermore, this method is very useful at the early design stage to identify critical intermediate stages of flooding. For the examples shown, a sudden capsize during the flooding process is observed after the vertical centre of gravity is increased by a specific threshold.

3.6 Weather routing and operational guidance

Most research with the aim of assisting the master in weather routing is focused on logistic optimization by formulating the problem of minimum time or minimum fuel consumption with constraints. Some efforts are aimed at weather routing taking into account seakeeping behaviour, loads and related measures and the consequences of weather routing on these parameters. These form the subjects reviewed in this section.

The research on weather routing can be divided into four types: (i) research with respect to a suitable and efficient optimization scheme, (ii) simplification of complex hazards in a seaway intended for on-line onboard operational guidance, (iii) monitoring of relevant measures onboard and (iv) a combination of the former three types to form an applicable onboard decision support taking into account the seakeeping behaviour and loads on a vessel.

The current state of the art in weather routing or operational guidance has not changed since the last report of this committee (ISSC, 2012b) The seakeeping characteristics of a vessel are considered through the RAOs. In combination with a standard wave spectrum and integrated sea state parameters, such as significant wave height and average zero-crossing period, the linear spectral analysis predicts the response of the vessel for all risk control options. A review of the current state of the art is published by Papanikolaou et al. (2014), where the importance of including uncertainties in the analysis and the consequential need for an efficient probabilistic method are emphasized. A simulation result is presented by Delitala et al. (2010). A route optimization software was applied to the output of a limited area weather model and to a wave model. They concluded that weather routing would improve ship performance and would support ship masters virtually.

A number of papers are devoted to the development of optimum path finding systems with the use of existing environmental data and mathematical models for ship response. Voluntary or involuntary speed reduction is taken into account in some of them; however, little progress can be found with regard to the load estimation. Lee et al. (2011) propose a multi-resolution planning method, which appears to be suitable for including wave effects as well. Panigrahi et al. (2012) advocate the use of Dijkstra's algorithm for a better handling of the voluntary speed loss in the optimization procedure. By applying a Bézier curve for the description of a ship's route, Ishii et al. (2010) demonstrate that only a few variables are needed to generate an optimum route. Though the model has only been tested to minimize transit time, it is possible to include ship responses as well. Lin et al. (2013) propose a 3D modified isochrome method to be applied for weather routing which is able to address safety concerns. Parametric rolling is taken into account as a risk by Maki et al. (2011), where the real-coded genetic algorithm technique is applied to globally search for the optimum route taking into account of the risk of parametric rolling as one of its objective functions. They concluded that it is easy to obtain a route that reduces parametric rolling probability using the proposed method.

More detailed investigations were carried out with reference to the load/response estimation as part of the routing simulation. A decision-analytic approach is introduced by Nichols et al. (2014) illustrating this approach using a detailed example of a ship in transit, where the goal is to minimize both transit time and probability of structural failure. Assuming that the structural integrity of the ship is governed by the aluminium stringers used in certain naval vessels for hull support, a simple model was used for predicting future damage states and estimating the probability of component failure by means of the spectral approach together with slamming impact force. The main conclusion is that a variable speed strategy compared to a fixed speed strategy is superior and the approach can be made adaptive to incorporate new information such as updated weather predictions. Decò and Frangopol (2013) set up a risk framework incorporating strength elements. In this work the midship section capacity is modelled using FE method including corrosion as a function of time and annual corrosion rate. The load effects are evaluated using strip theory. The dynamic VBMs are accounted for by general approximations based on L_{PP} and ships breadth. The framework is applied to the Joint High-Speed Sealift travelling between two points through a selected stormy sea weather map. In the case study the direct risk and reliability are precalculated such that the optimization process takes about 30 minutes. Three representative solutions with different normalized direct risk show that in relatively calm weather the optimum is the direct route, but in harsher weather the optimum route avoids the storm. Mao et al. (2010) presented a simplified fatigue model which can be used in ship routing. The simplified model is based on linear stress transfer functions, while whipping is considered by introducing a modified mean stress upcrossing frequency (f_z) based on the wave encounter frequency. Measurements on board a 2800 TEU container vessel showed that f_z is about 50% underestimated when using a linear approach. The modification of f_z is aimed at reducing the underestimation but accepting that the variability of the encounter frequency is transferred to the modified f_z. The comparison between the empirical distribution of the observed rainfall damage and the cumulated distribution of fatigue damage using the simplified method shows good agreement. The error of the accumulated damage based on the simplified method compared to the measurements is of the order of 10-20%. Mao et al. (2012) applied this procedure to two case studies, a 2800 TEU container vessel and a 4400 TEU container vessel. For most of the voyages, the highest fatigue damage can be decreased by 50% in the most optimal case.

Song et al. (2013) present an example of operational guidance to help the crew avoid dangerous situations by precalculations of roll motions using the IRF approach. The results are displayed in occurrence maps of parametric roll as a function of speed and heading, for a range of GM values and sea states. The authors address neither how the precalculations are efficiently presented to the crew nor the required quality of the input parameters, such as sea state and loading condition.

4. OFFSHORE STRUCTURES SPECIALIST TOPICS

The computational methods associated with the FSI of offshore-type structures have already been reviewed in Section 2.1. This section focuses on two important areas: namely vortex-induced motions and vibrations, and mooring systems. In addition, making use of the expertise in this Committee, a background review of lifting operations and floating offshore wind turbines is carried out. There is also a short section on wave-in-deck loads, due to differences with the green water problem of ships.

4.1 Vortex-induced vibrations (VIV) and Vortex-induced motions (VIM)

VIV and VIM are of concern in most offshore riser and platform designs when exposed to currents. The load induced by VIV and VIM could result in collisions of risers, fatigue damage of risers and mooring systems. Over the yeas substantial research work has been conducted to investigate, understand, predict, and verify VIV and VIM (Sarpkaya, 2004). Much progress has been made both numerically and experimentally toward the understanding of VIV and VIM. Nevertheless, there are still many challenges, such as how to deal with shear, how to evaluate single-span model test experiments versus continuous pipes, how to account for multi-modes and mode interference, how to suppress VIV at any Reynolds number (Re), large Re gaps between the computable and measurable ranges of VIV etc.

In offshore applications, the industry continues to rely on a semi-empirical method for the assessment of VIV-induced fatigue damage together with a relatively large safety factor, and rely on model tests for the motions of a floating unit due to VIM. Clearly there is still a lot of work ahead, not only because turbulence remains poorly understood but also because simulations are needed at a level that could be used for industrial design. In offshore engineering, most VIV studies have been focused on risers and VIM studies for spars, TLPs and deep draft semi-submersibles. This section covers the latest developments on the prediction, verification and mitigation of VIV and VIM in offshore applications.

4.1.1 VIV

Offshore risers are pipes that normally run from the seabed to a floater transporting oil, gas, water etc. Risers are susceptible to VIV, especially deep water risers due to their increased length which lowers the natural frequency values, thereby lowering the magnitude of current required to excite VIV. VIV is probably the single most important design issue for steel catenary risers for fatigue damage. Analysis methods currently used in the industry for the prediction of riser VIV mainly include frequency domain approaches and direct time domain simulations using CFD methods. One of the most important milestones of VIV frequency domain approach development is the research work in late 80s (Vandiver and Chung, 1989), and the software SHEAR7 was developed during that period using empirical models and mode superposition to calculate the motions of the riser. This software has been updated over the years to cover cylinders without uniform cross section, strakes and varying currents (Resvanis and Vandiver, 2011). Other popular frequency domain software for VIV analysis on slender marine structures are VIVANA and VIVA. Most current VIV analysis programs are limited to computing vibrations orthogonal to the current velocity only. Although riser VIV was once considered a cross-current vibration, it was found that the riser is actually oscillating in a figure 8-shape with an inline component. With the right current condition, the inline amplitude could reach the same level as that of the cross-flow component. Passano et al. (2012) reported the latest developments on VIVANA with its new inline prediction model.

It has been reported that all these software show a conservative bias in predicting fatigue damage by comparison with the data obtained from a number of full scale measurement campaigns in the fields. Tognarelli and Winterstein (2014) stated that software error statistics show markedly different behaviour in different regimes, e.g. for different levels of predicted damage. They suggested a non-parametric approach, in which software error statistics are sorted and separately analysed for different predicted damage levels. In a similar subject, Fontaine et al. (2013) presented a reliability based method which accounts for uncertainties in S-N behaviour, metocean conditions and software prediction for the assessment of VIV factor of safety for risers in the Gulf of Mexico.

Schiller et al. (2014a) investigated the effects of current profile, shear and directionality on the development and excitation of VIV for a deep water tensioned riser by employing a semi-empirical frequency domain approach. The study found that they all have an important effect on the development of VIV for the riser model studied. It was also observed in this study that uniform profiles, in particular those with high velocities, generate the largest VIV response of the riser. The findings are based on numerical sensitivity studies and there is a need to further understand how complex current profiles in the offshore regions affect VIV development in comparison to simpler profiles that are recurrent in model test conditions.

While the frequency domain approach is still the leading method in practical engineering for the fatigue damage assessments of risers due to VIV, there have been continuous efforts on VIV predictions using CFD approach. For example, Nguyen and Temarel (2014) investigated numerical simulations of flow past a circular cylinder in uniform cross-flow for a stationary cylinder, as well as forced and free oscillations of a cylinder using the 2D CFD RANS code ANSYS Fluent, at Re = 10,000. Comparisons with available experimental measurements and other numerical predictions, show that the essential features of the FSI are captured in the simulations with a reasonable mesh density. The authors draw attention to the influence of turbulence modelling on flow characteristics, such as lift and drag coefficients. Zhao et al. (2013) studied VIV responses of a cylinder in the combined steady and oscillatory flow by solving the 2D RANS equations, including k-ω turbulence model, using a Petrov-Galerkin FE method. It was reported that the lock-in regime in the combined steady and oscillatory flow is wider than either that in the pure steady flow or that in the pure oscillatory flow.

Holmes and Constantinides (2014) performed direct numerical simulations (DNS) of a riser VIV with large buoyancy elements and a general *lazy wave* shape through the use of efficient meshing strategies developed. A lazy wave riser is a riser with addition of buoyancy to provide this unique shape to reduce the dynamic stresses at the touchdown zone. To validate the developed method, comparisons between model tests and CFD model were made for the time history of displacement and RMS of the displacement from the mean position at 51 accelerometer locations along the riser. The CFD results show good agreement with the laboratory experiments. A general approach for building a CFD model with a length to diameter ratio of 10,000 and a lazy wave shape riser was presented and demonstrated with an example.

Tofa et al. (2014) presented two DoF numerical simulations of the flow-induced vibration of two equal diameter cylinders in tandem, with varying mass ratio, to investigate the effect of the upstream cylinder's mass ratio on the vibration of the downstream cylinder. The shear stress transport detached eddy turbulence model was used for the turbulent flow around the two cylinders. ANSYS-CFX software was used for the solution of the coupled FSI problem. The motions of the two cylinders were limited to the translational motions in the horizontal plane whilst other DoFs are fixed. It was reported that the upstream cylinder's mass ratio has a significant effect on the VIV of the downstream cylinder. This study may provide useful information on the assessment of potential risk of collision between closely spaced risers. The numerical results of a single cylinder subjected to two DoF vibration were validated with available experimental measurements.

Constantinides and Zhang (2014) presented a study on the VIV of a deep-water lazy wave riser using the AcuSolve FE N-S CFD solver. AcuSolve is based on the Galerkin/Least-Squares formulation and uses a fully coupled pressure/velocity iterative solver plus a generalized alpha method as a semi-discrete time stepping algorithm. The RANS model was selected for the analysis. VIV assessment of the riser was carried out using a CFD and semi-empirical software (VIVA, Shear7) approaches. The riser response at touchdown point obtained from CFD is close to that from VIVA, but larger than that from Shear 7. In the CFD simulation the lazy wave riser is modelled at full scale with actual structural models and the addition of buoyancy modules. It is the industry's first full scale CFD simulation for such a riser system. Different buoyancy region geometries are considered in the simulations. It was found that the selection of the buoyancy configuration is important for controlling VIV and the aspect ratio L/D of the buoyancy module is an important parameter for the riser's response performance.

A large number of model tests have been conducted for VIV during this review period. Jain and Modarres-Sadeghi (2013) presented experiments conducted on the study of VIV of a flexibly-mounted rigid cylinder placed inclined to the oncoming flow with one DoF. Angles of inclination from 0 to 75 degrees in the subcritical Re range of 500–4000 were considered. It was reported that the lock-in region started at a larger reduced velocity as the angle of inclination was increased. Sanaati and Kato (2012) performed experimental studies of the effects of axial applied tension on the vibration amplitude, the suppression of vibration, hydrodynamic force coefficients and inline and cross-flow frequency responses during VIV of a horizontally mounted flexible cylinder with a low mass ratio in the subcritical Re (= 1000–16000). The experimental results show that higher applied tensions could reduce the vibration amplitude and result in narrower lock-in bandwidths.

Gu et al. (2013) investigated the dynamic response of a vertical flexible cylinder vibrating at low mode numbers with combined x-y motion in a towing tank. The uniform flow was simulated by towing the flexible cylinder along the tank in still water. It was reported that the experimental model setup successfully simulated VIV phenomena and captured several useful characteristics of VIV, but the ratio between the cross-flow and inline motion was considered high compared with previous findings. Possible reasons could be the different characteristics of the riser model and experimental setup, as well as the small Re due to limitations of size and technical characteristics of the testing facilities.

Bourdier and Chaplin (2012) carried out experimental investigations to assess the influence of end-stops, placed on one or both sides of a beam connected to the spring-mounted frame supporting the cylinder, limiting the cylinder's motion through impacts with the end-stops on cross-flow VIV. Their setup, without end-stops, was validated against existing experiments. They used a range of offsets for placing the end stops. The impacts with the end-stops increase the stiffness of the system for particular offset values. Features observed in their experiments, depending on offsets used included: no evidence of lock-in, progressive growth in sub- and super-harmonics and chaotic motion. They also computed lift coefficients. Chaplin and Batten (2014) carried out a series of experiments with multiple DoF spring mounted cylinders. The carried out 3 sets of experiments (i) a cylinder with 1 DoF in both inline and cross-flow directions, (ii) a cylinder with 1 DoF in cross-flow direction operating in the wake of stationary cylinder, at a centre-to centre distance of 5 diameters, and (ii) a cylinder with 2 DoF in both inline and cross-flow directions operating in the wake of stationary cylinder, all in uniform current. For case (iii) a number of centre-to-centre and offset values were used. Their experiments show that, predominantly, wake-induced (low frequency) vibrations are in-line whilst vortex-induced (high frequency) vibrations are in the cross-flow directions.

Investigations were also focussed on mitigation of VIV of risers. It has been reported that properly designed helical strakes are effective in the mitigation of VIV fatigue damage for many riser applications. However, such strakes tend not to be applicable to offshore drilling riser applications due to increases in drag force as well as workability problems for drilling operations. Taggart and Tognarelli (2008) summarised studies on many VIV mitigation devices for drilling risers. It appears that the most effective method is to fit fairings along the riser string. Fairings can also reduce the current drag on the riser and extend the operability envelopes in strong current. The drawback is the additional cost of the fairings and the additional time to fit and strip the fairings during riser deployment and retrieval. On a different VIV mitigation method, Chen et al. (2013a) presented a study on utilizing a steady suction flow control method to mitigate VIV of a circular cylinder. The experimental study was conducted in a wind tunnel with a circular cylinder test model as a spring-mass system. The study includes the wind tunnel tests for a circular cylinder with and without suction flow and the results comparison. Five suction velocities were adopted to control the flow field surrounding the circular cylinder. The measurement results show good VIV suppression performance and the performance is related to the suction velocity. This was the first report of a project lasting for many years.

4.1.2 VIM

Floating platforms with cylindrical structures such as spars, TLPs, and semi-submersibles can be susceptible to VIM when exposed to currents. The occurrence of *lock-in* is related to the natural periods of horizontal motions of a platform, which is normally expressed in non-dimensional reduced velocity. VIM is most prominent in spar platforms, where most of the industrial experience has been acquired (API, 2008).

Spar platforms experience vortex-induced oscillations when their surge/sway or roll/pitch periods are close to the Strouhal number. Gonçalves et al. (2012) provided an overview of the influential aspects of the VIM of spars and single-column platforms, such as current heading, external appendages of the hull, concomitant presence of waves and currents, motion suppressors, draft condition, and external damping due to the presence of risers and mooring systems. Field measurements of VIM response have been recorded for 3 classic spars: Genesis, Hoover, and Neptune, and the measured data indicate inline motion is much less than that of cross-flow motion (API, 2008). It is also reported that no significant VIM responses have been recorded from the motion measurement systems installed on a number of truss spars. Helical strakes have commonly been used on spars to reduce VIM. Strakes can ideally be 95% effective in eliminating VIM. However, their effectiveness on spars depends on various factors, e.g. the exact layout and size of the strakes, appurtenances, and current profiles.

Although it has been noted that under certain experimental conditions multi-column floaters, such as TLPs and typical semi-submersibles, may experience limited VIM, there is no substantiated in-service evidence of VIM. Recently the semi-submersibles has become a favourable choice as a wet-tree or dry-tree floating platform supporting steel catenary risers (SCRs), mainly due to its capability of quayside topside integration and cost effectiveness. However, it is still a challenge for a conventional semi-submersible to support SCRs, particularly large ones, in harsh environments and relatively shallow waters due to its large heave motion. Deep draft semi-submersible with smaller heave motion could be a solution. Nevertheless, it has been reported that the deep draft (41m) semi-submersibles experienced VIM of the platform in loop/eddy current, which could pose a serious problem for riser and mooring fatigue life (Rijken and Leverette, 2009). Unlike spars, the studies on VIM mitigation for a deep draft semisubmersible are limited. Several new semi-submersible designs have been developed to reduce heave motion and VIM. Yu et al. (2013) presented a comprehensive overview of various technologies for dry-tree semi-submersibles.

Kyoung et al. (2013) presented Technip's design of HVS (heave and VIM-suppressed) class semi-submersible. The new design is a modification of the conventional deep draft semi-submersibles through the use of hull form optimization. The main characteristic feature of the HVS class semi-submersible is the redistribution of displacement from the pontoon to the column through the use of a column step that breaks up the vortex coherence along the column length and, in concert with the narrow pontoons, reduces VIM. Xu et al. (2012) presented the VIM validation study of the HVS semi-submersible through model tests and CFD simulations. In this study, the FE-based CFD software ACUSOLVE was used to predict VIM response of the hull configurations tested. Detached eddy simulation (DES), RANS with Spalart-Allmaras turbulence, and Large Eddy Simulation (LES) models were used. Model tests demonstrated that the HVS semi-submersible design reduces VIM response by approximately 50% compared to equivalent conventional semi-submersible design. CFD showed good correlation with the model test results. However, the sensitivity of the VIM response on the scale effect was not included in the study.

On a similar path, a new concept design of a paired-column semi-submersible (PC semi with 8 columns) has been developed by Houston Offshore Engineering to reduce VIM. The PC semi-submersible and a conventional semi-submersible are included in a project that will last for two years (REPSEA, 2013). The project is sponsored by Research Partnership to Secure Energy for America (RPSEA) and the scope of the project includes the testing design parameters for deep draft column stabilized floaters to determine which have the most impact on VIM, and which VIM mitigation strategies are preferred for deep draft semi-submersibles. A number of CFD simulations and model tests will be carried out for different conditions. Software Acusolve, ANSYS Fluent and STAR-CCM+ are used for the CFD simulations. The project is also to investigate the differences between CFD simulations of using model scale and full scale, as well as damping effects on VIM. The project is to produce guidelines on the use of CFD for VIM analysis and on the design of deep draft semi-submersibles with minimum VIM.

On a relatively broader scope, MARIN has organized a VIM JIP (2013-2016) to study VIM of offshore structures through model test, CFD simulations and prototype data evaluation. The JIP is to evaluate differences between model tests and CFD on the one hand and field observations on the other, and to provide guidance for VIM model testing and CFD studies.

Ma et al. (2013) presented the latest full scale VIM field measurements of a semi-submersible. It was reported that the actual severity and persistence of VIM is much less than forecasted according to field measurement data, whilst the results from CFD simulations, provided to the authors, and model tests are in good agreement. The paper provides some potential factors that could contribute to the differences between the model and full scale results, but the physical mechanisms behind the overprediction of VIM in model scale are still not fully understood. Investigations of the VIM of the same semi-submersible were also carried out by Wu et al. (2014), focusing on scale effect and damping effect due to mooring and risers, since a typical model scale in a VIM model test is 1:50, leading to the model scale Re being two to three orders of magnitude less than that at full scale. Furthermore, VIM model tests are typically performed in a towing tank without including mooring and risers. In this study, a CFD model is first built at model scale and the results are compared with model test data for validation. The CFD model is then modified to investigate, respectively, the scaling effects and the effects of mooring- and riser-induced hydrodynamic damping. The CFD analysis was performed using STAR-CCM+ and DES was selected as the turbulence model to resolve the unsteady vortex shedding at high Re. The motions of the hull in surge, sway and yaw is considered in the simulations and the equivalent damping effect was added to the simulations. The CFD results from the model scale were compared with model tests results, whilst the CFD results from full scale were compared with field measurement data. The results show a good correlation between the model tests and CFD simulations performed at model scale. Correlation is also found to be good between the CFD simulations performed at full scale and field measurements. The paper concluded that the full scale CFD simulation, with proper meshing and boundary conditions, can reproduce field VIM with confidence for headings that are critical for fatigue damage. The results also show that the hydrodynamic damping due to mooring and risers can act to reduce VIM substantially.

Holmes (2014) carried out studies on the VIM of a spar platform in a sheared current. This study was motivated in part by the problem of using flume tanks for the simulation of platform VIM in sheared currents. The AcuSolveTM FE CFD solver was used for the simulations to examine the effect of buoyancy forces, namely changes in density, on sheared current flows around offshore platforms. The study shows the buoyancy forces could have a strong effect on VIM. On alternative VIM analysis methods, Kondo (2011) reported a newly developed third order upwind FE scheme to solve the N-S equations numerically. The method has been applied to the analysis of inline and cross-flow vibrations of a 2D circular cylinder. The analysis results in good comparison with experimental results. Miyamura et al. (2014) presented numerical simulations for VIV of a cylindrical structure using Lattice Boltzmann method which is suited to parallel computation.

4.2 Mooring Systems

This section covers the latest developments on the methods and tools for mooring analysis, namely for calculation of fatigue and extreme mooring line.

It is possible to solve the cable dynamic equations in the frequency domain and a good option is to combine the nonlinear static solution with linearized dynamic solutions. The advantage is the computational efficiency. However, the lines' dynamic behaviour is inherently nonlinear and often the linear approach is not accurate enough. Most of the current state of the art procedures use nonlinear time domain solvers. There are basically two possibilities: the finite difference method and the FE method. The second is more general since it is able to better represent the slender elements' material properties. In fact, most of the models developed and applied in recent years are based on FE models of the mooring lines and risers.

Calculation of floating structures' mooring line tensions involves the solution of the coupled dynamic problem; that is to say, the motions of the floater, induced by waves, wind and current, are coupled to the mooring system (and risers) responses. Different solutions have been proposed in the past and they can be classified into frequency domain, time domain and hybrid frequency/time domain methods.

Frequency domain methods assume the mooring system forces are represented in the floater equations of motion by linear stiffness, damping and inertial matrices. The latter should be derived about the mooring system mean displaced position. The floater linear wave frequency dynamics and quadratic difference frequency responses are calculated separately and the relevant statistics combined afterwards. Frequency domain methods, e.g. Zimmerman et al. (2013), are efficient from a computational point of view and can sometimes be applied for fatigue analysis and ultimate limit state analysis, if adequately calibrated for those purposes. However, the linearity assumption is often not valid, especially for extreme line tension predictions; hence, they should be used with discretion.

Hybrid frequency/time domain methods solve the wave frequency responses in the frequency domain, assuming the related line vibrations are linear, and the low frequency responses, responsible for the large deformations, are calculated by nonlinear time domain simulations (Low, 2011).

Most of the methods and analysis presented during the reporting period are based on time domain methods. The objective is to include nonlinear effects, related to loadings on both the floater and the mooring system and risers, in the analysis. There is a range of options available for solving the coupled dynamic problem in the time domain, depending on the assumptions to: solve the wave-floater hydrodynamic interactions, solve the mooring system dynamic problem, and couple the floater dynamics and the mooring and risers systems. The different approaches can be grouped into partly coupled and fully coupled methods. The mooring analysis methods can be generalized for multi-body interacting floating structures by properly considering the hydrodynamic and mechanical coupling effects between the bodies.

Partly coupled methods solve the time domain equations of floater motions coupled to a quasi-static mooring system model. The hydrodynamic loading on the mooring lines can be considered in a simplified way. This approach is valid if mooring line dynamics can be neglected. Zhao et al. (2014c) applied a partly coupled time domain to study the dynamic behaviour of a side-by-side floating liquefied natural gas production platform (FLNG) and a LNG carrier. The FLNG is moored to the sea bottom with a turret system and the two vessels are coupled with linear hawsers and fenders. The numerical model is first calibrated by comparisons with model tests. The calibration is performed in terms of linear damping coefficients for each of the degrees of freedom. Comparisons with model test results, in terms of motions and lines' tensions, show a reasonable agreement – the dynamic behaviour characteristics identified in the experimental results are represented by the numerical predictions, but some differences are observed in terms of magnitudes. The calibrated numerical model is used to perform sensitivity studies to investigate the pretension and stiffness of the hawsers effects on the side-by-side system performance. It was concluded that the changing the two parameters indeed affects coupled responses between the two vessels. In general, partly coupled methods can be used for *screening* a large number of environmental conditions and select a small number for posterior fully-coupled analysis, such as the one by Aksnes et al. (2013).

There are two options for fully coupled methods: (a) the mooring and riser systems dynamics are solved at each time step using the floater motions at the fairleads and the floater equations of motion use the mooring forces applied to the hull, such as the work by Kim et al. (2013b), Kim et al. (2013a) and Aksnes et al. (2013); (b) the equations of floater motions and mooring lines/risers are set up and solved simultaneously, such as the work by Yang et al. (2012) and Jacob et al. (2012a). Fully coupled methods are the most accurate, but most time consuming as well. The use of fully coupled methods is justified by the need to consider the flexible slender systems' dynamic effects on the floater responses; hence, it is important for the model to include the risers, not considered in this section. The risers' damping effects on the floater motions are often particularly important.

Kim et al. (2013a) applied a fully coupled method to analyse the dynamics of a side-by-side floating storage re-gasification unit (FSRU) and LNG ship. Linear springs and dampers represent the mechanical coupling between the two vessels. It appears that the hydrodynamic coupling between the two vessels, which in principle should not be neglected, is not considered. The FSRU time domain equations of motion include the mooring system force vector, obtained by solving the mooring system dynamic problem with FE method. The two dynamic problems are solved iteratively at each time step. The authors compare the coupled responses with and without links between the two vessels and it is concluded that the linkage reduces the relative motions, which are critical for the offloading operation. However, the FSRU roll motion increases which means the linkage system characteristics need to be carefully selected.

A fully coupled mooring analysis tool was used by Aksnes et al. (2013) to investigate the failure of two leeward mooring lines of a floating storage unit operating at the North Sea. The analysis was carried out for a set of North Sea 100 years return period storms. This study is a good example of the level of detail which state of the art models can use to represent complex dynamic mooring line problems. The authors concluded that a possible failure mechanism originates when, in certain conditions, a transverse wave propagates upwards along the mooring line upper wire segment, which lead to a large curvature in the wire near the socket. The repeated high stresses at this location eventually lead to failure. This wave comes about when the link plate at the lower end of the upper wire segment impacts the sea bottom after being lifted. For this reason, the seabed contact was modelled carefully in the numerical analysis. The FE model of the mooring line makes use of beam elements for the upper wire segment to account for the bending and torsional stiffness, whilst the remaining lower segments are modelled with bar elements, considering only axial stiffness. The upper wire socket and the bending stiffener were modelled with beam elements of appropriate stiffness. In order to capture the travelling wave's strong dynamic behaviour, the upper wire segment was modelled with very small elements, between 0.5 and 1.0 m, which required very short time steps for the simulations.

Yang et al. (2012) presented a fully coupled time domain method for the analysis of moored floating structures. The wave-floater hydrodynamic interactions are calculated directly in the time domain, up to second order, by a HOBEM, as opposed to the more common approach of using retardation functions obtained from frequency domain coefficients and second order forces calculated from quadratic transfer functions. The mooring/risers dynamics are calculated by a FE method based on a global coordinate system and the theory of slender rods. The equations of body and mooring lines/risers motions are solved simultaneously at each time step. The method is first applied to a floating hemisphere connected to linear springs for validation by comparisons with frequency domain results. Subsequently it is applied to calculate the motion responses and mooring line tensions of a truss spar in regular waves. Fully coupled and partly coupled results are compared leading to the conclusion that the mooring damping and inertial effects are important for deep water.

Jacob et al. (2012a) compare two different formulations for the coupling between the floating structure hydrodynamics and mooring lines and riser dynamics. The simpler is designated as *weak coupling* whereby the coupling into the floater motion equations is established through forces applied at the hull. At each time step, the hull equations of motion are integrated by an explicit method, while the dynamics of each line are solved independently by a FE method with one, or more than one, time steps. The authors claim that the lag between the lines' forces calculation and their application to the hull may lead to numerical inaccuracies, especially if the slender elements connecting to the hull are stiff. For this reason they tested the *strong coupling*" formulation where all lines and risers are included in the FE model and the 6 DoF of the hull are associated to a node of the FE model. The floating body equations of motion are valid for large amplitude angular displacements by considering the complete transformation relating the body and the global coordinate systems. Nevertheless, it appears that the calculation of the hull hydrodynamic forces does not follow the large amplitude assumption. Both formulations are applied to a semi-submersible subjected to an irregular sea state (H_s = 7.2 m) and uniform current, moored at a water depth of 1800 m, with 4 clusters of 4 lines and including 47 risers and umbilicals. The authors conclude that the motion responses and fairlead mooring line tensions from both formulations are similar. The *weak coupling* method is computationally more efficient for systems with a large number of lines.

Fully coupled solutions are the most accurate for prediction of mooring line tensions; however, they are very demanding from a computational point of view, especially since a large matrix of environmental conditions needs to be considered for design or verification purposes. With the objective of improving computational efficiency, Jacob et al. (2012b) implemented domain decomposition strategies for the coupled analysis methods described by Jacob et al. (2012a). Parallel algorithms solve the equations of floater motions and the equations for each line in several processors.

One interesting intermediate option which often produces accurate extreme line tension results is to solve the floater dynamics with a partly coupled model as a first step, and use the resulting motions at the fairleads as prescribed for a cable full dynamic analysis as a second step. The assumption is that the dynamic effects of the mooring lines/risers do not influence the floater dynamics, or their influence can be represented with known global damping and inertial coefficients. Along these lines Christiansen et al. (2013) proposed a hybrid method which combines FE analysis and artificial neural networks (ANN). The ANN is trained to predict the relationship between the loads on a floating structure and the resulting tensions on a mooring line. The ANN learning is based on pre-generated training data, which should cover a broad range of wave characteristics. In this study, the authors used a partly coupled analysis, including a FE model of the mooring system, to generate the training data and demonstrate the procedure with a floating structure moored with 18 lines. The hybrid method results are compared with the results from direct dynamic simulations, in terms of accumulated yearly fatigue damage and fatigue life of a mooring line, and the results are very similar. The computational time with the hybrid method is 2 orders of magnitude lower. One should note, however, that some time is needed to setup and train the ANN.

Zimmerman et al. (2013) presented a coupled mooring and anchor translation analysis for a semi-submersible drilling unit. While the conventional mooring analysis considers the anchors as fixed points, in fact many of the offshore floating units use drag embedment anchors, which translate when exposed to loads greater than the previous highest load. This translation influences the mooring line tensions. The author applied a frequency domain mooring analysis method. During the first step the environmental static loads are calculated at the anchor and, if they are larger than the previous highest load, which could be the installation test load, the anchor translates according to its holding capacity until equilibrium is achieved. The dynamic analysis is carried out during the second step. Comparisons between the conventional method and the present method show that the predicted maximum line tensions are up to 10% lower when the coupled model is used and, therefore, the anchors are allowed to translate.

Whilst existing numerical methods (FE methods) provide quite accurate mooring line dynamics, including line tensions, for steel and chain catenaries, the uncertainty is larger for synthetic lines. Synthetic fibre ropes, which have advantages for deep water moorings, are characterized by much more complex nonlinear dynamic behaviour. This is related to the material properties, namely time dependent characteristics, viscoelasticity, viscoplasticity and large stretch, which need to be taken into consideration. Relevant experimental and theoretical/numerical work has been developed during the reporting period. For example, Liu et al. (2014a) carried out an experimental investigation focused on the dynamic behaviour of three types of synthetic fibre ropes under cyclic loading. These were polyester, aramid and HMPE (high modulus polyethylene). It is concluded that the mean load has a strong influence on the dynamic stiffness and the loading, but the strain amplitude and the number of cycles are important factors as well. An empirical expression, which takes into account the aforementioned effects, was proposed to estimate the dynamic stiffness evolution. However, several coefficients depend on the material properties and must, in principle, be obtained for specific types of fibre ropes.

Huang et al. (2012) proposed a numerical model to represent the time dependent creep and recovery behaviour of synthetic fibre ropes. The nonlinear constitutive model combines a viscoelastic theory with a viscoplastic spring-dashpot-slider model. An identification method based on creep recovery experiments is also proposed to estimate the model parameters. Comparisons of predicted viscoelastic and viscoplastic strains for aramid and polyester fibres with experimental data show good agreement and the authors suggest the method can be incorporated into existing codes and procedures for mooring analysis.

Accounting for the viscoelastic and viscoplastic properties of synthetic lines in deep water mooring analysis was of the aim of the time domain model implemented by Kaasen et al. (2014). A time domain nonlinear spring-dashpot model is implemented to represent, simultaneously, the recoverable instantaneous elongation, the slow elongation response, the irreversible instantaneous elongation and the long term elongation (creep). The lines are represented by finite elements, which means that a new element incorporating the aforementioned characteristics was implemented. Data from tension-elongation tests with polyester ropes was used to identify the model parameters. The new model was applied to the mooring analysis of a platform subjected to storm conditions and it was possible to identify the increase in rope's length and the consequent modification in mooring system characteristics as function of time.

A simple and practical engineering solution to account for the nonlinear and viscoelastic properties of polyester has been to consider two types of axial stiffness, namely a static and a dynamic stiffness, run the mooring simulation twice and take the largest extremes. This method tends to provide conservative values. The dual stiffness method presented by Tahar and Sidarta (2014) goes one step further. The authors proposed to use the static stiffness to calculate the mean platform motions, adjust the lines' length, and then use the dynamic stiffness to calculate the dynamic motions, all in a single fully coupled mooring simulation. The method was applied with a fully coupled code for the mooring analysis of a semi-submersible, using the 100-year wind and wave hurricane environment in the Gulf of Mexico. The solutions using the static stiffness, dynamic stiffness and the dual stiffness are compared. The authors conclude the new method can replace the previous procedure of running the simulations twice, for the static and for the dynamic stiffnesses.

Large stretch is one additional aspect where synthetic fibre ropes differ from chain and wire lines. Consistent FE models should take into consideration the large stretch characteristics. Webster et al. (2012) extended the dynamic model for a slender rod without stretch to include large stretch. The authors adopted a simple assumption regarding the stretch characteristics and include an existing model for the viscoelastic behaviour of the large stretch elements. The method can be implemented into FE models, as presented by Ma et al. (2014). They implemented the new element into a FE method and tested with a 3D extensible catenary. Comparisons with analytical solutions validate this method.

4.3 Lifting operations

With growing interest towards increasingly unconventional offshore exploration and exploitation, the in-depth understanding of nonlinear hydrodynamics involved in coupled multi-body offshore systems, such as heavy lifting and subsea installations, is becoming immensely important, if we are to ensure safe and profitable operation of such systems. It is for these reasons that this committee's report contains an in-depth review of developments in the modelling of loads due to offshore lifting operations. Offshore lifting operations, in general, include lifting in air and subsea lifting. Engineering analysis for design verification and lifting operation, normally, include calculations demonstrating the adequacy of the vessel's stability and station-keeping capability, either through dynamic positioning or mooring system, during heavy weight lifting operations and calculations demonstrating strength of the crane and supporting structures. The load for the strength assessment includes fixed loads (e.g. hull weight), and variable loads (e.g. portable cranes and machinery), dynamic loads, wind loads, loads due to trim or list, snow/ice loads and others depending on the area and nature of the operation. Modelling of the lifting appliance system should take the following aspects into account: basic dynamic factors based on boom tip velocities (API, 2012), buoyancy, added mass, drag, rope weight, resonance and sea bed suction ((ABS, 2014a), (ABS, 2014b)).

Various approaches for investigating the dynamics of crane vessels have been studied, especially during the last two decades. A brief review of studies undertaken during earlier years were summarised by Ellermann et al. (2002). Accordingly, all previous investigations use a common approach to define the motion of the payload, where the excitation of the payload is taken simply as a prescribed motion of the pivot point of the hoisting rope. However, the influence of the payload on the motion of the vessel is neglected. This method might be applicable for the scenario where the payload to vessel ratio is very small. The theoretical, experimental and numerical studies which have been documented in all these contributions reflect the strong interest towards the analysis of offshore crane vessel dynamics. Among them worth noting is the work by Wouts et al. (1992) aimed at monitoring two major offshore heavy lift operations of the time. These operations involved lifting of jacket structures from the cargo barge using large semi-submersible crane vessel (SSCV), lowering them in the water, upending and then setting on the seabed. Among the observed results, motion and tension spectra were correlated with model test data, as well as with data obtained from calculations based on the theoretical formulation of the wave spectra in order to evaluate the significance of lift dynamics involved in the process. It was noted that the calculation based results showed considerable deviations from the measured data, except for the computation of natural periods. However, comparison of other statistical quantities is not performed, because the recorded experimental data comprised of low, medium and high frequency components and the numerical formulations of the time were not capable of capturing these details effectively.

The first simplified, complete linear computer program to analyse the equation of motion of a crane vessel and its suspended load is attributed to Witz (1995) where the system was described by six DoF for the vessel together with three orthogonal displacements of the lifting mass. In this model all external forces were considered to be proportional to the motions of the floating crane and the cargo. Furthermore, the motion of the floating crane, as well as the wire rope force, were linearized and the off-diagonal terms of the added mass and damping matrices were neglected in the analysis. An improved model was developed by Kral et al. (1996) which is a 3D linear model solved in the frequency domain. In their model, the coefficients of the hydrodynamic forces were calculated as a function of the frequency and the inverse Laplace transformation was used to transform these coefficients into the time domain. The system, although considered a simple crane ship model with linear hydrodynamics, showed the full range of nonlinear phenomena from period doubling to chaotic behaviour with quasi-static changes of the hoisting rope length over 28 m. No comparison of the findings with experimental or other numerical methods is performed as such data appear to be unavailable at that time.

Clauss and Vannahme (1999) performed experimental studies in order to shed further light on this subject. Seakeeping tests were carried out using a Magnus crane barge model at a scale of 1:25 in regular head waves to analyse the influence of nonlinear mooring forces. All model tests were performed in the wave tank of the Berlin University of Technology. The experimental analysis showed that although the dynamic behaviour of moored floating cranes can be treated as linear in some cases, the coupled system of floating structure and swinging load shows distinctly nonlinear behaviour and parametric oscillations under certain conditions, e.g. at larger motion amplitudes, which are indispensable for heavy lift operations. Therefore, they recommended developing nonlinear numerical models in combination with a bifurcation analysis and followed by model test verification for improved results. Ellermann et al. (2002) and Ellermann and Kreuzer (2003) focussed their efforts on developing such models by adopting the potential theory approach for the FSI and the main objective of their investigation was to detect nonlinear phenomena, such as bifurcations and the existence of multiple attractors. Both theoretical and experimental studies were undertaken to achieve these goals. In the mathematical modelling part, the state space model was used where additional state variables needed to be defined in order to transform the frequency-dependent hydrodynamic radiation forces into the time domain. Two mathematical models of different levels of complexity were used to systematically determine the responses of the vessel-payload system to periodic forcing of waves. One technique was the multiple scales method which allows for the investigation of the nonlinear dynamical system in the frequency domain and which results in an analytical solution. The other technique applies numerical path following methods to trace bifurcations of periodic solutions. The comparison between experimental and numerical findings is rather limited, probably due to the incapability of the numerical model to simulate in-depth the details of the experimental setup. Nevertheless, comparisons of mooring line forces and the surge motion of the barge with experimental measurements are agreeable, within the limitations of the simplifications of the numerical model. However, quite a good agreement was achieved between the two computational methods.

Among more recent studies, Cozijn et al. (2008) proposed a combined physical scale model test, time domain computer simulations and full scale observation approach in order to determine the operational limits of the offshore installation process. The complete analysis comprised hydrodynamic scale model tests, time domain computer simulations and observations made during the actual installation offshore. The model tests were carried out in MARIN's offshore basin and the computer simulations were performed using the commercial multi-body linear time domain simulation tool LIFSIM, developed by MARIN. The model test results are first used to optimize the performance and accuracy of the simulation model LIFSIM. The damping parameters are also calibrated using the model test data. A large number of simulations are then performed to investigate the different environmental conditions, once reasonable agreement between the model test and simulation tool are obtained. Apart from this study, Cha et al. (2010) proposed a coupled model to simulate the dynamic response of cargo suspended by a floating crane. They set up the dynamic equations of motion considering the 6 DoF floating crane, in regular waves, and the 6 DoF cargo suspended in air based on multi-body system dynamics. The nonlinear hydrostatic and the linear hydrodynamic forces were considered as external forces and only the motion parameters of the crane barge and payload were calculated. To verify their equations of motion used, a comparison of the motions of the floating crane and the heavy cargo, was carried out with predictions from the Multi-Operational Structural Engineering Simulator (MOSES). This comparison shows similar patterns with small differences in amplitude and phase of the heave and pitch motions. They also performed parametric study to find the tension in the rope, connecting the cargo with the crane in barge, under different wave amplitudes, frequencies and heading angles. However, results for the tension were not compared with predictions from any other software. This model was extended by Park et al. (2011) to provide a more realistic approach by considering a floating crane and a heavy block which are connected using elastic booms and wire ropes. Extensive parametric studies were performed to highlight the differences between the numerical results obtained with rigid and elastic booms. No comparisons with other numerical and experimental results were performed due to the unavailability of such data. The main focus of both of these studies, however, is to analyse the behaviour of the cargo suspended in air with reference to the motion of the crane barge. It appears that mathematical model for the analysis of nonlinearity involved in the underwater motion of the cargo/payload, i.e. nonlinear hydrodynamics, near the free surface is not as yet available in open literature, probably due to the complexities of this problem.

On the other hand, a recent recommended practice report released by DNV (2010), on modelling and analysis of marine operations, provides some simplified methods for obtaining simple conservative estimation of forces acting on an object when lowered through the splash zone. In this report some guidelines are also provided on how to create a model for the coupled dynamic motion analysis during heavy lifts operations. In addition, a recent study performed by Bai et al. (2014b) describes the findings of a fully nonlinear time domain analysis of a fully submerged cylindrical payload hanging from a rigid cable and subject to wave actions. The numerical model is validated, against other experimental and numerical results available, for wave interaction with submerged fixed horizontal cylinder. The model provides very consistent results similar to other numerical models. The model also appears to be in good agreement with experimental results up to the point where viscous effect start to play significant role, Keulegan Carpenter number of 0.6. However, this fully nonlinear time domain model only considers the wave interaction of a single submerged payload with one rotational degree of freedom without coupling with the crane vessel. Hence, there exists ample scope to analyse and understand the coupled hydrodynamic behaviour of a crane barge and its submerged payload subjected to nonlinear waves.

4.4 Wave-in-deck loads

Further investigations for obtaining reliable estimates of extreme loads on platform decks due to possible wave in deck loading continued during the reporting period. Improved statistical methods combined with advanced fluid flow simulations using CFD have given enhanced insight into this loading problem, which is essential for the safe assessment of life extension of ageing platforms. Subsidence of seabed, updated wave data bases and improved methods for prediction of kinematics of extreme wave crests may result in considerable higher estimates of deck impact height with consequent impact loads higher than those used in the design of the platforms. Previous simplified global methods only providing the maximum impact force and detailed component approaches based on the momentum method providing time histories of impact load have been compared with more accurate CFD simulations, mainly applying a VOF method for free surface capturing.

Abdussamie et al. (2014) compared results obtained using a simple momentum method with a single phase VOF method and experimental results for a fixed rectangular box. Regular undisturbed incoming waves were assumed. It was found that the momentum method severely underestimates the magnitude of horizontal wave-in-deck force whilst for the vertical force the upwards force is underestimated and the downwards force ovepredicted during exit phase.

Scharnke et al. (2014) investigated experimentally wave-in-deck loads in regular and irregular waves for a detailed model of a complex deck structure of an existing jacket platform. The model tests were compared with a very simplified global design method based on impact height and kinematics of a fitted undisturbed 5th order Stokes wave. They concluded that the simplified load model underestimates the impact loads in both regular and irregular waves due to the underestimation of horizontal velocities in the wave crest of the theoretical wave model used. From the measurements it was also found that wave breaking during deck impact may increase the horizontal deck loads and decrease the vertical deck loads.

Iwanowski et al. (2014) reported results from VOF analyses for the same platform deck model used by Scharnke et al. (2014), applying both single- and two-phase flow models. The computationally more intensive two-phase flow model was used in order to quantify the possible effect of air pockets on the wave impact loads. It was concluded that the two-phase flow CFD solution, in general, shows a better agreement with the experimental results than the single-phase flow solution for regular waves. The comparison for the irregular wave was not conclusive.

Lu et al. (2014) presented results from CFD analyses, using OpenFOAM, of wave impact loads on platform deck and wave-bridge interactions. A two-phase flow model was used. Carefully focused extreme irregular waves, derived from NewWave theory and Jonswap wave spectra, were applied. The New Wave model was found to better approximate the *real* wave crest hitting the deck than a regular design wave.

4.5 Floating Offshore Wind Turbines

The success of several Floating Offshore Wind Turbine (FOWT) demonstration projects, for example Roddier et al. (2009) and Skaare et al. (2014), has shown great promise for this emerging new field. The numerical tools used to model FOWTs leverage many decades of research supported by the offshore oil and shipping industry, although wind turbines present new issues and complexities that involve a revisit of offshore mechanics theory. Several methods and software have been developed to address unique FOWT requirements, accomplished by coupling the aero-elastic behaviour of wind turbines with the hydrodynamic and station-keeping characteristics of floating offshore platforms, such as those by Jonkman and Buhl Jr. (2005), Larsen and Hansen (2007) and Bossanyi (2009). Important investigations in specific areas are also worth noting. Rotor aerodynamic thrust is efficiently modelled using the blade element momentum theory by Manwell et al. (2009). CFD activity is also applied toward capturing rotor wake deficits by Churchfield et al. (2012). Many approaches are available to account for vibration issues related to blade and tower flexibility, including variations of beam theory by Branner et al. (2012) and the more rigorous FE model by Heege et al. (2007). Beam theory is a popular applied method to balance computational speed with accuracy. A successful FOWT simulation method should entail coupling an aero-structure-elastic method with an offshore hydrodynamic and station keeping method to yield effective simulation tools, such as those recently developed by Thomassen et al. (2012), Cordle and Jonkman (2011) and Duarte et al. (2013).

Several studies explored the process to couple a wind turbine simulation tool with existing hydrodynamic/mooring programs to leverage validated toolsets and extend model capabilities. Cordle and

Jonkman (2011) provide a survey of the early programs used. Additional examples are given using AQWA (Huijs et al., 2014), Charm3D (Bae et al., 2010), OrcaFlex (Masciola et al., 2011), SIMO/RIFLEX+HAWC2 (Skaare et al., 2007), SIMPACK (Matha et al., 2012) and TimeFloat (Roddier et al., 2009). Various techniques to implicitly and explicitly couple the rotor aerodynamics, tower structural response, and platform hydrodynamics and expand model fidelity are discussed by Jonkman (2013). These tools must provide sufficient accuracy to address issues raised in international design standards, such as ISO 19900 for offshore platforms (ISO, 2002) and IEC 61400 series for wind turbines (IEC, 2005, IEC, 2009). The significance of second order sum-difference hydrodynamic effects on moored floating offshore systems is well documented in the marine industry. Findings by Roald et al. (2013) reinforce this to suggest second order sum-frequency hydrodynamic effects may impart loads targeting higher frequency bandwidth. This observation is based on global performance simulations. Xing et al. (2012), considered high order hydrodynamic theory to show these frequencies can coincide with the wind turbine drive train natural frequency to illustrate the importance of second order effects. The TLP system explored by Bachynski and Moan (2013) discusses application of first and second over hydrodynamic theory in a FOWT system, with added consideration towards the atmospheric modelling needs required for the wind turbine. This study reveals an increase in tendon tension with second order wave forces included, in line with observations experienced with conventional oil and gas TLPs.

Several of the proposed FOWT systems emulate geometries found in oil and gas platforms, but at smaller scales. The examples provided by Roald et al. (2013), Xing et al. (2012) and Bae et al. (2010) document instances where standard practice offshore simulation methodologies can be applied to advance offshore wind technology. The characteristic distinguishing FOWT from traditional oil, gas and shipping vessels is that wind turbines are designed to extract energy from the wind. Departing from traditional oil and gas modelling practices, wind turbines require accurate 3D turbulent wind field representations to capture the localized blade lift and drag forces. One common approach to model the torque and thrust loads in the wind turbine's rotor swept area is discussed by Ingram (2005). The premise of this approach is to calculate the localized force and moments along the wind section, and integrate this force along the blade span in a 3D wind field to produce the resulting time-varying torque and thrust loads. This is the essence of the blade element momentum theory as discussed by Madsen et al. (2007). The ensuing torque and thrust loads, plus the added motion of the floating support platform, lead to large tower-base and blade-root loads, which has motivated a desire for analysis codes and techniques to model FOWT systems, exemplified by Nielsen et al. (2006), Wayman et al. (2006) and Robertson and Jonkman (2011). Matha et al. (2011) led a study summarizing gaps in FOWT simulation tools. Two issues addressed by these authors, which have drawn the attention of the offshore community, include a FE mooring representation and higher order hydrodynamics theory. In the time elapsed since this study was published, research studies by Bae et al. (2010) and Hall et al. (2013) have addressed the mooring system considerations, and high order hydrodynamics concerns were investigated, for example, by Li et al. (2014a), Bachynski and Moan (2013) and Gueydon et al. (2014).

The role of FOWTs is to convert wind energy into electrical energy. This conversion results in large surge and heeling offsets as energy is extracted from the ambient environment. Energy capture is made more efficient through active control of the wind turbine blade pitch angles to regulate power generated. However, there is concern that blade pitch control strategies may inadvertently lead to negative platform pitch damping, which would lead to larger platform pitch offsets with the turbine operating (Nielsen et al., 2006, Jonkman, 2008). Control logic also affects power performance and fatigue of wind turbine components by damping the platform pitch response, as discussed by Skaare et al. (2007). Suzuki and Sato (2007) conclude that land-based rotor-nacelle-assemblies (RNA) can be applied to offshore systems, provided the platform motions are small. In light of the new environmental challenges facing FOWTs, Robertson and Jonkman (2011) showed, through simulations, that the loads experienced in the RNA components of offshore systems during normal operation are moderately larger than land-based counterparts due to the platform global motion. This study also reveals that the tower base moment significantly exceeds the magnitude found in comparable land-based systems. However, the conclusions drawn apply to FOWT in normal operations regimes with small wave heights. It is generally observed that high loads can be experienced in the FOWT RNA components occur during energy production phases, but greater loads can be experienced in the floating system and mooring foundations when the wave height is largest. Since there is a large degree of uncertainty on which environment conditions lead to the largest loads in the integrated FOWT system, the design and analysis procedure usually resorts to many simulations in a wide variety of sea states and wind conditions, discussed by Li et al. (2014a).

For the aforementioned reasons, accurate simulations to capture the control logic, aero-elastic behaviour, structural response and hydrodynamic interactions are crucial to the design of FOWT systems. Results were disseminated by Popko et al. (2012) as part of a multi-national effort under IEA (International Energy Agency) Wind Task 30 to conduct code-to-code comparisons of various fixed-bottom floating offshore systems and corroborate application of various theories. This project spawned the OC4 Phase II effort, which focused on code-to-code comparisons of a semi-submersible FOWT unit (Robertson et al., 2013). The purpose of both exercises was to observe if codes using/based on similar theories converged to the same results. Future IEA efforts will focus on comparing numerical models with experimental data, which will help identify recommended approaches for simulating floating wind systems. Findings from early FOWT model experiments are summarised by Coulling et al. (2012) who explored the requirements to scale a $1/50^{th}$ floating semi-submersible platform and wind turbine rotor against a full scale simulation. The paper discusses concerns related to blade scaling and matching the rotor aerodynamic thrust at the rated wind speed through the Reynold's number. The platform itself follows Froude scaling. Combining different scaling rules helps match experimental results with full scale simulations. Numerical and experimental validation efforts were carried out by Adam et al. (2013) for a TLP model in transit and operation cases. Adam et al. (2014) followed up with tests in scaled Baltic Sea conditions. Both papers demonstrate the importance of combining representative wind and wave conditions in the scaled model experiments.

Offshore wind is emerging as an alternative energy source. The Global Wind Energy Council (GWEC) estimated an installed capacity of 7 GW 2013, which is projected to grow to 10 GW by 2015 (GWEC, 2014). A majority of the global installed capacity are bottom-founded designs, which first took root as demonstration projects in the early 1990s. Floating offshore wind systems are following a similar path and historical learning curve as their bottom-founded counterparts, with present floating wind installations confined to a few demonstration projects (EWEA, 2013). Bottom-founded offshore wind installations become less economical as water depth increases, allowing FOWTs to reach economic parity (Musial and Ram, 2010). Wind turbine physics incentivise larger machines because generated power capacity scales proportional to the rotor diameter squared (Manwell et al., 2009). These factors combine to promote and encourage research in this area.

5. PROBABILISTIC MODELLING OF LOADS ON SHIPS

The ship design process needs to ensure the integrity of the hull, where wave-induced loads contribute significantly. These loads have to be representative of the environmental conditions encountered through the entire life of the ship, which involves statistical representation of the environment and the consequent loads, as well as computationally efficient methods simulating suitable design conditions. This section is, therefore, structured with the aforementioned thoughts in mind.

5.1 Probabilistic methods

Stochastic description of loads is required for fatigue spectral analysis and computation of extreme loads for ship design, as well as for the application of ship structural reliability methods. For longitudinal strength assessment of most ship types, basic load variables considered are VWBMs and SWBMs. Load combination of these two components is also considered, accounting for the fact that their maximum values do not occur simultaneously. SWBMs change from one voyage to another and they also vary slowly within each individual journey because of the use of consumables. However, such variation within a voyage is normally neglected in the load combination studies. Load combination of different components of global wave loads, such as vertical and horizontal bending moments (HBM), and torsional moments, and between global and local wave load components are also important (Mohammed et al., 2012).

In recent years, attention, by and large, focussed on ULCSs, where vibratory loads become important. For these flexible ships operating at high speed, the encounter frequency can overlap with the natural hull girder vibration frequency and cause resonance, denoted as springing. This steady state resonant vibration may arise from the two-node flexural mode or the coupled horizontal and torsional mode, the latter only subject to relatively few investigations. Both springing and, transient vibratory, whipping responses are relevant for the fatigue limit state check. For the ultimate limit state check whipping response is more important since it can significantly increase the extreme rigid body VWBM. In recent years a substantial number of studies dealt with stochastic description of combined rigid body and vibratory responses of ULCSs. There appears to be a tendency to consider these two load components together, rather than to study them separately and to combine them using load combination principles. This is partly due to the ascendance in coupled hydrodynamic and structural analyses, providing results of reasonable/acceptable accuracy, and partly due to the nature of model or full scale measurements. In these cases, rigid body and vibratory loads are explicitly included in the analysis and there is no need to combine them. The contribution of the vibratory response can be assessed either by performing analyses with and without elastic effects or by separating low and high frequency signals.

Mao and Rychlik (2012) presented a simple approach for the prediction of extreme response, for example, 100-year return stress, using Rice's method combined with Winterstein's transformed Gaussian model for stresses. The method requires description of long term variability of the standard deviation, skewness, kurtosis, and zero upcrossing frequency of ship response. It is assumed that the parameters are functions of encountered significant wave height, heading angle and ship speed. The accuracy of this model is validated using the full scale measurements of a 2800 TEU container ship. The parameters in the Winterstein transformation are given by analytical functions of significant wave height only. The proposed method is also used to estimate extreme responses of a 4400 TEU container ship, for which no measurements are available. Results were similar to the 2800 TEU ship. The presented investigation shows that having accurate wave environment model is extremely important for the reliable estimation of the extreme ship responses.

Lee et al. (2012a) presented an analysis procedure for determining values of wave-induced bending moments, considering the effects due to whipping, suitable for design application. The design bending moments due to whipping of the hull girder were determined by multiplying the design rule bending moments by correction factors for hogging and sagging based on the Lloyd’s Register’s guidance notes (Lloyd's Register, 2011). The correction factors for hogging and sagging of a 13000 TEU container ship were predicted by employing time domain nonlinear analysis and an Equivalent Design Sea state (EDS). In the nonlinear hydroelastic analysis, the correction factor for hogging was 1.42 for the ship and is 50% greater than the standard rule hogging correction factor of 0.94. The correction factor for sagging was 1.98 and is 60% greater than the standard rule sagging correction factor of 1.24. These nonlinear bending moments are significantly greater than the standard IACS- based rule wave bending moments.

The effect of hull girder flexibility on the VWBM for ULCSs was analysed by Andersen and Juncher Jensen (2012). A nonlinear time domain strip theory is used for the hydrodynamic analysis, whilst slamming forces are determined by a standard momentum formulation. The hull flexibility is modelled as a non-prismatic Timoshenko beam. The statistical analysis is carried out using the First Order Reliability Method (FORM) supplemented with Monte Carlo simulations. Strip theory calculations are compared to model tests in regular waves of different wave lengths, and good agreement is obtained for the longest of the waves. For the shorter waves the agreement is less satisfactory. The discrepancy in the amplitudes of the bending moment is explained by an underestimation of the effect of momentum slamming in the strip theory applied.

Ogawa et al. (2012) examined the relationship between the occurrence probability of a slamming induced vibration and sea state. These relationships were investigated based on the full scale measurement data of two large container ships, which operate on the same sea route, but at different periods. The effect of the variability of sea state on the occurrence probability of whipping-induced stress on the hull was examined using the computation of long term prediction and wave hindcast data. The probability of occurrence for high stress is different between the two container ships owing to the difference of period for full scale measurement, though these container ships navigated the same sea route. The stresses are, in general, same for the same wave condition. The difference of probability of wave height has much effect on the whipping and the magnitude of induced stress. It is also clarified that most of slamming induced vibration occurs in head or bow seas. The probability of occurrence for both container ships is consistent with the actual sea state. It is also found that the probability based on the IACS Recommendation 34 (IACS, 2001) is quite larger than the probability in the real sea state. It is noted that the operational effect is not negligible for the evaluation of the occurrence probability of slamming.

Andersen and Juncher Jensen (2014) analysed full scale measurements of the wave-induced amidships VBM of a 9400 TEU container ship. The focus was on assessing the effect of the hydroelastic high frequency vibration on the extreme hogging VWBM. In the extreme case, they noted that the high frequency vibrations were of the same magnitude as the wave frequency, i.e. so called rigid body, response. It was also noted that even though the ship is sailing in bow quartering seas, only the 2-node vertical vibration mode is apparently excited. Following the extreme event analysis and verification, three hours of strain measurements are used for establishing a Gumbel distribution for the extreme value prediction. Extreme value predictions using the measured results indicate that the probability of exceeding the rule design hogging VWBM by 50% could be of the order of 1.3% during three hours of operation in a sea state with significant wave height around 8 m.

Teixeira et al. (2013) assessed the probabilistic characteristics of the load combination factors for global still water and wave-induced VBMs of double-hull tankers. The calculations are performed based on loading manuals of oil tankers representative of the range of application of the IACS Common Structural Rules (CSR) design rules. Different load combination methods are used, including an analytical method that provides the combined characteristic value of still water and wave-induced bending moments based on the Poisson assumption for upcrossing events and using the first order reliability method in combination with the point-crossing method. The mean value and the standard deviation of SWBM in one random voyage are defined as 70% and 20% of the maximum value in the loading manual, respectively.

These values are used for statistical description of sagging bending moments in full load conditions and hogging bending moments for the ship in ballast. For the wave-induced loads, a Weibull distribution was adopted to describe the values of VWBM at a random point in time. A simplified approach for the Weibull model was adopted, in which the shape parameter was assumed as 1.0 and the scale parameter was defined from the IACS rule minimum value defined for design purposes. It was shown that the average load combination factors of the tankers decrease rapidly when the design period increases from 1 to 10 years and then tend to stabilize. It was also shown that the mean voyage duration demonstrates a strong influence on the load combination factors. From this analysis, average of load combination factors of 0.84 and 0.81 were obtained, respectively, for large (LTK) and small (STK) tankers in full load and for a reference time period of 20 years. In the ballast load condition, the average of load combination factors reduced to 0.80 and 0.76 for large (LTK) and small (STK) tankers, respectively, which differ on the probabilistic models of the voyage duration and time in port. These factors multiply the most probable VWBM to be added to the most probable SWBM in order to get the most probable combined bending moment.

Mohammed et al. (2012) presented a cross-spectral stochastic analysis methodology for the determination of the combination of global wave-induced dynamic loads. The methodology considers the use of bivariate probability density functions, for the cross-spectral probabilistic approach, or the co-variances of two random variables with their associated derivatives, for the cross-spectral Hamilton's method, and assumes only wave frequency hydrodynamic actions under steady forward speed conditions. A 3D source distribution based on Green's function was applied on the panel model to predict the ship motions and rigid body dynamic wave loads. The design extreme values of global wave-induced load components and their combinations for a container ship progressing in irregular seaways are predicted using these two cross-spectral methods together with the short and long term statistical formulations. It is shown that, in general, both cross-spectral analysis methods can be employed to assess the effects of loads in ship design and reliability analyses. However, the cross-spectral Hamilton's method predicts slightly higher load combinations than the cross-spectral probabilistic approach.

5.2 Equivalent design waves

The concept of design waves is used in direct calculations to reduce the number of load cases to be checked for yielding, buckling, ultimate strength or fatigue. A design wave is an equivalent wave or wave group representing the long term response of the dominant load parameter under consideration. Hence, the accuracy of the methodology highly depends on how the design parameters have been chosen. Several types of EDWs exist. General practice in industry is to choose a regular wave for the EDW, the main advantage being its simplicity. The EDW is then defined by the following parameters: frequency, heading, amplitude and phase. However, use of irregular design waves is on the increase, as they are a more accurate representation of irregular sea states. Response Conditioned Wave (RCW) or Most Likely Response Wave (MLRW) are examples of irregular design waves. The notion is to include both the wave spectrum and the ship response in the definition of the Design Wave. de Hauteclocque et al. (2012) compared the stress response of a FSRU computed with a long term spectral approach and with a set of equivalent design waves. The approach for selecting the heading of the applied EDW has been shown to have a significant impact on the accuracy of this method, especially when a regular design wave is used to represent short-crested sea states. The irregular design wave, that may include the directional spreading, produces more robust results at the expense of negligible additional computation costs. It is shown that using at least 10 EDWs, the accuracy (standard deviation of the ratio between the EDW stress and the long term stress) is of the order of 6%.

Sarala et al. (2011) proposed a method to derive an EDW from a response based analysis (RBA) to represent extreme loads on a weather-vaning FPSO. In this approach the combined effects of wind, wind-sea, current and swell are considered. RBA is based on three-hourly hindcast metocean data and uses results of heading analysis directly. EDWs are then derived based on the spectral characteristics of each response. This approach is compared with RAO based approach as generally applied in the industry, where the regular design wave is defined only from the RAO characteristics. Six different EDWs are derived based on RBA and RAO methods. It is concluded that the RBA approach provides more realistic responses compared to the RAO based method. Deriving equivalent design waves using only the RAO characteristics is found to give some non-conservative and unrealistic EDWs in some cases

The EDWs are often used to reduce the duration of the simulations to allow for computation of nonlinear loads with more accurate but time consuming software; that is to say, a three hour sea state or even 25 years' life time may be reduced to only a few waves. Derbanne et al. (2012a) used EDWs to compute the 25 years' extreme bending moment of an ULCS including the whipping response. The hydroelastic model couples a 3D hydrodynamic potential solver with 3D FE structural dynamics. Slamming loads are computed using a 2D generalized Wagner approach. Results using several type of

EDWs are compared with a 53 hour long simulation of a Design Sea State. Regular and irregular design waves are both providing a good estimation of the nonlinear bending moment. However, the method based on an irregular sea state with increased wave height is found to be more accurate, by comparisons with a very long simulation in the design sea state. The significant wave height of the design sea state is increased in order to artificially increase the upcrossing rate of the design value and to save on computation time.

Johannessen and Hagen (2012) were concerned with the accuracy of the estimation of wave induced design responses from model tests in irregular sea states. They showed that for a highly nonlinear response, such as wave-in-deck loading, it is difficult to have an accurate estimation of the extreme response. By increasing the sea state significant amplitude, it is possible to observe the relevant response more frequently, i.e. increased upcrossing rate; hence, reduce the number of model tests.

Juncher Jensen (2011) combined properties of the FORM analysis and Monte Carlo simulations to better predict the upcrossing rate of a given response. With Monte Carlo simulations the necessary length of the time domain simulations for very low upcrossing rates might be prohibitively long. Using a property of the FORM reliability index, assumed to be valid in the Monte Carlo simulations, makes it possible to increase the upcrossing rates and, thus, reduce the necessary length of the time domain simulations by applying a larger load spectrum than relevant from a design point of view by increasing the significant wave height. The mean upcrossing rate thus obtained can then afterwards be scaled down to its actual value. In this paper the usefulness of this approach is investigated, considering problems related to wave loads on marine structures. Here the load scale parameter is conveniently taken as the square of the significant wave height.

Kim et al. (2012a) estimated the long term midships VWBM and impact-induced bending of two hull forms, both experimentally and numerically. The experimental approach utilizes the lifetime maximum loads analysis based on the Weibull analysis technique. The numerical methods include a series of analyses based on Design Loads Generator (DLG), a tool that can construct an ensemble of short input wave time series, the extreme responses of which follow the theoretical extreme value distribution of a Gaussian random variable for a given exposure time. The exposure time associated with the distribution becomes a good measure by which the associated non-Gaussian responses can be bound. Based on this strategy, the design whipping response has been estimated. To show the responses of comparable exposure time, limited Monte Carlo simulations of combined wave and whipping bending moments are conducted numerically. The DLG approach has the potential to supplement or replace a typical lifetime load analysis based on the combination of operational *cells*.

Oberhagemann et al. (2012) discussed ways to embed time domain field methods in extreme value predictions, which require appropriate hydrodynamic codes capable of modelling all relevant nonlinearities. Approaches are suggested that appear to give most reliable results. They rely on Monte Carlo simulations, a reduction of parameter variations and extrapolation of exceedance rates over significant wave height. The computational effort is large, yet it can be handled with modern computer clusters. Further studies are recommended to gain more experience on the applicability of the extrapolation over the significant wave height, as well as the uncertainty related to this extrapolation. Finally, the discretization errors are a critical issue, which must be considered in combination

de Hauteclocque et al. (2013) evaluated the extreme nonlinear VBM, without whipping, for 70 ships (9 containerships, 19 tankers and 29 bulk carriers) using EDWs or long simulations in short-crested or long-crested sea states. Simulations are carried out in time domain, using linear potential theory with nonlinear hydrostatic and Froude-Krylov forces. It is found that the regular design wave fails to predict the nonlinear hogging bending moment correctly (mean error -19%, standard deviation 17%). The irregular design wave, even without spreading, gives a good estimate both in hogging and sagging (standard deviation of the error less than 5%).

Instead of defining the design wave from the linear response, Clauss et al. (2013) proposed a method that combines a nonlinear strip theory solver with an optimization algorithm to find a critical wave sequence corresponding to a predefined maximum response for the VBM, usually based on a rules value. The obtained shape of the critical wave sequences has been reproduced in the wave tank and model tests have been performed to validate the optimization results.

Seng and Juncher Jensen (2012) presented a study of slamming events in conditional waves, under the assumption of rigid body motions. Based on a time domain nonlinear strip theory, most probable conditional waves are generated to induce given short term extreme responses in sagging and hogging VBM at amidships on two container ships. The results of the strip theory are then compared against the results of free surface N-S/VOF CFD simulations, using OpenFOAM, under the same wave conditions. When bow flare slamming occurs the strip theory overpredicts the slamming momentum resulting in higher VBM compared to CFD results. The peak value of the VBM, however, occurs at approximately the same time, implying that the more accurate CFD results can be used to correct the momentum formulation in strip theory through a correction coefficient.

For the structural analysis, EDWs are used to define the few load cases for which structural checks, e.g. yielding and buckling, will be performed. It is important to check that these few load cases are representative of the whole life of the ship. Derbanne et al. (2013a) studied stress response of four different types of structures, comprising conventional ships and unconventional floating structures, using various design waves. Computations are carried out using a 3D linear hydrodynamic solver coupled with a 3D FE solver. It has been shown that with a limited number of design waves, between5 and 10, the difference between long term linear stress response and EDW stress response is of the order of 10%, for a large range of floating structures. The selection of the governing parameters is, however, the key point of the EDW method. If for a beamlike shape the usual design load parameters, such as VBM, HBM, vertical acceleration at FP and roll angle, are giving good results, it is important for other type of floating structures to define carefully the relevant governing parameters. For unconventional designs, when it is impossible to assume a relationship between a load parameter and the stress response, it is even sometimes necessary to define the EDWs from the linear stress response. In general, the irregular EDWs are performing better than the regular ones, because they are more consistent with the definition of the irregular sea states they are representing. They suffer, however, from a slightly higher bias in the response (underestimate), which can be corrected with a safety factor. On a case by case basis, this approach can be used to define a group of 5 to 10 design waves that represent the worst load cases for a given floating structure. For the development of rule load cases, this approach has to be applied to a large number of ships of different types, different size and different loading conditions. It has to be checked that the same set of governing load parameters can be used for all these ships to define the worst load cases.

5.3 Design load cases and ultimate strength

Various design loads used in the strength assessment of ship structures have been introduced by classification societies. Most of these design loads have been determined as standard loads. Hence, the relationship between design loads and sea states actually encountered by ships appear to be weak. Members of IACS developed some common unified requirements and recommendations. The most significant examples are the recommendation n° 34 (IACS, 2001) defining the wave statistics to be used for the design load computations and the unified requirement S11 (IACS, 2010) providing formulations for VBMs and shear forces.

However, when design loads are computed through direct computations, using the assumptions of recommendation n° 34, some important differences are found, compared to S11. Derbanne et al. (2013b) compared the nonlinearity of the design VBM (hogging/sagging asymmetry) predicted by the S11 formulations and computed through a nonlinear seakeeping analysis using design waves and design sea state for 56 different ships. Some important differences were found, especially for containerships, and new formulations are proposed. Work is currently ongoing in IACS to modify the S11 formulations in order to close the gap between direct computation results and rule formulations, and to keep the consistency with the assumptions given in recommendation n° 34.

The design loads are then combined to create some load cases, for which structural checks, e.g. yielding, buckling and fatigue, are to be carried out. These load cases are based on the concept of the aforementioned EDWs. Zhu and Shigemi ((2003), (2007)) developed practical methods for setting design loads. A series of calculations were performed using the strip theory approach for a total of 27 tankers and 22 bulk carriers. 38 wave-induced load components such as ship motions, accelerations, sectional forces and moments and hydrodynamic pressure were considered in this analysis. Dominant loads were identified and regular design waves were used to define each load case, using wave encounter angle, wave period and wave amplitude. Four prominent cases are defined as: (i) VBM (head sea), (ii) VBM (following sea), (iii) Roll (beam sea) and (iv) Hydrodynamic pressure at waterline (beam sea).

Harmonized structural rules are developed by IACS wherein common structural rules of bulk carriers and tankers are combined (IACS, 2006a, IACS, 2006b, IACS, 2013). Loads for strength and fatigue assessment are based on recommendation 34 assumptions (IACS, 2001), namely

- North Atlantic scatter diagram,
- Sea states described by a Pierson-Moskowitz spectrum,
- $\cos^2$ angular spreading for wave energy and
- equal heading probability.

The rule load cases for extreme loads and fatigue loads have been defined based on the EDW concept. For extreme loads, a design life of 25 years and a ship speed of 5 knots are considered. Seven EDWs have been defined to generate the dynamic load cases for structural assessment:

- HSM load cases: head sea EDWs that minimise and maximise the amidships VWBM, respectively;
- HSA load cases: head sea EDWs that maximise and minimise the head sea vertical acceleration at FP, respectively;
- FSM load cases: following sea EDWs that minimise and maximise the amidshipsVWBM respectively;
- BSR load cases: beam sea EDWs that minimise and maximise the roll motion;
- BSP load cases: beam sea EDWs that maximise and minimise the hydrodynamic pressure at the waterline amidships;
- OST load cases: oblique sea EDWs that minimise and maximise the torsional moment at 0.25L from the AP;
- OSA load cases: oblique sea EDWs that maximise and minimise the pitch acceleration.

For fatigue assessment a ship speed of 75% of the design speed is considered. The stress history is approximated by a two-parameter Weibull distribution. These parameters are scaling factor and shape parameter. A probability level of 10^{-2} is selected for determination of the scaling factor, and the shape factor is taken equal to 1.0. In previous rules, for double-hull oil tankers and bulk carriers, the reference probability level was 10^{-4} (IACS, 2006a, IACS, 2006b) The advantages of the 10^{-2} probability level have been explained by Derbanne et al. (2011) as follows: 'the most important contribution to fatigue damage is due to the stress ranges corresponding to a probability approximately 10^{-2}; if the design stress is directly defined at 10^{-2}, the influence of the shape factor on the total damage is nearly cancelled; hence, it can then be taken as a constant. Moreover it has been shown that the EDW method can be used to compute the 10^{-2} stress.

Five EDWs have been defined to generate the dynamic load cases for structural assessment: HSM, FSM, BSR, BSP and OST, as defined above. The load cases HSA and OSA, defined above, are not considered for fatigue assessment since they are redundant with load case HSM.

The approach for combining other responses or subjected loads with the maximized load under the EDW is obtained by the load combination factors (LCFs). The LCFs have been derived through direct analysis for a significant number of oil tankers and bulk carriers covering ballast, full load and intermediate loading conditions.

The hull girder strength is the most critical failure mode for the hull structure. As ships' length becomes longer, this strength is even more important. Hence, the hull girder ultimate strength check is required for ships with length of more than 150m. The vertical hull girder ultimate bending capacity is to be checked for hogging and sagging conditions, for the following design load scenarios:

- For bulk carriers: design load scenario A, for seagoing, harbour/sheltered water and flooded conditions.
- For oil tankers: design load scenario A, for seagoing and harbour/sheltered water conditions, and design load scenario B, for the operational seagoing homogeneous full load condition.

Partial safety factors to account for material, geometric and strength prediction uncertainties are defined for the aforementioned load scenarios.

6. FATIGUE LOADS FOR SHIPS

With increases in size of container ships, the contribution of high frequency vibrations to the fatigue strength/damage of the hull girder has been extensively studied in recent years. The peak values of the VBM and the resulting bending stress increase as a result of the high frequency vibrations due to whipping and springing of the ship. This observation is based on analysis of full scale measurements. It is not possible to distinguish springing from whipping in measurements; hence, most publications refer to the high frequency vibration as whipping, since it is usually considered that springing occurs in relatively calm seas. This section mainly deals with the effects of high frequency vibrations on the fatigue strength of ships.

Andersen and Juncher Jensen (2014) analysed the full scale VWBM measurements of a 9400 TEU container ship in bow quartering seas by using FFT and concluded that the high frequency vibrations caused by impulsive loads are observed to be of the same magnitude as the rigid body response and, thus, act so as to double the total VBM amidships in the extreme case, as discussed more extensively in Section 5.1. Storhaug et al. (2012) showed that this high frequency vibration contributed to increase the dynamic extreme stresses on deck amidships by 22-33% in hogging and 27-32% in sagging by analysing the maximum values every half hour. Their conclusions were based on the full scale measurements from two LNG vessels operating in typical worldwide trading patterns for more than 5 years, excluding the Trans-Pacific trade. Based on elastic backbone model test data of two ULCSs, 8600 TEU and 13000 TEU, respectively, in regular and irregular head waves, Zhu and Moan (2013) showed that the high frequency vibrations increase the sagging VBMs more significantly than the hogging VBMs, however, the hogging peaks are increased more by the high frequency vibrations in relatively short waves because of the behaviours of second and third harmonics.

After fatigue damage was identified on a large ore carrier, attributed to whipping, its effect on longitudinal strength was further examined. Onboard measurements and model tests with flexible models were performed, and it was shown that the contribution of the rigid body response to the total fatigue damage was relatively large (ISSC, 2012b). Storhaug (2012) showed that the high frequency vibration contributes to approximately 26% of the fatigue damage on a 2800 TEU container ship and 29% of the fatigue damage on a 4400 TEU container ship, based on measurements in the North Atlantic for a few years. Toyoda et al. (2012) applied the rainflow counting and Miner's rule to the full scale measurement data of two post Panamax container ships taken over a period of 2.5 years and showed that the fatigue damage is increased 3.9 times due to the effect of whipping. It should be noted, however, that the absolute value of fatigue damage is quite low, 10^{-13} level, say. Based on measurement campaigns onboard a Panamax and a post Panamax container ships, the effect of high frequency hull girder vibrations on fatigue damage was assessed by Rathje et al. (2012). The contribution of high frequency loads was found to be 35% of total damage for the Panamax ship, while it was 57% for the post Panamax ship. They concluded, however, that the screening of damage data bases for Panamax container ships indicated that no significant amount of damage had occurred on similar ships, even for ships operating worldwide for more than 20 years. Andersen and Juncher Jensen (2013) estimated the fatigue damage applying the spectral analysis to the full scale stress measurements onboard the hull of a large container vessel, 9400 TEU, during several months of operation. They concluded that the spectral analysis show satisfactory agreement with the results from rainflow counting. Fatigue damage was also evaluated using the model test data and numerical simulation, and the effect of high frequency vibration due to whipping and/or springing was discussed. Derbanne et al. (2012b) computed linear long term fatigue damage for 6 container ships based on bending moment RAOs. The conclusion is that for vertical bending damage the hydrostatic restoring effect and the low frequency dynamic amplification effects are cancelling out each other.

Wang et al. (2013) predicted springing responses of large ships using 3D hydroelastic theory and model experiments. They showed that the structural fatigue damage induced by combined wave loads is much more severe than that induced by rigid body loads when wave period is small. Choi et al. (2013) numerically evaluated the hull-girder responses including the springing effect for an ULCS based on coupling of Vlasov beam theory and time domain 3D Rankine panel method. They concluded that hydroelastic effect is not reflected sufficiently in the numerical simulation for harsh sea conditions when compared with the results of model tests. Koo et al. (2013) carried out the fatigue assessment of an 18000TEU container vessel using a spectral approach and taking into account the springing effect. They concluded that the fatigue damage due to the springing effect has been between 24% and 64% of total fatigue damage when carrying out a fatigue damage analysis; however, fatigue damage considering the springing effects of case studies with measured data is much lower than results from the analysis.

Usually the rainflow counting method of stress cycles, considering the memory effect during elastic-plastic material behaviour in notches, as well as the Palmgren-Miner rule, are applied to predict the fatigue damage under variable amplitude loading, yielding the so called life curve compared to the S-N curve. In the Palmgren-Miner rule, the damage due to small stress cycles below the knee point of the S-N curve, i.e. fatigue limit, is usually considered assuming a modified slope exponent of the S-N curve beyond the fatigue limit, i.e. the so called Haibach's correction. Another parameter affecting fatigue life prediction is the bandwidth of the stress spectrum, which becomes wider in cases when the load process contains several frequencies. A rainflow correction factor was introduced to consider bandwidth effects on rainflow counting and damage summation for different spectra and bandwidth (Fricke and Paetzold, 2013).

(Fricke and Paetzold, 2012) performed fatigue tests using simplified stress histories with superimposed stress cycles of different frequencies and concluded that almost the whole of the fatigue damage is caused by the stress cycles induced by wave-frequency (rigid body load) which is enlarged by whipping, whereas the additional small stress cycles can be neglected. Fricke and Paetzold (2013) also performed fatigue tests of a welded detail with variable amplitude loading to investigate the effect of whipping stresses on fatigue damage in ships and the suitability of the Palmgren-Miner rule for fatigue life assessment. Stress histories comprising of two sinusoidal functions and a stress history obtained from onboard measurements were applied. The traditional approach with rainflow counting and linear damage accumulation based on the Palmgren-Miner rule is found to be suitable for ship-typical stress histories with low-frequency stress cycles due to waves and high-frequency stress cycles due to whipping. Most of the fatigue damage is caused by the low frequency stress cycles, enlarged by whipping, as long as the whipping stress amplitudes are smaller than the wave-induced rigid body stress amplitudes. The contribution of the additional small stress cycles due to whipping is rather small. Osawa et al. (2013) developed new simple fatigue testing machines which can carry out fast and low cost fatigue tests of welded joints subject to high frequency vibration superimposed on to wave loadings. Fatigue tests of out-of-plane gusset welded joints subject to springing and whipping, superimposed on to wave loadings were carried out. They also showed that the enlargement effect of the total stress range has a dominant influence on the fatigue strength under the conditions chosen. However, they concluded that it is unclear whether similar results can be found for the cases under various wave loadings with high frequency vibration.

On the other hand, Gotoh et al. (2012) performed fatigue tests of centre-cracked tensile specimens with simplified stress cycles containing high cycle stresses with/without damping, which is attained by the transient stresses being 5 times as high as the cyclic stress. Tests are also conducted with the regular low cycle stresses representing the envelope of the simplified stress cycles. Numerical simulation of fatigue crack propagation based on an advanced fracture mechanics approach using the RPG (Re-tensile Plastic zone Generating) load criterion for fatigue crack propagation is conducted and an extracting procedure for the effective loading sequence during random loading is proposed with the use of RPG load criterion. The test results were compared with the traditional S-N approach using the more advanced RPG load criterion which was superior to the ordinary cycle counting method such as rainflow method, because the load sequence effects on fatigue life can be taken into account. It was found that the fatigue life was underestimated in some cases, which were mainly attributed to irregular stress cycles (history) or deceleration/delay in fatigue crack growth when small stress range cycles followed a large stress range cycle, which is usual in the case of whipping. Furthermore, it was also confirmed from the experimental results that the traditional fatigue life evaluation method based on the S-N curves approach with rain flow counting is inappropriate under superposed loading conditions. Although the enlargement effect of stress amplitude by high frequency component is a very simple way for the consideration of whipping stresses in fatigue analyses, it is pointed out that uncertainties still exist regarding the real fatigue damage under typical stress histories containing wave loads and high frequency vibrations.

It is accepted that the stress amplitude of a ship's hull girder increases due to whipping and springing vibrations, and that fatigue damage also increases as a consequence of the enlargement effect due to high frequency vibration components. This fact is confirmed through comparisons with fatigue test data using test pieces in several cases. Nevertheless, it is also an undeniable fact that damages attributed to such hull girder vibrations were rarely reported for well-maintained, properly operated ships. One reason for such occurrence may be attributed to the nature of the Palmgren-Miner rule. Fukasawa (2012) showed, from numerical simulation results, that the number of stress cycles increases also in the zero-crossing counting case, but the increase rate is lower than that corresponding to the local peak counting case. Derbanne et al. (2011) and Fukasawa and Mukai (2013) showed in their numerical simulations that the dominant stress range to the fatigue damage is that of relatively small amplitude whose occurrence probability is approximately 10^{-2} according to Miner's rule, and a certain stress range has a significant effect on the fatigue damage.

Another reason may be attributed to the ship handling and the seaway conditions encountered. It is quite usual nowadays to operate a container ship at a speed less than 20 knots to save fuel and the ship can avoid rough weather due to advanced weather forecasting. The operational effect is not negligible for the evaluation of the occurrence probability of slamming. Ogawa et al. (2012) investigated the effect of different sea states on the occurrence probability of whipping-induced stress. Their work was based on full scale measurements of container ships, and the long term predictions were conducted based on the measured stresses and wave hindcast data. They showed that the difference of probability in wave height has significant or large effect on whipping and the consequent magnitude of induced stress. They also noted that most of slamming induced vibration occurs in head or bow seas. Storhaug (2012) measured strains and wind speed and direction on 2 container vessels (2800 TEU and 4400 TEU) and showed that fatigue damage is largest in head seas for the larger vessel and bow quartering seas for the smaller vessel, and that the relative vibration related damage decreases from head to stern seas. Based on fatigue tests and fatigue crack growth simulation, Sumi et al. (2013) stated that shipping routes and ship operation, including influence of ship heading and speed, must be taken into consideration for the proper estimation of probabilities. Prasetyo et al. (2012) conducted fatigue crack propagation based assessment of a surface crack in a weld of a longitudinal stiffener using JWA (Japan Weather Association) hindcast data for the north Pacific Ocean region. Load history is generated based on third generation storm model, which can take into account fluctuations in storm duration. It was shown that the fatigue damage ratio of second generation storm model, which can only take into account the relation between wave height and wave period of the short term sea state, to third generation storm model is almost equal to the ratio of calculated crack propagation life in each storm. The proper choice of wave environment and seagoing condition is important in evaluating the effects of whipping and springing.

7. UNCERTAINTY ANALYSIS

This section reviews only uncertainties related to wave-induced loads and loading conditions.

7.1 Load uncertainties

The subject of modelling and implementing uncertainties in maritime technology related areas is vast and different approaches are used, mostly depending on the aim of the analyses. Thus, Papanikolaou et al. (2014) presented recent advances in the treatment of uncertainties related to two engineering applications, namely development of reliability-based code formats and development of modern decision support systems (DSS) as guidance to a ship's master. Whilst both applications of uncertainty modelling share some common issues, there are also obvious differences. For example, in the former application, there is a basic uncertainty of design scenario for ship operation, requiring appropriate selection of parameters and calculation methods. Accordingly, the general practice has been to adopt the North Atlantic wave climate as a reference condition because of its severity. The counter argument is that real operational scenarios should be used in probabilistically based design. Even if a ship route, other than the North Atlantic one, is known at the design stage, ship owners argue that the ship could be sold during her lifetime and possibly be used in the North Atlantic trading routes (Guedes Soares, 1996).

Such uncertainty is not important for the second application, i.e. the development of DSS, where other uncertainties dominate. One of the important uncertainties in DSS relates to the definition of threshold or limiting values of seakeeping parameters that are used to predict the sustainable ship speed and heading in certain sea conditions. General operability limiting criteria, such as RMS of vertical acceleration at FP, probability of slamming, probability of green water and probability of propeller emergence are usually defined as fixed values depending on ship size and type and then used for design purposes (Moan et al., 2006). However, for probabilistically based DSS more refined seakeeping criteria need to be defined, preferably as random variables, and then included in the limit state function for evaluation of different seakeeping hazards (Papanikolaou et al., 2014).

Accuracy of observations or measurements relating to parameters of sea state in which a ship is sailing is one of the dominating uncertainties in applications of DSS. Nielsen et al. (2013) produced sea state estimates by three different means: the wave buoy analogy whereby one is relying on onboard response measurements, a wave radar system, and an onboard system providing the instantaneous wave height. The presented results show that for the given data, recorded on five different days of continuous operation, the agreement between the estimated means is reasonable.

The principal global loads causing longitudinal hull bending of ship may be summarized as follows (Bai, 2003): (i) still-water bending moments, (ii) rigid body (wave frequency or quasi-static) wave bending moments and (iii) vibratory bending moments caused by whipping and springing. The still water bending moments result from the longitudinal distribution of the cargo onboard and other controllable factors which are changing for each departure condition. Although still water loads are deterministic in nature, during a ship's lifetime they fluctuate; hence, they can, and should, be considered as stochastic process.

Rigid body VWBMs are obtained from standard seakeeping analysis. Primary uncertainties sources in numerical seakeeping analysis, according to Kim and Hermansky (2014), are :

- different mathematical modelling of (initial) boundary value problem,
- different numerical modelling of the assumed mathematical model,
- non-converged or inaccurate hull geometry modelling,
- insufficient or incorrect knowledge regarding mass distribution, and
- human, i.e., user error.

In addition, uncertainties at different stages of spectral analysis, which according to Hirdaris et al. (2014) need to be also considered, are:

- type of wave spectra,
- the choice of wave scatter diagram,
- method for prediction of long term extreme values and
- the operation of the ship (human actions/factors).

As the aforementioned uncertainties relate to the linear hydrodynamic tools only, computational uncertainty of nonlinear effects in wave loads, especially different sagging and hogging bending moments, should be added to the total uncertainty.

Transient elastic vibrations of the ship hull girder due to whipping represent important contributions to the VBM of large slender ships, especially ULCSs. Whipping vibrations increase both the extreme and fatigue load effects occurring in ships. VBMs induced by the combined effect of wave bending and whipping can double the magnitude of the former, as previously discussed in Section 6. Thus, considerable efforts have been spent on predicting loads associated with slamming and consequent structural response. Drummen and Holtmann (2014) presented results of benchmark study on uncertainties in slamming and whipping undertaken in 2012 by ISSC. The ship used in this benchmark study was 173m long RO/RO ferry. Surprisingly, they noted large discrepancies, even in the estimate of the two lowest natural frequencies of the global flexural vibration modes. However, it is interesting to note that overall results, especially for 3-node vibration, are in better agreement to the experiment for *wet* than for *dry* modes. When participants applied different realistic, analytical, pulses to their model, significant differences in fatigue loading of up to a factor of five were observed. Furthermore, the computations considering the response to an impulse induced by a regular head wave showed significant differences between the experiment, the different participants, and applied methods. The computation of slamming loads was performed i) using 2D slamming sections and BEM, ii) hybrid approach for slamming pressure computation, where initially vessel motions were computed using a Rankine panel method and imposing these motions on a RANS model using ANSYS CFX, iii) as per ii) but the motions were calculated using RANS solver StarCCM+, iv) fully coupled FSI computation based on RANS solver Comet for fluid dynamics and Timoshenko beam structural representation. The resulting fatigue damage compared to the experimentally measured loads was in the range of 0.42% to 507%, where *experimental fatigue damage* reads 100%. The authors concluded that the benchmark emphasized the need to validate and gain personal experience with dedicated tools.

Corak et al. (2013) carried out a parametric study of the influence of container ship route and operational and environmental restrictions on the long term distribution of combined, rigid-body and vibratory bending moments. The problem is formulated in the frequency domain using standard engineering tools for load computation: a 3D seakeeping code for the rigid body response and a beam FE model for transient vibratory response. The von Karman approach, with correction for pile-up effect, is employed for bow flare slamming load assessment. As expected, the IACS rule VWBM is largely exceeded by the combined VBM for the North Atlantic sea environment. The choice of alternative shipping routes can significantly reduce the long-term extreme combined VBM. Thus, combined VBMs could be reduced by 6% in the case of the North Pacific and by 26% in the case of the Far East-North European shipping route. Voluntary speed reduction has a considerable influence on the total VBM. By employing the speed profile reduction from ship operability analysis, the combined VBM for the North Atlantic route could be reduced by 21% for a constant ship speed of 15 knots.

Research related to the whipping effects of container ships has intensified after the accident of the container ship MSC Napoli in the English Channel in 2007. Although whipping certainly occurred at the time of the accident, it is still not clear how much it actually contributed to the hull girder failure (Storhaug, 2009). Parunov et al. (2014), in their investigations of the MSC Napoli, proposed the structural reliability approach, which enables identification of the relative importance of various pertinent variables on the structural failure. Sensitivity analysis, which is regular part of the structural reliability study, showed that the most important random variable at the time of the accident appears to be the modelling uncertainty in the bending capacity (32%). Such large uncertainty is caused by the uncertainty in the material yield strength and the modelling uncertainty of the progressive collapse analysis method used to assess the hull girder vertical bending capacity. However, the overall importance of all variables related to the uncertainty of the rigid body VWBM (37%) exceeds the importance of the strength uncertainty. The overall importance of the whipping contribution (24%) is approximately 2/3 of the importance of the rigid body VWBM.

The importance of uncertainties in design and analysis of large container ships was emphasized once again due to the case of structural failure of the MOL Comfort container ship in the Indian Ocean in June 2013. The report issued by the Maritime Safety Committee (IMO, 2014a) reveals that the estimated total global bending loading at the time of the accident was of the order of 9.4 GNm, whilst the estimated bending moment capacity was 14.0 GNm. This indicates that the estimated load was approximately 67% of the hull strength and the conditions for fracture could not be simulated. For this reason, the authors of the report concluded that it would be necessary to consider uncertainties in further verification of both load and strength related calculations.

7.2 Uncertainties in loading conditions

The uncertainty of the weight and weight distribution and their consequences have not been the subject of scientific analysis in the usual journals, nor any ISSC committee. Nevertheless, these uncertainties have been identified by industry as a considerable problem, and not only in the context of the recent ship accidents of MOL COMFORT and MSC NAPOLI. According to the world shipping council some customs, namely Ukraine, Poland and India, have investigated container weights. The IMO, in May 2014, approved draft amendments to SOLAS chapter VI requiring mandatory verification of the gross mass of containers (IMO, 2014b), which were approved in November 2014.

Within the European research project ADOPT (Nielsen and Michelsen, 2007) the variation of deadloads corresponding to six months' loading conditions from a RORO vessel were analysed. The analysis showed deadloads up to 16% of the displacement, that is up to approximately 1300 tonnes, with the dominant range from 200 to 900 tonnes. Deadload is the excess between the vessel's calculated deadweight, based on draught readings, and known weights such as cargo, fuel ballast, water etc. The uncertainty of cargo weight and distribution for RORO, ROPax and heavy lift vessels is mentioned in the report of the research project lashing@sea but it is concluded that since the accident rate has not increased, it is not considered a problem for such ship types (Koning, 2009).

Cargo that is heavier than declared is not only a problem for the establishment of maximum allowable loads on ships but also an important factor in the collapse of container stacks, loss of containers at sea, stability failure and transportation on shore. One of the issues noted within the lashing@sea project was that no centralized data base of shipping incidents of cargo loss and damages are kept (Koning, 2009). This makes an analysis of the extent and severity of the uncertainty of cargo weight difficult.

Within the investigation of major structural failures of container ships, the uncertainty of cargo load has been evaluated whenever possible. The accident reports of the MSC NAPOLI (MAIB, 2008) stated that this ship often had large deadloads on completion of loading. The deadload on departure from Antwerp, prior to the cracking, was about 1250 tonnes (approximately 1.6% of displacement). During the removal of containers, the position of 700 containers on deck were compared with the position recorded by the terminal operator. Of these units 53 (7%) were in the wrong position or misdeclared. It is generally agreed within the container industry that up to 10% of containers loaded onto a vessel might not be in their planned positions. Since the two parts of the MOL COMFORT sank, the contribution of the uncertainty of weight and weight distribution cannot be accounted for. The effect of the uncertainty of container cargo weight on the SWBM, based on the hull deflection obtained through draught measurements at the time of departure, is difficult to assess (MAIB, 2008).

A submission to IMO (2012) summarizes some incidents due to, amongst others, misdeclaration of container weights. For example,

- Containership Deneb in Algeciras (CPIAIM, 2012): According to this report, the weight of the cargo used for calculating the stability was 332 tonnes, approximately 9% of displacement, lower than the calculated weight;
- P&O Nedlloyd Genoa (MAIB, 2006): Two containers were overweight, but the results show that the remaining containers were close to their declared weights.

Based on information obtained from the world shipping council it is known that the Ukrainian customs, over a two week period in October 2012, weighed all packed containers discharged in Ukrainian ports. 56% of the containers had an actual weight greater than the weight stated in the manifest based on the shipper's declared weight as provided in the shipping instructions.

Based on current evidence, it is difficult to speculate on the consequences of the uncertainties in loading conditions. In the case of the structural failure of MSC NAPOLI the overloading of the vessel, i.e. the resulting deviation to the SWBM, would have been extremely small by comparison to the potential variability of the wave loading. Therefore, the effect of the discrepancies alone would have been insufficient to cause hull failure. Nevertheless, they would have contributed to the reduction of the safety margin available (MAIB, 2008). Whether this conclusion holds true for other vessels cannot be established due to poor and incomplete evidence.

8. CONCLUSIONS

On *Zero speed case*: The potential flow model remains, in general, one of the dominated efficient solvers for numerical simulation of wave-body interactions at zero speed, including the influence of a range of nonlinearities. Therefore, further development of 3D FNPF solvers is still valuable. The versatility and increased accuracy of N-S type solvers for capturing important characteristics of wave-body interactions has been demonstrated. Nonetheless, there are very promising developments in 3D models combining potential flow solver and N-S solvers, which should continue.

On *Forward speed case*: Potential flow solutions continue to be dominant also in the case where forward speed is non-zero, albeit with inclusion of a range of nonlinearities. The focus in these applications is the generation of practically applicable solution packages, capable of coupling with phenomena, such as slamming, sloshing and green water. Use of N-S solvers focuses in the main on the seakeeping problem with improved accuracy of predictions. Hybrid solutions for computational efficiency, involving nonlinear potential flow and N-S solvers, are amongst the promising developments.

It is interesting to note that the state-of-the-art for either zero or forward speed cases is very similar, in spite of differences in operational and environmental frameworks. Furthermore, the need for measurements to validate computational methods is paramount for both cases.

On *Sloshing*: The majority of investigations into sloshing focus on numerical simulations using RANS CFD methods and experimentation, 3D simulations and realistic excitations for both. Analytical investigations can be useful in terms of providing simple formulae useful in design. Recent advances include studies on sloshing with internal suppressing structures and investigation on the coupling between sloshing and ship motions, both numerically and experimentally. It is expected that these studies will continue in order to improve the accuracy of numerical simulations.

On *Green water/wave-in-deck*: The green water problem has been investigated experimentally and numerically, but with very limited success. The issues arise due to the fact that green water is very difficult to measure either under laboratory conditions or in the field, and very difficult to simulate numerically. The problem, due its fast moving, multiphase and highly turbulent nature, is not very amenable to accurate numerical simulation, although 3D models help to better understand and simulate the mechanisms of green water impinging on deck. Green water load computation with various wave headings is still a challenge. Qualitative benchmark studies are required to validate and improve numerical approaches. The issues for the wave-in-deck problem are similar, but applicable to structures fixed or moored in an extreme environment.

On *Loads from abnormal waves*: Research and early findings raise the some critical questions: should we design future ships for abnormal waves or for the upper tails (essentially beyond 99% quintiles) of wave statistics and will be these ships economically viable? Here we need to differentiate between merchant and naval ships, as their mission profiles differ significantly. Also, the design problem of offshore structures, which cannot avoid extreme environmental loads, is inherently different from that of ships, for which operational measures and guidance to the master to avoid dangerous environmental loads appear more efficient than an increase of design loads and safety factors.

On *Hydroelasticity*: The main progress in hydroelasticity analysis is in the development of BEM based nonlinear FSI methods through coupling with FE models. Coupling between RANS and FE solvers, currently used for slamming related problems, is also being applied to predict the *rigid body* and springing related loads. The success of the latter will depend on the computational efficiencies made and the improvements in accuracy obtained with reference to potential flow based predictions.

On *Slamming*: Prediction of slamming loads has recently covered some aspects that were of secondary importance in the past with respect to the determination of the pressure peaks over the impacting bow: water-exit phase, presence of both vertical and horizontal components in the water-entry velocity, oblique or asymmetric impacts, wavy surface are some of them. Hydroelastic effects have been dealt with different approaches ranging from semi-analytical methods to coupled finite element and RANS solvers including 3D fluid-structure interaction and composite materials. Indeed, many of these studies have been oriented toward analysis of containerships since their flexibility poses challenging questions to numerical simulations.

On *Measurements*: Recent advances in measurement techniques and fabrication technology have indeed broaden the capability to design experimental setups where scaled models can reproduce the full-scale elastic behavior and provide high quality data for code validation. Thus, much effort focused on the assessment of physical models to be used in FSI tests and their mechanical and structural properties. The analysis of transient phenomena, such as slamming, has benefited from the application of advanced signal analysis techniques. Full scale monitoring of environmental conditions and hull structures has also greatly improved, thus allowing for real ship response investigations at a reasonable cost, as well as assessing our capability for modeling numerically and experimentally.

On *Loads following damage*: The motivation for increasing research on damaged ship is the implementation of risk based methods in rule development, where residual strength of ships in different foreseen damage situations is required in addition to that of the intact ship. The use of reliability based methods demands realistic estimates of loads on damaged ship. Thus, the main driving force for further research, is the development and understanding of both deterministic and probabilistic models for load assessment in accidental situations.

On *Weather routing*: Development of optimization schemes and simplified mathematical models for complex hazards, such as fatigue damage form the basis of the research into weather routing. The necessity of embedding an uncertainty analysis into an operational guidance has been identified, but not accounted for in most research. The reliability of the guidance, e.g. identifying and mitigating false predictions, has not been an issue; neither the transmission of information gained to the master, the crew and the ship operators to enable sound decisionmaking under uncertainties.

On *VIV:* Although industry practice continues with the use of semi-empirical methods, the pace of development is picking up, involving both academic and industrial research. Operations in deeper waters, possibility of collision in riser bundles and fatigue damage and relevant high safety factors used provide the incentive for such developments in experimentation, simulation and validation studies.

On *VIM:* The technology dealing with VIM is advancing constantly especially using CFD simulations, as well as focusing on suppression arrangements. However, in current industry practice model tests are still required to derive VIM design criteria. A hybrid methodology that considers both full scale CFD results and model test results may have potential use in the VIM design assessment instead of using model test results only.

On *Mooring Systems*: Research focuses on a range of methods for coupling the dynamics of mooring lines, floaters and risers and assessing the validity of partly, fully coupling methods, as well as frequency, time and hybrid frequency/time domain approaches. In addition research into different materials, and their properties, used in mooring lines is of great importance in terms of including in the dynamic simulations and assessment of fatigue damage.

On *Lifting Operations*: The review of this subject clearly shows the progress achieved in the last few decades in coupling the payload and lifting vessel dynamics. Current investigations focus on nonlinear potential flow hydrodynamics and measurements for validation. There is room for improvement on the nonlinear system and environment characteristics used.

On *FOWT*: Development of simulations tools for FOWT systems benefited from past experience by combining wind turbine aerodynamic/elastic and offshore structure hydrodynamic and station-keeping methods and tools. With the quest for higher energy recovery and the use of larger turbines, an increase in experimental validation and refinements in simulation tools are expected.

On *Probabilistic methods*: These are, by and large, employed to study short and long term distributions of ship responses. Load combination studies of still water and a range of wave loads are also performed. Although a significant amount of research is dedicated to the design-oriented probabilistic methods for prediction of extreme combined wave-induced and vibratory responses, we are of the opinion that practical methods, applicable for conceptual and preliminary ship design, are still lacking.

On *Design methods for ships*: The focus of investigations has been on developing and verifying equivalent design waves. The selection of the characteristics of such waves, such as increased sea state significant wave height, aids in cutting down the amount of simulations required.

It is expected that the rule based approach and the direct calculation approach should give same answer in terms of the acceptance of the particular ship structural design in the near future.

On *Fatigue loads for ships*: Crack initiation and propagation behaviours are nonlinear phenomena and there may be some limitations in the application of Miner's rule in terms of accuracy of estimated fatigue damage. Further investigations are necessary to clarify the effect of hull girder vibration upon the fatigue strength of a ship by accounting for stress histories which are effective in crack initiation and propagation. Full scale measurements, model tests and numerical simulations, such as the aforementioned crack propagation analyses, should be combined to clarify the fatigue life characteristics of a ship in waves.

On *Uncertainties*: The importance of uncertainties can be seen in comparative studies predicting ship motion and structural loads, such as that on a large containership arranged by the 2nd ITTC-ISSC Joint Workshop in 2014. We are of the opinion that systematic uncertainty assessment is one of the main issues requiring resolution for the advancement of marine structural design. Development of sophisticated computational tools should be followed by uncertainty analysis of their predictions, including operational uncertainties as one of the main contributing factors in definition of design loads.

Final comment: The review in the reporting period indicates two specific trends for fluid-structure interaction problems: (i) a *systems approach* which should be extended to include coupling between propulsion/control devices, in ships, and mooring/riser systems, in marine structures, to enable a more accurate and complete evaluation of loads; (ii) the pursuit of *hybrid* solutions for computational efficiency, which should continue and expand towards data fusion, namely solution systems bringing together a range of computational predictions and measurements, and making use of data-rich and data-sparse analyses.

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