Highlights and future research areas from ISSC 2022

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Review Article

Highlights and future research areas from ISSC 2022

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ABSTRACT

The International Ship and Offshore Structures Congress 2022 (ISSC 2022) held in September 2022 covered most of the essential topics related to marine and offshore structures. The proceedings of ISSC 2022 include Committee Reports for Environment, Loads, Quasi-Static Response, Dynamic Response, Ultimate strength, Fatigue and Fracture, Design Principles and Criteria, Design Methods, Accidental Limit States, Experiment Methods, Materials and Fabrication Technology, Offshore Renewable Energy, Special Vessels, Ocean Space Utilization, Structural Longevity and Subsea Technology [1,2,3]. While the nature of ISSC Committee work is focused on state-of-the-art review based on the latest publications, the future work and research areas, which are most relevant to stimulate more R&D effort, are presented here, focusing on Loads, Quasi-static response, Fatigue and fracture, Experimental method, Material and fabrication technology, Offshore renewable energy, Structural longevity, and Subsea technology.

1. Introduction

The International Ship and Offshore Structures Congress (ISSC) is a forum for the exchange of information by experts undertaking and applying marine structural research. ISSC 2022 includes 16 Committees: Environment, Loads, Quasi-Static Response, Dynamic Response, Ultimate strength, Fatigue and Fracture, Design Principles and Criteria, Design Methods, Accidental Limit States, Experiment Methods, Materials and Fabrication Technology, Offshore Renewable Energy, Special Vessels, Ocean Space Utilization, Structural Longevity and Subsea Technology. Each of the 16 ISSC 2022 Committees conducted extensive reviews of the research in progress and presented the evaluation and investigation of the research (which in some cases included Benchmark studies in emerging technologies). Details of the outcome are described in the ISSC 2022 proceedings [1]. Sections 2 – 9 of this paper provide the key findings

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from Committees of Loads, Quasi-static response, Fatigue and fracture, Experimental method, Material and fabrication technology, Offshore renewable energy, Structural longevity, and Subsea technology. These are followed by Section 10 of this paper, which is the summary of future work and research areas, recommended by these 8 Committees. Finally, conclusions can be found in Section 11.

2. Loads

2.1. Wave loads on ships

Linear frequency-domain potential theory methods (both 2D and 3D), are still the primary design tools in assessment of seakeeping and hull girder load effects. For low and moderate ship speeds, Green function methods with "speed-correction", as in the traditional strip theory of Salvesen et al. [4], are widely used. For higher ship speeds, and for problems including nonlinearities in the free surface boundary condition, the Rankine panel methods are usually preferred. The Rankine source is more robust and easier to implement as compared to the translating and pulsating Green function, and nonlinear effects can more easily be included. The Rankine methods also avoid the problem of irregular frequencies, but they require that the free surface is discretized. Hybrid, or multi-domain, methods, in frequency-domain [5] Fig. 1 or time-domain [6], aim at combining the merits of the Green function methods and the Rankine methods, by applying the Rankine method in an inner domain and matching this with a Green function formulation used for an outer domain.

Most research on potential theory methods today focuses on 3D methods. Research challenges include finding efficient ways of handling the ship's forward speed, and to efficiently include the nonlinear effects that are important in order to assess the wave-loads with sufficient accuracy. Nonlinear hydrostatic and Froude-Krylov forces are often included in time-domain formulations, and forces due to slamming can influence the ship motions and especially the hull girder load effects. Efficient methods for calculating added resistance and for simulating ship maneuvering in waves have gained much attention in the last few years. Ley & el Moctar [7] and Lee et al. [8] discuss linear and nonlinear potential theory approaches for assessment of wave-loads, ship motions and added resistance.

Field methods, solving the Navier-Stokes equations in the entire fluid field near the body, are becoming increasingly popular. For turbulence modelling, using the Reynolds-Averaged Navier-Stokes Equations (RANSE) is common, and has proven to give accurate results for hull girder load effects in steep waves, as demonstrated in the benchmark study performed by the ISSC 2022 Committee I.2 Loads [9]. Most of these approaches use the Finite Volume method (FVM) together with a Volume-of-Fluid (VOF) scheme for capturing the free surface.

For ships with liquid cargo, sloshing in cargo tanks is of concern. Violent fluid motions in the tanks cause high pressure loads on the tank walls, which may lead to failure of the tank structure. Sloshing involves complex highly nonlinear and three-dimensional flow, often involving wave breaking, flow separation, air/gas entrapment, heat exchange, fluid/gas compressibility and hydroelastic effects. Pressures are extremely localized, and results from small-scale tests are difficult to extrapolate to full-scale values. An overview of state-of-the-art is given in Malenica et al. [10]. They conclude that, for prediction of the sloshing pressures and responses of the compartment structure, no acceptable calculation method exists, and there is currently no rational methodology for determination of the representative design conditions. Prediction of fluid motions and sloshing pressures is usually performed using a Navier-Stokes solver based on e.g. an FVM/VOF formulation or a meshless method such as Smoothed Particle Hydrodynamics (SPH). Due to the complexity of the problem and the localized pressures, these methods still do not manage to fully reproduce physical behavior, and the high computational efforts render these methods impractical for producing long time series. However, the Navier-Stokes solvers can be used for evaluation of sloshing severity i.e. for the identification of the critical sloshing conditions in a qualitative manner [10].

The fluid motions in the tanks may also influence the ship motions. This applies in particular to the roll motions, but other modes may also be influenced; an example is found in Seo et al. [11] who found that sloshing can have an effect on added resistance through the pitch motion. To capture the effects on ship motions, the forces on tank walls must be included in the ship motion simulations. Calculating sloshing forces is easier than calculating pressures, since the very localized effects need not be considered. Methods range from those using linear frequency-domain potential theory (PT) for both ship motions and sloshing [12–14], via those using linear PT for ship motions and nonlinear sloshing formulations [15,16] and those using nonlinear ship motions and RANSE for sloshing [17] to application of RANSE for both the ship motion and the sloshing problems [18,19].

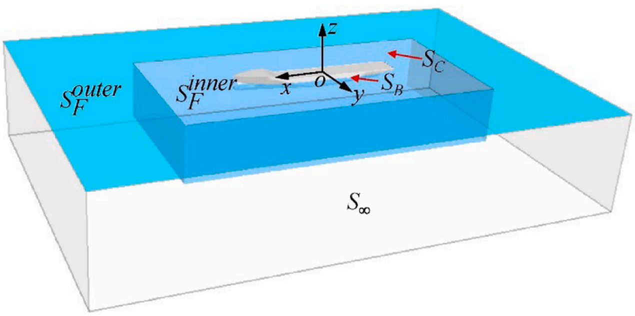

Fig. 1. Domain decomposition in hybrid Rankine / Green function method. From Yang et al. From Yang et al. [5].

2.2. Wave loads on stationary floating structures

Stationary floating structures, used in the oil and gas industry and for floating offshore wind turbines (FOWT), often consist of single or multiple vertical columns that penetrate the water surface, such as spars, semisubmersibles and TLPs. Assessment of mean forces and slowly varying forces due to waves and current are important in designing moorings and Dynamic Positioning systems. Mean second order forces are obtained from the first order potential flow solution by including second order terms when calculating the pressure and when integrating it over the wet surface. To assess the difference-frequency and sum-frequency forces, the second order velocity potential must be calculated. These calculations give the quadratic transfer functions (QTF's) relating the difference-frequency and sum-frequency forces to the square of the amplitude of the wave components. To avoid having to calculate the full matrix of QTF's for the difference-frequency forces, Newman's approximation is often used, where only the diagonal terms are needed, and these are obtained from the first order potential. The second-order difference-frequency forces are generally small compared to the first order wave forces, but if their frequency coincides with a natural frequency, they can increase the motions significantly. The lateral motions of a column-based floater usually have low natural frequencies, and for these modes Newman's approximation generally works better than for modes with higher natural frequencies, such as heave, pitch and roll. The approximation works less well when the mode has low damping, and the transfer function varies rapidly around the resonance frequency [20]. It also becomes more uncertain when the water depth decreases. Hence, it is becoming increasingly common to calculate the full matrix of QTF's, and several commercially available potential theory solvers have this capability.

The validity of using Newman's approximation on semi-submersible type FOWT has been investigated in several recent studies [21,22]. It was found that, compared to using the full QTF's, Newman's approximation significantly underestimates the resonant motion in heave, and in particular in pitch. When the water depth becomes small, it also underestimates the resonant surge motions, and hence the mooring line tension.

Within the EXWAVE JIP [23], wave forces on four semisubmersibles with different column diameters and configurations have been studied experimentally and numerically, including wave-current interaction and viscous forces. Fonseca et al. [24] conclude that viscous drag forces become increasingly important for the mean and low-frequency horizontal wave forces on semis in higher sea states, when waves are large compared to the column diameter. Viscous effects are also important for cases with wave-current interaction, and potential theory codes underestimate the lateral forces also in such conditions. Potential loads higher than second order may also play a role. It was also found from the model tests that the damping of the low-frequency lateral motions increases significantly with increasing sea-state and with increasing current velocity. The EXWAVE JIP also produced an updated version of the semi-empirical correction formula [25] to account for wave-current interaction and viscous effects on the surge and sway forces.

In the presence of current, or during towing, columns, such as spar-type floating wind turbines, may be subject to vortex induced motions (VIM). The phenomenon can also occur for structures with multiple columns, such as semisubmersibles. The load mechanisms exciting VIM are similar to those involved in the well-known vortex induced vibrations (VIV) phenomenon, and Morison-type load models are used with various additional load terms. Hence, coefficients derived from physical tests and/or computational fluid dynamics (CFD) simulations are essential input. These semi-empirical methods are frequency- or time-domain, and focus is mostly on single columns; see e.g. Passano et al. [26] Fig. 2. With multiple columns there will be interaction effects that increase the complexity, and direct CFD simulations of the floater is a promising method for these more complex structures [27]. A systematic review of recent research on VIM can be found in Yin et al. [28].

For slender structures, the vortex shedding leads to the well-known VIV phenomenon, and today's industry practice is to consider current-induced VIV using frequency-domain semi-empirical methods. Recent developments in time-domain methods [29,30] allow nonlinear responses, time-varying flow due to both current and waves, as well as loads/responses at several frequencies

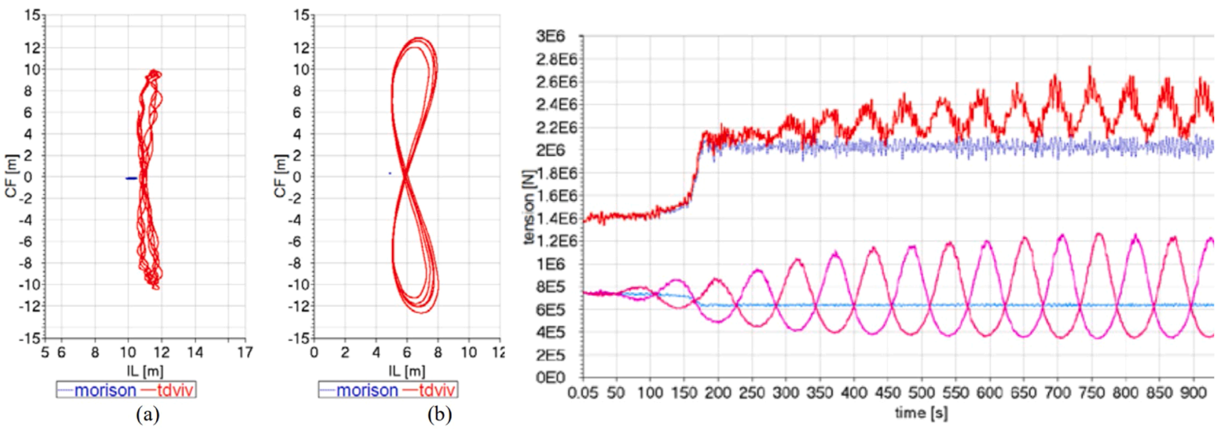

Fig. 2. Time-domain VIM simulations (red/magenta) of spar-type floating wind turbine with 3 anchor lines. Left: Motion in horizontal plane (In Line - Cross Flow) at waterline (a) and at spar bottom (b). Right: Tension in the upstream anchor line (top) and the two downstream anchor lines (bottom). Blue lines are from simulations with classical Morison current and wave loads. From Passano et al. [26].

simultaneously. However, the frequency-domain semi-empirical methods are still needed for screening, since they are much faster than the time-domain methods.

Recent research on airgap and wave impact loads has been motivated by concerns that high-order nonlinear effects may give larger crests than what has been taken into account in existing designs [31–33]. Moreover, it has been realized that the distribution of crest elevation over a deck *area* is significantly larger than the crest distribution at one specific point. There is also uncertainty about the importance of breaking wave kinematics in deck loading. Based on extensive laboratory testing, new empirical distributions for crest heights with and without the area effect have been proposed. However, experimental work on wave impact loads show that the largest wave-in-deck load may not coincide with the largest crest, since other wave properties are also important. Therefore, the simple approach of first estimating the crest elevation with the prescribed return period and then calculating the deck load by a regular wave with the same crest height may not be accurate. This concern has led several groups to investigate the long-term distribution of wave-in-deck *loading* by Monte Carlo simulations of the full long-term environment, using either empirical or CFD-based methods to incorporate nonlinear effects and breaking in the wave description. Recent projects on airgap include the AWARE project [34], the LOADS JIP [35] and the BreaKin JIP [36].

2.3. Wind loads

For calculation of wind loads on ships and offshore structures, CFD has become a good alternative to wind tunnel tests. CFD simulations, steady RANS being most common, are cheaper and more flexible, and can be done with full-scale values. One also avoids possible difficulties associated with mounting of the physical model, where e.g. gaps between the model and the turntable can give incorrect flow patterns. However, wind tunnel tests are still widely used and are important for validation of CFD models.

Berto et al. [37] reported from a blind comparative study of a semisubmersible organized through the SNAME OC-8 Panel, including comparison of three approaches to wind load estimation, namely, the empirical building block method, wind tunnel testing, and CFD simulations. Results were provided from 5 different wind tunnel test facilities, CFD results came from 10 organizations, and 8 sets of estimates using empirical methods were presented. The drag forces and overturning moments for various relative wind headings predicted by the wind tunnel tests and the CFD simulations were in good agreement. The results from the empirical methods displayed a large scatter, and the estimated forces and moments were generally significantly higher than those from CFD and wind tunnel tests.

Another blind comparative study was presented by Yeon et al. [38], Fig. 3, where results from the Reproducible Offshore CFD JIP showed that CFD simulations can give reliable results that compare well with model tests. They studied a semisubmersible rig in even-keel and inclined conditions and an FPSO at even-keel, using blind-tests with 3 – 5 participants. Scatter in results for forces and moments was within 3 - 6%, except for roll, pitch and yaw moments for the FPSO, where the scatter was larger. The authors point out that a major bottleneck in application of CFD is the work involved in ensuring that CAD models have water-tight surfaces.

For ships, it is common to use existing sets of wind coefficients obtained for vessels with a similar superstructure configuration to get quick estimates of the wind load coefficients. It is however difficult to manually map results from alternative similar ship profiles into the best set of wind coefficients for the vessel configuration at hand. Prpić-Oršić et al. [39] presented a Generalized Regression Neural-Network method that is trained with existing results to map frontal and lateral vessel contours, described mathematically with a series of Elliptic Fourier Descriptors, into wind load coefficients. The method was applied to a large container ship with different container configurations.

A large number of papers on wind loads on wind turbine blades have been published in recent years. The Blade Element Momentum

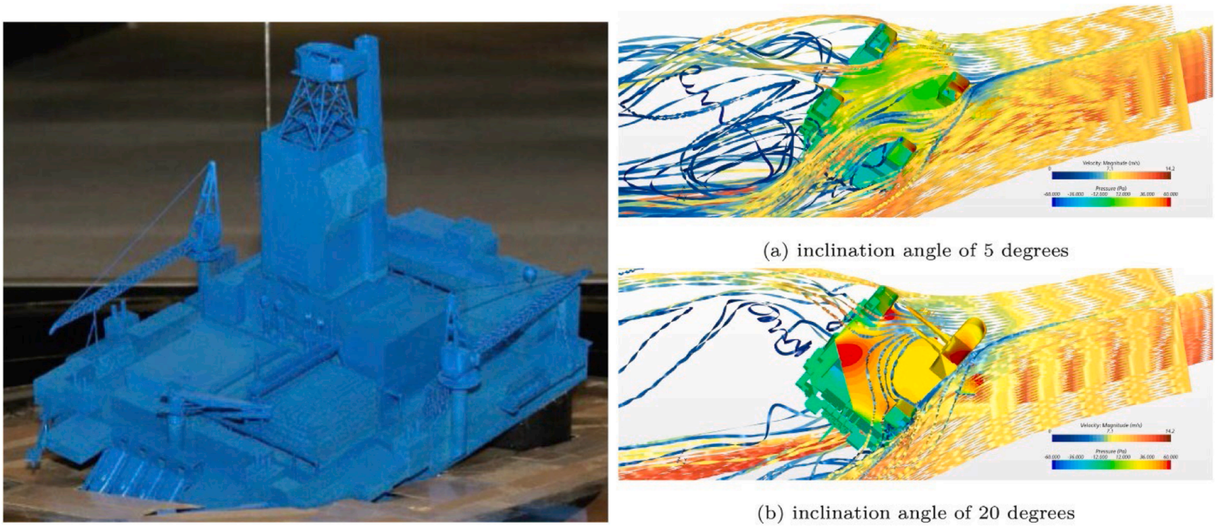

Fig. 3. Wind tunnel tests with inclined semisubmersible, showing gaps between model and turntable (left). Pressure distributions from CFD simulations (right). From Yeon et al. [38].

(BEM) method is the most commonly used in industry practice. Various corrections have been introduced to try to account for effects that violate the basic assumptions of the BEM, such as large blade deflections, skewed flow caused by yawed inflow or turbine tilt; and large rotor motion as for FOWT. CFD simulations have been shown to capture many of these complicated flow phenomena, but the computational efforts are still large. The vortex methods constitute an intermediate fidelity range, and the so-called free vortex wake method overcomes many of the limitations of the BEM, while being less computationally demanding than CFD.

2.4. Ice loads

Ice loads may be divided into local loads at the point of ice contact, and global loads. Local loads can be critical for structural integrity, whereas global loads give increased resistance for ships, increased mooring loads for stationary floating structures and jeopardize the integrity of fixed column-based structures. Further, since there are many types of ice, with very different physical characteristics, and different interaction scenarios, such as e.g. brash ice, pack ice, level ice, floe impact and pressured ridges impact, there is no universal method for assessing the ice loads.

Recent research on ice loads includes full-scale measurements, model-scale experiments and further developments of analytical, numerical and statistical modelling approaches. An overview of numerical simulation methods for ship-ice interaction is given by Xue et al. [40].

Recent full-scale measurements of local ice loads on ships are reported by Kotilainen et al. [41], Adams et al. [42], Böhm et al. [43] and Kong et al. [44], while global ice loads on ships are reported in Liferov et al. [45] and Nyseth et al. [46]. Full-scale measurements on other offshore structures are reported by Paquette & Brown [47], Savin et al. [48] and Wang et al. [49].

Model tests are performed in refrigerated ice tanks [50–52], but also in conventional hydrodynamic laboratories using synthetic materials to mimic the ice, such as ice floes made of polypropylene and used in ship resistance tests [53], and synthetic pack-ice resistance tests [54].

The nine refrigerated ice tanks in active operation today commit to the guidelines if the ITTC [55], but all use different combinations and concentrations of added chemicals as well as different crystal grain structures, as noted by von Bock und Polach et al. [56], who introduce two new model ice types: 'model ice of virtual equivalent thickness' and 'wave model ice'. The motivation is that standard model ice has been found to be too compliant in bending, and this can lead to an exaggerated ride-up of a ship onto the ice, yielding additional resistance due to the heave and pitch motions. Moreover, when testing vertical structures exposed to drifting ice, the exaggerated flexural deformation of model ice during crushing leads to failure modes and loads that do not correspond to full-scale observations. Finally, ice breakup during model tests in waves occurs at a too high wave steepness.

There is a continuing development in theoretical approaches for assessment of ice loads on marine structures. To be able to calculate the total loads and motions of a marine structure, while capturing the details associated with the ice failure process, extensive computational efforts are required. Therefore, simplified empirical, semi-empirical and analytical methods are often used, and some recent examples can be found in e.g. Karulina et al. [57], Dobrodeev & Sazonov [58], Huang et al. [59] and Huang et al. [60].

During ships breaking level ice, the ice breaks primarily due to out-of-plane bending caused by the downward forces from the ship's bow, and the interaction speed is relatively large. When ice interacts with more vertical structural elements, such as the sides of the ship [61] or a fixed/moored offshore structure, the in-plane forces become much larger, and the interaction speed is normally lower. Hence, models intended for ice breaking bows may fail to produce accurate results for other cases.

The main ice failure modes in ice-structure interaction are splitting and bending [61]. Modelling approaches for crack propagation include FEM with element erosion technique, cohesive element method (CEM), the discrete element method (DEM) with cohesive contacts and the extended finite element method (XFEM) [62]. DEM appears most beneficial for cases where it is required to model discrete ice blocks [63]; the method is less accurate when it comes to modeling the whole fracturing process from the continuous to discontinuous phase [64].

When applying the above numerical modelling approaches, it is quite common to exclude hydrodynamic effects, based on the assumption that the relative vertical velocity between the structure and the ice is low. The water is then considered as an elastic foundation, where only the buoyancy and, sometimes, drag forces are modelled [40]. When hydrodynamics matter, potential theory is sometimes used, but since viscosity is important in ice floe kinematics [65], SPH or, more frequently, CFD is applied. Mintu et al. [66] used SPH-DEM coupling, while CFD-DEM was used by Luo et al. [67] and Huang et al. [68] (Fig. 4).

Li et al. [61] propose an efficient method for calculating ice loads on ship shoulders and sides by using a neural-network that is trained with results from XFEM-based numerical simulations.

A meshless particle method, known as Peridynamics, has shown promising results when applied to ice-structure interaction involving ice fracture. Recent applications include Vazic et al. [69], Zhang et al. [70] and Wang et al. [71].

3. Quasi static response

The true loading and response of marine structures in a seaway is dynamic. However, dynamic analysis methods are generally not suitable for design, until the maturity of the structural arrangement has progressed to a level that these methods can be meaningfully implemented. Quasi-static methods fit well in the early design stages and are the basis of many Classification Society Rules and design standards.

For the purposes of the review of Quasi-Static methods presented by the ISSC 2022 Committee II.1 [72], consideration was made for methods where the effects of structural dynamics (structural inertia and damping) may be neglected. In this regard, the time component, or time derivatives, may be neglected. To adopt a Quasi-Static method, the true time-dependent loading must be

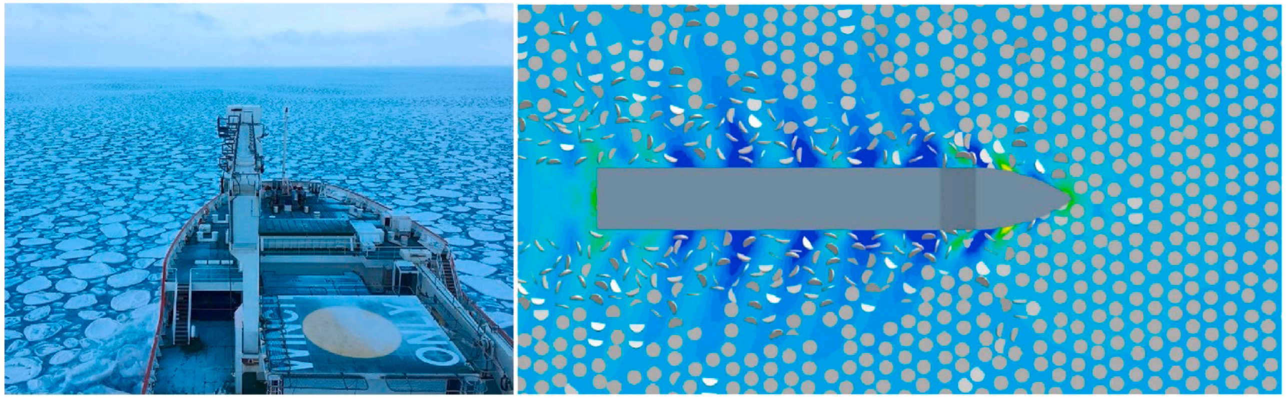

Fig. 4. Ship in ice floes. Left: Full-scale. Right: CFD-DEM simulations. From Huang et al. [68].

sufficiently slow in relation to the structural response not to coincide with resonant response frequencies. Due to this ‘slow’ progression, during analysis, the system may be considered to be in static equilibrium at all time instances.

Across the review, methods included first principal calculation approaches, calculation approaches with Classification Society Rules and design standards, as well as methods implementing finite element analysis to assess the structural response. In addition to the structural response, the review covered methods whereby the structural loading is simplified to apply a quasi-static representation.

In general, there was found to be a slow incremental advance in the development of Quasi-Static methods over the term of the review. In the area of load application, developments were presented in ice-loading and crack propagation using peridynamics and full-scale measurements [71,73], as well as loading from hydrocarbon explosions [74]. For structural modelling, literature was presented on methods for stress analysis by direct calculation, optimisation based analysis and fatigue analysis, as well as the influence of material properties and degradation in structural response. Quasi-Static approaches for assessment of ultimate strength were presented, demonstrating the continued use of implicit finite element solutions for ultimate strength assessment, and the Quasi-Static relationship to real-world marine structures. These included assessment of stiffened plates [75,76] through to hull girder strength assessments [77–79].

In addition to the use of Quasi-Static methods for direct calculation of structural scantlings in design, Quasi-Static methods are often applied as the basis to reliability analysis. In reliability analysis the analyst looks to quantify the uncertainty in the loading and structural response to derive a probability of failure within a defined service-life of the structure. Derivation of Quasi-Static approaches may be from first principles or analysis of results from physical tests or numerical analysis, and so have a level of uncertainty within the calculation method that is not often accounted for within the reliability analysis. Within the presented review, the committee looked to identify where authors had quantified the level of uncertainty within Quasi-Static methods. The committee found limited publications presenting validation and quantification of uncertainties in Quasi-Static methods. It is the opinion of the Committee that focus should be provided on such quantification, as well as consideration by researchers whether Quasi-Static methods can be derived from the increasingly complex dynamic analysis being undertaken across academic institutions, to continue to support the needs of designers across the industry.

4. Fatigue and fracture

Over the past four years, the Fatigue Fracture Committee [80] has reviewed and proposed routes for further research into crack initiation and growth under cyclic loading conditions, unstable crack propagation rates, and failures in ships and offshore structures. The applicability and uncertainty of physical models and testing were properly considered, and practical application, statistical description, and fracture control methods were considered in design, manufacturing, and maintenance.

Research on fatigue and fracture loading in ship and offshore structures has focused on studying the statistical properties of short- and long-term wave loads. Statistical modelling and numerical methods have been used to obtain reliable load conditions for fatigue design. However, uncertainties remain compared to full-scale measurements. Digitalization in shipping is expected to provide more in-situ measurement data for future wave load modelling and fatigue assessment. Modern methods, such as digital twins, are being used to monitor fatigue accumulation and assess the integrity of future structures [81].

The current state of fatigue design and assessment technologies, including topics like fatigue and fracture issues in metallic materials have been discussed. It highlights the popularity of the hot spot structural stress concept in engineering for welded joints governing fatigue-sensitive locations. The review also discusses the development of simplified finite element procedures and semi-analytical approximations to reduce computational efforts. The review also discusses the stochastic nature of the fatigue damage process, particularly for polycrystalline metals, and the development of stochastic fatigue sources, weakest link theories, and advanced fatigue resistance relations. Random fatigue limit models have been developed to provide better fatigue strength and lifetime estimates [82].

The hot spot structural stress concept is widely used in engineering for welded joints governing fatigue-sensitive locations. Adding local information, such as effective notch stress or notch stress intensity concepts, shows convergence at the macro-scale. Developments focus on simplified finite element procedures and semi-analytical approximations to reduce computational efforts. Equivalent stress fatigue damage criteria based on crack growth relations provide accurate fatigue strength and lifetime estimates. Damage mechanics concepts are used to assess fatigue resistance of advanced materials but also extend to notched geometries like welded joints. These developments bridge the continuum mechanics-based and fracture mechanics-based criteria [83].

The mean value can be used to define a loading and response cycle in space, influencing fatigue damage in welded joints. Recent developments include new results with existing mean stress models applied for both plane and notched geometries, continuum mechanics, fracture mechanics, and damage mechanics-based fatigue criteria. Artificial intelligence (AI) techniques are adopted to incorporate the influence of mean stress [84]. Frequency domain calculations are common to reduce computational effort, but limitations include significant fatigue damage, overestimation, and lack of robustness. Fatigue resistance can be impacted by several environmental variables, including hydrogen, temperature, and corrosion. Usually, empirical models are used in experiments to establish the influence. As with air, modelling can be broadly categorized into two categories: using cracked geometry parameters (which pay special attention to the crack growth process) and using intact geometry parameters (which focus on the entire damage process, without distinguishing between initiation and growth contributions). Recent investigations include simulation of corrosion in a lab environment and modelling the chemical and mechanical aspects, including the (typically fatigue governing) corrosion pit mechanics loading, and geometry-induced stress concentrations. Particular attention regarding corrosion fatigue modelling is generally paid to pit-to-crack transitions. The (chemical) corrosion process is in charge up to a critical pit size, and the (mechanical) fatigue crack growth process governs afterwards.

A discussion about Damage Tolerant fatigue assessment using fatigue crack growth analysis, focusing on defects, crack initiation, fracture mechanics parameter determination techniques, and fracture toughness assessment [85,86] has been made. It highlights the progress made in numerical fracture mechanics parameter determination techniques and the need for improvement additionally a discussion about the crack arresting technology was also introduced.

Advances in fatigue improvement of ship and offshore structures have been discussed, with a focus on weld quality and additive manufacturing [87]. Carbon fiber-reinforced polymer patches are the most studied method. Fabrication processes, curing, draping quality, and fiber misalignment are crucial for performance. Continuous monitoring of structural loads using fiber optics or strain gauges, Fiber Bragg Gratings, sensor-based visual detection, digital image correlation (DIC), X-ray scans, and ultrasound scans are used for real-time measurements [88].

New guidelines for fatigue design of welded structures addressing the fatigue properties of welded joints and components, covering all state-of-the-art verification methods were discussed. The changes include increased time in heavy ballast conditions for bulk carriers and increased time in the corrosive environment for water ballast and oil cargo tanks [89]. The guidelines also provide quantitative and qualitative measures of geometric features and imperfections for welds of steel or aluminum plate-type structures to ensure they meet specific fatigue strength demands. The guidelines also highlight the influence of flaw types and imperfections on the fatigue strength of butt and fillet welded joints. The guidelines also guide the inspection and quality control of welds.

5. Experimental methods

The ISSC Committee V.2 on experimental methods was concerned with the latest scientific developments concerning experiments in the following areas: structural model and full-scale testing and in-service monitoring relevant for ship and offshore structural design, construction, inspection and maintenance. The goal was to provide guidance on theory and methods to the reader interested in carrying out such experiments. The topics covered are: scaling laws relevant to any experiment and specific aspects concerning DIC, hydrodynamics of flexible structures, wave-in-deck, hybrid models, friction, vibrations, fatigue at low temperatures, corrosion, large scale impact, large scale wind turbine blades, full-scale ice loads, health monitoring and digital twin models.

In conclusion, it can be stated that experimental techniques allow for a greater understanding of the underlying material and structural behaviour and generate extensive data clouds for processing and evaluation. Recent applications of scale models can be found in field of offshore wind turbine structure and ice testing [90–92]. The use of DIC increases in laboratories and in the field for experimental analysis of ship and offshore structures. Jones and Iadicola et al. [93] provide extensive details towards standardization and the development of best practices for DIC. Banks et al. [94] used DIC to assess the structural behaviour during fluid-structure interaction without influencing the flow and Friedrich and Ehlers [95] for crack propagation assessment during fatigue testing. Hydrodynamics of flexible structures are important for the response prediction under waves and currents, especially when VIV occurs. Song et al. [96] and Wu et al. [97] introduce an inverse finite element method to reconstruct hydrodynamic coefficients distribution along a flexible pipe. Ren et al. [98] discovered an amplification of the drag coefficient up to 10-times, which may lead to safety problems. Concerning wave impact loads on structural deck elements near the free-surface there is considerable uncertainty about the magnitude and distribution of wave impact loads. Therefore, Mohajernasab [99] presents the scaling effect of air entrapment during wave-in-deck conditions. To overcome such scaling aspects, one solution can be hybrid model testing, which combines physical model test and numerical simulations to solve problems that physical model tests alone cannot conveniently or reliably address, i.e., Sauder et al. [100] developed Hybrid model testing of an offshore wind turbine in an ocean basin. Relevant to essentially any experiment is the assessment of friction. Standard friction tests are well covered by standards and guidelines, but larger set-ups are to be tailor made and require a good understanding of the physics. While Canestrari et al. [101] listed a large range of methods and ASTM standards [102], larger or even real size specimens should be used to confirm the actual behaviour. Another aspect relevant for the design and analysis of ship and offshore structures are vibrations. Lately, various effective vibration mitigation concepts have been presented [103–105]. When exposing ship or offshore structures to extreme conditions, such as sub-zero temperatures, corresponding material behaviour is needed, where special attention is required to the set-up and instrumentation of experiments. Experimentally validated fatigue assessment methods for sub-zero temperatures are presented, i.e., by Braun and Ehlers [106] and Zhao et al. [107]. Another important phenomenon to be investigated experimentally is corrosion testing, where often a large spread is observed in measured corrosion rates especially when non-uniform corrosion is considered. Therefore, non-linear prediction models include how the spatial surface distribution changes with time [108–111]. If large scale wind turbine is to be tested, the standardisation by International Electrotechnical Commission (IEC) is to be considered. Due to the high cost of dynamic tests for large blades [112], simultaneous multidirectional loads and/or testing at higher loads and fewer cycles as well es tests of blade parts are proposed.

For ship or offshore structures subjected to ice loads it is mentioned that full-scale ice load measurements are likely to be applicable for the conditions where the data was recorded, and models based on ice-mechanics and ice physics are not yet able to predict ice loads exerted on structures. Further, the scatter when testing compressive strength of ice is significant [113]. Common to all structures is the interest of their current state, and therefore Structural Health Monitoring (SHM) and digital twin models can bridge the relationship between the degradation in the material and the structure using data fusion, signal processing, AI-based trend detection algorithms and reliability analysis methods [114–117].

To visualize the influence of the accuracy of experimental investigations, a seemingly simple experiment of a free vibration of a cantilever beam is carried out as a benchmark study to demonstrate the vast possibilities to carry experiment followed by a discussion of the results achieved. Two specimens were used, a mild steel and a composite sandwich beam. Naturally, there is a range of choices to perform experiments. Therefore, understanding the effect of the choices on the end result is essential, i.e., a heavy sensor can influence the natural frequency a lot. The first natural frequency can be targeted by manual excitation, but also damping and higher order modes when using an instrumented hammer could have been obtained enhancing the measurement range but likely also its scatter and uncertainties.

6. Materials and fabrication technology

This Committee has covered trends in ship production, the development of new materials and joining processes, in particular the development of composite materials and fibre-reinforced polymers (FRPs), adhesives and coatings, and the process of qualification and approval of these new materials and processes for use in ship and offshore structures like hulls, superstructures, structural bulkheads and deck houses. For welding methods, focus has been on Additive Manufacturing, primarily for structural parts, and on monitoring of the welding processes. Within the concept of Industry 4.0, or rather the digital transformation, we have covered the increased use of augmented reality, the use of Digital Twins integrated with Discrete Event Simulation (DES) software and the integration of DES with Product Lifecycle Management (PLM) platforms. Finally, software for thermo-mechanical simulations of fabrication processes has been surveyed and the capacity to simulate problems in manufacturing have been demonstrated in two benchmarks, the calculation of the load capacity of a sandwich panel (glass fibre skin and low-density core foam) [118], and residual deformations in a fillet welded stiffened plate [119].

The progress in the use of composite materials in ship structures is shown below in Fig. 5, a full scale demonstrator in composite materials from the EU-project Fibreship, http://www.fibreship.eu/ and the infusion of a 6 m vertical high hull structure in one shot from the EU-project RAMSSES (https://www.ramsses-project.eu/).

Work to establish guidelines and codes for the approval and certification of composites, FRPs in ship (and offshore) structures has been intensive. The main obstacle to replace steel or equivalent materials is fire safety. Attempts to extend International Maritime Organization (IMO) interim guidelines, have been addressed in two EU-projects: RAMSSES, with a new step for the qualification of innovative solutions, named Smart Track to Approval (based on a database of pre-approved solutions and materials test results, fire risk scenarios covering a range of similar applications and analysis and modelling tools, including numerical or statistical models that may replace physical testing in the future) and Fibreship with a long term approach detailed in the Fibreship Guidance Notes (requirements for structural design and fire safety for large-length composite materials vessels), (https://cordis.europa.eu/project/id/723360/results). One example of the need to establish codes for structural integrity for new materials is shown in the Fig. 6 below, which shows results from a benchmark, see Josefson et al. [118] where the load capacity for a sandwich panel made of glassfibre skins and a low-density core foam is simulated and compared with experimental results and analytical solutions, developed by Bureau Veritas, for different skin failure modes.

The ship industry has started to adopt Industry 4.0 and the digital transformation, key examples of progress within this concept are: monitoring of welding processes, using statistical process control to identify common Gas Metal Arc Welding defects during panel line welding, and with time, use big data and machine learning to identify specific trends which can retune welding systems in real-time [120].

Augmented Reality (AR) is now used by several ship builders, not only provides the workforce new and more agile options to interact with digital representations on the factory floor, but in the design phase, virtual reality, AR and mixed reality has been used to ensure that a ship's design is refined earlier in the process. In manufacturing, AR assists the production flow, see Fraga-Lamas et al. [121], and quality assurance systems, and in operation, the digital twin of the ship is augmented with maintenance tasks, which is particularly useful in remote operations for fault finding and servicing tasks.

Several examples of the application of Digital Twins in Production have been found, used in combination with DES software for scheduling and planning of the manufacturing and assembly of ship and offshore structures. Recently DES software has also been integrated with existing PLM platforms to fully integrated platforms. However, such collaborative platforms require a steep learning

Fig. 5. Fibreship demonstrator (left), RAMSSES hull structure infusion (right).

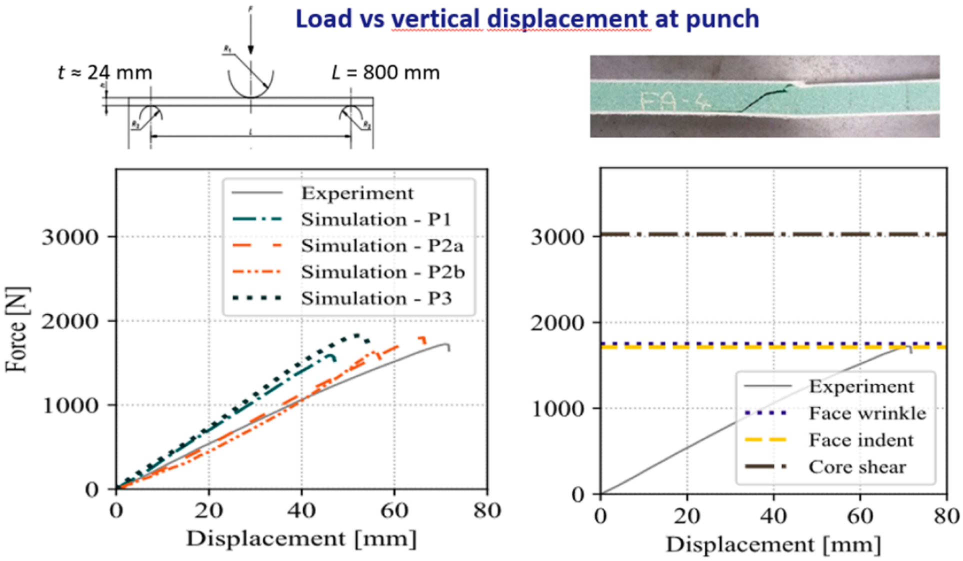

Fig. 6. Capacity for sandwich panel loaded in three-point bending. From Josefson et al. [118].

curve and the requirement for highly educated personnel to implement but also to use them, and a large amount of information interconnections and processes integrations. The transformation to these fully integrated systems is so far limited, many firms, especially smaller ones, are opting for the classic solutions they are accustomed to. Though, we believe that large collaborative digital platforms are a necessary foundation for the integrated digital shipbuilding enterprise.

The increased use of thin sections, high strength, and lightweight structural metal makes modular assembly more challenging due to more widespread distortions at various interim product levels. This fact together with the introduction of new welding processes for thin plate sections put challenges also for the software and analysis technique to simulate resulting deformations and stresses from the joining processes. However, it is found that the current status of Finite Element software, and knowledge of the material behavior, is not sufficient to reliably model complex manufacturing situations. This is also demonstrated in one benchmark, residual deformations in a fillet welded stiffened plate [119].

7. Offshore renewable energy

Since 2016, the ISSC's Specialist Committee V.4 on Offshore Renewable Energy has reviewed offshore renewable energy technologies. Their mandate has broadened to include addressing extreme environmental conditions, seabed interactions, reliability-based design, and safety in integrated design, which is central to the forward movement in offshore renewable energy. The committee's work has been instrumental in steering offshore wind energy towards the ambitious 2050 net-zero emissions targets. This endeavor encompasses a comprehensive synthesis of over 500 sources, including peer-reviewed articles and industry reports, to capture the field's developments, challenges, and innovations from August 2017 to August 2021.

7.1. Bottom-fixed offshore wind turbines

Recent advancements in bottom-fixed offshore wind turbines (BFOWTs), particularly monopiles, have been highlighted. Monopiles, favored in Europe, are chosen for their ease of installation, cost efficiency, and proven success in offshore sectors. Turbine capacities are increasing with projections to exceed 15 MW by 2025–2028, driven by advancements in numerical modelling, analysis, and experimental validations, including soil-pile interaction models. A comprehensive design approach integrates aerodynamics, structural dynamics, and control strategies, challenging traditional theories like the BEM theory under unsteady conditions and leading to the adoption of advanced tools like FAST and BHawC.

Recent studies have focused on improving the soil-pile interaction models, which are crucial for reducing installation uncertainties and costs while influencing the structural dynamic response and fatigue damage of BFOWTs. For instance, Wu et al. [122] discussed the advancements in the application of finite element analysis and cone penetration testing for enhanced soil characterization, which significantly affects the stability and longevity of monopiles in extreme weather conditions. SHM systems play a key role in damage detection and fatigue assessment, with updated standards such as IEC 61,400 [123] incorporating significant technical changes for extreme weather phenomena. Another significant contribution is the work by Wang et al. [124], which reviews advanced design approaches and highlights the necessity of integrating multidisciplinary analysis for optimizing monopile designs.

7.2. Floating offshore wind turbines

Developments in floating wind turbines signify a major leap in renewable energy. The Hywind Tampen wind farm, with eleven 8 MW turbines on concrete spars, leads this progress alongside other notable pilot projects like Hywind Scotland, Kincardine, and Windfloat Atlantic [125] Fig. 7. These projects demonstrate the growing viability of floating wind farms, with additional pilot projects in France and the Maine floating wind project also making headway. Challenges in stability highlighted by incidents like the capsizing of the BlueSATH prototype have prompted the issuance of new guidelines by IEC and major classification societies [126].

Recent research has focused on improving the stability and safety of floating turbines, particularly in harsh environmental conditions. Research by Baniotopoulos et al. [127], highlights the advancements in the simulation of aeroelasticity and hydrodynamics interactions in floating wind turbines, which are critical for predicting their performance under dynamic loading conditions. Moreover, the integration of CFD and potential flow methods is increasingly being used to improve the accuracy of these simulations, although challenges remain in fully dynamic scenarios. In addition, Faraggiana et al. [128] have provided insights into the operational stability of floating wind turbines under various sea states, emphasizing the need for enhanced control strategies.

7.3. Wave energy converters

Wave energy converters (WECs) have significantly developed in recent years, although only a small fraction of prototypes reach full-scale deployment. Innovations like floating moored spherical hulls, submerged caissons, and oscillating water column devices are notable. Numerical modelling and analysis in WECs involve various methods, including Numerical Wave Tanks for wave-array interactions and Boundary Element Methods for mooring effects. Power Takeoff systems, essential for energy conversion, face challenges related to the oscillating loads they encounter.

In 2021, Garcia-Teruel et al. [129]. published a comprehensive study on optimizing WEC designs, particularly focusing on reducing mooring costs and improving the overall energy efficiency of the devices. Their research emphasizes the need for innovative solutions to overcome the current limitations of WECs in capturing wave energy effectively under diverse climatic conditions. Additionally, Ahamed et al. [130] discussed advancements in materials and structural designs that enhance the durability and energy capture efficiency of WECs under extreme sea conditions.

7.4. Tidal energy

Tidal energy developments have shifted towards floating devices and midwater moorings, complementing traditional seabed-mounted turbines. Projects like TIGER https://interregtiger.com/ and full-scale tests with turbines like SCHOTTEL Instream have demonstrated promising alignment between experimental data and predictions [131]. However, challenges remain in accurately modelling the complex currents, waves, and turbulence interactions.

Recent studies by Li et al. [132] have contributed to understanding the dynamic loading on tidal turbines, providing insights into the design optimizations needed for reliable operation in harsh marine environments. In addition, a significant contribution by Finnegan et al. [133] highlighted the use of advanced computational tools for predicting and mitigating load fluctuations in tidal turbines, which is crucial for their longevity and energy output efficiency.

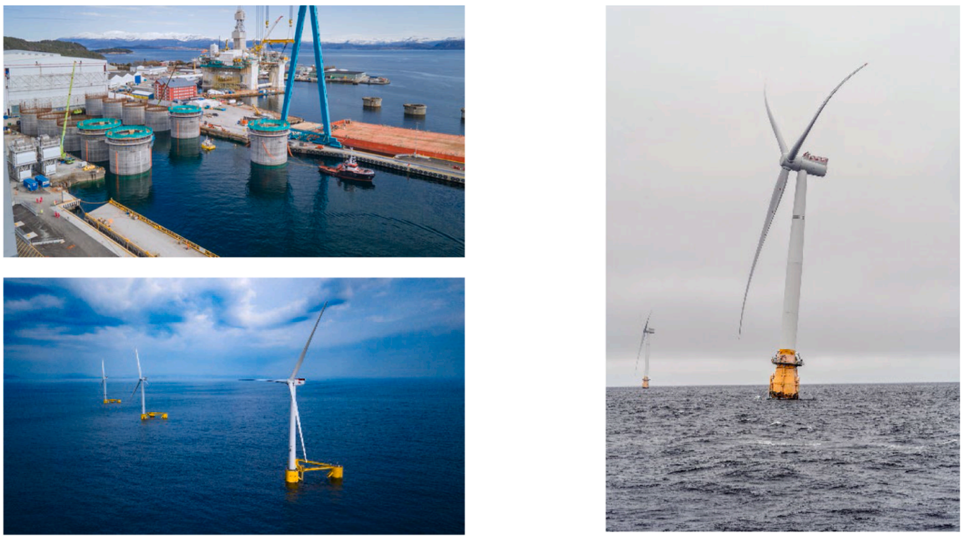

Fig. 7. The Hywind Tampen wind farm under construction (top left), the Kincardine farm after completion (bottom left) and the Hywind Scotland farm in operation (right). From Gomes et al. [125].

7.5. Hybrid solutions and other technologies

Recent research has focused on integrating floating wind turbines with wave energy converters and other hybrid renewable energy systems. Hybrid solutions offer potential advantages, such as improved energy capture efficiency and the ability to provide coastal protection. However, these systems also face significant challenges related to mooring design and optimizing device spacing in multi-device arrays.

In 2023, Hassan et al. [134] published a detailed analysis of the potential of hybrid renewable energy systems, particularly focusing on the integration challenges and the economic viability of such systems in offshore environments. The study by Cao et al. [135] also adds to this discussion by analyzing the impact of combined wave and wind loading on hybrid systems, suggesting design improvements that could enhance these systems' structural integrity and performance.

7.6. Life-cycle cost and operational management

The maturity of wind energy has led to more accurate cost calculations and the adoption of high-fidelity cost modelling techniques. A notable trend is the industry's shift from the Levelized Cost of Energy metric to more comprehensive Key Performance Indicators.

The committee pointed out that cost modelling for wave, tidal, and other ocean energies needs to be thoroughly revisited, especially considering reliability and survivability factors. The introduction of machine learning techniques in operational management has shown promise in optimizing maintenance strategies, as discussed by Elyasichamazkoti and Khajehpoor [136]. Furthermore, Ferraz de Paula and Carmo [137] provide an in-depth analysis of life-cycle costs for offshore renewable energy projects, emphasizing the need for integrating environmental impact assessments into economic models.

7.7. Mooring design for floating wind turbines

A benchmark study on synthetic fibre mooring lines revealed significant discrepancies in safety standards among classification societies. Analyzing a hybrid chain-polyester-chain mooring system for the Olav Olsen Life 50+ benchmark floater [138] using OpenFAST to model the coupled dynamics of wind turbines, including aerodynamics, hydrodynamics, structural dynamics, and control systems, showed non-compliance with some standards, indicating a need for unified guidelines in synthetic mooring line safety. Table 1, presents a cumulative table of the safety factors for intact mooring lines based on different standards.

Recent studies by Ma et al. [139] have highlighted the critical importance of standardizing mooring design practices to ensure the safety and reliability of floating wind turbines, particularly in deep-water installations. Finally, additional research by Sørum et al. [140] discusses advanced materials for mooring lines that offer enhanced durability and reduced environmental impact, which are crucial for the next generation of floating wind turbines.

8. Structural longevity

The scope of work for the ISSC 2022 Committee V.7 report on structural longevity of ship, offshore and other marine structures has included the diagnosis and prognosis of structural health and prevention of structural failures including corrosion and fatigue. Moreover, it has taken into account the lifecycle management and maintenance aspects including the development of software and hardware tools for the inspection and monitoring of ship and offshore structures. The work performed has been included in four chapters. In the following paragraphs, the authors have delved into the lifecycle assessment and management for structural longevity approaches and tools, lifecycle assessment and maintenance management including the data-driven maintenance aspects, digital twin applications, and reliability-based research efforts. The Committee members also highlight the trends and developments in inspection and monitoring techniques to improve the structural longevity of ship and offshore structures. These concepts are complemented by the examination of hull monitoring systems, remote and autonomous testing and sensors applications for structural monitoring; the employment of AI applications and cloud-based data acquisition and management systems. The models and applications developed in relation to offshore structures are included looking into the deterioration mechanisms (corrosion, crack growth, erosion and wear), mechanical limit states, implementation of methods and procedures for safe operation and aspects of risk-based integrity management

Table 1
Safety factors stated by classification societies for intact mooring systems.

Code Issuing Entity	Reference Design Code	Intact Condition, Non-Redundant Mooring System			
		Return Period of Environment	Safety factor		
			Steel	Polyester	Other Fibres
ABS	Guide for Building and Classing Floating Offshore Wind Turbine Installations	50 YRP	2	2.25	2.25
BV	NI572 Classification and Certification of Floating Offshore Wind Turbine	50 YRP	2	2.2	2.4
DNV-GL	ST-0119 Floating Wind Turbine Structures	50 YRP	(1.5 * Tmean + 2.2 * Tdyn) / 0.95 * Tmax		
IEC	61,400–3–2 Wind Energy Generation Systems - Design Requirements for Floating Offshore Wind Turbine	Refers to ABS, BV, DNV-GL			

are also discussed together with associated longevity methods and examples, such as the prediction of longevity, failure modes contributing to longevity assessment and also presenting a more detailed case of a polar supply and research vessel.

The key findings of Committee V.7 on structural Longevity suggest that research developments have increased in the area of structural maintenance management and associated tools used such as Dynamic Bayesian Networks for the development and application of data driven models on inspection and maintenance as suggested by Zhu et al. [141] and Yang and Frangopol [142]. Moreover, other approaches including structural Condition Based Maintenance (CBM) can assist in reducing maintenance costs as described in Hwang et al. [143]; Liu et al. [144]; however, considering that the use and analysis of historical data is still mainly used within the ships and offshore structures domain.

The need of accurate data gathering from verified and validated sensor systems is of paramount importance and the data needs to be able to support the given objective of CBM, or performance tracking as discussed by Leser et al. [145] and Drazen et al. [146]. Structural life cycle management approaches may include probabilistic and non-probabilistic/deterministic optimization approaches (e.g. multi attribute group decision making, Technique for Order Preference by Similarity to Ideal Situation and value of information computation) in order to define the optimal ship maintenance strategy [147,148].

Additionally there have been a number of developments and research in the area of monitoring techniques including magnetic flux leakage ultrasonic testing eddy current testing, and ultrasonic guided waves vibration monitoring for long term applications as well as the use of unmanned vehicles for remote inspection of ships and offshore structures [149–152] and on the development and application of new sensors, data networks, and data management systems [153–155]. Significant benefits were identified in the case of tools and approaches employing Acoustic Emission monitoring to identify defects related to plastic deformation, fatigue-induced damage and fracture [156,157] and various types of corrosion patterns [158].

Moreover, Risk-Based Maintenance scheduling and Risk Based Inspection planning continue to be used as a framework to estimate the probability of failure and respective consequences of ships and offshore structures; considering the ship safe operation requirements and inspection costs as well [159,160]. These approaches can now be supported more and more by robotic and automated structural inspections using Unmanned Aerial Vehicles for ultrasonic plate thickness measurements, crack and corrosion detection by image analysis as discussed through Bonnin-Pascual and Ortiz [161]; Stensrud et al. [162]; Wang et al. [71]; Wen et al. [163] and Autonomous Underwater Vehicles for the inspection of pipelines in deep sea areas as mentioned in Ghis and Fischer [164]. Suggested obstacles in these applications include challenging GPS connectivity, poorly lit environments, computer vision issues for detection of cracks, and use of hyperspectral imaging to detect rust mechanisms and the chemical composition of coatings.

Other advances suggest the use of AI [165,163] and a combination of inertial and visual sensors in real-time [166] in an effort to reduce operating costs, improve efficiency by making faster/better decisions and increasing workforce productivity. With particular reference to harsh environmental conditions such as those in the polar regions, Memmolo and Moll [150] suggested hull monitoring for steel and composite-based maritime structures by using several nodes of sensors. However, challenges including misinterpretation of measured signals, inducing false alarms and potentially missing damage detection should be considered.

The Committee report also suggested that a combination of multi-sensor and hybrid sensor nodes can provide enhanced structural health monitoring such as embedded sensors in composite materials and additively manufactured sensors used within offshore and maritime structures [167–169]. Especially related to offshore structures, digital twin models have been developed and refined considering computational efficiency when such models are combined with data from continuous monitoring systems for SHM [146]. The latter aligns with the report findings on accuracy, robustness and efficiency as some of the important aspects on identifying models and procedures that are associated with prediction of the longevity and life-cycle optimization for offshore structures. This is dealt with by the application of big data analysis and machine learning algorithms. This implies an increasing degree of automation beyond the control of the end-user which is why appropriate level of expertise and knowledge is required for the development and implementation of machine and deep learning tools and approaches.

Crack propagation methods based on fracture mechanics are currently being developed to include associated benefits related to small fatigue cracks that appear around welds that can be tolerated and analysed [170,171], also considered the effects of low temperature on the ductile fracture behavior of high tensile strength steel plates as in Cerik and Choung [172]. In addition to the above, the unpredictability of random wave loading on ship structures continues to be a major challenge and provides the space for ongoing research. Furthermore, the application of reliability-based methods could provide support when considering particular ship cases and examples for the determination of corrosion wastage, load, strength and fatigue resistance of ship structures.

Finally, the whipping responses of a polar supply and research vessel which is prone to slamming effects was presented by Bossau et al. [173]. It was shown that although bow-slamming was expected due to the ice-going design of the ship, the flat extended transom experienced stern slamming in mild sea states with waves < 1 m, followed by whipping which lasts for as long as 40 s [174]. Moreover, the vessel motion response is shown to be high in head seas, and mostly attributed to rigid body motion. When the ship is stationary in following seas, waves initiate a large flexural whipping response; highlighting the effect this may have in research vessels conducting oceanographic research activities near the stern of the vessel.

9. Subsea technology

The mandate for subsea technology was related to the safety and structural reliability of subsea production systems for oil and gas offshore. The report was separated into topics related to subsea equipment for production and processing, flowlines and risers, and with emphasis on design, fabrication, qualification, installation, inspection, maintenance, repair, life extension and decommissioning.

Subsea developments are attractive, e.g. in the Norwegian Continental Shelf, it is expected that 68 out of 88 discoveries will be developed with a subsea solution. Forecasts indicate that oil and gas as a primary energy supply is set to peak in 2030, and renewables will increase their share as a major energy supplier (DNV Technology Outlook 2030) https://www.dnv.com/publications/technology-outlook-2030–164962/. The power and renewables business will also require more subsea solutions like power cables, hence subsea technology will play an important role in the coming years. The Macondo accident [175] was an eye opener for the whole industry, and the Petroleum Safety Authorities of various countries challenged the industry on different levels to mitigate the associated risks and implement barrier management at the design stage. One of the challenges is the increased focus on design of subsea production system for oil and gas offshore in terms of safety and structural reliability of the system and its inherent management. There is currently a strong interest in exploring the use of existing pipeline subsea infrastructures to transport carbon dioxide (CO2) in its dense phase or hydrogen gas (H2) as a part of the new energy mix.

Today, gas turbines account for some 80 % of CO2 emissions offshore. Electrification offshore is expected to have the most impact underwater and will contribute positively to reducing carbon footprint by use of existing infrastructure. Cost-efficiency is the main driver for all-electric subsea solutions, but other advantages include elimination of safety to personnel and minimizing the risk for hydraulic fluids polluting environments. It is expected that all-electric subsea systems to be the norm by 2030 due to cost and safety advantages. The next level of electrification is to further explore the concept of subsea power distribution with the goal to provide power, ranging from 750 kW to >11 MW, to subsea systems, from pumps to compressors. The safety and capability of an all-electric production system was discussed by Mahler et al. [176]. Scott et al. [177] presented the development and deployment of electric surface-controlled subsurface safety valves showing the qualification program of the valve and valve system. Monteverde et al. [178] presented a qualification program of a new all-electric control system according to the API 17 N and DNV RP-A203 requirements. More recently, MacKenzie et al. [179] also presented the development of an all-electric control system to replace existing electrohydraulic ones.

Another trend is the need for higher pressure and higher temperature (HPHT) often in combination with ultradeep waters. One of the fields that have taken the new specifications for HPHT equipment is the 2000 psi rated subsea Chevron's Anchor subsea field development in the U.S. Gulf of Mexico. Technical guidance for HPHT equipment can be found in the new API "High-pressure High-temperature Design Guidelines", 17TR8 published in 2018 and amended in 2019 [180]. The guideline is not intended to be a stand-alone specification or standard and refers to ASME and API codes for design.

Failure of bolts in subsea installations has a huge cost and possible environmental impact, and several bolt failures have been reported in the last years [181]. High strength bolts are used to a large extent for subsea application. The bolts are in general only designed for static loading and limited guidance on fatigue is provided in API 6A, API 16A, API Spec 17 D and API 20 E. There is currently an initiative within API to explore the fatigue life of 1″ up to 3″ bolts for subsea application.

Carbon capture and storage has been identified as a key abatement technology for achieving a significant reduction in CO2 emissions to the atmosphere where pipelines are likely to be the primary means of transporting CO2 from point-of-capture to sites. The issue is related to the risk of corrosion, and the potential to experiencing sour conditions in the pipeline. It has recently become clear that the original Battelle Two Curve Method does not perform well when applied to dense phase CO2 pipelines [182]. Recent large-scale tests point to requirements for high toughness to arrest running ductile fracture, for a summary see Michal et al. [183]. Such high Charpy V-notch energy values could be difficult to document for older Carbon-Manganese CMn-pipelines and could point to the need for considering alternative solutions, e.g., the use of crack arrestors. To evaluate if existing pipeline infrastructure may be taken into use on the condition that the pipelines are re-qualified for CO2 transportation. Guidance is provided in both DNV-RP-F116 https://www.dnv.com/energy/standards-guidelines/dnv-rp-f116-integrity-management-of-submarine-pipeline-systems/ and DNV-RP-F104 https://www.dnv.com/energy/standards-guidelines/dnv-rp-f104-design-and-operation-of-carbon-dioxide-pipelines/. As a general rule, the re-qualification shall comply with the same requirements, when it comes to safety and operation as for a pipeline designed specifically for transportation of CO2 [184].

There is currently a strong interest in exploring the use of pipelines for hydrogen transport. ASME B31.12 Hydrogen Piping and Pipelines (2019) are mainly developed for onshore applications focusing on the burst limit state. For offshore pipelines carrying hydrogen, DNV-ST-F101 https://www.dnv.com/energy/standards-guidelines/dnv-st-f101-submarine-pipeline-systems/ is the recommended code to be applied with modifications and possible gaps have been identified and evaluated by Collberg et al. [185]. The main concerns when introducing hydrogen to pipelines relate to the effect on the pipeline steel toughness and ductility due to hydrogen embrittlement. Implicitly this affects the steel fatigue and strain capacity [186]. The reported crack growths are dependent on hydrogen pressure and the material microstructures, testing indicates that steels with yield strengths up to X70 do not exhibit higher fatigue crack growth rates than e.g. X42 and X52 [187,188]. Some key observations from these studies are that for higher ΔK levels the presence of H2 may lead to 30–40 times higher cyclic crack growth rate compared to in-air testing [189]. The implication of this and low material toughness is that the critical size of a flaw in hydrogen can be 2 or 3 times smaller than in natural gas and very hard to reliably detect by use of Non-Destructive Testing.

Marine risers are the crucial part of the subsea structures for oil and gas production systems. They are the main connections between the wells or pipelines on the seabed and the offshore platforms. Steel catenary risers have been installed in nearly 3000 m water depths and Top Tension risers down to 2500 m water depths, where the most common riser type installed are flexible risers [190]. The main concerns on the design of risers through the years have been the proper modelling of soil–riser interaction on the Touch Down Zone (TDZ) and VIV, which may cause fatigue damage accumulation on the riser structures. Hejazi et al. [191] proposed a Bayesian Machine Learning model for rapid estimation of fatigue failure probability of SCRs on the TDZ. Pereira et al. [192] proposed the Equivalent Damage Method and Response Surface Method to reduce the computational time to estimate the fatigue damage in risers. Various studies investigating the fatigue performance of SCRs and TTR under different conditions including VIV which become more challenging as the water depth becomes deeper and deeper. Hong and Shah [193] conducted an extensive literature survey on the VIV response of risers under current flow and vessel motion along with the active and passive control techniques of VIVs. Liu et al. [194]

presented recent progress on VIVs research, involving dynamic response under high Reynolds Numbers, multi-mode response, flow-induced vibrations between multiple risers, and VIV of inclined risers. Teixeira and Morooka [195] introduced a numerical procedure for predicting vortex-induced forces on marine risers in real time.

Subsea inspection is a requirement for reliable operation of offshore structures with decadal service lives. However, many subsea structures are too deep for human divers to access, and it is necessary to use robotic platforms and sensors for inspection. The cost of preparing, planning and executing structural inspections and the safety and operational risks related to structural integrity are two main drivers which push for the development of new ways of monitoring structures. Various approaches were proposed to monitor subsea structures by utilizing different types of robotic inspection, optical fiber sensors, accelerometers, inclinometers, etc. to detect different damage mechanisms such as corrosion and fatigue. Several developments are needed to increase the autonomy of complex ROV operations, including autonomous docking [196] and autonomous manipulation using visual feedback [197] show great promise for fully autonomous missions. Arcangeletti et al. [198] proposed a methodology of predictive maintenance of subsea processing systems from a diagnosis using data acquired during operation and a machine learning process. Pionetti et al. [199] demonstrated a method for monitoring the thermo-mechanical behaviour of an undersea pipe.

The main failure events experienced by the industry concerning pipelines, risers, and umbilical cables as well as their causes, consequences, and severity, have been identified by Drumond et al. [200]. In particular, impact is indicated as the most frequent cause of failure, representing 56 % of the incidents in the North Sea and internal corrosion is responsible for 31 % of offshore pipeline incidents in the US. Regarding subsea risers, approximately 85 % of them are of a flexible type. Cai et al. [201] proposed a data-driven Dynamic Bayesian Network framework to assess the remaining life of structures affected by corrosion, fatigue, and erosion. Teixeira et al. [202] have derived model uncertainty factors for various collapse strength models based on available experimental results, which are then used to assess the safety of pipelines with local corrosion defects subjected to external pressure.

Khan et al. [203] have recently reviewed the use of risk-based methods for different integrity management elements and their application at different stages of the pipeline's life cycle. The objective was to provide insight into the research evolution and on the role of risk-based methods in the management of pipeline integrity. Overall, it is concluded that integrity management has gradually evolved to take advantage of emerging technologies. This has led to the wide-spread use of In-Line Inspection technologies [204] and non-destructive testing, resulting in an abundance of data on degradation processes [205]. Li et al. [206] have proposed an integrated framework for subsea pipelines safety analysis in terms of an index-based risk evaluation system, which incorporates interdependence among risk factors and the effect of hazard coupling on subsea pipeline failure.

The Risk-based inspection process should be considered as a complement of the risk-based integrity management process [207]. Advanced inspection and monitoring technologies provide an accurate and effective data basis for RBI and integrity assessment of SPSs, as recently reviewed by Zhang et al. [152]. More advanced degradation models including pitting and corrosion-fatigue processes on subsea pipelines have also been modelled by Dynamic Bayesian Networks [208].

Several of the offshore fields are approaching the end of their design life and a cost-effective solution to maximize production is to document that life extension is feasible as an asset. Studies related to life extension have been made to several components of subsea fields to promote enhanced production, or even to provide a subsea design that can be easily upgraded to extend its operational life, this will become important in the near future [209].

The decommissioning activities have grown a lot in the last years and nowadays several papers have been published in relation to this subject. One important aspect of decommissioning activities is that the "best option" to be adopted depends on several factors. Basically, on technical, environmental, financial, social and safety aspects. Gourvenec and White [210] have developed interesting work about the in-situ decommissioning option. Not only aspects related to the integration between the subsea structure and the local biome but also the difficulty to remove such structures, considering the geotechnical issues, are explored. The engineering challenges associated with the management to remove subsea equipment were described by Alwi [211] and Abidin and Mahasan [212]. Finally, Gourvernec [213] proposed the reshape of offshore structures based on the challenges related to decommissioning activities in the near future. The aim of the study is to conciliate design with the future abandonment of such structures aiming at reduced costs and benefits to future generations.

10. Future work and research areas

Each Committee mentioned in Sections 2 to 9, through their review work, also identified future work and research areas. Those can be summarized in the following categories.

10.1. Practical methods for numerical analysis and simulation

The need for practical methods is particularly highlighted under the topic of Loads. For calculation of ship motions and hull girder load effects, there is a large leap in computational requirements when going from the weakly nonlinear potential theory methods to the RANSE-based field methods, and it is still not practical to produce long time-series with the field methods. Hence, there is a need for more research to develop practical methods that include the most important nonlinear effects, in addition to the nonlinear Froude-Krylov and hydrostatic forces. Slamming forces are important, and these are often modelled with the Generalized Wagner method. However, this method assumes 2D flow, which may be too crude assumption in the bow area; and generalization of the method to 3D is difficult. More research is therefore needed to develop practical and sufficiently accurate methods for prediction of slamming loads. Water exit loads and their influence on the hull girder load effects also deserve more attention. This applies to the water exit of both bow and stern.

For wave loads on stationary floating structures, it has been found that when neglecting wave-current effects and effects higher than second order, the diagonal surge QTF's are underestimated compared to model test results [24]. Hence, more research is needed to account for wave-current effects and effects higher than second order. Viscous effects contribute significantly to the excitation forces in severe sea states and to damping forces in general. More research is needed to establish practical methods for including viscous forces and appropriate damping models. There is a need for more physical testing and CFD simulations to establish proper coefficients for the vortex-induced loads for different column length/diameter ratios and relevant Reynolds numbers. More validation with full-scale data, especially for inline vortex loads, is needed. Research should be carried out to assess the importance of VIM for semisubmersible floaters, and to find practical methods for use in design. Scale effects in model tests should be further investigated; Jiang et al. [27] found significant scale effects in an initial CFD analysis of a three-column FOWT semisubmersible. Systematic and careful validation of CFD and other calculation methods should be performed. Finally, more studies on the influence of waves on VIM are needed.

For loads on slender structures, research needs within VIV are identified by Wu et al. [29]. In present design practice, only cross-flow responses are considered, due to lack of reliable cross-flow/in-line load models and associated hydrodynamic parameters. Hence, more research on combined cross-flow/in-line VIV is needed. There is also a need to consider more realistic modelling of variations in current direction with depth, since present methods make the simplistic assumption of constant direction. With today's frequency-domain methods, VIV-induced fatigue due to current and waves are calculated separately. More analyses with VIV in combined waves and current using time-domain methods should be carried out.

When we assess loads due to wind, several studies indicate that steady RANS methods give accurate predictions of wind loads on ships and semisubmersibles, but further validation for various structures would give more knowledge about the capabilities and limitations of CFD methods. Practical methods to speed up modelling and simulations are needed. Simplified methods for quick assessment of wind load coefficients should be further developed, and Neural-Network methods, with expandable databases of structure contours and associated wind coefficients is one promising approach.

On the other hand, loads due to ice, challenges and uncertainties remain in predicting ice loads on ships and other marine structures. There is still insufficient knowledge in ice mechanics to model structure-ice interaction processes, and more research is needed to improve the physically based ice material models. The many different geometries and different material properties of various ice types make modelling of ice challenging. Due to the complexity of ice-structure interaction, empirical or semi-empirical approaches will continue playing an important role until adequate progress has been achieved to model all the involved problems with first-principal approaches [61]. Among the numerical models, the coupled CFD-DEM and Peridynamic methods may gain significant attention in coming years. We may also see faster methods for practical use based on neural networks trained with results from the computationally demanding numerical methods.

The Committee of Quasi Static Responses considers that there continues to be value in the development of Quasi-Static methods for application in structural design and will continue to be a fundamental basis of rule-based design approaches. The Committee believes that analysts undertaking physical experiments, or numerical analysis implementing more complex dynamic analysis of marine structures, should consider the possibility of deriving Quasi-Static methods from their results, or where such studies may act to verify Quasi-Static methods, to quantify uncertainties in methods, or provide further guidance as to the suitability and boundaries of their use.

The Committee of Fatigue and Fracture concludes that the fatigue damage approaches, where rather than developing new continuum mechanics, fracture mechanics or damage mechanics-based fatigue criteria, the current focus is on refinement, incorporating fatigue influence factors (as reflected in the complete strength criteria), relating fatigue crack initiation and growth characteristics (as observed for total life criteria) and establishing the relationship between fatigue phenomena at different scales (as shown for multi-scale criteria). This process seems to be expected to continue. At the level of the material, defects govern fatigue-sensitive locations and criteria typically developed for polymer composite and (wire) arc additive manufactured materials. Notches and hot spots are the governing locations at the structure's level, and the focus is still on arc-welded joints in metal structures. Combinations of (global) finite element modelling advances and (local) analytical models seem straightforward to balance accuracy, complexity, and effort. At the same time, a natural amount of scatter will most likely remain because the fatigue damage accumulation process is stochastic by nature.

There is a need to find reliable predictive methods for residual stress and distortion predictions for complex industrial structural industrial manufacturing / joining applications, i.e. Finite element software. Shrinkage strain-based methods are promising, further research is needed. The benchmark carried out by V.3 Materials and Fabrication Technology on residual deformations in a fillet welded plate emphasizes the need for good material knowledge, but also for good documentation of the geometric situation during and after a joining operation for a good estimation of the residual deformations, necessary in manufacturing of sections.

The Committee of Offshore Renewable Energy recommended further research is needed to enhance the hydrodynamic, aerodynamic, and structural performance of floating support structures. This involves focusing on the entire lifecycle, including adaptability for mass manufacturing, installation, and maintenance efficiency. Establishing uniform standards for wave and tidal energy converters is essential for performance optimization and ensuring consistent quality and safety. Optimizing mooring system designs for floating foundations needs to focus on integrating mooring and cable designs for overall stability and cost-effectiveness.

The move of the oil and gas industry towards deep and ultradeep waters poses new challenges on subsea pipelines design and safety. New high strength materials, thick pipelines and pipe-in-pipe configurations are being used as cost-effective design solutions in such scenarios. However, appropriate strength models and uncertainty evaluations are still necessary to assess the safety of these new designs and the effect of the relevant degradation processes on their safety.

10.2. Experimental methods, measurement and monitoring

For sloshing addressed in Committee Loads, there is a need for more high-quality reference data for validation of numerical methods and better understanding on how to extrapolate results from model tests to full-scale values. As concluded by Malenica et al. [10], full scale measurements and monitoring of real LNG ships would be helpful for better understanding of the loads and responses, and practical ways of performing such full-scale measurements is a research topic by itself. Application of advanced RANSE-solvers to gain more insight into the problem is important, but efforts should also be devoted to developing practical methods for use in design.

There is also a need for more experimental data for validation, and this should include studies of the repeatability of measured low-frequency responses for floating offshore structures. Semisubmersible concepts used for wind turbines will experience significant pitch and roll motions, which should be systematically studied in experimental campaigns. In airgap and wave-in-deck studies, more work is needed within wave crest statistics, wave kinematics and load/response predictions, including effects of air entrapment, hydro-elasticity and hydroplasticity. The relationship between waves in laboratory tests and those in the field needs further investigation [33], and more research is needed to study the effects of model scale and ambient pressure, since tests indicate that these have a significant influence on the load [36].

For slender structures – VIV, Reynolds number effects on the hydrodynamic parameters is still an uncertainty, and more full-scale data are needed. There is also a need to develop a common design practice that accounts for the influence of higher harmonic loads, which can increase fatigue damage significantly. The influence of floater motions and subsequent variations in the touch-down point should be investigated. There is a strong need for more VIV field measurements with sufficient instrumentation density on relevant slender structures.

Experimental techniques allow for a greater understanding of the underlying material and structural behavior and generate extensive data clouds for processing and evaluation. As a result, we recommend that a future chapter in the next ISSC Committee Experimental Methods report focus on data evaluation and statistical approaches; this can provide an in-depth look at state of the art of processes utilized for evaluating the extensive data captured/utilized during experiments. Offshore wind turbine structures are subjected to complex phenomena such as wave loads and drifting forces, scale models should be able to consider particular applications, i.e. ice flows, continuous winter sea ice, and icebergs. DIC methods are fit for a wider application, where surface strain behavior is of interest. For wave-in-deck impact on offshore structures, considerable uncertainty remains about the magnitude and distribution of wave impact loads on structural deck elements near the free-surface. Effects of the columns of the floating platform on the wave-in-deck forces have not been systematically studied. The measurement, estimation and simulation of local pressures due to wave-in-deck impact events on all types of offshore structures remain challenging and should be addressed in further research. Combined numerical-experimental wave-in- deck investigations on floating offshore structures are not currently available in the open literature. Hybrid model testing requires further research to mature the techniques for reliable and generally applicable findings. While friction testing using standard tests is well covered by standards and guidelines, the larger set-ups are to be tailor-made and require dedicated knowledge to ensure reliable results. Measurement and mitigation methods for vibrations in ship and offshore structures are still to be developed. Material selection for ships and offshore structures exposed to sub-zero temperatures are lately well covered in the literature, cryogenic conditions are however not. Corrosion modelling and analysis still require simplifications to overcome the need to include too many details of the corrosion surface. Here common strategies and procedures are needed to overcome the associated challenges. The collected data concerning ice-structure interaction is often incomplete: although local and global ice forces can be recorded during ice action, the ice properties (compressive strength, porosity etc.) might remain unknown, because ice samples cannot be taken during ice action.

In the area of material and fabrication techniques, monitoring systems take the classic approach of analyzing welding variables such as current, voltage and travel speed, but in new developments, high speed cameras, arc seam tracking, and thermal measurement systems are introduced. However, the use of an arc energy measurement based on mean voltage and current gives wrong results since waveform control processes involve rapid transient variations in arc parameters. This method of measurement is incorrect. The approach recommended by ISO/TR 18,491 must be applied more consistently.

The Offshore Renewable Energy Committee suggests developing algorithms for estimating the remaining life of ageing offshore wind turbines and end-of-life decision-support frameworks. Advanced monitoring strategies and data management techniques are necessary for predictive maintenance and operational efficiency. This area is key to data-driven asset management.

The Committee on Structural Longevity would suggest extending the research on lifecycle management and maintenance to include the combination of probabilistic and non-probabilistic/deterministic approaches. Additional effort should be also concentrated on Structural SHM and analysis of data to consider wider measurements on a full ship for more complete and diverse structural loading information. The deployment of novel tools and methodologies for monitoring structural health without hindering the offshore/ship operations should be considered, related to the stochastic nature of the dynamic loading which necessitates the use of continuous monitoring. In this respect, Acoustic Emissions monitoring in combination with other non-destructive methods is suggested as a tool for improved reliability assessment of ships and offshore structures.

Concerning the use of robotic platforms and applications for automated inspections, additional case studies and examples in real life conditions should be considered to minimize the challenges related to the use of unmanned vehicles for structural monitoring offshore. Mobile-SHM and cloud-SHM are additional topics that require further research and development alongside the management of intensive computing power required by the processing algorithms. In the same area of developed technologies used for the structural assessment of ships and offshore platforms, the AI-based image recognition software can be helpful in automatic flaw detection and evaluation, supporting surveyors in their decision-making process in a faster, safer and easier way. In this respect, the deployment of optimized sensor systems and their layout can lead to the enhancement of the quality of the acquired signals and the extracted essential features on condition monitoring of offshore structures.

The user-friendly interface and applicability of big data applications and analytics used for monitoring of offshore structures could be investigated as well. Moreover, the development and practical implementation of crack propagation methods on ship's structures should be further investigated along with reliability and risk-based methods for the maintenance of ship structures for the optimal planning of inspection intervals and appropriate repairs.

The offshore and subsea industry is getting more complex with higher pressures, higher temperatures and increased water depths. Future work will have to support technological developments to enhance novel subsea concepts like all-electric, new subsea processing technologies, further integration between process control and process safety systems and use of sensors to monitor process condition and integrity of safety systems.

In the subsea technology area, the wish to better know the condition of equipment and thus be able to plan and perform maintenance before a critical failure occurs has existed for many years. Early leak detection of liquid and gas are a critical task for economic and safety reasons. Early failure detection is still not at a desirable level of maturity and requires further study.

Various approaches are proposed to monitor subsea structures by utilizing different types of robotic inspection; optical fiber sensors, accelerometers, inclinometers, etc. to detect different damage mechanisms such as corrosion and fatigue. Early failure detection is still not at the desirable level of maturity and requires further study.

10.3. Innovative technology applications

The Greenhouse gas reduction challenge set by the IMO requires that international regulations and rules must evolve to introduce new materials on board. FRP offer opportunities to construct ships and offshore structures with optimised performance, like lower weight and better fuel economy. But further research on the susceptibility of composite materials to fire and impact events, and on the high susceptibility to in-service impact damage for laminated fibre-reinforced composites is needed. Joining methods also need to be improved, also for hybrid joints, i.e. joints between metals and composites, and between different metals, like explosive joining. Then the ability to select the most suitable joining techniques for dissimilar materials will be improved. More efficient testing and simulation methods to assess strength, durability and other properties of hybrid structures need to be developed to cope with the increasing complexity of problems.

There is also a need for a quicker uptake of composite materials, like FRPs. The ISSC 2018 and 2022 Committee V.3 Materials and Fabrication Technology has held interim meetings to try to create a sustainable maritime materials innovation platform, and a database on new materials and test results, to be used by the industry. This work to develop an innovation-friendly environment should be continued, also the parallel work on adhesive bonding, to reduce deterioration caused by long-term exposure to UV rays and seawater, and to further improve fire resistance and recyclability.

For coatings the research on eco-friendly marine coatings and complete exclusion of toxic biocides from Anti Fouling coatings should be continued, also to improve adhesion and mechanical strength of Fouling Release Coatings at low speed (or during the idle period) and under deep sea freezing temperatures.

Work should be continued to introduce FRP elements in shipbuilding, through guidelines (composite materials, adhesive bonds) employing results from current or past research projects, also the work to certify and approve the use of FRPs in hulls, superstructures, structural bulkheads, deck houses.

Additive manufacturing has been successful in several marine applications, in particular Wire Arc Additive Manufacturing for structural, load-bearing components. To be a reliable manufacturing method, standards need to be in place, and quality systems are required to detect or reduce the likelihood of manufacturing defects. This latter suggestion, the detection of manufacturing defects, requires further research on monitoring systems. Improved monitoring systems will also improve process flow and certification, but one research goal will be to reduce the need for post Non-Destructive Testing.

The Committee's work on Offshore Renewable Energy underscores the dynamic and evolving landscape of offshore renewable energy, necessitating continued innovation, collaboration, and strategic planning to meet global energy demands sustainably and efficiently. Developing integrated operation & maintenance strategies for wind farms is crucial. These strategies should balance power generation, load management, grid value addition, and predictive maintenance scheduling. These areas of future research and development are essential for optimizing efficiency, sustainability, and cost-effectiveness in the offshore renewable energy sector.

The energy transition to renewable energy requires new high voltage, long distances power subsea dynamic power cables for power transmission, and further research within this field is expected in the years to come.

One of the upcoming focus areas will be the support of green transition which will require the theoretical background and tools for design of safe and cost-efficient transport of H2 and CO2 in existing and new pipelines.

Oil and gas operators want to extend production from subsea fields to extract more value from the field. A lot of research is currently undertaken but further work will still be needed within this field to enhance for increased life extension, and when decommissioned both re-use and recycling of aged assets will be critical in the circular economy model.

10.4. Application of digital technologies

In the area of fatigue prediction, AI techniques establish more common ground to cover (typically non-linear) relations between different fatigue-related parameters. Although physics is not explicitly modelled, at least the (unknown) relations are established to improve the fatigue strength and lifetime estimate accuracy and may even reduce computational efforts because of the complexity of physical models.

Augmented reality, to link digital information to the real world, gives the operator informed decisions in real-time, and visualizes the location of products and tools, such as head-mounted displays, in hidden locations. Here we recommend research on several possible developments in quality control and in assisting the manufacturing process (assembly, augmented communication and predictive maintenance).

Further development of the digital twin for production has seen more advanced digital integration of the shipbuilding process. Research should continue the integration of DES system with PLM platforms and dedicated SW, and make use of AI tools, big data analysis, and machine learning. Challenges are to resolve security issues with cloud computing, integrate existing software for planning with newer software, and provide education and training of users/operators that comes with the integration of DES platforms with dedicated software.

Adapting modeling tools for novel floating wind systems and integrating digital twins and AI for predictive analytics is vital for future developments.

Considering the limitations of both numerical and experimental work in subsea technology, data science can be regarded as a valuable tool to quantify the uncertainties, caused by the assumptions and scale effects, on the outcomes of the numerical studies and experiments. Data analytics and machine learning coupled with specific domain knowledge will give insight and decision support in a completely new manner compared with today's practices for verification and validation of components and assets. For novel as well as highly optimized subsea designs, a possible future trend can be away from prescriptive rules and towards database-driven safety factors. In the near future, more works covering the application of data science in subsea engineering, are expected to come up in the scientific literature.

11. Conclusions

Traditional topics in ISSC, such as Loads, Quasi-static response, Experimental method, Material and fabrication technology, Offshore renewable energy, Structural longevity, and Subsea technology, are highlighted in this paper to provide a summary of the work conducted by the ISSC 2022 Committee members. However, the recommendations for future work and research areas clearly demonstrate the transition from the traditional approaches, such as practical methods for numerical analysis and simulations and experimental methods, measurement, and monitoring, to the non-traditional approaches, such as innovative technology applications, and the application of digital technologies. This transition is partly due to the complexity of the problems and, more importantly, to the technological advancements in the past years, for example, sensor and digital technology. The regulatory-driven demand for sustainable solutions calls for holistic consideration for marine and offshore structural-related research.

CRediT authorship contribution statement

Xiaozhi Wang: Writing – original draft. **Ole Andreas Hermundstad:** Writing – original draft. **James Underwood:** Writing – original draft. **Yordan Garbatov:** Writing – original draft. **Sören Ehlers:** Writing – original draft. **B Lennart Josefson:** Writing – original draft. **Athanasios Kolios:** Writing – original draft. **Iraklis Lazakis:** Writing – original draft. **Agnes Marie Horn:** Writing – original draft. **Neil Pegg:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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