Committee V.5: Special Vessels

Ermina Begovic[1](✉), Jason Ali-Lavroff[2], Dario Boote[3], Alexander Egorov[4], Mark Rodriguez[5], A. Salcedo[6], Junji Sawamura[7], Harleigh C. Seyffert[8], Jean Baptist Souppez[9], Lyubomir Toshkov[10], Nikola Vladimir[11], and Fuhua Wang[12]

[1] University of Naples Federico II, Naples, Italy
begovic@unina.it
[2] Australian Maritime College (AMC), Launceston, Australia
[3] University of Genoa, Genoa, Italy
[4] Marine Engineering Bureau, Odesa, Ukraine
[5] Jacksonville, USA
[6] Navantia, Madrid, Spain
[7] Osaka University, Suita, Japan
[8] Delft University of Technology, Delft, Netherlands
[9] Birmingham City University, Birmingham, United Kingdom
[10] Sofia, Bulgaria
[11] University of Zagreb, Zagreb, Croatia
[12] Shanghai, China

Committee Mandate. Concern for structural challenges of non-conventional, special surface craft, including uncertainties in established design methods and modelling techniques.

Particular attention shall be given to mega yachts, naval craft, offshore service vessels and work boats, which can be characterized by particular structural configurations and materials (wide openings, large unsupported structures, unconventionally shaped superstructures, etc.) and/or are to sustain specific loading conditions (harsh environment, severe cyclic loads or extreme operational ones).

Keywords: High Speed Vessels · High-Speed Catamarans · Yachts · Sailing Vessels · Fishing vessels · Naval Unmanned Surface Vessels (USV) · Ice Vessels · Offshore service vessels · Fishing Vessels · River – sea ships · Ballast Free Ships · Slamming · Dynamic Structural Loads · Vibration and Noise · Glazing · Comfort on Board · Fatigue

1 Introduction

This report is the continuation of the Special Craft report (Truelock et al. 2018) and Special Vessel Committee (Truelock et al. 2022). In the first report, the Committee's focus was broad and largely on highlighting "Special" craft through market segments (naval, offshore operation vessels and yachts) or as special craft with the appurtenance structure. Market analysis of naval vessels, offshore operation vessels and yachts has

W. Wu and J. Ding (Eds.): ISSC 2025, LNME, pp. 359–441, 2026.
https://doi.org/10.1007/978-981-95-2786-1_5

been reported, together with the list of recommended vessel types for future V.5 Committees. The second report further discussed those markets giving an accent to reduced emission vessels, offshore installation vessels, and ice polar vessels, and as conclusions and recommendations identified unmanned surface vessels, digital twin and offshore renewable energy vessels. Yachts have been discussed in the 2018 and 2022 reports and the benchmark was undertaken by the Committee investigating various calculation and analysis methods on window glazing as a structural material.

This report reviews recent research on the structural design of various vessel types: High-Speed Craft, Pleasure Craft, Workboats, and Ice-Polar vessels. It highlights challenges and advancements in methodologies for predicting wave loads and ship responses and design, both experimental and numerical.

For all considered special vessels, from the state of the art publications, it can be seen that the scientific community is working on the validations of advanced numerical simulations, assessment of the realistic loads, and impact of the required environmental friendliness on design. It is also noted that the industry and design offices are proposing very advanced solutions but do not publish their results. More in detail, in High Speed Craft field, can be observed an increasing number of very complex experimental campaigns with the measures of motions and wave induced loads. The application of Fluid-Structure Interaction (FSI) calculations is very relevant for this field. Can be highlighted the interest of the scientific community in the verification and validation of case studies, as well as the wider use of full-scale data and machine learning techniques for improved accuracy in slamming and fatigue prediction. For high-speed catamaran, ride control systems have been seen as promising solutions in mitigating wave loads and improving passenger comfort. Large pleasure crafts increasingly prioritize comfort, leading to research on applicable seakeeping criteria, vibration and noise reduction, which was finalized in the issuing of the new ISO 22834 Standard. Superyachts aesthetics standards impose demanding challenges related to large openings and glazing. In the small pleasure crafts field, mainly driven by offshore sailing race, innovations, particularly in composite materials and multihull configurations, influenced the design of new boats and updates of the ISO standards. The naval Unmanned Surface Vessels (USVs) and the development of structural digital twins are among the most important emerging trends in naval architecture, presenting both opportunities and challenges. The extensive research in ice load measurements in full scale and laboratory and structural challenges, such as ice-propeller interaction and fatigue damage testimonies the growing interest in human activities and shipping routes in the Arctic region. The Committee members identified and discussed challenges for offshore service vessels, ballast free ships, fishing vessels and river/sea vessels and emerging trends in both commercial and government sectors.

1.1 ISSC 2022 Special Craft Recommendations and Official Discusser Feedback

Truelock et al. (2022) concluded their work recommending that future work focus on new vessel types such as unmanned surface vessels, digital twin vessels and offshore renewable vessels. The importance of the impact of the exponential growth of ships on green shipping and the structural challenges associated with very large ships has been pointed out by both the Committee and Official Discusser. These were the starting points for the Committee members for the present report. Committee members agreed to consider only the publications from 2020 to 2024; the older references can be taken into consideration only for the vessels which have never been considered before.

1.2 Special Vessels Addressed

The committee report is a consolidation of previous reports and the most significant references that contribute to research and development in the areas of load predictions, analysis techniques and design improvements in Special Vessels. The covered vessel types and report structure are schematized in Table 1.

Table 1. Special Vessel Coverage

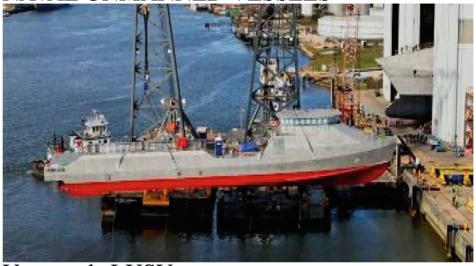
<table>
<tr><th>Special Vessel Type</th><th>Committee Mandate Focus</th><th>Special Vessels</th></tr>
<tr><td>HIGH SPEED CRAFT

Bolide 80
https://www.boatinternational.com/yachts/the-register/fastest-yachts-in-the-world%2D%2D25053, accessed 15th November 2024</td><td>Specific Loading Conditions – Slamming, Accelerations
Structural Challenges: Hydroelasticity, Ride control
Methodologies: EFD, CFD, FEM, FSI. ML
Number of references: 48</td><td>• Planing Craft
• High Speed Monohull
• Multihulls
• ACV</td></tr>
<tr><td>LARGE PLEASURE CRAFTS
Benetti BNow 50 M

Courtesy of Azimuth - Benetti group</td><td>Specific Loading Conditions – not relevant
Structural Challenges – Solar radiation - Glazing – Noise -Vibration - Comfort
New regulations
Number of references: 32</td><td>• Motor yachts larger than 24 m
• Sailing yachts larger than 24 m</td></tr>
</table>

(*continued*)

Table 1. (*continued*)

Special Vessel Type	Committee Mandate Focus	Special Vessels
SMALL PLEASURE CRAFT  Figaro 3, Beneteau https://www.beneteau.com/it/figaro/figaro-beneteau-3, accessed 15th November 2024	Specific Loading Conditions – ***slamming, rig loads, torsional moment, bending of crossbeams*** Structural Challenges – ***strength of composite laminates – appendages design*** New regulations Number of references: ***56***	• Motor yachts under 24 m • Sailing yachts under 24 m
NAVAL UNMANNED VESSELS  Vanguarda LUSV https://aresdifesa.it/varato-loverlord-unmanned-surface-vanguard-negli-stati-uniti/	Specific Loading Conditions – ***classifications according to mission and/or size*** Structural Challenges – ***Not relevant*** Class rules Number of references: ***9 + 37 URL references for database***	• Naval Unmanned Surface Vessels
WORK BOATS  DAMEN Fishing Vessel https://www.damen.com/vessels/fishing-vessels, Courtesy of DAMEN shipyard	Specific Loading Conditions – ***Accident analysis, Seakeeping operability*** Structural Challenges – ***underwater radiated noise. Use of new materials, energy efficiency*** Number of references: ***16***	• Fishing vessels

(*continued*)

Table 1. (*continued*)

Special Vessel Type	Committee Mandate Focus	Special Vessels
WORK BOATS  https://www.damen.com/insights-center/news/damen-presents-floating-offshore-wind-support-vessel, accessed 13th January 2025	Specific Loading Conditions –***Seakeeping operability for safe transfer*** Structural Challenges – ***motion-compensating equipment***, Number of references: ***9***	• Offshore service vessels
WORK BOATS  Courtesy of A. Egorov	Specific Loading Conditions –***Cargo loading and unloading*** Structural Challenges – ***buckling failure***, Number of references: ***9***	• River and river/sea ships
ICE POLAR VESSELS  S.A._Agulhas_II https://en.wikipedia.org/wiki/S._A._Agulhas_II, accessed 27th November 2024	Specific Loading Conditions – ***Ice Loads*** Structural Challenges – ***fatigue, ice-hull/ ice-propeller interaction*** Number of references: ***71***	• Icebreakers • Research vessels • Offshore wind turbine in ice

* *EFD – Experimental Fluid Dynamics*
* *CFD – Computational Fluid Dynamics*
* *FEM –Finite Elements Methods*
* *FSI – Fluid – Structure Interaction*
* *ML – Machine Learning*

2 High Speed Craft

2.1 Introduction - Concepts and Challenges

High-speed marine crafts are particularly advantageous options for ferry operators for transporting passengers and cargo over shorter durations when compared to conventional craft. To achieve high Froude numbers, these vessels are designed with special features including slender hulls or a hard chine hull form for reduced resistance. High-speed displacement ships include catamarans, trimarans, and high-speed monohulls. Hull form optimization for high speed, vessel motions and structural loads must be considered since the early design stage. To this end, research on these special vessels is continuing to identify methods for reducing ship motions and shiploads to improve passenger comfort and structural design.

High speed vessels have been thoroughly addressed in the previous report and this one recalls the same classifications (fast monohulls, fast multihulls, and planing craft), adds Air Cushion Vehicles (ACV) and brings the updates from the period 2021–2024. The research in the High Speed Craft field has been mainly focused on load identifications using model experiments, full-scale analysis, and CFD analysis. Development and validation of nonlinear potential flow coupled with structural analysis is the first step forward based on the existing fast numerical methods. More sophisticated methods, based on Computational Fluid Dynamics (CFD) and Finite Elements Methods (FEM) two-way hydroelastic coupling, are gaining importance as numerical power is increasing. New techniques based on big data analysis using machine learning are foreseen as prominent methods to obtain slamming and fatigue prediction based on full-scale measurements.

Specifically for multihulls, a major structural consideration is slamming loads on the wet deck. Even though there have already been many investigations on this subject in the previous period, research has continued in this area to learn more about the slamming phenomenon, determine links between slamming pressures and different design features, and possibly implement solutions to mitigate slam events.

2.2 Loads and Structural Challenges

2.2.1 High-Speed Monohulls and Planing Craft

Due to the complexity of the interaction between water waves and high speed ships, the research in this area has been mainly focused on improving numerical and experimental techniques. To better understand nonlinear fluid–structure interaction and rarely occurring events on ships in the realistic ocean environment, advanced CFD-FEM simulations, hydroelasticity and model measurements (including large-scale models) are recognised as promising tools for both slender monohulls and high-speed planing craft.

Van Walree and Thomas (2023) reported the validation of PanShip(NL) for the Rigid Hulled Inflatable Boat (RHIB) in heavy seas against the experimental campaign, shown in Fig. 1. PanShip(NL) is a potential flow method based on 3D Green functions for diffraction and radiation forces, 3D panel methods to account for the Froude-Krylov, and restoring forces on the instantaneous submerged body. The results for the motions and accelerations show that PanShip(NL) provides adequate predictions of motions and accelerations for operability analysis purposes in low amplitude yet steep, regular waves.

Even non-linear events in head seas, such as jumping out of wave crests and acceleration peaks in steep and heavy irregular seas, are well predicted. Similar conclusions are reported in Van Walree and Sgarioto (2023) where authors compared two potential flow methods against experimental results for predicting landing craft motions.

Fig. 1. Model of landing vessel shipping water, after van Walree and Thomas (2023)

Parunov et al. (2024) presented a benchmark study on Canadian patrol frigates for motion and global wave loads, with nine participating institutions, quantifying the hydroelastic responses. The results for heave, pitch, vertical wave bending moment (VWBM) and whipping moment (WHBM) at midship, obtained by codes based on the strip theory, 3D panel method in frequency and time domain and CFD are given in Fig. 2. As expected, uncertainties in ship motions are lower than those of rigid-body load effects. The Authors underlined that the number of codes in each group of methods is too small to group uncertainties according to the method. Much larger uncertainties are found in the whipping responses, which deserve further attention. The differences in the seakeeping codes are not so large to be the prime reason for discrepancies in the whipping prediction, therefore the conclusion is that large uncertainty in the whipping response is the consequence of different approaches to the modelling of the slamming load.

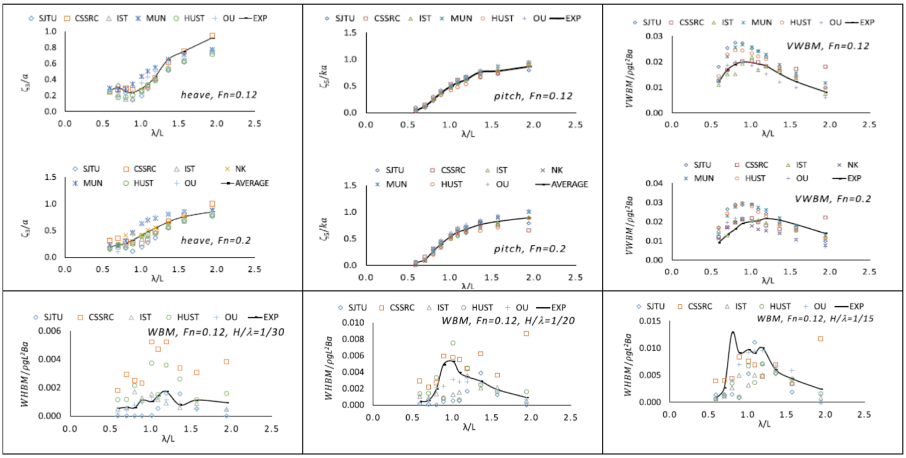


Fig. 2. Comparison of heave, Pitch, VWBM and WHBM, after Parunov et al. (2024)

Li et al. (2022a) performed an experimental study on the stern slamming of a large cruise ship using a segmented model in the head and following waves. Under moderate and large wave conditions, the greater relative velocity and impact area lead to significant stern slamming. However, the longitudinal deadrise angle is much smaller in the following waves, which reduces the slamming duration. The distribution of pressure peaks indicates that an increase in the longitudinal deadrise angle directly reduces the peak values of the slamming pressure. The combined influence of these two factors means that the whipping problem is much more serious in the following seas. Stern slamming significantly increases the magnitude of the VBM at midship. Ibrahim and Judge (2024) presented experimental results on the hull girder slamming factor of the segmented model of U.S. Coast Guard Fast Response Cutter (FRC-B) vessel. The tests in regular waves, performed at three Froude numbers, were conducted to investigate the effect of wave parameters and vessel motion on the slamming factor. The irregular wave tests were conducted to estimate slamming factors in moderate operational sea conditions (sea state 4) that could be useful for fatigue life calculations and in sea state 6 that could be used for structural design.

Jiao et al. (2021) discussed opportunities and challenges in load assessment (vertical bending moment, impact pressures, slamming and whipping) based on the published experimental campaign for large scaled models of 7 naval and 2 container ships. The Authors concluded that the large-scale model testing technique is positioned as a supplement to the classical tank tests and full-scale trial, expecting that they can be conducted prior to the design and construction of full scale ship to derisk new technology and commercial cost.

The works on wedge impacts have been numerous, dealing with curved wedge (Wen et al. (2022), deformable edge using Smooth Particle Methods (Zhao et al. 2022a), Cui et al. (2023), Zhang et al. (2022a)), hydro elastic wedge drop experiments Ren et al. (2021a), symmetric and asymmetric wedges (Xin et al. (2022).

Hosseinzadeh et al. (2023a) reported an overview of the research on wedge impacts and a concise summary table of 19 works dealing with the experimental wedge impacts, 11 of them were performed from 2017 to 2022. In their research, the impact loads were measured on a non-prismatic aluminium wedge with a stiffened panel during free-fall water entry. Two different plates were considered on the bottom of the wedge to study the influence of flexural rigidity on hydroelastic slamming. A description of the experimental conditions, including the geometry of the wedge, material properties, and the test plan is provided. The same conditions were studied numerically using two-way CFD-FEM coupling in Hosseinzadeh et al. (2023b). Both works discuss in detail the effects of water impact velocity, deadrise angle, mass of the wedge, and bending stiffness on the slamming pressures and structural responses. Comparison of vertical acceleration, slamming pressure, and strain responses showed a slight discrepancy in the maximum value of pressure and strain predicted by numerical methods, in the Authors' opinion due to the different coupling techniques that were applied in the Fluid-Structure-Interaction (FSI) simulations.

Allaka and Groper (2020), Rosén et al. (2020) presented a validation of a mathematical model based on the Zarnick theory with incorporated previously developed improvements for added mass estimation, deadrise-dependent hydrodynamic coefficients, near-transom pressure correction, and dynamic drag. Allaka and Groper (2020) commented that from the comparison of the measured vs. predicted accelerations and motions, it was observed that implementing a full near-transom pressure correction in the initial stages of the planing mode (inception of planing) does not provide sufficiently accurate results. It was also observed that the near-transom pressure correction has to be applied as a linear/quadratic growing function of increasing Froude number. To examine the effects of the incorporated improvements in the calculation of hydromechanic forces, the authors reported that the accuracy of the new method predictions for motion and acceleration of two different crafts was in the range of 3–23% for vertical accelerations and 4–20% for pitch motion when compared with the experimental results. Shao et al. (2023) developed a new Modified Logvinovich Model for a prediction method based on a 2D+t and variable deadrise angle for the vertical force of planing craft. The authors compared the results against CFD and the original 2D+t method in calm water, showing improvements in the prediction of the trim angle and longitudinal vertical force distribution along the hull with respect to the 2D+t and very close agreement with the CFD results. Detailed validation of the numerical model from Rosén et al. (2020) has been published in Begovic et al. (2020).

Diez et al. (2022) developed tools for multidisciplinary design optimization of a deep-V grillage panel on a generic prismatic planing hull subject to slamming loads, first considering regular waves only. The authors considered fluid-structure interaction experiments, computational fluid dynamics, and computational structural dynamics, and optimized a design with a weight reduction of 35% and a safety factor of 1.72. The authors follow up in part II of the publication, Lee et al. (2024), by further considering the effect of irregular waves. Here, the authors find that their computational methods can lead to more efficient designs than the American Bureau of Shipping Rules for Building and Classing Light Warships, Patrol, and High-Speed Naval Craft (2021). From the results presented by Begovic et al. (2024) and Diez et al. (2020) it can be seen excellent agreement of both methodologies: Nonlinear strip method+FEM and 3D CFD methods+FEM, against the experimental data, and clearly there is an important advantage in terms of computational efforts when use of nonlinear strip methods, in particular if the irregular waves or extreme accelerations have to be assessed.

Marlantes and Maki (2022) presented a machine learning method for predictions of nonlinear ship motions in a range of wave conditions when trained on response data from only a single seaway. The method was applied to predict the nonlinear heave and pitch responses of a Generic Prismatic Planing Hull (GPPH) model in head seas at a single forward speed. The training and testing data were computed using the nonlinear theory of Faltinsen (2005) for the development of the method. Although the results of their study are promising, the authors underlined that there are still many limitations, such as different forward speeds and underwater hull geometries which must be addressed before the method may be useful in practice.

Dessi et al. (2023) explored Machine Learning (ML) for slamming event identification. Raw experimental data were acquired from sensors placed on a scaled flexible model of a fast monohull tested in the towing tank under different combinations of sea states and forward speeds. The authors discussed the advantages of using ML models instead of physics based or condition-based ones. The first point concerns the scalability of ML models in terms of features. Physics-based algorithms for slamming detection are based on deterministic criteria between significant variables alone. ML models take into account all the variables which the phenomenon may potentially depend on, even if this dependence is not direct. This leads to include more parameters than those strictly necessary to verify slamming criteria. On the other hand, scalability allows to predict the slamming in the presence of missing information due to sensor failure. It is interesting to note that one of the most critical pieces of information, *i.e.*, the relative motion, upon which physics-based criteria for slamming detection are based, can be recovered by other information available. The second point concerns the ability of ML models to process data in a simple and parallel way. The latter implies that the different features are computationally independent. Indeed, in physics-based identification of Ochi's slamming events, the water entry velocity must be evaluated exactly at the time of impact, that is, at a precise draft value. Thus, errors in synchronizing data or errors in draft measurement may produce rather different results. The previous considerations also indicate that ML models are more robust than physics-based ones, and more resistant to measurement noise. As a final point ML approaches can be easily reshaped to get new targets. For instance, training may be done on information about whipping levels which is not available later. In this case, the ML algorithms will predict slamming more sensitive to whipping.

2.2.2 Multi Hulls

Research on large high-speed catamarans has placed a continued focus on improving ship motions but also reducing ship structural loads and slamming through the implementation of Ride Control Systems (RCS). Incat Tasmania have incorporated RCS on their wave-piercer catamarans (Fig. 3) typically by using stern tabs mounted at the rear of the vessel and a centrally mounted T-foil located behind the center bow (Fig. 4).

Fig. 3. Incat Hull 061 98 m Wave-Piercer Catamaran (https://incat.com.au/vessel-gallery/061/, accessed 28/11/2024).

Fig. 4. Schematic of Hull 061 showing location of stern tabs and T-foil (Lau et al. 2022a).

Although recent work has been undertaken on slamming at full-scale as reported by Almallah et al. (2021), it is still necessary to quantify the effects on motions and loads to develop a better understanding for ship design. Model scale experiments and numerical analysis provide the opportunity to quantify these effects in controlled environments as opposed to the limitations encountered at full-scale due to random weather conditions and the challenges associated with sensors and data collection.

Davis (2023) performed high-speed time domain simulations of a catamaran including the use of active motion controls. He found that using (inactive) fixed T-foils can reduce slamming loads by up to 65%, and that active controls can further reduce these loads up to 79% in 3 m seas. In general, it was reported that local feedback control is the most effective way to reduce catamaran slamming.

To simulate more closely at model scale the conditions experienced at full-scale, Javanmard et al. (2023) conducted experiments in random head seas (Fig. 5). Similar outcomes were found to regular seas, thus confirming a reduction in motions, loads and Motion Sickness Incidence (MSI) (Javanmard et al. 2024) with the implementation of ride control based on an active stern tab and centrally mounted T-foil.

Fig. 5. 2.5 m hydroelastic catamaran model based on the 112 m wave-piercer catamaran shown tested in irregular head-seas with ride control using active stern tabs and centrally mounted T-foil (Javanmard et al. 2023).

It was clear from these model experiments that there were substantial gains to be achieved with the deployment of ride control systems on high-speed vessels. To expand on this further, more recent work has aimed to analyse data collected at full-scale to quantify the effects of the Ride Control System (RCS) on the full-scale catamaran vessel.

Incat Hull 061 was instrumented with strain gauges, accelerometers, wave radar and a motions inertial device to collect data during very specific and targeted wave conditions based on sea trials conducted in 2003 by the Naval Warfare Surface Centre Carderock Division. Ship data was analyzed with and without Ride Control Systems to determine the effects on motions, MSI, accelerations (loads) and passenger comfort (Lau et al. 2022a, b). From these results it was also proven at full-scale, although with greater uncertainty due to the random nature of sea conditions, that a reduction in motions and MSI was effectively achieved in head seas and bow quartering seas with the RCS deployed. These results emphasize the importance of ride control in mitigating wave loads and reducing loads on the hull girder for future design.

Further analysis of this full-scale data redirected an emphasis towards slam detection and global slam loads using various techniques. Alsallah et al. (2021) used Empirical Mode Decomposition (EMD) on vibration signals post slam events on Incat Hull 061 to identify wave impacts by decomposing the signal into many components thereby isolating the signals to identify wave impact events, as further reported by Alsallah et al. (2024). These techniques using EMD were then extended to develop new insights into the structural responses of catamarans subject to slamming. Tracing delays were found between sensors, showing the propagation of structural waves through the ship structure. These waves could then be traced back to the epicenter to identify the location of the wave slam. It was found that although the vessel was heading into head seas the slam load applied to the structure was asymmetric.

Gebrezgabir et al. (2023) developed a new method of response reconstruction using transmissibility based on wave slam load data collected on Incat catamaran Hull 061. Global wave load responses were reconstructed using transmissibility concepts based on linear response theory. It was demonstrated that longitudinal bending strains, roll, pitch and yaw rates due to slamming could be reconstructed based only on two strain gauge readings, two triaxial accelerometers at the bow and an accelerometer at the longitudinal centre of gravity. The developed techniques can reduce the number of onboard sensors needed but more importantly, extrapolate limited measurements to identify stresses at any point in the ship for quantifying design decisions on future vessels.

Fatigue remains to be an important consideration for the structural design of large high-speed catamarans to develop a greater knowledge on the parameters influencing ship longevity but also for improving structural design. Warren et al. (2022) investigated vessel stresses based on large amounts of data collected during passenger voyages on a 111 m catamaran operating in the Canary Islands. This data was used for fatigue analysis where reference was made to classification society rules in relation to fatigue design. To achieve this, long term distribution of stresses was compared to load spectra to find that the simplified methods used by classification societies were highly conservative when compared to fatigue results based on measured data (Fig. 6). A proposed combined Weibull fit method was found to increase the accuracy of fatigue analysis methods.

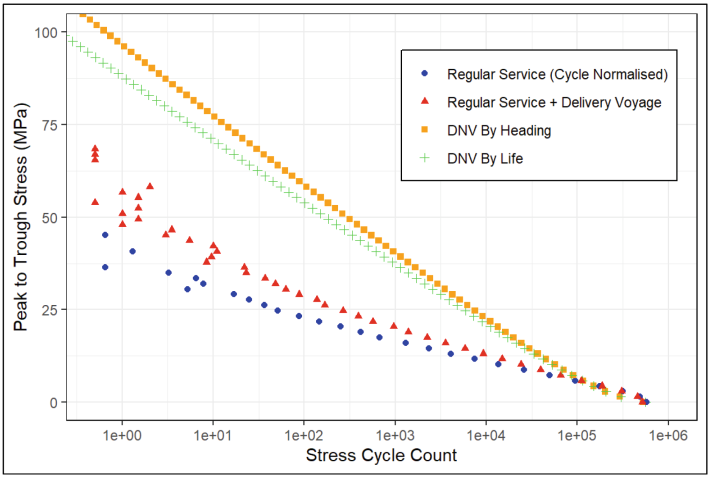
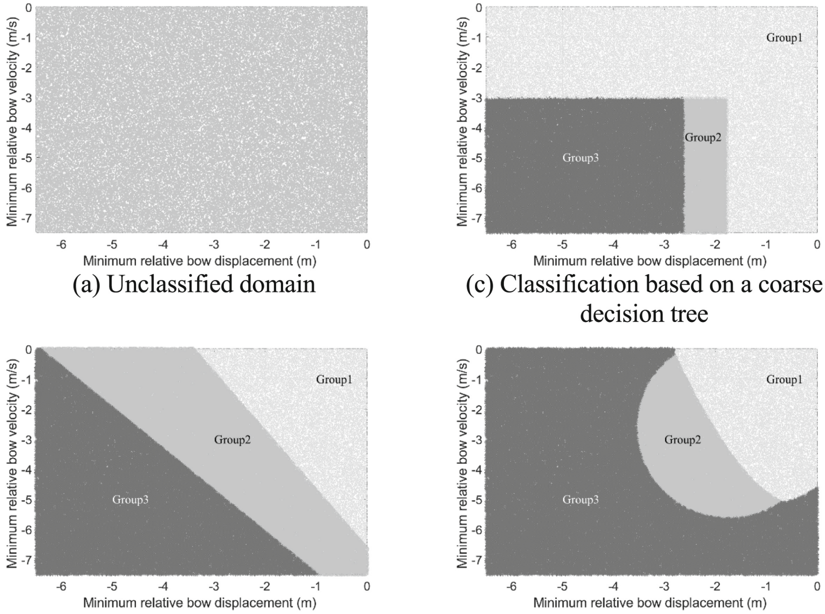


Fig. 6. 111 m wave-piercer catamaran stress spectra formulated using the DNV GL methods compared to spectra developed using in service ship data, Warren et al. (2022).

Full-scale data collected on a 111 m catamaran was further analyzed to compare results from linear elastic fracture mechanics against a linear damage hypothesis or SN curve-based methods for determining crack growth in ships (Warren et al. 2023). The results from the investigation found significant differences in the estimated life when comparing the two methods. It was speculated that the differences are due to the limitations in the linear fracture mechanics model during the crack initiation phase. Parameter changes in the fracture mechanics model also influenced the fatigue life and to obtain good accuracy, material parameters need to be known. Despite this, the linear fracture mechanics methods were shown to have a higher potential for customization when compared to linear damage hypothesis methods. This leads to benefits such as in the assessment of changes to vessel configuration, usage profiles or tracking of known flaws in the vessel.

Intelligent monitoring of catamaran vessels was further extended by Shabani et al. (2023) by introducing machine learning to classify bow entry events especially important for slam classification. The developed methods are useful in identifying slams when big data is concerned either for determining stress cycles during peak loads or to provide real time warnings due to slamming. To enable this machine learning methods were incorporated into monitoring systems (Shabani et al. (2021)). Two vessels were considered. Hull 091 a vessel operating in the Canary Islands). Machine learning models were trained using the data from both these vessels based on supervised and unsupervised models and were found to be beneficial for the classification of bow entry events based on key kinematics parameters. The events were clustered into 3 groups with respect to 6 kinematic parameters as follows: 1. Moving average bow acceleration, 2. Vertical bow acceleration above the moving average, 3. Peak frequencies obtained from wavelet analysis, 4. Peak magnitudes from the wavelet analyses, 5. Relative bow displacement and, 6. Relative bow velocity. These features were determined from strain measurements, vertical bow acceleration and bow relative motion data. Based on this ship data, a comparison was made using different algorithms including linear support vector mechanics, naïve Bayes, and decision tree for bow entry classification with results from the analysis as shown in Fig. 7. The machine learning models developed were used to group and cluster bow entry events, and by doing so this provided a basis for undergoing slam probability analyses to determine the likelihood of wave slamming that has a direct implication on structural loads and design.



(a) Unclassified domain

(c) Classification based on a coarse decision tree

(b) Classification based on a linear support vector machine (SVM) model

(d) Classification based on a Gaussian naïve Bayes model

Fig. 7. Supervised machine learning models developed by Shabani et al. (2021) for classifying bow entry events using 6 key kinematic parameters clustered into 3 groups based on features from strain and acceleration data collected on Incat catamaran vessels.

2.2.3 Small Waterplane Area Twin Hull SWATH

In the recent period, there was an increasing interest for small size SWATH vessels as an option for offshore service vessels, but also there was a research by Ma et al. (2023a, b) to examine slamming loads and the possible effects of air cushion on SWATHs. Ma et al. (2023a) performed a set of drop-test experiments for a SWATH segment model to examine the air cushion effect on the resulting wetdeck slamming pressure. Their experiments showed that the slamming pressure has multi-frequency oscillations, caused by the air cushion effect, and that the air cushion effect can reduce the wetdeck slamming pressure. Further, Ma et al. (2023b) performed towing test models of a SWATH in regular waves, again confirming the pressure oscillation after the maximum slamming peak due to air cushion effect. These experiments found that the peak value of the slamming pressure at the wetdeck midpoint is larger compared to other location on the same cross section, but that slamming pressures were not strongly affected by significant wave height due to air cushion effect.

2.2.4 Trimarans

Multiple authors have used physical drop tests to better understand the effects of slamming and the expected loading. Li et al. (2021a) performed drop tests on a generic trimaran section to investigate the influence of the main hull profile on the resulting wet-deck slamming loads. The authors proposed a “weakening hull method” to modify the generic design with a lengthened main hull to hopefully minimize the flow field disturbance during hull penetration. The modified model experienced only a single slamming peak, as opposed to the original model’s dual slamming due to the spray from the main hull’s initial water penetration.

Duan et al. (2022) examined the effect of drop height and heel angle on slamming pressures on trimarans and offered a Gaussian distribution fit to predict the peak slamming pressure and duration time for different trimaran working conditions (considering the impact velocity and angle). Pan et al. (2023) examined slamming loads on a trimaran using an elastic model, finding that a concave trimaran shape produces more air cushion effect and that the maximum pressures are found on the side hulls and connecting bridge.

Numerical experiments and calculations are further being employed to investigate trimaran slamming. Sun et al. (2020) performed a CFD study to investigate slamming loads on trimarans and how the loads are affected by different parameters and entry types. They found that entry velocity was more dominant (over entry type) in affecting the pressure peaks and that the slamming characteristics are strongly correlated with the penetration depth.

Chen et al. (2023) examined the use of Equivalent Dynamic Coefficients (EDC), which combine static and dynamic analyses to predict the structural responses of trimarans under slamming loads. EDC are defined by applying a calculated slamming pressure to a grillage model and taking the stress from both a static and dynamic analysis; the EDC is then the ratio of the peak value from the dynamic analysis to the peak value from the static analysis. The authors found a difference of EDC values based on the added impact of the transverse bending moment, where the EDC is larger when including transverse bending modes. The authors further proposed a new method to consider material nonlinearity and an equivalent method for the transverse bending moment of the cross deck, as these two factors indirectly produced additional structural responses.

Qu et al. (2023) numerically examined the water surface evolution, slamming pressure, and structural response of a trimaran during slamming events. The authors found that relative velocity impacts the structural response but have a small impact on the resulting strain duration and pattern. Jiang et al. (2022) experimentally and numerically examined the air cushion effect for trimaran slamming via drop tests to determine the evolution of the flow field near the trimaran cross deck during the water entry moment.

2.2.5 Air Cushion Vehicles ACV

Xu et al. (2020) reviewed the progress of the studies in air cushion dynamics, skirt structure dynamics and hydrodynamics of the wave field, and analyzed relevant factors leading to the nonlinearity of ACV dynamics, such as fan characteristics, skirt materials characteristics and cushion compressibility.

The skirt, a unique flexible structure made of rubber-coated fabric material, undergoes great deformation when the ACV hovers over waves. As a consequence, analytical methods cannot hold high accuracy for the actual 3D skirt under various working conditions. In numerical simulations, high fidelity results can be achieved, however, only idealized planar finger seals or a couple of bow skirts instead of whole skirts are considered by CFD methods due to expensive calculations. Jiang and Tang (2021, 2022a) developed a numerical methodology to simulate the water entry of the flexible bag based on the Control Volume (CV) method and the Arbitrary Lagrange Eulerian (ALE) method. The reasonable accuracy of the method is validated by a water entry test of the flexible bag of an ACV. The investigations concerning the water entry of the flexible bag vertically or with pitch angles were conducted systematically by the proposed numerical method, and the results of skirt deformation, internal pressure, and maximum principal stress were discussed comprehensively. In Jiang and Tang (2022b) the same approach has been used to analyse the effects of solitary waves on the flexible bag characteristics: pressures, forces, maximum deformations, and maximum principal stresses at the joints.

Gao et al. (2021) proposed a hybrid analytic-FEM approach for the simulation of the flexible skirts of an ACV under typical working conditions, including hovering condition and skirt-water contacting condition. The method adopts the dynamic explicit algorithm to solve the large deformation of the skirts, the hydrodynamic force obtained via semi-analytical calculation is updated every time increment and then dynamic simulation of typical skirts is performed by FEM solvers. The Authors concluded that validation examples showed good agreement with the traditional analytical method and previous CFD simulation, highlighting the method's potential to model an ACV with its full skirts for simulation of six-degree-of-freedom motion in future work.

Yang et al. (2023) experimentally studied seakeeping performances of Partial Air Cushion Supported CATamaran (PACSCAT) in regular waves and discussed the effect of the waves on pressurized flow leakage and consequent change of dynamic trim and increase of accelerations. Minty et al. (2023) studied the dynamics of the air plenum of Surface Effect Ships (SES) ship analytically and experimentally performing forced oscillations of air plenum volume. The Authors discussed vibrations magnitude in the wide range of frequencies and pointed out that the measured natural frequency of the heave deck was significantly less than the theoretical natural frequency of a rigid-walled plenum, demonstrating that flexibility of the seals and water surface under SES is likely to significantly affect the natural frequency of the heave deck.

2.3 Conclusions

From the reviewed research papers dealing with the High Speed Vessels it can be underlined the increased interest in Air Cushion Vehicles and the importance of improving the methodological approach for more accurate prediction of wave loads and ship responses. The possibility of sensoring ships and the availability of big data from full scale measurements facilitate the development of machine learning techniques and it can be expected that it will be the area of researchers' interest.

3 Large Pleasure Crafts

3.1 Introduction – Concepts and Challenges

The world of yacht construction, both sailing and motor yachts, is experiencing record in Global Order Book 2023 (Montigneaux et al. (2023)), with a growth of 17.5% in orders and 6.3% increase of total gross tonnage. According to the number of projects and total

Gross Tonnage, the top builders' nations are Italy, The Netherlands, Germany, Turkey and Taiwan. The continuous growth of yachts' dimensions makes them closer to ships with similar design and construction problems, challenging designers and shipyards to develop new design approaches and construction technologies. For the same reasons, Classification Societies have dedicated more attention to develop new focused rules for design loads, structures scantling and plant layout and components.

Shenoi et al. (2009) and Boote et al. (2012) focused on sailing and motor yachts respectively; Truelock et al. (2018) addressed larger pleasure yachts, primarily in excess of 30 m, so-called "super yachts". In this report, pleasure boats are divided according to their dimensions and applicable rules to: Large pleasure crafts (over 24 m) and Small pleasure crafts, both considering motor yachts and sailing boats.

3.2 Loads and Structural Challenges in Yachts Design

Design accelerations are a driving subject for very fast vessels and often the values imposed by the Rules are too severe to keep the structural weight compatible with the required speed. This subject has been widely assessed on the occasion of the redesign of a fast patrol vessel from light alloy into composite material (Hydar et al. (2022), Souppez et al. (2020)) by comparing the acceleration values imposed by CS Rules and those obtained by experimental tank tests and direct calculations.

In Boote et al. (2023) the comparison of different composite materials: E-glass, carbon and hybrid glass/carbon fibers for hull constructions was carried out. At first, the three solutions were evaluated by laboratory tests determining the tensile, bending, shear and interlaminar ultimate values. After that, the hull structure scantling was designed for the three composite materials by RINA HSC Rules with the resulting three versions accurately weighted and then optimized by FEM evaluations. From this comparison, carbon composite showed the best results in terms of weight reduction (but not in terms of cost) for a series production where E-glass composite could assure acceptable results at lower costs.

In hulls of modern superyachts, large openings are often required for inner basins, tender garages, balconies and large side windows. These openings strongly affect the hull strength which should be accurately evaluated and compensated with additional structural elements. This subject has been widely assessed in meetings, workshops and other technical events but, as known at this moment, no specific papers are available in the literature.

The same problem affects superstructures equipped with large windows. The combined action of bending and compressive loads, together with the fact that superstructures are usually made of aluminium light alloy, can be the cause of buckling phenomena with severe consequences on structure and glass integrity. Studies carried out by Boote et al. (2017a, b) aimed to evaluate the contribution to steel hull strength of light alloy superstructures with large openings by the finite element approach. The contribution of glazing windows to the primary response to global bending moment was assessed as well.

Even if not affecting the hull strength, thermal loads could cause important effects on the deformations of the hull side plates, giving rise to unpleasant optical wave effects which can lead to harsh owner claims. The effects of solar radiation on the hull warming and the quantification on the side plate distortion were reported in Kumar et al. (2016), Boote et al. (2017c). The study was developed by FEM structural analyses on a portion of a superyacht hull in the region of aft sides, shown in Fig. 8 where the flatness of the shell makes more visible distortions possible. Both steel and aluminium materials were considered, covered by filler layers of different kinds and thicknesses. A preliminary experimental investigation was performed on several steel and aluminium plates covered by different filler types exposed to a warming lamp to calibrate the numerical models.

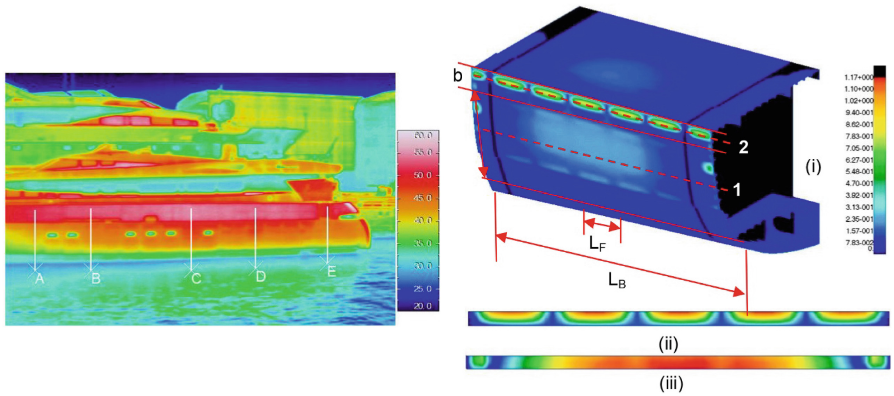


Fig. 8. Effects of solar radiation on yachts: (a) temperature measurements by thermocamera; (b) FEM simulation of plate deformation under thermal loads (Boote et al. 2017c)

3.2.1 Comfort

The comfort level on board modern superyachts is currently one the most important characteristics which make them commercially attractive, where the maximum speed previously took precedence. Comfort on board mainly means vibrations and noise control and, as they strongly depend on the hull and superstructure layout, comfort is the reference index which drives designers in structure scantling. The lack of standards and criteria for the assessment of the ship motion related to the risk of discomfort onboard large yachts was reported to be an important issue for the industry, brokers, owners and representatives. In 2022 ISO 22834 Large yachts—Quality assessment of life onboard—Stabilization and seakeeping guidelines were delivered to address the lack of a recognized and accepted procedure, criteria, and rating that can be used to compare yachts among each other and evaluate the impact of stabilization systems in the improvement of the comfort.

In Begovic et al. (2023) this new standard was applied to yachts with three different bow shapes: classic bow shape, vertical bow and bulbous bow. Even though the differences in comfort were small, the obtained ranking among the design solutions on a reference large yacht is the option nested with a bulb, contradicting the expectations of a vertical bow concept. The authors discussed some critical points of the methodology and the suitability of the proposed standard.

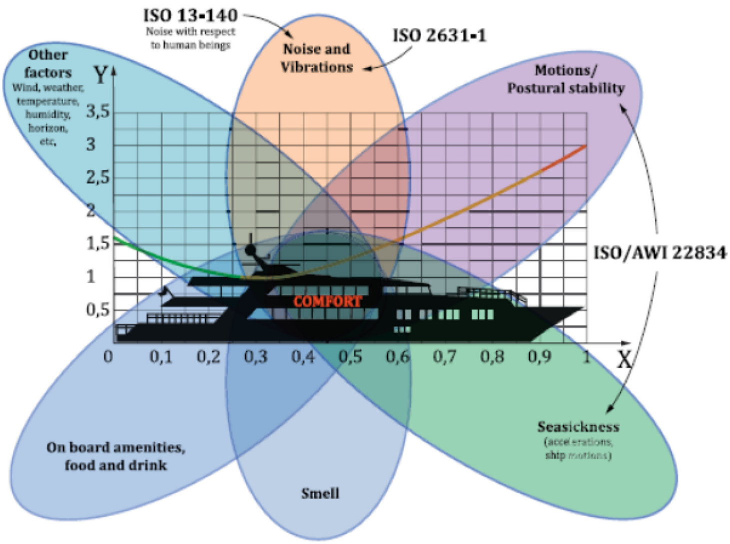


Fig. 9. List of elements contributing to comfort onboard (ISO 22834)

As seen in Fig. 9, ISO 2631 is the reference standard for the vibrations felt by humans, such as those induced by slamming as Whole Body Vibration (WBV) and Vibration Dose Value (VDV). Engelbrecht and Bekker (2023) conducted an extensive study on full-scale vertical acceleration measurements conducted near work and accommodation areas on the vessel together with the daily operational diary survey to gather human responses among passengers on polar research vessel. Results of the study reported a threshold for Vibration Dose when 50% of respondents indicated discomfort and discussed the RMS threshold. More research on this topic is needed to assist the cruise/pleasure yachts/high speed craft industry to specify criteria that will ensure comfortable vessels.

3.2.2 Vibrations

Apart from the effect of yacht motions, noise and vibrations are very important factors for the sensation of comfort on board and for these reasons the most important Classification Societies issued new rules and regulations for the evaluation of noise and vibration maximum levels. Such rules, usually named “Comfort Class Rules”, contain both the general criteria for noise and vibration measurements in various yacht areas and maximum limit values which such measurements should fall into.

Vergassola et al. (2019b), Vergassola (2020) conducted research addressing the start of a measurement activity, starting from the choice and acquisition of the electronic equipment up to the first real scale measurement campaign carried out in cooperation with some Italian yacht shipyard, have been presented. A calculation procedure to preventively determine hull vibrations which can be problematic for crew and passenger comfort was set up and then applied to a case study steel yacht with light alloy superstructures. The dynamic behaviour of the same vessel was monitored during the various construction phases. Different FEM models of the reference yacht were set up by two multipurpose

FEM codes to identify the natural frequencies of local structures such as bulkheads, main deck and aluminium super-structure decks. The results of this first modal analysis were validated by real scale measurements carried out on the hull structures during construction.

The objective of this part of the investigation was to verify the reliability of numerical models with different refinement levels, starting from single parts of the hull structure, moving to more complete ones, up to the global model of the yacht. All the models were analyzed with and without outfitting. As confirmed by the analysis results, if models are properly refined, the results gathered on partial models can be as reliable as global models. This approach is useful to reduce FEM analysis time, especially when only local vibration modes are of interest (Fig. 10).

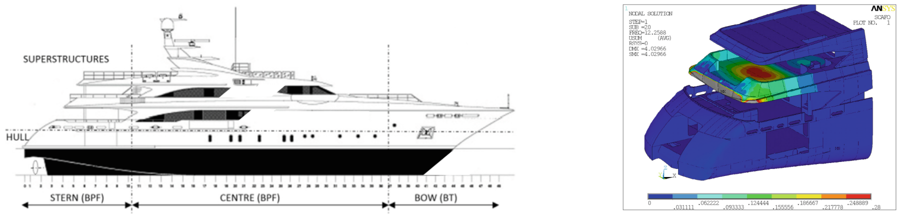


Fig. 10. Longitudinal view of the case study superyacht and FEM results of dynamic analysis (Vergassola et al. 2019b)

Lloyd et al. (2020) considered the recent advances in predicting and mitigating the noise and vibrations caused by propeller cavitation, specifically linking to concerns for yachts. The authors discuss propeller design aspects for yachts and specifically note that the empirical tip vortex method to predict broadband underwater radiated noise and hull-pressure changes due to vortex tip cavitation can be useful for design optimization.

Zambon et al. (2021) analyzed measured vibrations of super-yachts due to propellers and found that the common empirical Holden Method and similar methods suggested by classification society design standards overestimate propeller-induced hull excitations. They suggest an updated regression-statistical analysis method to consider propeller vibrations is needed for super-yachts and small cruise ships.

Fassola and Kustermann (2022) measured noise and vibration levels on a 50 m yacht and compared them against statistical energy analysis and finite element analysis, finding good agreement between prediction and measurements.

In the field of composite vessels, the modal and harmonic analyses of a 25 m motor yacht in composite materials were carried out to investigate the structure's dynamic behaviour and improve the comfort level (Hydar 2022). The modal analysis was carried out for two configurations (engines installed with rigid and elastic connections) to determine all the global and local natural frequencies and to check the possibility of the occurrence of the resonance phenomenon. Silvestri et al. (2024) reported results of sea trial measurements on a 52-metre superyacht equipped with traditional 2 five-bladed propellers, using vibration signal processing methods to identify vibrational components and shown that the proposed method can be a reliable tool for propeller cavitation monitoring.

3.2.3 Noise

Given the stricter Rules issued by Classification Societies (CS) about comfort Class, especially for yachts of more than 65 m in length, the reliable evaluation of vibration and noise levels at the earlier design stage becomes extremely important with particular attention to the difficulty of reliably predicting noise. Structure-borne noise generated by diesel engines on board yachts is strictly related to the intrinsic dynamic characteristics of both the diesel engine and the engine supporting system. To keep the structure-borne noise at low levels, the selection of the most suitable structural configuration of the engine foundation is one of the main aims of the ship designers. Prediction and optimization of the engine foundation dynamics are based on the knowledge of the diesel engine seating mobility levels. This can be achieved by FEA simulations once they have been properly calibrated on experimental data

In Vergassola et al. (2018) some numerical tools which allow prediction of noise propagation on board before sea trials to be carried out were presented. Because of the FEM technique limits in the range of high frequencies, numerical tools such as Statistical Energy Analysis (SEA) have been used to assess the noise level with accuracy at the early stages of a project, when structural changes can be made without additional time and cost. The level of uncertainties in SEA calculation is higher than for a deterministic approach like Finite Element Analysis (FEA) and this has to be taken into consideration while performing global analyses on vessels. For these reasons, experiments have to be carried out to improve the confidence of analysis to an error level up to ± 3 dB. In the paper, a procedure for the calibration of the input power due to propulsion engines has been studied in depth using a hybrid SEA+FEA model.

A study about noise propagation carried out by Statistical Energy Analysis (SEA) technique is reported in Vergassola (2020) where the propagation of noise throughout laminated glass was addressed with particular attention by a dynamic effective thickness equivalence.

The impact of Underwater Radiated Noise (URN) by ship traffic has gained increasing interest among scientists, ship designers and builders. As an example since 2017 the Port Authority of Vancouver (CA) has introduced important incentives and tax relief for those merchant ships that prove to be particularly virtuous in terms of noise emissions radiated into the water. Not many studies are available regarding pleasure crafts and large yachts. For this reason, the University of Genoa, in cooperation with an important yacht shipyard, issued an experimental campaign for the measurement of the underwater radiated noise of one large yacht (Boote et al. 2022). The noise was measured for several operative conditions and speeds ranging from zero to maximum speed.

3.2.4 Glazing

Glazed openings are particularly interesting for the V.5 Special Vessels Committee as many of the yachts have unique structural configurations allowing for very large or numerous wide glazed openings (i.e., windows, portlights, skylights) (Fig. 11).

Artefact, 2019, Nobiskrug, https://www.nobiskrug.com/fleet/artefact/, The total amount of glass on board is 750 m^2, photo by Francisco Martinez, accessed on 27/11/2024

Fig. 11. Artefact 2019, https://www.boatinternational.com/yachts/editorial-features/nobiskrug-superyacht-artefact, accessed on 27/11/2024, photo by Francisco Martinez

The glazing of vessel openings therefore has a very important role which brings about a variety of rules and requirements to determine the adequacy of the glazing for use in operation at sea. The Committee V.5 in the previous mandate performed a Benchmark to open the door to further research and discussion. The scantling of a large window of monolithic Tempered Toughened Safety Glass (TTG) is performed according to the class rules and results of FEM analysis by different software were compared. The conclusion of the Committee is that there is a need for a common methodology across Classification Societies and Standardisation Organisations for the calculation of specific design pressures dependent on glazing location, material and loading event. It was highlighted that each regulatory body has a different approach to the calculation of design pressure, as seen in Fig. 12. Although all utilise the same fundamental first principle formulas for flat plate bending to achieve the glazing design thickness.

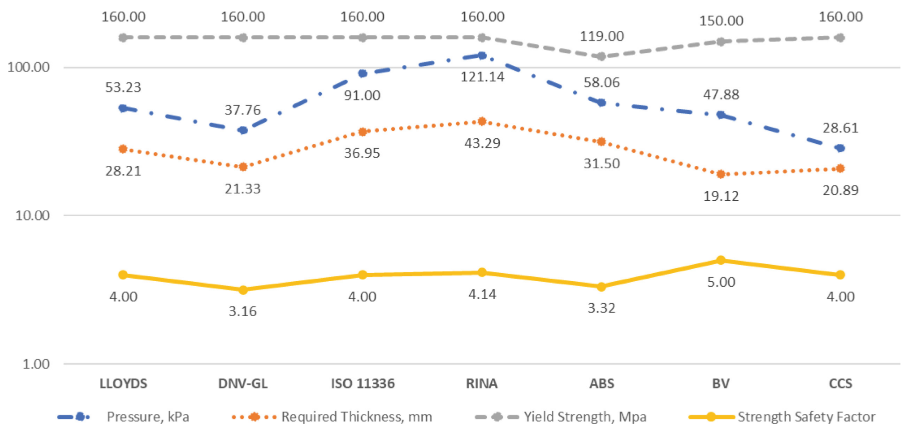


Fig. 12. Results from Class and Standard Glazing Analyses, Truelock et al. (2022)

Laminated glass is currently a common composite material in the construction of yacht windows thanks to its capabilities of safety glass and its sound insulation properties. In Boote et al. (2017c) the damping coefficient at natural frequencies of laminated glass has been obtained by different experimental modal methods and the Reverberation Time test is proposed to assess the coefficient in the whole frequency range of interest. In Vergassola and Boote (2020) a simplified method for the evaluation of a dynamic effective thickness of laminated glass plates is presented. The Authors proposed an interactive procedure to derive a dynamic equivalent monolithic glass with the same natural frequencies of the laminated one and analyzed the effect of thickness in the vibroacoustic characteristics of laminated glass. It has been highlighted that, even though the common practice in shipyards, passing from a 3 layered window to a 5 layered one, is not always the best solution, since the new natural frequencies can be resonant with the main external sources.

Wium et al. (2022) considered how to integrate glass into the yacht structural design, specifically how the glass can contribute to the structural stiffness and bear loading. The authors discussed the challenges of glass, specifically connection points/methods between the glass and other structures are examined. The authors concluded that there is a lack of knowledge on how structural glass components will perform within a ship's structure.

Moupagitsoglou (2020), Block et al. (2021) summarized the typical requirements a glass window in superyacht applications needs to fulfil, the most important design standards and testing. Furthermore, Moupagitsoglou (2020), reported an example of

FEM calculations using linear static formulas (prescribed by standards ISO 11336-1:2012 and BS MA 25:1973) and non-linear geometry analysis for two chemically strengthened panels. The author concluded that as a rule of thumb, non-linear geometry finite element analysis provides more accurate results when the yacht glass is deflected more than half of its thickness. This is usually the case for large span windows at the lower levels of the vessel due to the high design pressures. Linear static analysis using FEA or simplified formulas is adequate for smaller glass panels.

3.3 Structural Analysis and New Regulations

The rising complexity and specific needs of modern yacht design have motivated the revision and new editions of regulations by CS. Key areas of focus include:

- **Design Loads:** There have been significant revisions in structural rules to enhance safety standards, addressing the pressures on hulls, glazing practices, fire protection, and tank scantlings.
- **Technological Advancements:** The inclusion of regulations for hybrid propulsion systems and the proper management of lithium-ion batteries.
- **Innovation in Design Elements:** The regulatory updates reflect modern design practices, including new criteria for glazing, and considerations for innovative materials and construction methods.

3.3.1 Bureau Veritas (BV)

Bureau Veritas Regulations for Yachts are contained in a single collection which provides specific requirements for both commercial and private use. The first edition was issued in 2012 with some minor amendments in 2016, it was majorly revised in 2021 and subsequent amendments were issued in 2022 (Bureau Veritas 2022a). The main subjects which have been revised in the last version of their Rules reflect the present trends in yacht development.

- Particular attention is devoted to the evaluation of the pressures acting on the hull and to the scantling criteria for hull structures.
- A more specific procedure has been set up for glazing dimensioning and positioning.
- New fire protection requirements have been introduced.
- Because of the growing diffusion hybrid propulsion systems additional class notation for on-board installation of lithium batteries has been issued (reference to NR_467, Part F).
- A new section is dedicated to high density polyethylene structures with specific scantling criteria.
- Some changes have been applied to the equipment number calculation.
- Wind Propulsion System notation has been updated.
- New requirements have been introduced for composite propeller shafts

3.3.2 Lloyd's Register (LR)

For the 2024 edition of the Special Service Craft Rules (Lloyd's Register, July 2024) the following updates will be applied:

- In the structural rules updating particular attention has been addressed to the definition of the design loads for displacement vessels such as hydrodynamic and impact loads, design accelerations and wave height parameter for longitudinal strength. Other changes are planned for structure minimum thickness, for the applicability of ice class and hull openings (shell doors). Another focus point is dedicated to the structural criteria and arrangements of double bottoms
- Additional mitigation measures will be introduced to evaluate large glazing openings below the freeboard deck subject to Flag Administration acceptance.
- About tank scantling procedure a significant re-arrangement regards minimum test pressure, exemptions for very small tanks and removal of minimum overflow height for design pressure.
- Minor updates are SDA notation, sliding doors, openings in sheerstrake, azipods, fatigue limit for aluminium, bimetallic joints, virtual freeboard deck, fin stabilisers.
- New requirements will be introduced for guardrails on yachts with a load line length > 24 m.

3.3.3 Red Ensign Group (REG) (REG Yacht Code: Part A, (June 2023))

The REG rules revisions have been discussed jointly with Industry, Classification Societies, Management Companies, Associations and industry bodies in Amsterdam on May 2022 and June 2023 and will now apply to contracts signed (or keels laid if building on speculation) on or after 01 July 2024.

For what the structural aspects of motor and sailing yachts are concerned the following issues have been further developed:

- Design Criteria for shell doors, hinges and hydraulic control systems
- Alternatives to traditional sills for openings on the weather deck e.g. recessed/negative sills
- Clarification & simplification of the requirements for glazed openings, deadlights & balustrades
- Design considerations for glazed openings in way of and below the waterline
- Clarification of marking - Load Lines and Deck Lines
- Clarification of criteria for launching lifeboats, life rafts and Marine Evacuation Systems under adverse angles of heel and list
- Structural Fire Protection measures – Garages for <500GT to be protected
- Option to utilise bulkhead between ECR & engine room in lieu of the provision of a trunk
- Requirements for the storage of compressed gases and paint
- Lithium-Ion Batteries: simplification of fixed installations by harmonising with Class Rules and adoption of MGN 681 (M) Fire safety and storage of small electric powered craft on yachts
- Helidecks, Hangars & Re-fuelling Facilities: additional clarifications added
- Recreational dive facilities – Scope expanded to include wider range of diving equipment

3.3.4 Registro Navale Italiano (RINA)

The news on RINA Rules for yachting 2024 is the merge two current Rules for Pleasure and for Yachts Designed for Commercial Use in one unique «R*INA Rules for Yachting*» containing the requirements for yachts of any length (above and below 24 m) and any gross tonnage (above and below 500GT), designed both for pleasure and commercial activities carrying up to 12 passengers when in commercial use.

The 2 current set of Rules, the one for Pleasure yachts (applied to private vessel above 16 m), and the one for Yachts Designed for commercial Use (applied to Charter yachts of more than 24 m LLL) were already aligned since the last years for what it concerns the structural aspects (the major differences within the 2 set of Rules was relevant to systems and fire protection).

In particular, in the last years, the following updated have been done to Pleasure – Charter:

- The requirements for glazed bulwarks have been added. The design loads (weather and impact) for the scantling have been defined and the required test (impact test in acc. with EN 13094) for typical arrangement has been added. The use of different material has been considered and also relaxations for vessel of less than 24 m.
- Added the limitation (maximum area according to the distance to the deck of the lower edge of the window) for openable windows fitted on the hull subject to the acceptance of the Administration in case of charter service.
- Following a request of an Administration additional requirements are set for the scantling of side doors acting as platform when open. In addition to the load of the person and equipment that can be carried on the platform also the buoyancy and sea loads have to be taken into consideration for the scantling of the platform and its blocking and securing arrangement when in open position.
- Added the approach to be followed for the scantling of glazing partially submerged. Considering that these solutions have been only recently adopted in the rules it is stated that these arrangements will be considered on a case by case base (according to the dimension of the yachts, the stability criteria the yacht is subject to, the dimension of the glazing etc.…)
- Revised some coefficients for the scantling of bottom plating and inner bottom stiffeners for steel and aluminium vessels. After a verification of the formulas on very large yachts (about 60–70 m) and the comparison with the required values on passenger ships made of the same material in accordance to the marine rules it has been found that a reduction of about 10% was necessary.
- Some clarifications has been set for the scantling of rudder with blades and/or stock made of composite (grp or carbon) material.
- RINA Rules for Ship (structural aspects in particular) has been recalled for yachts wishing to obtain the ice class notation (IAS, IA, IB, IC and ID).
- For the new 2024 merged edition the following amendments to the previous rules have been done:
- A new approach for the scantling of water freeing arrangement in line with the new edition 2024 of REG A. In particular the possibility of reducing the area of water freeing arrangement on upper deck of lateral external corridors has been added.
- Added the possibility of use negative sill height in line with the new edition 2024 of REG A instead of the traditional ones. The scantling (depth, length and width) of such negative sill in in line with the requirements of the most common used Large yacht Safety Codes and also the possibility of use alternative scantling subject to the satisfaction of a practical test of draining has been introduced.

- Added the possibility of use of glazed deadlights as an alternative to metallic one subject to the acceptance of the Flag Administration in case of charter service. This possibility has been added in a general way saying that the arrangement is subject to verification on a case by case base with the idea of applying the approaches in the new ISO 11336-1 as far as it is practicable.
- Small modification in the safety factors for keels of sailing yachts. The verification of grounding and pounding have been added.
- New requirements for tank testing in accordance with IACS UR S14 for "SOLAS-exempted" ships has been introduced for yachts equal or more than 500GT and new requirements for tank testing in accordance with IACS UR S14 for "non-SOLAS" ships has been introduced for yachts of not more than 500GT
- The table of minimum thickness of GRP vessels after many years of use of Part.B, Ch.4 for composite vessels has been found not more necessary and has been deleted.
- The requirements for anchors weight and chain cable length for yachts of more than 500GT have been increased and an additional class notation assignable on voluntary base has been added for yachts of any GT with anchors heavier and chain cable longer than the minimum requirements set in Part B. The notation may be assigned at different level according to the partial of full compliance with the IACS UR A1 relevant to anchoring equipment on ships.
- The minimum number of mechanical tests on GRP structures (monolithic or sandwich) for new building have been clarified in Part D.
- A dedicated section of Part A will be dedicated to the tests required and procedure for acceptance of all the hull structures and outfitting according to the different hull material for new buildings.

3.4 Conclusions

The last decade witnesses the continuous increase in the building of "superyachts", solely on powerside, sailing yachts accounts for 5.9% of Global Order Book (Boat International 2023). The design practice faces challenges to answer on key market trends like comfort and bigger spaces, the newest technologies and accessories on board, the introduction of sustainable materials, and propulsion solutions like fuel cells or hybrid propulsion. The final product is sophisticated and design practices are often very advanced to achieve the goal, but this experience is rarely shared and published within the scientific press.

4 Small Pleasure Crafts

4.1 Introduction – Concepts and Challenges

Owing to their smaller size, faster production rate and lower costs compared to ships, yachts offer an ideal design and innovation platform for proofs of concepts that could be applied to ships. For instance, the scaling of composite structures from small crafts to ships has been thoroughly investigated by the RAMSSES (Realisation and Demonstration of Advanced Material Solutions for Sustainable and Efficient Ships) (2023) and FIBERSHIP (2023) projects, demonstrating the feasibility and weight savings associated with composited, as opposed to steel, ships. Extrapolating from advances in composite ship sizes, Lowde et al. (2022) forecast the launch of the first 100 m composite ship for 2042 (see Fig. 13), showcasing the impact of advances in yachts onto ships.

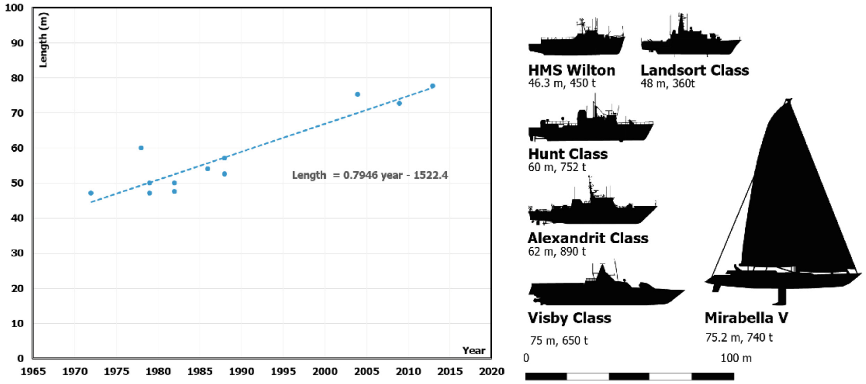


Fig. 13. Evolution in composite ship size over time (left) and scaled drawings of large compositevessels (right) (Lowde et al. 2022)

As such, recent developments in the structural design and analysis of yachts provide valuable insights into emerging trends and future developments, particularly with respect to the structural challenges associated with reduced emission vessels. Indeed, the report of the ISSC V.5 2022 (Truelock et al. (2022)) revealed there exist structural challenges to be addressed to support the development of low or reduced-emission vessels.

The main challenges identified were:

- the use of composite materials to achieve lightweight structures,
- the adoption of multihull configuration for reduced drag,
- the increasing use of hydrofoils, also intended to reduce resistance; and
- the implementation of novel propulsion methods, such as wind assisted ships, which parallels development in sailing yacht rig structure.

These four areas coincide with recent developments in small craft structures and their associated regulations, namely the ISO 12215 and its sub-parts. Additionally, the ISSC V.5 (Truelock et al. 2022) provided a benchmark on glazing given the prominence of large openings on yachts, which echoes recent developments in the ISO 12216 for small crafts and ISO 11336 for large yachts, each governing the strength and watertightness of glass windows.

4.2 Loads and Structural Challenges

4.2.1 Composite Monohull Structures and ISO 12215-5

The ISO 12215-5:2019 (ISO 2019) is concerned with the design pressures, stresses and scantlings determination for monohulls. The latest version, introduced by Souppez & Ridley (2017) and published in 2019 (ISO 2019), brought substantial changes to the structural analysis of sailing yachts (Souppez 2018a), power crafts (Souppez 2019) and commercial vessels (Souppez 2018b) below 24 m in length, prompting further research on workboats under this new regulations (Jang et al. 2019). The revision was motivated by advances in composite materials and manufacturing over the decade since the previous 2008 publication of the standard.

This prompted comparative assessments with respect to other class rules, tackling both the materials (Han et al. 2023) and loads (Souppez et al. 2020) to identify the commonalities and differences with other class rules and further experimental work to compare the mechanical properties with the default values of the ISO 12215-5. For a quasi-isotropic E-glass-epoxy laminate, Souppez and Laci (2022) revealed the conservative nature of the ISO ultimate flexural strength, the accuracy of the ultimate tensile strength, and raised concerns about the ultimate compressive strength, especially for vacuum-bagged samples, with the main cause identified as the value of the ultimate compressive breaking strain for chopped strand mat. The results are presented in Fig. 14. This provides recommendations that could inform future revisions. An additional area of further development was presented by Oh et al. (2022), who quantified the mechanical properties of glass laminate for varying fibre weight fractions. This work enables to de-rate the mechanical properties of composite laminate for fibre weight fractions beyond the ranges currently covered by the rules. Indeed, with advances in composite manufacturing techniques affecting the fibre weight fraction of the laminates and resulting mechanical properties, Han et al. (2020) demonstrated the higher accuracy of direct measurements compared to estimates and impact on calculated properties.

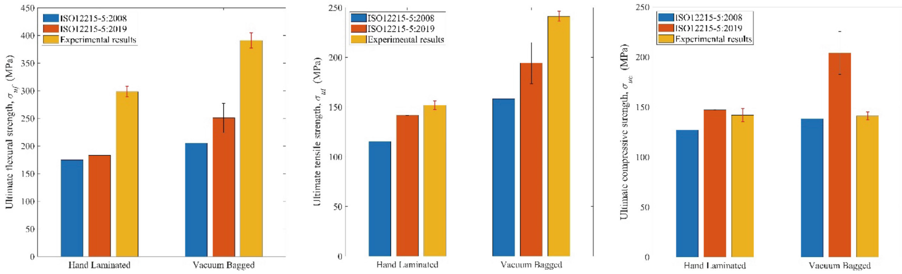


Fig. 14. Validation of the flexural (left), tensile (centre) and compressive (right) strength of quasi isotropic laminated (Souppez and Laci 2022).

Two further areas of development have attracted interest. Firstly, the use of timber as a sustainable composite material, either on its own (Souppez 2023) or combined with metal (Barry 2022), again with a focus on the comparison of the mechanical properties with that of the ISO 12215-5 (Souppez 2021). Secondly, more advanced structural designs and their optimisation, such as the concurrent multi-component optimization of stiffened-plates presented by Lorimer and Allen (2022). The advances further contribute to the design of lightweight structures, particularly when compared to steel or aluminium, thereby supporting the reduction of emissions thanks to lighter vessels. Further gains may be achieved hydrodynamically by moving to multihull configurations.

4.2.2 Multihull Configurations and ISO 12215-7

Multihull configurations include catamaran, trimarans and stabilised monohulls, all yielding significant displacement and fuel consumption compared to a monohull equivalent, as shown in the previous ISSC V.5 report (Truelock et al. 2022), thanks to a lesser hydrodynamic drag. This has, for instance, motivated work on Unmanned Robot Sailbots (URS) to maintain high speed without sacrificing stability, including that of Zhu et al. (2023), and Lin et al. (2023). Such configurations, however, are subject to global load cases. This is the purpose of ISO 12215-7:2020 (ISO 2020a), which covers the global load cases associated with multihulls. A total of six global load cases are provided, namely:

1. Diagonal load in quartering sea, ensuring suitable design torsional moment assuming the vessel is supported by two adjacent wave crests, one at the fore starboard hull (or starboard float for trimaran) and one at the aft port hull (or port float for trimaran).
2. Rig loads, specific to sailing yachts, and arising from the relevant regulations, namely the ISO 12215-10 (ISO 2020b), later discussed.
3. Asymmetric broaching loads, also specific to sailing yachts, where transverse horizontal pressure is applied at the fore end of a catamaran's hulls, or a trimaran's centre hull and leeward float.
4. Longitudinal broaching, also known as pitchpoling, where longitudinal deceleration loads are experienced as a result of the stems digging in a wave.
5. Longitudinal force, i.e. shock on the hull, representative of an impact (e.g. floating object, marine mammal), with resulting shear force and bending moment applied in the cross structure (cross beams or wet deck)
6. Bending of crossbeams, specifically those of motor vessels

Despite specific global loads for multihulls, their local scantlings remain based on ISO 12215-5. However, the slamming loads on the wetdeck of multihull vessels are of particular interest, with both numerical and experimental studies (Sun et al. (2021), Wu et al. (2021)). This is accentuated by the increasing presence of hydrofoils on multihulls to minimise emissions, be they greenhouse gas emissions thanks to lower drag (Hashimoto et al. 2021; Asgaree 2022; Firdhaus and Suastikab 2022), but also wash (Terui et al. 2023). Lastly, the inclusion of a hydrofoiling sailing catamaran class, namely the Nacra 17, since the Tokyo 2020 Olympics has triggered numerous research outputs (Graf et al. 2020; Marimon Giovannetti et al. 2022; Patterson and Binns 2022; Knudsen et al. 2023). In turn, this has triggered further interest in the structural design of appendages

4.2.3 Appendages and the ISO 12215-9

Despite the benefits of hydrofoils for both sailing (Souppez et al. 2019b; Bagué et al. 2021) and power boats (Budiarto and Firdhaus 2021; D'Amato et al. 2023), it is advances in wind assisted ship propulsion, as reported by Khan et al. (2021) and Petković et al. (2021), that have seen a novel interest for ship appendages, such as low aspect ratio keels (van der Kolk et al. 2021; Kramer and Steen 2022). Appendages, however, remain beyond the scope of ship regulations associated with wind assisted propulsion. Therefore, it is small craft regulations, namely the ISO 12215-9:2012 (ISO 2012) which covers sailing craft appendages, which can offer valuable insights.

The current 2012 version of the standard is currently undergoing revision (Lyons et al. 2024), ahead of a revised publication in 2025. The motivation for the revision is threefold. First, it follows significant regulatory advances in hull scantlings (ISO 12215-5), and the launch of new parts governing multihulls (ISO 12215-7) and rig loads and attachments

(ISO 12215-10), all covered in this chapter. Then, while investigations did not yield any concerns on the suitability of the ISO 12215-9:2012, loss of keels leading to loss of lives, such as that of the sailing vessels *Cheeki Rafiki* (Marine Accident Investigation Branch MAIB 2015), *Capella* (Federal Bureau for the Investigation of Maritime Accidents FEBIMA 2017) and *Showtime* (Lyons 2021), demonstrate the vital role of keel structures and the importance of fatigue life (Raju et al. 2010). Lastly, improvements in yacht performance over the past decade, coupled advances in the understanding of welded joints fatigue (Grimm 2016; Braun et al. 2018; Braun et al. 2021), flutter effects (Mouton and Finkelstein 2015; Mouton et al. 2018), load monitoring (Russell et al. 2016) and the behaviour of centreboard and daggerboard for dinghies (Graf et al. 2020; Guida et al. 2020; Bagué et al. 2021) further motivate a revision of the 2012 standard.

The configurations and load cases covered by ISO 12215-9 are as follows:

1. Fixed keel during a 90° knockdown.
2. Canting keel canted at 30°, including dynamics overload.
3. Vertical pounding.
4. Longitudinal impact.
5. A 90° knockdown for a capsize recoverable dinghy.
6. Dynamic loads sailing upwind.

Hydrofoils remain excluded from the scope of the Recreational Craft Directive (European Parliament 2013) and Recreation Craft Regulations (Office for Product Safety and Standards 2017) and thus may not be included in the ISO standard. However, the undeniable growth in hydrofoiling technology and configurations, depicted in Fig. 15, may lead to their eventual inclusion in small craft regulations, which would further support their wider adoption (Truelock et al. 2022).

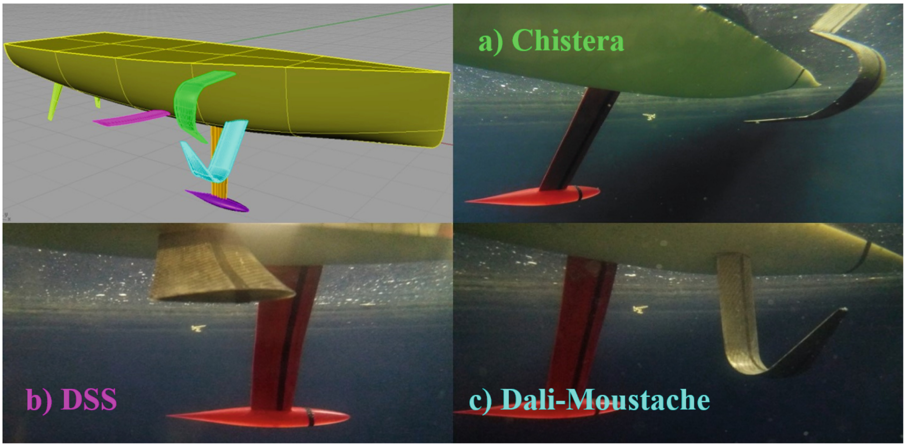


Fig. 15. Hydrofoil configuration in the benchmark of Dewavrin and Souppez (2018)

4.2.4 Rig Loads and ISO 12215-10

In parallel to the interest in keels, wind assisted ship propulsion is also concerned with the aerodynamic forces of the various systems available (Khan et al. 2021; Tillig and Ringsberg 2020; Reche-Vilanova et al. 2021; Dupuy et al. 2023). While class societies are yet to fully cover rig structures, existing regulations for yachts include the Nordic Boat Standard, reported by Larsson et al. (2022), and the guidelines for the design and construction of large modern yacht rigs by DNV-GL (2016), with most of the present research has been focused on rig loads for larger vessels.

The right way to define quantitatively the dynamic loads on a scientific base passes through the seakeeping analysis of the sailing boat under study. An interesting measurement campaign on mast acceleration values is reported in Boote et al. (2021) where two large sailing yachts were instrumented with accelerometers at the mast center of gravity during the transfer voyage from Cape Town and Genoa.

Not many papers are available about hull structure scantling of sailing yachts based on the global rig loads. One of particular interest is Ocera et al. (2017) where the authors present a simplified analytical method to evaluate the longitudinal strength of large sailing yachts taking into consideration the dock tuning load which is, for sailing yachts, of the same order of magnitude of still water and wave bending moment. The core of the method consists of the approximation of the longitudinal distribution of hull cross-section momentum of inertia by calculating cross-section geometrical properties of only 5 transversal frames, equally distributed at the stern and bow zones, at 25%, 50% and 75% of the overall length. The obtained results have then been validated by FE calculations carried out on three different case studies on which dock tuning loads, provided by the shipyard, have been applied to the numerical model.

A numerical method for the structural assessment of tall ship rigs is presented in Vergassola et al. (2023). It allows investigating complex rig layouts of large sailing vessel, composed of different types of masts (armed with both square and Lateen sails), yards, stays and spreaders. For these types of vessels, Classification Societies do not provide any direct calculation approaches, but only a mere comparison between cross sections and thicknesses with reference values as a function of the mast length. The provided approach can overcome this lack and it is based on considerations and calculations of real aerodynamic forces and the experimental evaluation of the pretension load of stays and shrouds. The herein proposed approach is very practical and can be adopted as a reference for this type of vessel, also with different mast configurations.

High performance sailing yachts are generally designed and built to a minimum weight objective often using very advanced composite materials such as pre-preg carbon fibers reinforcements not only for the hull but also for 'non structural' components, such as inner outfit and furniture. Vergassola et al. (2019b) carried out a study to verify at which level these components can be considered contributing to the hull local and global strength. Two different FE models of a 94 ft. sailing yacht, with and without 'non structural components', have been carried out in order to evaluate their contribution to the primary hull response to longitudinal bending moment and dock tuning load.

Most recently, namely since 2020, rig loads and rig attachments are also the subject of ISO 12215-10:2020 (ISO 2020b) for small crafts, building on the knowledge acquired from larger vessels. It is also anticipated these sailing yacht regulations may inform further development in regulatory structural arrangements for wind assisted ships. However, these may need to account for the greater righting moment achieved by hydrofoiling vessels (Souppez et al. 2019a), and the latest advances in sailing yacht aerodynamics that yield an increase in performance (Souppez et al. 2019b, Souppez and Viola 2024).

4.3 Conclusions

Recent advances in small pleasure crafts and their associated structural regulations have focused on composite materials, global loads for multihulls, and sailing specific areas such as appendages and rigs. These latter aspects are forecasted to develop further, owing respectively to the greater use of hydrofoils and the rise in wind assisted ships. As such, these developments contribute to the design and manufacturing of lower emission vessels, as part of a global effort to decarbonise the maritime industry.

5 Naval Vessels

Structural design methods for naval vessels including uncertainties in modeling techniques, including the blast loading, vulnerability analysis and specialised naval structures have been reported in Dow et al. (2015). Truelock et al. (2018) discussed the types of naval ships, naval rules, standards and state of the art of naval craft. The Committee evidenced that the ultimate purpose of naval craft "to deliver ordinance on target" distinguishes their design requirement and objectives from other (profit-driven) ships. In the previous report 2022, the Committee recommended focusing on digital twins and naval Unmanned Surface Vessels (USVs), which are expected to see significant development in the near future. Digital twins are another trend that will be applied across several sectors, even though most of the resources are currently focused on naval platforms.

5.1 Digital Twins

Digital Twins are virtual model of an intended or actual real-world physical product, system to process that serves as a digital counterpart of it for purposes such as simulation, integration, testing, monitoring and maintenance. (https://en.wikipedia.org/wiki/Digital_twin)

Starting from the definition of digital twins, Committee members discussed and agreed that it is a design method but still the importance and impact on the design and development of new machine learning tools, should the mention.

An example of a structural digital twin in naval vessels is the work carried out in the reference (Hageman and Thompson 2022) where real stress measurements of the "physical object" and simulation are correlated. They compared two methods: one using the ship as a wave buoy (SAWB) with motion data, which aligned well with strain measurements in high sea states but overestimated stress in mild conditions; the other using Hindcast data, which provided acceptable accuracy for fatigue accumulation in general but underpredicted it during higher sea states, leading to significant deviations. Another example is the work of Fujikubo et al. (2024) where the digital twin for ship structures aims to grasp the stress responses over the entire ship structure in waves by data assimilation that merges hull monitoring and numerical simulation. The image below shows an example of the concept of digital twin for structural monitoring (Fig. 16).

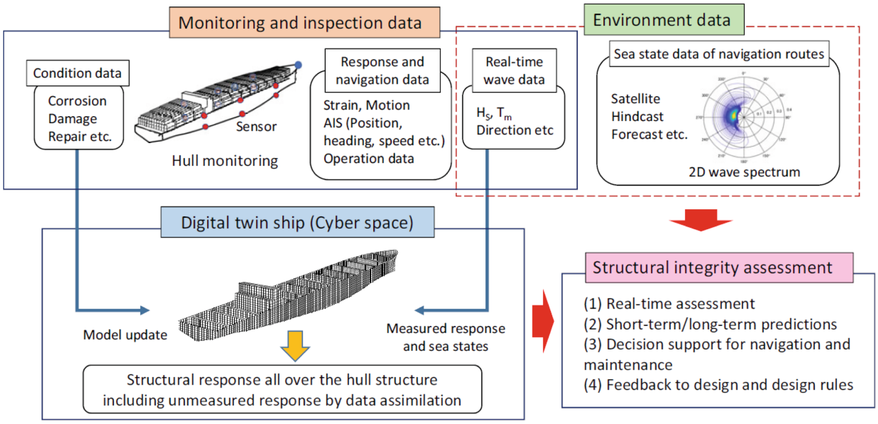


Fig. 16. Concept of digital twin system for ship structure (Fujikubo et al. 2024)

Other examples of structural digital twin are the projects ValiD I, II, III (https://www.marin.nl/en/jips/valid-participants, accessed 15th November 2024.) and FReady (https://www.marin.nl/en/jips/fready, accessed 15th November 2024), where the main goal is to optimize fleet deployment and structural integrity management through a combination of virtual and physical monitoring. The projects' objectives are to improve ship design tools, enhance hull structure monitoring, and develop forecasting techniques for fleet deployment.

The digital twins are becoming precious tools in the design and service of the ships. It is expected that the real time monitoring of ship responses: motions, accelerations, deformation and the comparison against numerical simulation, will further improve the knowledge of the phenomena and improve the definition of structural criteria used in the design such as: yielding, buckling, corrosion, fatigue, structural vibration, slamming, vulnerability, longitudinal and local structural loads, impacts loads, etc.

5.2 Naval Unmanned Surface Vessels (USV)

The first use of unmanned vessels dates back to ancient times, when they were employed as "torch ships." In modern times, they began to be used for military purposes, mainly as targets for testing in 1920. During World War II, they were also used for minesweeper.

Unmanned Surface Vehicles (USVs) represent one of the most recent and exciting developments in naval technology. These vessels, which can operate autonomously or be controlled remotely, have revolutionized the way we think about maritime exploration, ocean research, and other civilian and naval applications.

The primary use of this technology has shifted towards civilian applications, focusing on offshore and environmental domains. This transition has been marked by significant technological advancements, which in recent years have been increasingly integrated into the naval industry. Unmanned Surface Vehicles (USVs) have seen considerable improvements in autonomous navigation, high-precision sensors, and real-time communication systems. These innovations have enhanced operational efficiency and safety, enabling their deployment in various scenarios, from scientific research and environmental monitoring to complex maritime operations. The adaptation of these advanced technologies within the naval sector not only underscores the versatility and potential of USVs but also signifies a broader trend towards the modernization and digitalization of maritime assets Cubides Garzón et al. (2024), Curtolo et al. (2024), Ljulj et al. (2024).

In recent years there has been significant development of military Unmanned Surface Vehicles (USVs). According to Global Data Intelligence, the USV market is projected to grow from $894 million in 2023 to $1.5 billion in 2027, signalling potential advancements in their design (https://www.azom.com/news.aspx?newsID=61616). These USVs can be seen as automated or remotely operated vessels which can be capable of delivering explosives as a single vessel or in swarms making them difficult to counter.

All this suggests that the use of this type of vessel is promising for navies around the world. There are some advantages if we compare to traditional naval vessels:

Pros:

- Minimize risk to human lives.
- Flexibility to adjust the impact zone as it approaches the target.
- Capability to adapt to various types of weapon systems.
- Low cost compared to traditional ship price.
- Mass production in remote non-coastal locations.
- Multi-capability for simultaneous swarm attacks.
- Endurance, as it does not rely on human limitations and can operate in challenging environments.
- Automatic systems allow humans to focus on the target.

Cons:

- Susceptibility to electronic warfare.
- High vulnerability: not designed to withstand threats that a traditional military vessel could endure. Easily neutralized with an increase in specific anti-USV defenses at ports

5.2.1 Naval USV Classified by Sizing

There are different ways of classifying USVs according to their size, the following is the US NAVY's classification based on length (Navalnews 2021) as we define below:

Classification

- Large Unmanned Surface Vehicle (LUSV): Length >50 m
- Medium Unmanned Surface Vehicle (MUSV): 12 m $<$ Length $<$ 50 m
- Small (SUSV): 7 m $<$ Length $<$ 12 m
- Very Small (VSUSV): Length $<$ 7 m

5.2.2 Naval USV Classified by Missions Types

Naval USV's can in turn be classified according to their mission, some of them are listed below (Navalnews (2021), Boretti (2024), Galway (2008)):

- Mine hunting:
- Mine Sweep
- Mine Neutralization
- Electronic Warfare (EW)
- Mine CounterMeasures (MCM)
- SUrfase Warfare Mission (SUW)
- Antisubmarine Surface Warfare (ASW)
- Anti Surface Warfare (ASUW)
- Logistics, Refueling
- Armed Escort
- Communication Relay
- Counter Piracy
- Intelligence, Surveillance and Reconnaissance (ISR)
- Patrol
- Defence
- Cyberwarfare
- Radar coverage

5.2.3 Naval USV Data Base

In Table 2, a list of Naval USV currently in service or under design pending completion is reported:

Table 2. List of Naval USV's currently in service or under design pending completion

Name/ID	Manufactured/designer	Manufactured Country	Sizing type	Reference Link
Seagull	Elbit systems	Israel	SUSV	https://elbitsystems.com/products/uas/unmanned-surface-vehicle/

(*continued*)

Table 2. (*continued*)

Name/ID	Manufactured/designer	Manufactured Country	Sizing type	Reference Link
Sea Hunter	RAFAEL	United States	MUSV	https://navyrecognition.com/index.php/naval-news/naval-news-archive/2023/september/13558-dsei-2023-leidos-displays-sea-hunter-usv-unmanned-surface-vehicle.html#:~:text=The%20Sea%20Hunter%20is%20an,speeds%20up%20to%2027%20knots.
Sea Baby	Security service of Ukraine (SBU)	Ukraine	VSUSV	https://defenceredefined.com.cy/ukraine-sea-baby-magura-mamai-and%CE%B25-hydra/
MAMAI	Security service of Ukraine (SBU)	Ukraine	VSUSV	https://defenceredefined.com.cy/ukraine-sea-baby-magura-mamai-and%CE%B25-hydra/
B5 Hydra	Security service of Ukraine (SBU)	Ukraine	VSUSV	https://defenceredefined.com.cy/ukraine-sea-baby-magura-mamai-and%CE%B25-hydra/
ALBATROS-T & K	ASELSAN	Turkey	SUSV	https://en.wikipedia.org/wiki/Aselsan

(*continued*)

Table 2. (*continued*)

Name/ID	Manufactured/designer	Manufactured Country	Sizing type	Reference Link
ULAQ	ARES shipyard & Meteksan defence of Turkey	Turkey	SUSV	https://www.ulaq.global/
The Protector	RAFAEL	Israel	SUSV	https://www.mindef.gov.sg/home
Inspector 90	ECA Group	France	SUSV	https://www.ecagroup.com/en/solutions/unmanned-surface-vehicle-inspector-90
Spartan Scout 7 m	US Naval Undersea Warfare Center, Radix Marine, Northrop Grumman & Raytheon	United States	VSUSV	https://www.globalsecurity.org/military/systems/ship/spartan-scout.htm
Spartan Scout 11 m	US Naval Undersea Warfare Center, Radix Marine, Northrop Grumman & Raytheon	United States	SUSV	https://www.globalsecurity.org/military/systems/ship/spartan-scout.htm
MAST	ASV Limited	United Kingdom	SUSV	http://www.navaldrones.com/MAST.html
MAST-13 (MadFox)	L3 Harris	United Kingdom	MUSV	https://www.bairdmaritime.com/work-boat-world/maritime-security-world/unmanned-systems/vessel-review-madfox-usv-designed-for-surveillance-and-force-protection-missions/
SALVO USV	DEARSAN	Turkey	MUSV	https://marinejetpower.com/references/dearsan-usv-salvo/

(*continued*)

Table 2. (*continued*)

Name/ID	Manufactured/designer	Manufactured Country	Sizing type	Reference Link
SANCAR	HAVELSAN & Yonca-Onuk shipyard	Turkey	MUSV	https://www.janes.com/defence-news/news-detail/lima-2023-turkish-navy-to-receive-first-two-usvs-during-2023
MIR	ASELSAN	Turkey	MUSV	https://wwwcdn.aselsan.com/api/file/MIR_ENG.pdf
Marlin	Sefine and TAIS shipyards & Aselsan	Turkey	MUSV	https://www.taisshipyards.com/en/usv-15-unmanned-surface-vehicle-marlin
RNMB Hebe (Catamaran)	L3 Harris	United Kingdom	MUSV	https://www.royalnavy.mod.uk/news-and-latest-activity/news/2021/june/21/210621-final-autonomous-minehunter-delivered
ARCIMS (Catamaran)		United Kingdom	SUSV	https://www.atlas-elektronik.com/solutions/mine-warfare-systems/arcims.html

(*continued*)

Table 2. (*continued*)

Name/ID	Manufactured/designer	Manufactured Country	Sizing type	Reference Link
RNMB Apollo	Thales	United Kingdom	SUSV	https://www.thalesgroup.com/en/worldwide/defence/press_release/thales-uncrewed-surface-vessel-passes-significant-milestone
Katana USV	Israel Aerospace Industries	Israel	SUSV	https://www.iai.co.il/sites/default/files/2023-03/KATANA%20%D7%97%D7%96%D7%99%D7%AA%20%D7%92%D7%91.pdf
Eclipse USV	AI Seer Marine & 5G International	United States	SUSV	http://www.navaldrones.com/Eclipse.html
Textron CUSV	Textron systems	United States	SUSV	https://www.textronsystems.com/sites/default/files/_documents/003_SEA_SYSTEMS_CUSV%20Datasheet_2022_DIGITAL_SINGLE.pdf
DEVIL RAY T38	MARTAC	United States	SUSV	https://martacsystems.com/products/t38/
DEVIL RAY T24	MARTAC	United States	SUSV	https://martacsystems.com/products/t24/

(*continued*)

Table 2. (*continued*)

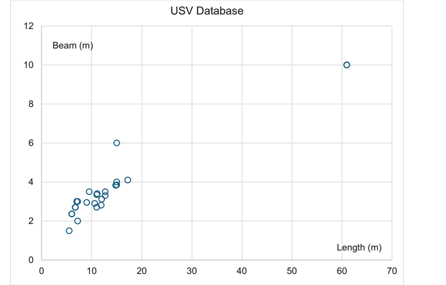
Name/ID	Manufactured/designer	Manufactured Country	Sizing type	Reference Link
Magura V5	Special Techno Export	Ukraine	VSUSV	https://www.navalnews.com/event-news/dsei-2023/2023/09/ukraines-magura-v5-usv-on-the-stage-at-dsei-2023/
Okham	Kayaci Defence	Turkey	SUSV	https://www.navalnews.com/event-news/dimdex-2024/2024/03/new-turkish-usv-breaks-cover-at-dimdex-2024-okhan/
Kaluga DS	Utek, Leonardo Hispania & Miltech	Spain	VSUSV	https://utek.es/kaluga_ds/
Kunai	Utek	Spain	VSUSV	https://utek.es/wp-content/uploads/2023/08/Utek_Ficha-de-producto_Kunai.pdf
OUSV 1 Ranger	Austal USA	United States	LUSV	https://www.naval-technology.com/projects/ghost-fleet-overlord-unmanned-surface-vessels-usa/
OUSV 2 Nomad	Austal USA	United States	LUSV	https://www.naval-technology.com/projects/ghost-fleet-overlord-unmanned-surface-vessels-usa/

(*continued*)

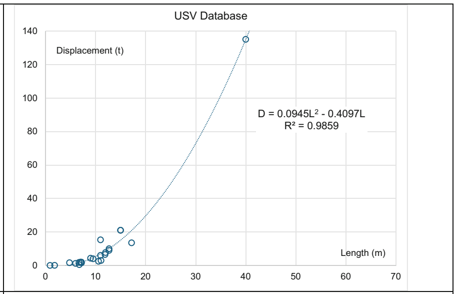
Table 2. (*continued*)

Name/ID	Manufactured/designer	Manufactured Country	Sizing type	Reference Link
OUSV 4 Mariner	Austal USA	United States	LUSV	https://www.naval-technology.com/projects/ghost-fleet-overlord-unmanned-surface-vessels-usa/
ADARO USV	SeaLandAire	United States	VSUSV	https://defence-blog.com/u-s-navy-showcases-new-type-of-unmanned-surface-vessel/
MUSCL USV	SeaLandAire	United States	VSUSV	http://www.navaldrones.com/MUSCL.html
GARC	Maritime Applied Physics Corporation	United States	VSUSV	https://defence-blog.com/us-navy-receives-new-garc-drone-boats/
Suhail USV	Performance Marine & L3Harris	Qatar	SUSV	https://breakingdefense.com/2024/03/qatari-shipbuilder-joins-forces-with-l3harris-debuts-suhail-usv-at-dimdex-2024/
B5 Hydra	Swarmly	Cyprus	VSUSV	https://www.edrmagazine.eu/swarmly-and-leonardo-join-forces-on-the-b5-hydra-armed-usv

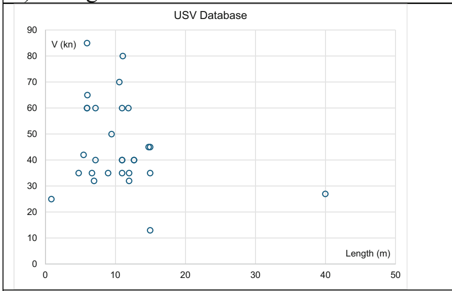
In Fig. 17 the some of principal characteristics of USV database are summarized.



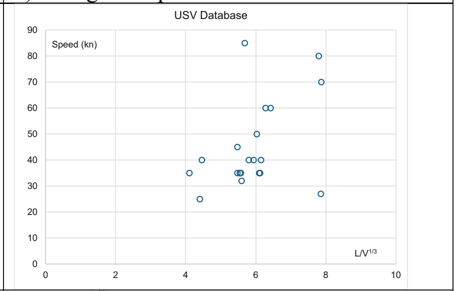
a) Length-Beam of USV vessels database



b) Length-Displacement of USV vessels



c) Length – speed of USV vessels database



d) $L/V^{1/3}$ – Speed of USV vessels database

Fig. 17. Naval USV database summary

5.2.4 Classification Societies Rules for USV

Faced with this new type of ship, classification societies are developing new guidelines, standards, certificates that regulate the design, construction and operation. Below is a summary of the work of the main European and American Classification Societies

BV (Bureau Veritas 2022b) The classification society Bureau Veritas has the standard NR681 "Unmanned Surface Vessel USV", where it refers the ship's scantling to the naval standard NR483 and, in the case of requirements for the construction material to be used and analyzed:

- Steel, defined in rule note NR216
- Aluminum, defined in the rule note NR561
- Composite and/or plywood, defined in rule note NR546

LR (Lloyd's Register 2017) Lloyds Register has a Code for Unmanned Marine Systems that includes a chapter where define in a high level the: goal, functional objectives, and performance requirements.

The code defines the structure shall be designed and constructed to:

(a) *Enable the UMS to operate in all Reasonably Foreseeable Operating Conditions.*
(b) *Carry and respond to all foreseen loads in a predictable manner with a level of integrity commensurate with operational and safety requirements.*
(c) *Meet requirements for watertight, weathertight and fire integrity.*
(d) *Enable the maintenance and repair in accordance with the maintenance philosophy.*

DNV (DNV 2021) DNV has DNVGL-CG-0264 Autonomous and remotely operated ships, which does not contain any structural requirements detailed for USVs.

5.2.5 Structural Challenges Associated with the Naval USV

Reviewing the requirements of the previous classification societies and the structural publications on USVs, the technological challenge of this type of vessels is not in structural, this type of Naval USV does not present a major challenge compared to other vessels of its size, except for some naval structural requirements that should be eliminated or relaxed, such as: fatigue, residual stress analysis, vulnerability, corrosion, etc., as they should not be required in all situations.

5.3 Conclusions

USVs have made a strong appearance in recent years, with relative success in the Ukrainian-Russian war; the technology is still innovative and immature, with many questions as to whether it will replace naval warfare as we know it today. Answers to that question will require some time, as questions remain regarding the new forms of defense systems against them (Boretti, s.f.).

The use of digital twin in naval structures is a new service being evaluated and presents advantages to navigation support, maintenance support, rule improvement, and product value improvement (Fujikubo et al. 2024). In the case of naval USVs, it is a very useful tool to know the structural state and predict the structural state without crew.

Other types of unmanned military vessels include unmanned underwater vehicles (UUVs), which will also play an important role in future conflicts. Examples of UUVs range from small to extra-large, with the ORCA from the US Navy representing a significant extra-large UUVs (https://www.twz.com/orca-drone-submarine-delivered-to-navy, accessed 15/02/2024), (https://www.navsea.navy.mil/Media/News/Article-View/Article/3623016/us-navy-accepts-delivery-of-first-extra-large-unmanned-undersea-vehicle-test-as/, accessed 15/02/2024).

It is evident that navies globally will be exploring and developing various naval USV options over the coming decade.

6 Work Boats

During the last two mandates Committee analyzed the offshore operation vessels – according to their types and particular purpose (i.e. heavy lift, self-elevating vessels, subsea drilling, floatover installation vessels, walk to work vessels, etc.) and their structural challenges have been discussed. In this mandate, the Committee wanted to bring to the attention challenges related to fishing vessels and river and river/sea vessels. Design and hull forms of both types are strongly influenced by the local tradition, operating on relatively short range and often are old fleets with important structural and safety problems. Committee members observed an interest of the scientific community in these two categories and even though they are not "work boats" in the same manner as offshore operation vessels, they have been categorized here according to their specific (special) purpose. Finally according to the recommendations of the last mandate, the offshore service vessels used for floating offshore wind farm

6.1 Fishing Vessels

Recent research and developments in the fishing vessel sector are scattered among various aspects of the industry and naval architecture. The fishing industry is a prominent sector providing livelihood to billions of people across the globe and therefore the global fishing vessel market is estimated to significantly grow in near future. The topics of recent publications include risk-based maintenance methodology for fishing vessels, accident analysis, and improving hull strength using new materials and designs. New areas of research include implementing an extended emission index for energy efficiency, alternative powering options for fishing vessels, and the potential of lithium iron phosphate batteries for electrification. The integration of fully electrified fishing vessels remains as an area of future expansion as research into electric energy systems and cost reduction strategies for fishing vessel production continues to grow.

Domeh et al. (2022) presented a Risk-Based Maintenance (RBM) methodology to develop a maintenance plan for fishing vessels, to handle machinery faults, resulting in the main propulsion system (MPS) failure. The study used a new method, the "Goal-directed risk identification technique (Goal-DRIT)", to define the risk factors employed in developing the so called "MPS OOBN (Main Propulsion System Object-Oriented Bayesian network) model". The RBM methodology has been benchmarked against publicly available literature and has been shown to yield a 24.78% savings in the budgeted maintenance cost, using a fishing vessel operating in Ghana as a case study. The methodology and proposed models are recommended to the commercial fishing industry, chief engineers, and superintendents of marine vessels to aid their maintenance program design needs. Uğurlu et al. (2020) used Bayesian network, chi-square method to analyze accidents occurring between 2008 and 2018 in fishing vessels, with full lengths of 7 m and above. These networks allow to understand the occurrence of accidents in fishing vessels and to estimate the occurrence of accidents in variable conditions. It was also found that there was a significant relationship between accident category and vessel length, vessel age, loss of life and loss of vessel. Santiago Caamaño et al. (2019) employed statistical methods to consider real-time stability changes in fishing vessels. Following this Santiago Caamaño et al. (2023) proposed a combination of Empirical Mode Decomposition with the Hilbert-Huang Transform as a means of aiding a real-time stability monitoring system for fishing vessels. Rosano et al. (2023) described the development and testing of an on-board system that monitors lateral accelerations on ships, specifically a mid-sized Galician fishing vessel. The system estimates short-term extreme acceleration values and was validated using simulations and experimental data. The effectiveness of the system is verified for combinations of sea states through numerical simulations and experimental data. In all considered cases, the application of the decision support system has confirmed its capability to discriminate between safe and unsafe conditions.

Santoso and Nasution (2021) analyzed the strength of fishing vessels with composite bow by means of the finite element method in case of collision induced loads. Similarly, Windyandari et al. (2022) analyzed bow structure damage of a hybrid material combination of a coir-glass fiber composite fishing boat hull subjected to front collision load. A numerical simulation model was applied to the traditional fishing boat colliding with the fishery harbor quay wall, and the scenario was defined by varying the boat speed and the types of laminates adopted on the hull structure.

In a study conducted by Choiron (2023), a collision model for fishing vessels was developed to simulate collisions with an impactor in the form of a mooring pole during extreme weather conditions, featuring a wave height of 6 m and wind speeds 30 knots. The simulation model considered variations in ship velocity, frame spacing and weather conditions, to determine differences in structural deformation, energy absorption, and plasticity due to collisions.

Burella and Moro (2021) focused on developing noise control interventions to reduce noise-induced fatigue on small fishing vessels, rather than just addressing hearing loss risks. Using Statistical Energy Analysis (SEA), experimental measurements, and graph theory, the research analyzes noise transmission paths and the contributions of airborne and structure-borne sources on a Newfoundland and Labrador fishing vessel. The study identifies practical, cost-effective solutions to mitigate onboard noise, which could be applied to similar vessels in the region.

Helal et al. (2024) evaluated the underwater radiated noise emitted by a typical fishing vessel in Atlantic Canada to identify key noise sources and their contributions. Using hydrophones and a numerical model, the study found that over 70% of noise at lower frequencies (63 and 250 Hz) and 40% above 1 kHz was due to the diesel engine and propeller. The findings aim to inform future fishing vessel designs to reduce noise impacts on the marine ecosystem.

Recent research efforts in the field of fishing vessels have primarily focused on improving their energy efficiency and environmental friendliness. As part of this work, Koričan et al. (2023a) formulated the extended emission index (EEI) for fishing vessels, similar to the Energy Efficiency Design Index (EEDI) for merchant ships, which includes the carbon footprint in the numerator and the amount of landed fish in the denominator. However, the authors emphasize the necessity for further improvements since benefit for the society is significantly different for various fishing vessel types (i.e. purse seiners versus trawlers), while numerator values are directly dependent on the power system itself. In this sense, it is important to mention studies of Koričan et al. (2022) and Perčić et al. (2023) who analyzed alternative powering options for trawlers and purse seiners, respectively. According to these studies, electrification is recognized as a promising decarbonization option, but market-based measures are still needed to be competitive to conventional power systems with diesel engines as prime movers.

Within the scope of electrification of fishing vessels, Perčić et al. (2024) performed life-cycle performance and cost assessments of different battery chemistries. The study recognized Lithium Iron Phosphate as the most promising technology, however, the model used in the study ignores safety and specific requirements related to the marine environment covered by classification society requirements. Koričan et al. (2023b) considered the integration of fully electrified fishing vessels into isolated electricity grids of islands. It is confirmed that this holistic approach could enhance both the decarbonization of marine operations and the penetration of renewables into isolated energy systems.

In order to decrease production costs of fishing vessels, which are rather case-specific both in terms of technical and operational characteristics (compared to other vessel types)

Saral and Köse (2023) proposed a dimensionless offset table which can be utilized to ensure the standard production of Black Sea type fishing vessels with consistent quality.

6.1.1 Conclusions

The literature in the field of fishing vessels demonstrates fragmented industry challenges which involve: accident analysis, structural integrity, and energy efficiency, and therefore it seems that a more integrated and standardized approach could accelerate innovation. The push for decarbonization and improved energy efficiency is evident, with the development of metrics such as the Extended Emission Index (EEI) and research into alternative power systems. Electrification, particularly with lithium iron phosphate batteries, has emerged as a promising pathway for decarbonization, though safety and classification requirements need further exploration. Techniques like the Risk-Based Maintenance (RBM) methodology and noise control interventions demonstrate potential to optimize costs and improve safety. Case studies have validated these methods, suggesting broader applicability for the fishing industry. Studies on materials and collision modelling highlight ongoing efforts to improve structural resilience and safety under extreme operating conditions, while innovations in composite materials and numerical simulation methods offer practical solutions for vessel durability and energy absorption. The integration of fully electrified vessels, real-time monitoring systems, and extended emission indices represents good ground for further research.

6.2 Offshore Service Vessels

Europe remains the global leader in offshore wind power, having pioneered the first commercial offshore wind farm in Denmark in 1991. According to the latest data from WindEurope (https://windeurope.org/intelligence-platform/product/latest-wind-energy-data-for-europe-autumn-2024/, accessed 30th November 2024), the total installed capacity of offshore wind farms in European waters had surpassed 35 GW. The United Kingdom continues to boast the largest capacity, approximately 15 GW, followed by Germany (about 9 GW) and the Netherlands (around 4.7 GW). Some of the world's largest offshore wind farms, including the Hornsea Projects, are located off the coast of England. Looking ahead, the European offshore wind project pipeline now exceeds 100 GW, underscoring the strong momentum in this sector. In alignment with the EU's Offshore Renewable Energy Strategy, Europe has set its sights on expanding offshore wind capacity to 54 GW by 2030 and 300 GW by 2050 to support its climate and energy goals.

Offshore installations, compared to their onshore counterparts, have the advantage of being able to exploit greater wind speed, thanks to the absence of natural obstacles, and consequently to produce more power. The placement offshore of big wind farms solves also the problems of visual impact and noise because the towers are located beyond the visible horizon, more than 3 km far from the coast, and also the environmental problems related to the danger posed by the towers for birds, raptors and migratory birds in particular, and bats are much more limited.

In Hong et al. (2024) comprehensive reviews of the installation challenges and opportunities for Floating Offshore Wind Farms (FOWFs) are presented. FOWFs allow wind turbine deployment in deep waters, offering advantages like higher energy yield and reduced environmental impact compared to fixed turbines. However, the installation process is complex, involving high costs, weather-related delays, and the need for specialized vessels and equipment. The review examines different floating foundation types, including spar, semi-submersible, and tension-leg platforms (TLP), each with unique installation requirements. It highlights ongoing research efforts aimed at optimizing the installation process, reducing costs, and improving efficiency through better vessel designs and innovative installation methods. The paper also stresses the importance of strategic planning, robust logistics and maintenance.

The real negative aspect of the installation of offshore wind farms is cost. The turbine represents just one-third to one-half of the costs in offshore projects today, the rest comes from infrastructure, oversight and maintenance being this last one the activity that follows commissioning to ensure the safe and economic running of the project.

Maintenance is, therefore, a fundamental aspect on which it is necessary to work to reduce costs because it accounts for approximately one-quarter of the life-time cost of an offshore wind farm, nominally 20 years, and still, there are no standardised technical and commercial practices. In addition, because future installations will be placed farther and farther away from the coast, it is necessary to identify new logistics solutions.

Maintenance activity is the up-keep and repair of the physical plant and systems. It can be divided into preventative maintenance and corrective maintenance:

- Preventive maintenance consists of checking and replacing components on a scheduled basis in order to preserve the characteristics of the system over time.
- Corrective maintenance includes the reactive repair or replacement of failed or damaged components.

Each offshore wind project has different characteristics which determine the optimal maintenance strategy. The main factors are:

- Distance from onshore facilities;
- Average sea state;
- Number, size and reliability of turbines;
- Offshore substation design.

Among these, the distance from the mainland is the most important aspect. Currently, to access the turbines small work boats equipped for the purpose, usually catamarans (12–24 m) are used, and sometimes it is necessary to use helicopters. Workboats, usually called Wind Farm Supply Vessel (WFSV) are relatively inexpensive and can carry significant numbers of technicians, but response times and accessibility are limited by transit time and sea state. Costa et al. (2017) presented the design and development of the WFSV-PL, a 26-meter hybrid carbon composite catamaran with the main aims of reducing construction costs and time by using carbon composites instead of metal. Key features include high-speed capabilities (up to 30 knots), capacity for 12 technicians, and innovative safety and comfort measures such as shock-mitigated seats and flexible cargo decks. Structural integrity is ensured through laboratory tests on composite materials, and hydrodynamic optimization in calm water by CFD (RANSE) simulations and towing tank tests.

In the fourth edition of TNO (2020), an updated review is provided on commercially available and proven access systems for offshore wind farms. The systems are categorized into three types based on the access point to the wind turbine: (i) access to the boat landing, (ii) access to the platform on the transition piece, and (iii) access to the helicopter hoisting platform located on top of the nacelle. While the traditional method of accessing the boat landing via Crew Transfer Vessels (CTVs) remains widely used, the past decade has seen the emergence of motion-compensated gangways installed on Walk-to-Work (W2W) vessels or specialized Service Operation Vessels (SOVs). This innovation has facilitated the relocation of significant portions of the maintenance base offshore. The analysis in this report highlights that the expansion of this market aligns with the growing demand for safer and more efficient transfer solutions for technicians and equipment to wind turbines.

Kjær et al. (2024) focus on improving roll motion predictions for Wind Turbine Installation Vessels (WTIVs) through Computational Fluid Dynamics (CFD). WTIVs, crucial for offshore wind turbine installations, present unique challenges due to their wide breadth, shallow draught, and high vertical center of gravity. Traditional empirical methods often overestimate roll damping for these vessels, leading to less accurate predictions. This study uses CFD to simulate free roll decay under varying loading conditions and includes experimental model tests for validation. Results show that CFD accurately predicts roll damping, which decreases with higher centers of gravity. Adding bilge keels significantly reduces roll motions.

Ren et al. (2021b) present a study on a novel approach for floating offshore wind turbine (FOWT) installation using a catamaran vessel equipped with an active hydraulic heave compensator (AHC). The turbine's tower, nacelle, hub, and rotor are preassembled onshore and transported to the installation site. The key challenge is minimizing relative motion between the catamaran and the floating spar foundation during the mating process, particularly in harsh sea conditions. A control system is designed using singular perturbation theory to manage the AHC, which compensates for wave-induced heave motions. The goal is to ensure the smooth lowering of the turbine assembly onto the spar, reducing relative velocities and displacement. Numerical simulations, verified in MATLAB/Simulink, demonstrate that the AHC significantly improves operational success by reducing relative displacement and velocity by over 95% and 93%, respectively, in various sea states. The study concludes that the AHC-equipped catamaran enables safer and more efficient installation, expanding the weather window for FOWT deployment.

In Li et al. (2022b) the authors evaluates the suitability of SWATH vessels for walk-to-work (W2W) operations in offshore wind farms, comparing their performance to traditional monohull vessels in terms of motion behavior, fuel efficiency, and operational limits. SWATH vessels showed consistent high operability across wave headings, especially under transversal and longitudinal transfer methods. Monohull vessels performed well under head seas but had significant operability declines in beam and quartering seas due to larger sway and roll motions. Optimization of SWATH geometry and the addition of damping mechanisms could further enhance performance.

A study addresses the challenges associated with launching and recovering Remotely Operated Vehicles (ROVs) from small Offshore Service Vessels (OSVs) using a Single Point Mooring System (SPMS) has been carried out by Deng et al. (2021). The research focuses on managing wire tension, specifically snap loads, which occur when ROVs pass through the wave zone during deployment. The paper presents a numerical model validated by experimental results and provides new strategies for safer and more efficient ROV operations.

Service Operation Vessels (SOVs) are critical to the efficient maintenance of offshore wind farms, particularly those located far from shore. SOVs are equipped to carry technicians, tools, and spare parts for prolonged offshore missions, reducing downtime caused by weather or logistical delays. Maintenance operations require careful planning, as turbine components are exposed to varying weather conditions, impacting their reliability. Weather forecasts and failure probabilities are factored into planning to optimize repair kits—a selection of spare parts tailored to the expected needs of each maintenance trip. Neves-Moreira (2021) proposes a tactical model to define the optimal composition of repair kits and an operational model to validate these kits in real scenarios. These models consider constraints like vessel capacity, repair demands, and emergency resupply capabilities. An SOV's ability to stay offshore for weeks, combined with helicopter-assisted resupply, helps address unexpected failures efficiently. Simulated scenarios demonstrated the importance of adjusting repair kits based on weather forecasts, reducing downtime and maintenance costs. A decomposition approach was introduced to simplify complex planning problems, improving decision-making for large-scale wind farms. The findings offer practical insights for optimizing SOV operations and advancing offshore wind farm maintenance logistics.

Lazakis & Khan (2021) develop a novel optimization framework designed for daily route planning and scheduling of maintenance vessel activities in offshore wind farms to reduce costs, minimize fuel consumption, and maximize wind farm availability. The framework incorporates heuristic optimization and clustering techniques, considering climate data, vessel specifications, turbine failure types, and operational constraints such as weather conditions and technician requirements. By dividing tasks into sequential sessions (drop-off and pick-up), "OptiRoute", the name the authors gave to this tool, optimizes routes for both SOVs and CTVs while integrating fuel efficiency calculations. A graphical user interface (GUI) enabling real-time visualization and planning is provided as well. Case studies validate OptiRoute's effectiveness, showing reduced maintenance times, fuel costs, and improved resource allocation. The study concludes by highlighting OptiRoute's potential for practical deployment and suggests further exploration into integrating long-term maintenance planning.

The study carried out by Tusar & Sarker (2023) develops an integer programming model addressing the multi-source and multi-destination (MSMD) nature of vessel routing and technician allocation, considering vessel types, capacity, cost, and operational constraints. A case study, involving 60 turbines divided into clusters, demonstrated the model's ability to select cost-minimizing fleet configurations. Using commercial optimization tools like IBM ILOG CPLEX, the model proved effective for short-term planning. Managerial insights include prioritizing large vessels for strategic investment and integrating small vessels to optimize costs in favorable conditions. Most significant findings result to be that larger vessels improve maintenance efficiency by reducing travel and downtime costs, a mix of large vessels and smaller crew transfer vessels (CTVs) enhances cost-effectiveness, especially under favorable weather. The optimal fleet configuration depends on vessel capacities, technician demands, and operational constraints such as weather windows and maintenance schedules.

6.2.1 Conclusions

Future projects involve the installation of wind farms at increasing distances from land. To reduce transit times, it will be necessary to use offshore bases, on which the technicians will live for a period of time, usually two weeks, and will then be transported on turbines using vehicles with sea-keeping characteristics better than the current ones. The base itself may be either fixed accommodation modules, similar to those used in the oil and gas sector, jack up or offshore support vessel boats with the function of 'MotherShips' the so-called WFMS. The optimization of the fleet size, and introduction of the autonomous ships are seen as possible pathways to reduce operation and maintenance costs.

6.3 River and River-Sea Vessels

A substantial portion of river-sea vessels, which are river vessels capable of marine operations due to class restrictions, often undertakes extensive operations within marine environments. The safety of river-sea vessel operations within marine environments is facilitated by imposing restrictions based on: region, season, distance to safe harbor, and wind and wave conditions. The presence of these restrictions allows for a substantial reduction in the cost of river-sea vessel construction and is primarily achieved by lowering requirements for longitudinal and local strength, sea-keeping qualities, characteristics of equipment and gear and main engine power. Consequently, river-sea vessels feature enhanced cargo capacity at fixed draft depths at the expense of lightship weight and an increased block coefficient when compared to traditional sea vessels (Kang et al. (2024)).

However, after 5–7 years of normal operation, there is a genuine risk of fatigue damage for the most heavily loaded structural components such as longitudinal strength members, decks, and sheer strakes. Additionally, there is a possibility of water leakages in the outer shell, and inner bottom.

Typical damages to river-sea vessel hulls can be attributed to technological and constructive deficiencies that occur during the design, construction, and vessel modernization stages. These defects are aggravated by operations in exceeding limit sailing areas.

6.3.1 Structural Challenges Associated with the River and River-Sea Vessels

Analysis of the operation of these vessel types enabled the identification of factors that exert the greatest influence on risk levels throughout their entire lifetime (Nilva (2020), Pei et al. (2020), Motok et al. (2022)). Due to reduced strength standards, river and river-sea vessels possess lower strength reserves than their analogous, unrestricted counterparts. Consequently, factors contributing to overdesign for still water and wave loadings can lead to severe consequences for these vessels' hulls, due to the amplified ramifications due to these hazards.

River and river-sea vessels operate in challenging conditions characterized by shallow water and frequent lock operations during the summer and ice-covered conditions in winter. These conditions exacerbate the severity of the relevant danger by diminishing the hull's strength capacity due to the accumulation of deformation and abrasion of the shell plating. For example, a Danube river barge passes through the locks about 250 times a year during normal operations; self-propelled vessel passes the locks 300 times a year (Radojcic et al. 2022). In a typical year, with normal operational intensity, barges complete 14 voyages along the entire Danube-Main-Rhine (DMR) system, resulting in approximately 1,100 lock passages annually. Conversely, a self-propelled vessels, complete 18 voyages annually, and navigate through locks approximately 1,500 times per year. The significance of these hazards and their consequences is clear: the contact between the vessel and lock or canal walls contributes to additional scuffing of shell plating, specifically the sheer and bilge strakes. Additionally, strake stiffeners may experience deformation, with fore end members being particularly vulnerable.

Another notable characteristic is that European river vessels typically operate within shallow waterways of densely populated and developed river systems within countries with stringent environmental regulations and influential environmental organizations Economic Commission for Europe (ECE 2017–2023). As a result, grounding events occur more frequently than in other basins for river vessels within the DMR system. The hazards caused by the waterway conditions are expressed in different ways, both directly and indirectly. Direct hazards are the primary cause of emergencies, such as hull breakage, which occurs due to contact with lock and canal walls, or grounding incidents. Meanwhile, indirect hazards encompass the accumulation of damages to the bottom, bilge, or sides of the vessel, leading to a significant reduction in hull capacity. This accumulation of damage can subsequently initiate hull breakage in other situations, such as during cargo or repair operations.

The utilization of floating cranes, which are extensively used in port road transshipment complexes, can inadvertently lead to damage to the side constructions of river and river-sea vessels during boom turns, wave-induced swinging, or when navigating in close-quarters. This situation can be particularly hazardous at the onset of loading or the conclusion of unloading, as the low-depth hull of the floating crane, equipped with ample fender protection, may come into contact with the barge's unprotected side shell plating.

Comparable damages to side constructions, such as sheer and bilge strakes, can also occur when a vessel contacts the walls of locks and canals.

A relatively high share of technical faults in analyzed accidents both in Austria (where technical faults were the second most frequent cause of all accidents) and in Serbia (where technical faults, together with operational causes, were the most frequent cause of accidents) indicates that the technical reliability of vessels should be improved even if the present level of manning is maintained. The first step towards this would be certainly a thorough examination and revision of the current requirements for systems and equipment contained in technical standards for European inland cargo vessels Bačkalov et al. (2023).

An extensive analysis of repair documents, cargo operation books, and logbooks for over 140 vessels with a considerable operational history enabled the identification of typical defects and damages affecting their hulls. This analysis, in turn, facilitated the determination of the primary sources of hull damage for river and river-sea vessels. Typical hull damages for a classic river barge of the "Europe-2B" type (ECE 2020) are shown in Fig. 18.

Most hull breakages occur during cargo loading and unloading procedures, as the absence of waves results in an unchecked and potentially dangerous surge in the bending moment.

By simulating various loading and unloading scenarios for dry-cargo river barges vessels, the following configurations shown in Fig. 19 have been found to be crucial in maintaining vessel strength during cargo operations.

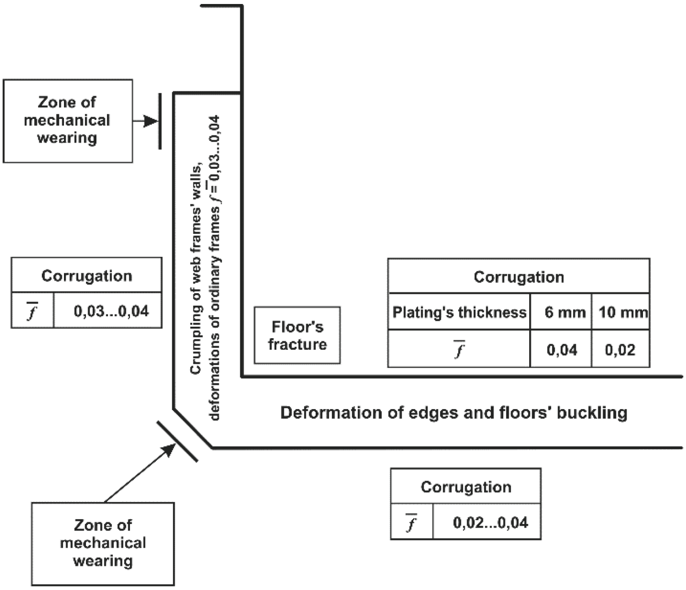


Fig. 18. Hull's damages of barge type "Europe-2B". $\bar{f}$ – relative deflection

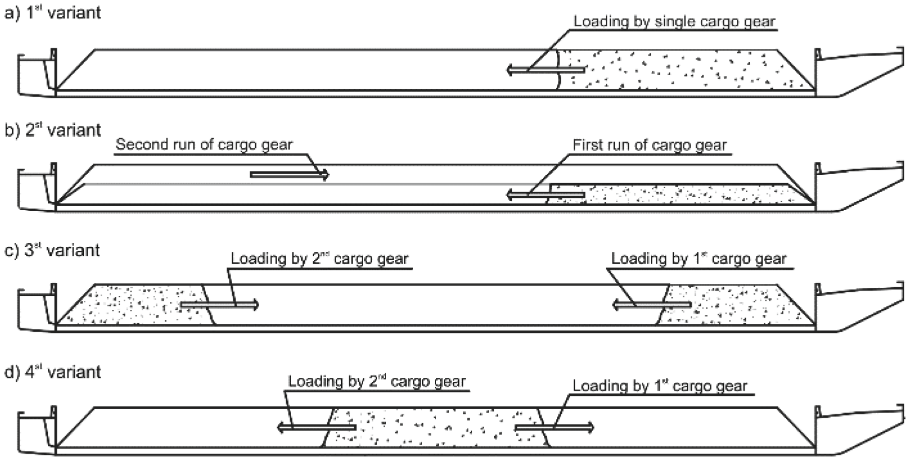


Fig. 19. Variants of cargo operations

The first and second variants are cases of “regulated” or “controlled” cargo operations. Namely such variants are typical for Loading Manuals (LM) and for typical calculations of hull’s strength for the existing river and river-sea vessels. The third and fourth variants are the most dangerous cases of “uncontrolled” organization of cargo operations as the loading variant from the ends to the midship (the third variant) leads to the maximal possible hogging of the hull, and the loading variant from the midship to the ends (the fourth variant) leads to the maximum possible sagging condition. Of course, such violations may look somewhat artificial, but exactly such schemes give the maximal deviation in comparison with regulated operations (13–48%).

An overwhelming majority of river and river-sea hull breaches (particularly within the DMR system, where significant waves are absent) result from buckling failures of the compressed strake of the hull girder. This phenomenon is undoubtedly linked with the extensive utilization of transverse framing systems in European river shipbuilding.

Quantitative and qualitative enhancement of the longitudinal strength standard can be achieved through the following measures to mitigate the listed hazards:

- increasing of thickness and sizes of hull members, i.e. increasing the total of steel weight;
- modifying the load calculation method for longitudinal bending, considering additional designed wave and impact bending moments for specific vessel classes; monitoring load non-linearity and flooding; conducting longitudinal strength checks during cargo operations based on Loading Manual (LM) intermediate cases; carrying out longitudinal strength checks during trim changes for screw survey, potentially leading to enlarged member sizes;
- changing of the method of longitudinal strength calculation due to safety factor increase; checking of the strength for hull by the end of lifetime taking into account wearing and deformations that may also lead to an increase of members’ sizes;
- changing of the transverse framing system of the hull girder extreme strakes to a longitudinal system;

- enhancing the buckling strength of longitudinal members within the longitudinal framing system by decreasing frame spacing and raising the cross-sectional inertia moment of these members.

Replacing the transverse framing system with a longitudinal one for the “Europe-2B” type barge resulted in a 43% increase in ultimate bending moment capacity in the sagging condition, with minimal metal consumption increase (+2.5 t). This decision enabled the attainment of equal hull strength for both hogging and sagging. This principle is crucial for river vessels, as still water bending moments during cargo operations represent the primary loading and principal hazard (Pei et al. (2020), Motok et al. (2022)).

Reliability based methods was used in analysis of the still water bending moments for more than 400 load cases of 37 prominent river-sea tankers. It is found that if some load case like 3 full after cargo tank or cargo operation procedure like one-run procedure is prohibited, the possibility of still water bending moment exceedance than the rule value will be decreased greatly (Motok et al. (2022)).

Reliability-based design optimization was also used for cargo hold structure design of a river-sea going container ship which sails in the Yangtze River and the East China E1 navigation route. The weight is reduced about 3.2%, and the value of failure probability is $10^{-7.3}$ which meets the requirement of 25 years design life. Compared to it the deterministic optimization design could reduce more weight which is about 5.1%, yet its failure probability is 0.00827 which is much lower than the 25 years design life requirement. The bilge plate, side plate, inner side plate and almost all the longitudinal scantlings are bigger by reliability-based optimization design than deterministic optimization design (Kang et al. 2024).

6.3.2 Conclusions

A systematic approach should be implemented throughout the entire vessel lifecycle encompassing classification phases, adhering to rules and requirements, designing, construction, operation, surveys, repairs, and modernization. A tailored strategy should be adopted for existing river and river-sea vessels, considering aspects such as operational conditions, transported cargoes, loading-unloading methods, waterway and port limitations based on overall vessel dimensions, and ice conditions.

New vessel construction should introduce superior quality standards for all components, including double bottom and double sides, increased hull strength reserves, thicker hull elements, more robust and dependable engines and mechanisms, modern automation and control systems, including construction and equipment redundancies

7 Ice Vessels

7.1 Introduction – Concepts and Challenges

This report is a continuation of the previous ISSC2022 report, which focused primarily on structural design, with an emphasis on the structural response based on full-scale measurements. This report expands on structural design under ice load, presenting relevant new results. The report first describes the measured structural response under ice load, which does not involve any new measurement methodology but is a crucial part of understanding the ice load mechanism in structural design. Next, the report discusses ice load evaluation, which includes ice material properties, ice load (pressure) acting on the structural component, and the structural response. These components are essential to understanding the principles of ice load. Finally, the report introduces several new topics related to ice vessels and offshore structures in ice-infested waters.

7.2 Ice Load Measurement on Vessels

Ice loading is commonly estimated using structural response data obtained from full-scale measurements in the field and model tests conducted in controlled environments. The measured structural response provides valuable information that helps us understand the transfer mechanism of ice loading during ship-ice interactions. However, there are several challenges associated with obtaining full-scale ice load measurements in the field due to the difficulties in measuring the load and the rapidly changing sea ice conditions caused by global warming. The lack of measured data is the main problem in estimating the ice loads. As an alternative to full-scale measurements, laboratory tests can be conducted to obtain data. However, these tests also present their own set of challenges. Controlling the model ice in an ice tank can be difficult, which can also create gaps in available data sets.

7.2.1 Full-Scale Measurement

Ice loads are transmitted to a ship's hull through the collision between sea ice and the vessel. When the ice pressure distribution on the hull at the collision area can be directly measured, the structural response to under the ice load can be accurately calculated. However, direct measurement of ice load using a spatial panel has difficulties in terms of spatial and temporal resolution. Therefore, a measurement system that captures the shear stress on the hull frames transferred from the ice pressure on the shell plating remains in use. Li et al. (2021a, b) analyzed full-scale data obtained from the Antarctic voyage of the Polar Supply and Research Vessels (PSRV) S.A. Agulhas II during 2018/19. Due to the lack of publicly available full-scale data covering ship performance and ice loads for various ice thicknesses, concentrations, and floe sizes, the datasets include ship navigation data, machinery data, local ice load measurements, and ice condition data, such as ice thickness, ice concentration, and ice flow size. Statistical analysis was conducted to seek suitable probability distributions that fit the measured ice loads and can be used as parent distributions for long-term estimation (Li et al. 2021b).

Ice forces converted from shear strains measured on the starboard side at the bow, bow shoulder, and stern shoulder, were utilized for the analysis. Fang Li et al. (2021a) investigated the relationship between local ice load, ship performance, and ice conditions. Suominen et al. (2021) studied the effect of manoeuvres on the characteristics and statistics of ice-induced loading at different hull areas, including the bow, midship, and stern area, using the ice trial data of S.A. Agulhas II in the Baltic Sea. Cho et al. (2021) proposed a new approach to derive an Influence Coefficient Matrix (ICM), which represents the relationship between the measured shear strains and the local ice pressure on the hull plate. The measured strain data obtained from the full-scale trial of the Korean icebreaking research vessel ARAON operating in the Ross Sea, Antarctica, in December 2019, was used for analysis. The new method used in-plane stress components (σ_x, σ_y, and τ_{xy}), taken from the hull data to derive a three-dimensional (F_x, F_y, and F_z) ice load. Oh et al. (2022), Heo et al. (2022), Wang et al. (2023a), and Kong et al. (2021) investigated the influence of missing shear strain data in the ICM. The resolution of the shear strains strongly depends on the accuracy of ICM. Due to the harsh measured conditions, the missing data will be collected occasionally during sailing in polar regions. Oh and Ha (2022) estimated the missing data of strain gauges applied to the hull of ARAON using the artificial neural network deep learning method. Heo (2022) analyzed the measured strain data using signal similarity analysis and proposed a method for reliably estimating ice load even in the case of missing data. Wang et al. (2023b) studied the effect of missing strain data on ice load identification of the ship structure using measured and simulated strain data of the Chinese icebreaker Xue Long 2 and proposed a practical solution to identify the ice load using ICM. Kong (2021) developed an ice load identification model for far-field measurements, where strain gauges were installed on the hull approximately 2 m above the waterline.

The importance of past data cannot be overstated due to the limitations of acquiring sea ice data in the field. In a recent study, Frederking (2021, 2023) reanalyzed previous ice loading data, which were measured during the icebreaking trials of the Research Vessel (R.V.) POLARSTERN in 1984. A direct measurement system was installed at two locations in the bow, where ice forces were measured using special panels. The measured ice forces of the pressure panel were then compared with strain-gauged frames on the R.V. Polarstern and the Canadian Coast Guard icebreaker Louis S. St-Laurent. The results of the comparison revealed significant differences in the nature of ice forces in terms of frequency and duration.

7.2.2 Laboratory Scale Test

Full-scale measurements can be very expensive, and identifying real-sea ice conditions, such as ice thickness, size and shape, and concentration during these measurements is challenging. Therefore, laboratory-scaled experiments have been proposed as an alternative method to understand ice-structure interaction. To date, model-scale tests of ice collision at slow speed (quasi-static) have been primarily conducted. However, due to wave-ice interaction and iceberg collision, ice collision speeds in ship-ice interactions become higher. He et al. (2022) conducted a laboratory-scale ice collision test measuring the dynamic response of a simple stiffened panel subjected to ice loading. An ice load identification model was proposed using the Green's function method and a comparison performed studying the effectiveness of the influence coefficient matrix method and the Green's function method in identifying ice loads, validating the feasibility of the Green's function method. Zhu et al. (2020) investigated the nonlinear elastic-plastic responses of plates impacted by an ice wedge striker and an idealized rigid striker, experimentally and numerically. The ice/steel striking wedge collided with the plate specimen. The plastic deformations, energy absorption of the plate, and energy dissipation of ice damage were investigated. Yu et al. (2023) reported an experimental and numerical study on the behavior of stiffened panels subjected to the impact of a wedge-shaped ice block. A new numerical ice model was proposed that represented the quasi-brittle manner and ice failure, implementing it in commercial software ABAQUS/Explicit. The numerical simulations using the proposed ice model compared well with the ice impact test.

Model scale tests of offshore structures are being conducted with increased frequency. Petry et al. (2022) performed Ice Basin experiments on mixed-mode failure of ice cones in the Aalto Ice and Wave Tank. The experiment aimed to investigate the effects of varying mechanical properties of model ice on the failure process against two types of structures: the cylinder and cone structure. Lemström (2022a, b) conducted model-scale experiments of the ice loading process against a wide, inclined structure in shallow water in the Ice Tank at Aalto. The study primarily investigated the effect of ice strength on the development of ice forces acting on the structure. Despite the advancements in model scale testing, a discrepancy between medium (laboratory) scale tests and full-scale measurements remains in the assessment of both ship structures (dynamic) and offshore structures (quasi-static). This scale problem is primarily caused by using model ice to represent the mechanical properties of sea ice.

7.2.3 Ship Monitoring under Ice Load

Ice load estimation in the field is a task that requires precise data of the ice conditions encountered. Although the estimations of ice thickness from satellite data were proposed, the spatial resolutions of satellite data are insufficient for estimating ice load on a ship's hull. Moreover, the size and features of ice forms, such as individual ice floes, level ice, pack ice, ice ridges, and multi-year ice, cannot be identified by satellite images. Shipboard monitoring can offer valuable data for ice load estimation. Chen et al. (2022) and Zhang et al. (2022b) applied the convolutional neural network method to identify areas of sea ice using sea ice images obtained from an onboard camera during the Antarctic expedition of the Xue Long vessel. Their proposed method demonstrated accurate recognition of the sea ice boundary. Similarly, Dowden et al. (2021) proposed semantic segmentation for automated detection and classification of sea ice types using camera pictures onboard an ice breaker.

In addition, Russia launched a new Ice-Resistant Self-Propelled rifting Platform (IRSPP), called "North Pole," equipped with an Ice Load Monitoring System (ILMS) (Maksimova et al. 2021). The ILMS has two functions: operational function, which ensures the safe operation of the IRSPP in ice conditions, and scientific function, which measures the ice load and the destruction of ice during ice-structure interaction.

Furthermore, Li et al. (2023) proposed using neural networks to increase accuracy of vessels operating in ice-covered waters outfitted with structural health monitoring systems. The neural networks were used to achieve optimal stress-strain prediction of ship structures. A model test was conducted, and nine strain gauges were arranged on the ship hull to monitor stress data. The results showed that the neural network could predict strain in the hull structure when operating in ice-covered waters, reducing prediction time and cost compared with conventional methods.

7.3 Evaluation of Structural Response

The determination of a structural response under ice load is crucial for evaluating ice load during ice-ship interaction, which includes ice strength, ice failure, and ice load (pressure) acting on the hull. The ice load evaluation method has been continually updated. However, research on the evaluation of structural response under ice load is not as widely published, due to the uncertainty surrounding the determination of ice properties and ice load on the hull. Recent studies on the determination of structural response are summarized below.

Structural damage to vessels operating in ice-infested waters poses a significant risk, as the loads involved are large and the interaction between deformable ice, the deformable structure, and water is complex. Experiments designed to investigate these interactions must account for hydrodynamic effects to accurately capture deformation in ship-grillage structures. To assist with this, the National Research Council of Canada, in collaboration with Defense Research and Development Canada and the US Navy, is developing a new facility called the Heavy Impact Test Theater (HITT). This facility will enable full-scale or near full-scale ice/ship-grillage impact experiments in water. In a related study, Gagnon et al. (2023) conducted a numerical simulation of a large, massive impacting object colliding with a massive hybrid ice-structure target, similar to ocean-going vessel collisions with ice masses (Gagnon et al. 2020, 2022).

Choung and Yoon (2022) and Yoon et al. (2023) conducted numerical investigations into the effects of radiation and wave excitation forces acting on the Korean icebreaker ARAON, as well as the structural damage caused by ship-iceberg impacts. Ship collision or ramming with ice floes result in energy absorption by the ship's hull, necessitating the use of suitable ice models for accurate ship-ice interactions. Yu et al. (2021) proposed a numerical solver for the coupled simulation of glacial ice impacts, which accounts for hydrodynamic-ice-structure interactions. The solver includes the BWH (Bressan-Williams-Hill) criterion for steel, a hydrodynamic pressure-dependent plasticity-based material model for constitutive modeling of ice, and liner potential flow theory for hydrodynamic loads. This solver was implemented in LS-DYNA and applied to simulate ice collisions on a semi-submersible platform column. In a separate study, Yoon et al. (2023) simulated the impact of ice blocks on a stiffened palate, utilizing the Mohr-Coulomb mathematical model (Herrnring and Ehlers 2022) for ice modeling, and was also implemented in LS-DYNA. The ice model uses a node splitting technique to preserve mass and energy during spalling and breaking of ice. The results showed that the agreement between experiments and simulations depends on the rotation angle of the ice blocks, which causes a change in the contact condition with the structure.

Mokhtari et al. (2023) conducted a numerical simulation of an aluminum plate subjected to an ice impact load, utilizing a rate and pressure-dependent elastic-plastic model for ice. The proposed ice material model was validated against physical ice-crushing tests, demonstrating a good correlation between experimental and numerical results. Wu et al. (2021) investigated the missing references dynamic response and energy absorption characteristics of aluminum honeycomb sandwich panels (AHSPs) under ice wedge impact, both numerically and experimentally. A three-dimensional nonlinear finite element model of AHSP under ice impact was established based on a concrete constitutive model of ice in the commercial package ANSYS/LS-DYNA. The numerical results of ice wedge-AHSP dynamic impact response was found to be consistent with experimental results. Banik et al. (2021) studied the low-speed impact of ice on CFRP sandwich composites, noting negligible damage with thicker face sheets. Cheemakurthy et al. (2022) investigated lightweight structural concepts in bearing impact load during ice-hull interaction using the dynamic finite element method LS-Dyna parametrically. The results indicated that the candidate structures were metal grillages and carbon-fiber reinforced plastic (CFRP) sandwich panels.

Cai et al. (2020) proposed an ice material model based on a soil and concrete material model. Using the proposed ice model, numerical simulations were conducted to study the dynamic behavior of a plate under ice impact, with results compared to a model test (Zhu et al. 2020), demonstrating the accuracy of the simulations. Cai et al. (2022a) proposed an analytical plastic damage prediction method for a ship plate impacted by an ice floe, combining the rigid-plastic theory method with the energy approach of ice crushing. The analytical results were compared with experimental (Zhu et al. 2020) and numerical (Cai et al. 2020) results. Furthermore, Cai et al. (2022b) studied the dynamic responses of steel plates subjected to repeated ice impacts based on experimental (Zhu et al. 2020) and numerical methods (Cai et al. 2020).

The Unified Polar requirements (UR) that govern the design of ice-class and polar-class vessels utilize a plastic limit state for ship structural design. However, these polar rules do not specify requirements for the connections between rule-defined shell plating and framing and the deeper supporting structure. Gosse et al. (2023) conducted a study using non-linear finite element analysis to examine connection designs on the ice strength of a vessel. The authors analyzed various connection designs between vertical stiffeners and longitudinal stringers in the ice-strengthened region of Polar Class 2 (PC 2) vessels, proposing connection designs that require less steel and welding while maintaining structural strength. Valtonen (2020) proposed a robust and straightforward assessment methodology and acceptance criteria for the practical non-linear analysis required by the IACS Polar Class Rules. The proposed method demonstrated the requirements set for non-linear analysis in the IACS PC Rules.

Shamaei et al. (2020) analyzed the relationship between ice pressure and the local design area using ship line-load data. The full-scale ice load measurements from the Kara Sea, Barents Sea, and Antarctic Ocean were considered. Pressure-area results obtained using the new definition of line load area (new definition of ice load) were compared to those obtained using the conventional local design area definition. The study found a good general agreement between the two methods. Veltheim (2022) used an inverse method to determine ice load magnitude and load patch on a ship hull. The load path and magnitude obtained using the inverse model were compared and agreed well with the full-scale data. Suominen et al. (2023) applied the Empirical Mode Decomposition (EMD) method to separate the noise from ice-induced load time histories measured onboard S.A. Agulhas II in the Baltic Sea. The full-scale data of the structural response (strain) under ice load include noise in the data. As the order of magnitude of the smallest loads and the load level related to intermediate crushing and flaking are at the same level as the noise, the identification of the smallest loads and actual changes in the load level from the measurement signal is necessary. The proposed method demonstrated its good applicability in separating the noise and the actual loading from the time history measurements.

The two main rule sets used in the marine industry are the International Association of Classification Societies (IACS) Polar Class rules and the Finnish Swedish Ice Class Rules (FSICR). Specifically, the lowest Polar Classes (PC7 and PC6) align with the two highest FSICR Ice Classes (IA super and IA). Oldford et al. (2023) examined the structural scantling differences between these ice classes (PC7 and IA) using finite element models of the structure for comparison.

During winter, the Northern Sea Route (NSR) is covered by level ice, necessitating icebreakers to assist LNG carriers in navigating the narrow ice channels. In such scenarios, ship-ice collisions typically occur on the shoulder, which is structurally weaker than the bow. Andryushin et al. (2022) analyzed sea ice forms, ice load, and hull strength during operation in the NSR for large-capacity Arctic vessels. The study presented permissible speeds, ice performance of large-capacity LNG carriers, and recommendations for ice class support vessels.

The use of simulator training for ice navigation provides an inexpensive and low-risk training method for ice-covered conditions. To effectively train individuals for ship operation in such conditions, Miller et al. (2023) developed an Ice-load algorithm that provides real-time feedback during simulator training. The ship-ice collision energy using the Popov energy method, as it was adapted for IACS Polar Class rules, was calculated using a given ice thickness, strength, and contact geometry from the simulator environment. The calculated energy was turned in to rectangular ice pressure. Using finite element analysis with the ice pressure as the input, a safe energy limit was calculated for ship structural of Polar classes (PC1-PC7). The safe collision energy limits were implemented into the simulator training to provide real-time feedback to participants about the safety of ship-ice collisions.

The interaction between ships and sea ice ridges can result in significant ice loads, which present additional challenges to the structural safety of icebreakers operating in polar regions. Sawamura et al. (2023) investigated the structural response of the Japanese icebreaker SHIRASE during its Antarctic voyage, which encountered various ice conditions including level ice, pack ice, ridge ice, and multi-year ice.

7.4 Structural Challenges Associated with Ice Vessels and Offshore Structures

This section introduces new topics, specifically structural challenges, in the Polar region. The interaction between ice and propellers results in thrust reduction and severe damage to the propeller, but this process has not been thoroughly understood due to the complexity of ice-propeller interaction. Recently, there has been a growing focus on fatigue damage in steel structures located in polar regions, particularly in offshore structures with slender bodies, such as wind turbines. This is because the vibration resulting from ice-structure interaction is especially severe in these structures. Additionally, renewable energy is a popular topic in arctic regions, with the number of studies on wind turbines in icy waters rapidly increasing.

7.4.1 Ice-Propeller Interactions

Azimuth propulsors are commonly used as the main propulsion unit on icebreakers and ice-going ships due to their high maneuverability and effective performance in ice management. These thrusters are designed to operate in ice-covered waters and must withstand impact loads from ice bodies, which can occur at high speeds when ships are traveling in channels with brash ice. Perälä et al. (2022) conducted two tests to study the impact forces and crushing phenomena associated with these impacts. The first test was a pendulum-type impact test carried out using real sea ice in the Baltic Sea, while the second test took place in the VTT towing tank and focused on the dynamics of the impact, including the movement of ice blocks and the vibration of the thruster.

The behavior of ice-classed azimuth propulsors under different ice load cases has been studied using the finite element method (Zhou et al. 2023). Ice-propeller collisions can result in extreme impulse loads, which are transferred through the propeller shaft to the sliding bearings of the stern tube and can eventually lead to the failure of the entire propeller system. Liu et al. (2023) conducted a numerical simulation of the ice-propeller milling process, using the cohesive element method and the elastoplastic softening constitutive law to simulate the crushing and deformation of sea ice. The calculated ice loads were found to be in good agreement with model test results. A sensitivity study revealed that the ice load is affected by the propeller rotation speed, advance velocity, and cutting depth to varying degrees.

In the study conducted by Xie et al. (2023), CFD-DEM coupling methods were presented to estimate the self-propulsion performance of an ice-strengthened Panamax bulk carrier in a brash ice channel. The hydrodynamic performance of a propeller was simulated by CFD, and ice load was calculated by DEM. The thrust, developed power, propulsion efficiency and ice load were calculated. The model test was carried out at HSVA and compared with numerical results. The difference of simulated and measured power is 7.38%. Gilges et al. (2023) conducted hydrodynamic simulations and multi-body simulations based on field measurements to investigate the influence of ice collision loads on the contact conditions in the bearings of the stern tube of the research vessel SA Agulhas II. They identified the operational condition thresholds, specifically the propeller torque and rotational speed that cause mixed-friction conditions in stern tube bearings during propeller-ice collisions. To monitor the health of propulsion system components in ice-covered seas, it is necessary to quantify the loading they are subjected to. However, direct measurements can be challenging in ice conditions. Therefore, it is necessary to measure elsewhere on the propulsion shaft to determine the ice-induced propeller moment.

Nickerson et al. (2022, 2023) have constructed a scale laboratory test rig to determine the ice-induced propeller moment through an inverse problem. The input loads and output responses are measured simultaneously during experiments with the scale model. Measured output responses are provided to the inverse model, and its estimation of the input load is compared to the measured loads, which are measured elsewhere on the propulsion shaft. The estimated loads are compared with the measured loads to demonstrate the accuracy of the estimations by the inverse model. To understand the interaction and failure between an ice specimen and a propeller blade-type edge, Böhm et al. (2022) conducted splitting tests of laboratory-made granular ice with a propeller-blade-like indenter at varying interaction velocities and two different blade thicknesses. The experiments indicated that the failure of the ice interacting with a propeller-blade-like indenter is a rather local process, while the failure in common compressive tests is a global process. Kistner et al. (2022) developed an FEM-based calculation procedure to identify and examine the vibratory stresses arising in the propulsion shaft of a container vessel in sea ice. The developed method provides the dynamic response of the shafting system subjected to torsional vibrations for different engine operation conditions.

7.4.2 Fatigue Damage

The current structural design rules do not sufficiently consider the effect of ice loading on fatigue life due to the lack of studies on the fatigue strength of welded joints under the combined action of wind, waves, and ice. Vessels navigating through ice-covered waters may be subject to fatigue damage due to repeated ice loading. Although researchers have proposed various approaches for the fatigue damage assessment of ships navigating in ice fields, a complete procedure is still lacking due to uncertainties in ice-ship interaction. Zhao et al. (2022b) proposed a procedure for assessing the fatigue damage of a ship's local structure caused by ice loads in level ice using numerical simulations. The study provides a numerical example for the Chinese icebreaker Xuelong 2, in which the ice-load peaks acting on the local hull due to ship-ice interaction were obtained through a long duration time-domain numerical simulation. The extreme value statistics of the line load peaks were predicted, and the fatigue stresses caused by the ice loads were estimated using beam theory. The fatigue damage was then calculated based on S-N curves and the Palmgren-Miner formula. Jeon and Kim (2022) conducted a similar fatigue damage estimation for the Korean icebreaker ARAON in level ice. They emphasized the importance of lifetime ice data collection, including ice type, ice collision frequency, ice thickness, and ice concentration, as it is crucial for the estimation of fatigue damage.

The effects of ice-induced loads and their consequences for the fatigue life of offshore structures are still not fully understood. Braun et al. (2020) and Braun (2022) have investigated the fatigue strength of the welded joints in ship and offshore structures subjected to sub-zero temperatures. The fatigue tests of butt-welded joints of normal and high-strength steel structures were conducted at room and sub-zero temperatures. They analyzed the impact of temperature on the fatigue strength. Braun et al. (2022) present the Variable-Amplitude Loading (VAL) spectrum for fixed offshore wind turbines (OWTs) and the corresponding VAL time series. The study then compared the results of fatigue tests to typical fatigue damage sums for regular and similar stress spectra. The FATICE (Fatigue Damage from Dynamic Ice Action) project, which was launched in Europe between 2018 and 2022, aims to address the challenge of fatigue damage in fixed offshore structures caused by drifting sea ice. This is a critical issue for various marine industries, including those involved in oil, gas, and offshore wind. Høyland et al. (2021) studied the fatigue damage on fixed offshore structures exposed to drifting ice in the FATICE project. For the fatigue load assessment of OWTs in sub-Arctic regions such as the Southern Baltic Sea, occurrence probabilities of ice thickness, ice-drift speed and wind-ice misalignment are required. Hornnes et al. (2022) estimated the drift ice thickness using a method based on modelled data on ice conditions from a large scale air-ice-ocean dynamics model from Copernicus, the European Union's (EU) earth observation program. They investigated the effect of the uncertainty in ice thickness and occurrence on the fatigue damage of the OWTs. Shin and Kim (2021) proposed a fatigue assessment procedure for a sloped offshore structure operating in drifting level ice. The ice breaking force induced by the ice-structure interactions was calculated using the ISO 19906 and analytical procedure. Fatigue damage was then calculated with the design S-N curve of welded joints proposed by Det Norske Veritas.

7.4.3 Offshore Wind Turbine in Sea Ice Conditions

Fixed offshore wind turbines (OWTs) are increasingly being developed for high latitude areas, where not only wind and wave loads must be considered, but also moving sea ice. To ensure that these wind turbines are safe for the environment while keeping them economically competitive, better guidelines and regulations should be developed through collaboration between European industry and academia (Høyland et al. 2021).

Many research projects related to offshore wind turbines have been launched, including the SHIVER project, which aims to address uncertainty regarding vibrations. This project is a collaboration between TU Delft, Siemens Gamesa Renewable Energy, and Aalto University. In the SHIVER project, a real-time hybrid test setup for dynamic ice-structure interaction of fixed structures has been designed for basin tests (Hendrikse et al. 2022). They proposed a classification of ice-induced vibrations that encompasses experimental observations for offshore wind turbines, based on the periodicity in the structural response at the point of ice action (Hammer et al. (2022, 2023)). An experimental campaign was carried out in the Aalto ice tank in Espoo, Finland, to investigate sea ice ridge interaction with bottom-fixed structures. The study investigated scaled ridge properties, ice growth, consolidation and failure processes, and the scaling of ridge forces with respect to cylindrical and conical structures at the water line (Heinonen et al. 2021; Salganik et al. 2021; Jiang 2021).

Fuglem et al. (2022) presented an analysis of 50-year iceberg impact parameters for four platforms off the coast of Newfoundland and Labrador, including a spar, a barge, a semisubmersible, and a Tension Leg Platform (TLP). Thijssen et al. (2022) analyzed 50-year mooring loads due to sea ice interactions for four types of floating wind platforms at various locations offshore of Newfoundland Canada. The potential advantages and disadvantages of the different designs with respect to ice actions were investigated.

Offshore platforms in the China Bohai Sea, Alaska, Canada, and Russia, as well as lighthouses and channel markers in Northern Europe, have all experienced severe Frequency Lock-In (FLI) vibration, leading to structural collapse or production shutdown. FLI vibration was examined for bottom-fixed wind turbines (Zhu et al. 2021). They developed a new ice-induced vibration (IIV) analysis model to mitigate the large structural response in FLI for monopile OWT. Ice-induced loads on offshore structures in the Baltic Sea are calculated by Tabri et al. (2022), and Heinonen and Mikkola (2023). Tabri et al. (2022) conducted the numerical assessment to evaluate the ice load history, load maxima, and vibration for a wind turbine foundation design in Estonian territorial waters near the Saaremaa of the Baltic Sea, where these locations is a potential wind farm development site. Heinonen and Mikkola (2023) simulated dynamic ice load excitation on a bottom-fixed channel marker structure (a slender monopile structure) in the Northern Bothnian Bay and analyzed the horizontal acceleration response at vertical positions in the structure.

7.5 Conclusions

Human activities in the Arctic region are increasing, primarily related to shipping routes, natural resource exploration (such as oil and gas), and the operation of ships and offshore platforms. Due to these increasing developments in the Arctic region, evaluating the safe operation and structural response will continue to be critical.

Full-scale measurements and laboratory experiments continue to be essential research topics in this area. Since the wave height is increasing due to the retreating of the sea ice area, the ice collision speed to the ship hull may increase due to the increase of wave height. Therefore, the research related to structural response under ice impact in high collision speed becomes a new, important research topic. Ice modelling including ice failure is continuously important topic for estimating structural damage with ice collision. Furthermore, the growing interest in setting up wind turbines in ice-covered waters, such as the northern Baltic Sea, has the potential to further activate research into ice-related fatigue damage.

8 Emerging Trends

8.1 "Bigger, lighter and faster"

Jagite et al. (2022) wrote: " *When technically specifying ships for the future, the following aspects are examples of what we will have even more focus on than today: bigger, lighter, and faster*." This trend is observed in the last decades for all ships but especially for containerships, cruise ships and yachts. As reported by Rinauro et al. (2024), "*economics and logistics experts analyzed the trends of container ships growth based on economies of scale, port infrastructure, demand, and environmental tendencies, to predict the ship size limits. According to Malchow* (2017), *a* ***30000 TEU*** *container ship with approximately* ***20 m draught****, should be the ultimate limit because of the depth constraints in the Malacca Strait and the Suez Canal*. "The growing number of container losses accidents due to the parametric roll or onboard injuries due to excessive lateral accelerations and in particular, well known accidents of APL China in 1998 and Chicago express in 2008 were triggers for the IMO to start developing second generation Intact Stability Criteria and to increase awareness on safety and correct considerations of stability in waves and to related accelerations experienced by people onboard and cargo. Furthermore, large container ships are very flexible and their structural natural frequencies can fall into the range of the encounter frequencies in an ordinary sea spectrum. The classical approach to determine ship motions and wave loads based on the assumption that the ship hull acts as a rigid body is not reliable for the ultra large ships due to the mutual influence of the wave load and structure response. The methodology of predicting the ultimate strength of ULCS is continuously improving both with the most advanced numerical methods and through the validation against full scale data.

8.2 Ballast Free Vessels

The problem with the moving of invasive species from one water basin to another with the ballast water of the ships has been recognised by the end of the 20th century and in 2004 the IMO prepared regulations “Ballast Water Management Convention”.

In the University of Michigan, Kotins and Parsons (2007, 2010) and Kotinis et al. (2004) proposed and patented ships with no water ballast tank. Their project excluded some compartments of the hull to reduce the displacement, there is a water flow from fore to aft and always connected to the outside water. This approach later on was developed by Godey et al. (2012) suggesting the water instead of flowing throughout the ship hull between steel structures to flow in special ducts (pipes).

Kashiro (2016) presented concept designs for Minimal Ballast water Ship (MIBS) and NO Ballast water Ship (NOBS), characterized by a midship section with an inclined bottom and reduced bow draught (greater trim compared to the conventional ship).

Since all variants of the ballast free ships have increased height of the transverse section many researchers tried to improve the arrangement of the longitudinal structures (inner bottom, inner boards, keel, bottom girders, etc.) to reduce the thicknesses and this way to minimize the increasing of the steel weight. Bending moments were found to be similar to the ones for the ballast ships and also appear during similar load cases, so the increased heights lead to increased section moduli.

Su et al. (2019) made multi-objective optimization of a cargo hold from an unmanned ballast free 30000 t oil tanker. As objective functions are used cargo hold capacity, water immersion and bending moment in a three dimensional model. As an optimization technique is used multiobjective Particle Swarm Optimization (PSO) algorithm. As a result, the optimal value and the subdivision schemes based on each object are obtained. The same ship and the same optimization objectives have been further studied by Radial Basis Function (RBF) method (Su et al. (2021)), where the Authors shown that after the optimisation the weight of the cargo hold was reduced by 1.15% and the stiffness was increased by 4.3%. In Su et al. (2022) the optimization for a compartment in the cargo hold of the same tanker is performed using the SUMP topology optimization method. As optimization constraints are taken the height of the transverse girders and the minimum width of the vertical girders as per the China Classification Society (CCS) and also structural yield. As a result the structural strain energy (compliance) is reduced by 6.8% and the stiffness is improved significantly.

The ballast free vessels are looking prospective for many types of ships and especially for those which run either loaded or ballasted, i.e. without the necessity to take some ballast in laden cases – tankers, bulk carriers, gas carriers. And even if the design of such ships seems to be a problem of the future (more or less close) it must be pointed out that Bureau Veritas, Lloyds’ Register of Shipping, Class NK and probably DnV and CCS have approval in principle for similar projects. Structural analysis and uncertainty in modelling techniques is still not an issue in ballast free ships as they are in the concept stage. It has been known that the first similar ship is already built under LR Class for German company Hanseatic Ship Management $-7600\ m^3$ LNG in Hyundai Mipo Ulsan Shipyard (Fig. 20). (https://www.lr.org/en/about-us/press-listing/press-release/building-the-worlds-first-ballast-free-lng-bunkering-vessel-with-hmd/, contacted 09/01/2024)

Fig. 20. Ballastless m/v Kairos IMO: 9819882. https://www.vesselfinder.com/it/vessels/details/9819882, accessed 30/11/2024

8.3 Life Cycle Assessment of Structural Design

While life cycle assessment (LCA) has been applied to both the end-of-life of metal ships (Rahman et al. 2016) and low-emission propulsion systems (Fernández-Ríos et al. 2022), there is an emerging interest in the application of LCA in early design stages for composite special vessels. This need was identified in the systematic review of Jacquet et al. (2024), highlighting the growth of this research field in the past decade, and particularly over the past few years. This has been applied across all special vessels covered in the scope of this chapter, namely yachts, superyachts (Del Pero et al. 2024) and ships (Han et al. 2024). The latter publication identified the advantages of sandwich composite structures, as opposed to single-skin ones, from a sustainability point of view while showcasing how material selection may be influenced by LCA in composite vessel design. However, there remain limitations associated with the underpinning LCA databases and in the application of a consistent LCA methodology to enable clear decision-making and comparisons) Jacquet et al. 2024). Consequently, this is seen as an emerging trend and it is anticipated the next ISSC V.5 committee will be able to provide a detailed account of this topic as further research emerges in the next few years.

9 Conclusions and Recommendations

This report is the continuation of previous reports Truelock et al. (2018, 2022) and provides a review of advancements, challenges, and future trends in the design and structural assessment of: high-speed crafts, pleasure boats, naval unmanned surface vessels, workboats, and ice-polar vessels. Even though a huge variety of ship types have been analyzed, some of the common features can be highlighted as the overall conclusions and recommendations for the next mandate.

The research approaches include numerical methods like CFD-FEM coupling, model and full-scale experiments, and machine learning to improve load prediction accuracy and structural design. The emerging trends from the last report remained the same: digital twins, unmanned surface vehicles, unmanned underwater vehicles, and the growth of ship size. The ballast free ships are looking prospective for ship types which run either loaded or ballasted, but at the moment, up to the knowledge of the Committee, only one of these ships has been built and it's difficult to say whether they will enter in the market.

In the field of pleasure craft and naval ships, due to the industrial competitiveness and highly confident information, there is a lack of peer reviewed papers dealing with the practical structural challenges solved by the most advanced methods. The majority of the published articles on these vessels are coming from the academy and the comparison against the real data is missing. Therefore, the closer collaboration of industry and class societies with the academy and education of new naval architects would be desirable.

As recommendations for the next Special Vessels mandate, the Committee members would highlight the following ship types and topics:

- autonomous ships and convey of ships in which only the front ship is manned, while the others follow autonomously
- unmanned surface and underwater vehicles
- wind assisted ships
- alternative fuels impact on design and structural scantling
- use of AI for scantling optimization

References

ABS American Bureau of Shipping: ABS guidance notes on ship vibrations. 2006. Updated February 2018 (2018)

Bureau Veritas: Rules for The Classification and the Certification of Yachts, NR500 DT R03 (November 2022a)

Bureau Veritas: NR 681 Unmanned Surface Vessels (USV), NR681 (July 7, 2022b). https://erules.veristar.com/dy/data/bv/pdf/681-NR_2022-07.pdf

Det Norske Veritas Germanischer Lloyds: Design and Construction of Large Modern Yacht Rigs. Det Norske Veritas Germanischer Lloyds, Baerum (2016)

DNV Det Norske Veritas: Autonomous and remotely operated ships (2021)

Lloyd's Register: Special Service Craft Rules, Southampton, (July 2024)

Lloyd's Register: Design Code for Unmanned Marine Systems (2017)

Red Ensign Group Yacht Code: Part A (June 2023)

RINA: Rules for yachting (2024)

Allaka, H., Groper, M.: Validation and verification of a planing craft motion prediction model based on experiments conducted on full-size crafts operating in real sea. J. Mar. Sci. Technol. **25**, 1199–1216 (2020). https://doi.org/10.1007/s00773-020-00709-6

Almallah, I., Ali-Lavroff, J., Holloway, D.S., Davis, M.R.: Slam load estimation for high-speed catamarans in irregular head seas by full-scale computational fluid dynamics. Ocean Eng. **234**, 1–11 (2021). https://doi.org/10.1016/j.oceaneng.2021.109160

Alsallah, A., Holloway, D., Mousavi, M., Lavroff, J.: Identification of wave impacts and separation of responses using EMD. Mech. Syst. Signal Process. **151**, 1–19 (2021). https://doi.org/10.1016/j.ymssp.2020.107385

Alsallah, A., Holloway, D., Lavroff, J.: Reducing wave impacts on high-speed catamarans through deployment of ride control: analysis of full-scale measurements. Ocean Eng. **292** (2024). https://doi.org/10.1016/j.oceaneng.2023.116581

Andryushin, A., Zuev, P., Voronin, A., Fedoseev, S., Ryabushkin, S., Kuteinikov, M.: Ensuring of the Strength of Large Arctic LNG Carriers and Oil Tankers for Year-Round Transportation in the Arctic Conditions. ISOPE2022, 1391 (2022)

Asgaree, M.: Hydrodynamic resistance reduction in catamaran assisted hydrofoils. J. Adv. Mater. Eng. (Esteghlal). **24**(1), 251–269 (2022)

Bačkalov, I., Vidic, M., Rudakovic, S.: Lessons learned from accidents on some major European inland waterways. Ocean Eng. **273** (2023). https://doi.org/10.1016/j.oceaneng.2023.113918

Bagué, A., Degroote, J., Demeester, T., Lataire, E.: Dynamic stability analysis of a hydrofoiling sailing boat using CFD. J. Sail. Technol. **6**(01), 58–72 (2021)

Banik, A., Zhang, C., Khan, M., Wilson, M., Tan, K.: Low-velocity ice impact response and damage phenomena on steel and CFRP sandwich composite. Int. J. Impact Eng. **162**, 104134 (2021)

Barry, C.D.: CNC enabled wood/metal composite construction of (relatively) high performance sailing yachts. J. Sail. Technol. **7**(01), 152–185 (2022)

Begovic, E., Della Valentina, E., Mauro, F., Nabergoj, R., Rinauro, B.: The impact of different bow shapes on large yacht comfort. J. Mar. Sci. Eng. (2023). https://doi.org/10.3390/jmse11030495

Begovic, E., et al: Experimental modelling of local structure responses for high-speed planing craft in waves. Ocean Eng. **216** (2020). https://doi.org/10.1016/j.oceaneng.2020.107986

Block, V.L., Lerner, S.D., Miller, S.R.: Glazing Safety and Resilience: New High-Performance Options, SNAME Maritime Convention 2021 27–29 October. SNAME (2021)

Böhm, A.M., Herrnring, H., Polach, F.v.B.u.: Splitting-Tests of Laboratory-Made Granular Ice With a Propeller-Like Indenter. OMAE2022-78186 (2022)

Boote, D., Hydar, V., Vergassola, G.: Re-design of a fast vessel from light alloy to composite material. International Conference on Materials, Science, Engineering & Technologies, Singapore. 7–9 September, 2023 (2023).

Boote, D., Gaggero, T., Pais, T., Rizzuto, E., Vergassola, V.: Underwater radiated noise from a large pleasure craft. In: Proceedings of the International Congress on Sound and Vibration (2022)

Boote, D., Vergassola, G., Delfino, P., Faloci, F.: Real scale measurements of yacht's mast accelerations. Ships Offshore Struct. **16**(10), 2021 (2021). https://doi.org/10.1080/17445302.2020.1816747

Boote, D., Vergassola, G., Di Matteo, V.: Strength analysis of superyacht superstructures with large openings. Int. Rev. Mech. Eng. **11**(1), 1–9 (2017a)

Boote, D., Vergassola, G., Pais, T., Kramer, M.: Finite element structural analysis of big yacht superstructures. Int. Rev. Mech. Eng. **12**(1), 1–9 (2017b)

Boote, D., Vergassola, G.M., Giannarelli, D., Ricotti, R.: Thermal load effects on side plates of superyachts. In: Marine Structures, vol. 56, pp. 39–68. Elsevier Ltd (2017c)

Boote, D., et al: Committee V.8 YACHT DESIGN. In: 18th International Ship and Offshore Structures Congress. 09–13 September 2012, Rostock, Germany (2012)

Braun, M., et al: Fatigue Strength of Fixed Offshore Structures Under Variable Amplitude Loading Due to Wind, Wave, and Ice Action. OMAE2022-78764 (2022)

Braun, M., Hensel, J., Song, S., Ehlers, S.: Fatigue strength of normal and high strength steel joints improved by weld profiling. Eng. Struct. **246**, 113030 (2021)

Braun, M., et al: Sub-zero temperature fatigue strength of butt-welded Normal and high-strength steel joints for ships and offshore structures in Arctic regions. In: Proceedings of ASME 2020 39th International Conference on Ocean, Offshore and Arctic Engineering, Fort Lauderdale, FL, USA. June 28–July 3 (2020)

Braun, M., Grimm, J.H., Hoffmeister, H., Ehlers, S., Fricke, W.: Comparison of fatigue strength of post-weld improved high strength steel joints and notched base material specimens. Ships Offshore Struct. **13**(1), 47–55 (2018)

Budiarto, U., Firdhaus, A.: Analysis of the effect of hull vane on ship resistance using CFD methods. In: IOP Conference Series: Earth and Environmental Science, vol. 649., No. 1, p. 012051. IOP Publishing (2021)
Burella, G., Moro, L.: Design solutions to mitigate high noise levels on small fishing vessels. Appl. Acoust. **172**, 107632 (2021) 16p
Cai, W., Zhu, L., Gudmestad, O.T., et al.: Application of rigid-plastic theory method in ship-ice collision. Ocean Eng. **253**, 111237 (2022a)
Cai, W., Zhu, L., Qian, X.D.: Dynamic responses of steel plates under repeated ice impacts. Int. J. Impact Eng. **162**, 104129 (2022b)
Cai, W., Zhu, L., Yu, T.X., et al.: Numerical simulations for plates under ice impact based on a concrete constitutive ice model. Int. J. Impact Eng. **143**, 103594 (2020)
Cheemakurthy, H., Barsoum, Z., Burman, M., Garme, K.: Comparison of lightweight structures in bearing impact loads during ice–hull interaction. J. Mar. Sci. Eng. **10**(6), 79 (2022)
Chen, Z., Zhao, W., Liao, X., Du, M.: A simplified methodology for dynamic responses of cross-decks of trimarans under slamming loads. Ships Offshore Struct. **18**(2), 231–239 (2023). https://doi.org/10.1080/17445302.2022.2035563
Chen, X., Ma, Y., Ji, S.: Study of Semantic Segmentation on Sea Ice Image Based on Deep Learning. POAC, 2022, Paper105 (2022)
Cho, S., Son, B., Choi, K., Jeong, S.Y., Ha, Y.S.: Enhanced Influence Coefficient Matrix for Estimation of Local Ice Loads on IBRV ARAON. POAC21-009 (2021)
Choiron M.A.: Development of fishing boat collision models in extreme weather using computer simulation (2023). https://doi.org/10.21303/2461-4262.2023.002601
Choung, J., Yoon, D.H.: Effects of Radiation and Wave Excitation Forces Acting on an Icebreaker on Ship Motions and Structural Damages during Iceberg Collision, p. 22123. IAHR ICE2022 (2022)
Costa, V., Boote, D., Pais, T., Ferrari, A., Sugalski, K.: WFSV-PL – an hybrid carbon composite wind farm supply vessel. In: Proceedings of the 27th International Offshore and Polar Engineering Conference, pp. 998–1004. San Francisco, USA (June 2017)
Cubides Garzón, D.M., Castaño Padilla, A.M., Vergara Pestaña, H.D.: Perspectives for the development of unmanned surface vehicles in Colombia: COTECMAR case. Ship Sci. Technol. **17**(34), 27–33. January 2024 – Cartagena (Colombia) (2024). https://doi.org/10.25043/19098642.247
Curtolo, P., Russo, T., Pacigìfic, G.Z., Begovic, E., Mancini, S.: Concept design on a Large Unmanned Surface Vehicle (LUSV). In: RINA Conference Autonomous Ships 2024, 20th November–21st November 2024, Copenhagen, Denmark (2024)
Cui, J., Gu, C.J., Chen, X., Li, M.Y., Masvaya, B.: Numerical study of wedge entry in still water and waves using smoothed particle hydrodynamics methods. Ocean Eng. **280**, 114776 (2023). https://doi.org/10.1016/j.oceaneng.2023.114776
D'Amato, E., Notaro, I., Piscopo, V., Scamardella, A.: Hydrodynamic design of fixed hydrofoils for planing craft. J. Mar. Sci. Eng. **11**(2), 246 (2023)
Davis, M.R.: Operation of T-foils and stern tabs to improve passenger comfort on high-speed ferries. J. Ship Res. **66**(04), 277–296 (2023). https://doi.org/10.5957/JOSR.07200047
Del Pero, F., Dattilo, C.A., Giraldi, A., Delogu, M.: LCA approach for environmental impact assessment within the maritime industry: re-design case study of yacht's superstructure. Proc. Inst. Mech. Eng. Pt. M J. Eng. Marit. Environ. **238**(1), 153–170 (2024)
Deng, Y., Ren, X., Nuernberg, M., Tao, L.: Launch and recovery of a work class ROV through wave zone in small offshore service vessel. Ocean Eng. **309**, 118541 (2024). https://doi.org/10.1016/j.oceaneng.2024.118541
Dessi, D., Sanchez-Alayo, D., Shabani, B., Ali-Lavroff, J.: Bow slamming detection and classification by machine learning approach. Ocean Eng. **287** (2023). https://doi.org/10.1016/j.oceaneng.2023.115646

Dewavrin, J., Souppez, J.B.: Experimental investigation into modern hydrofoils-assisted monohulls: how hydrodynamically efficient are they? Int. J. Small Craft Technol. **160**(B2), 111–120 (2018). https://doi.org/10.3940/rina.ijsct.2018.b2.223

Diez, M., et al: Experimental and computational fluid-structure interaction analysis and optimization of deep-V planing-hull grillage panels subject to slamming loads – part I: regular waves. Mar. Struct. **85** (2022). https://doi.org/10.1016/j.marstruc.2022.103256

Domeh, V., Obeng, F., Khan, F., Bose, N., Sanli, E.: A novel methodology to develop risk-based maintenance strategies for fishing vessels. Ocean Eng. **253**, 111281 (2022). https://doi.org/10.1016/j.oceaneng.2022.111281

Dow, R.S., et al: Committee V.5 naval vessel design. In: 19th International Ship and Offshore Structures Congress, 7–10 September 2015, Cascais, Portugal (2015)

Dowden, B., De Silva, O., Huang, W., Oldford, D.: Sea ice classification via deep neural network semantic segmentation. IEEE Sensors J. **21**(10), 11879 (2021)

Duan, W.Y., Liu, J.Y., Liao, K.P., Ma, S.: Experimental study of slamming pressure for a trimaran section with different drop heights and heel angles. Ocean Eng. **263**, 112400., ISSN 0029-8018 (2022). https://doi.org/10.1016/j.oceaneng.2022.112400

Dupuy, M., Letournel, L., Paakkari, V., Rongère, F., Sarsila, S., Vuillermoz, L.: Weather routing benefit for different wind propulsion systems. J. Sail. Technol. **8**(01), 200–217 (2023)

ECE: Inventory of Main Standards and Parameters of the E Waterway Network (Blue Book), ECE/TRANS/SC.3/144/Rev.3 (with amendments) (2017–2023)

ECE: Recommendations on Harmonized Europe-wide Technical Requirements for Inland Navigation Vessels, ECE/TRANS/SC.3/172/Rev.2, Resolution No. 61 Revision 2. (2020)

Engelbrecht, M., Bekker, A.: (2023) A discomfort threshold for impulsive whole-body vibration on a slamming-prone vessel. Appl. Ergon. **109** (2023). https://doi.org/10.1016/j.apergo.2023.103992

European Parliament: Directive 2013/53/EU of the European Parliament and of the council of 20 November 2013 on recreational craft and personal watercraft and repealing directive 94/25/EC. Off. J. Eur. Union. (2013)

Faltinsen, O.M.: Hydrodynamics of High-Speed Marine Vehicles. Cambridge University Press (2005)

Fassola, E., Kustermann, L.: Noise and vibration: comparison between prediction and measurements on yachts. In: Technology and Science for Ships of the Future. SAGE Publications Ltd (2022)

FEBIMA: Report 2017–02 on the Investigation into the Capsizing and Subsequent Rescue Mission of the Sailing Vessel CAPELLA off the Belgian Coast with the Loss of Three Lives on July 1st 2017. Federal Bureau for the Investigation of Maritime Accidents, Brussels (2017)

Fernández-Ríos, A., et al: Environmental sustainability of alternative marine propulsion technologies powered by hydrogen – a life cycle assessment approach. Sci. Total Environ. **820**, 153189 (2022)

Fibreship: Fibreship (2023). http://www.fibreship.eu/. Accessed 24 Nov 2023

Firdhaus, A., Suastikab, I.K.: Experimental and numerical study of effects of the application of hydrofoil on catamaran ship resistance. Revolution. **4**, 104–110 (2022)

Frederking, R.: Nanisivik Revisited: Ice Pressure Measurements from Winter 1985–86. POAC21-018 (2021)

Frederking R.: Ice forces on the R. V. "POLARSTERN" during 1984 labrador trials ISOPE2023 (2023)

Fuglem, M., Shayanfar, H., Liu, L., King, T., Paulin, M.: Evaluation of floating offshore wind turbine platforms with respect to iceberg impacts. IAHR Ice. **2022**, 22114 (2022)

Fujikubo, M., et al: A digital twin for ship structures – R&D project in Japan. Data-Cent. Eng. **5**, e7 (2024). https://doi.org/10.1017/dce.2024.3

Gagnon, R., Quinton, B., Mackay, J., Robbins, I., Rodriguez, M.: Design-purpose Numerical Simulations of the NRC Heavy Impact Test Theater (HITT). POAC, 2023 Paper85 (2023)
Gagnon, R., Quinton, B., Mackay, J.: A Numerical Simulation Study of Boundary – Condition Effects on the Damage of Ship Grillages Due to Ice Impacts. (R) IAHR Ice 2022, 22116 (2022)
Gagnon, R., Wang, J., Seo, D., Mackay, J.: Numerical Simulations of Naval Vessel Collisions with Ice R, pp. 339–360. IAHR 2020 (2020)
Gao, X., Xu, S., Tang, W.: Hybrid analytic-FEM approach for dynamic response analysis of air-cushion vehicle skirts. Mar. Struct. **79**, 103062 (2021). https://doi.org/10.1016/j.marstruc.2021.103062
Gebrezgabir, S., Holloway, D., Ali-Lavroff, J.: Slam and wave load response reconstruction in high speed catamarans using transmissibility on full scale sea trials. Ocean Eng. **271**, 1–12 (2023). https://doi.org/10.1016/j.oceaneng.2023.113822
Gilges, M., Saleh, A., Jain, M., Bekker, A., Lehmann, B., Jacobs, G.: Influence of Propeller-Ice Loads on the Wear Development in Stern Tube Bearings of Marine Propulsion Systems and Identification of Critical Operating Conditions. OMAE2023-102785 (2023)
Godey, A., Misra, S.C., Sha, O.P.: Development of a ballast free ship design. Int. J. Innov. Res. Dev. **1**, 10 (2012)
Gosse, J., Quinton, B., Daley, C., Kendrick, A., Bond, J.: Using Non-Linear Finite Element Analysis to Analyze the Effects of Connection Designs on the Ice Strength of a Vessel. OMAE2023-104860 (2023)
Graf, K., Freiheit, O., Schlockermann, P., Mense, J.C.: VPP-driven sail and foil trim optimization for the Olympic NACRA 17 foiling catamaran. J. Sail. Technol. **5**(01), 61–81 (2020)
Grimm, J.-H.: Extended Fatigure Recommendations for High Strength Steel Yacht Keels. Det Norske Veritas Germanischer Lloyds, Hamburg (2016)
Guida, P., Marimon Giovannetti, L., Boyd, S.: Three-dimensional variations of the NACRA 17 main foil for benchmarking shape optimizations. In: The 5th International Conference on Innovation in High Performance Sailing Yachts and Sail Assisted Propulsion, Gothenburg (2020)
Hageman, R.B., Thompson, I.: Virtual hull monitoring using hindcast and motion data to assess frigate-size. Ocean Eng. **245** (2022). https://doi.org/10.1016/j.oceaneng.2021.110338
Hammer, T.C., Owen, C.C., van den Berg, M.M., Hendrikse, H.: Classification of Ice-Induced Vibration Regimes of Offshore Wind Turbines. OMAE2022-78972 (2022)
Hammer, T.C., Willems, T., Hendrikse, H.: Dynamic ice loads for offshore wind support structure design. Mar. Struct. **87** (2023). https://doi.org/10.1016/j.marstruc.2022.103335
Han, Z., Jang, J., Souppez, J.B.R.G., Oh, D.: Environmental implications of a sandwich structure of a glass fiber-reinforced polymer ship. Ocean Eng. **298**, 117122 (2024)
Han, Z., Jang, J., Souppez, J.B.R., Seo, H.S., Oh, D.: Comparison of structural design and future trends in composite hulls: A regulatory review. Int. J. Nav. Archit. Ocean Eng. **15**, 100558 (2023)
Han, Z., Jeong, S., Noh, J., Oh, D.: Comparative study of glass fiber content measurement methods for inspecting fabrication quality of composite ship structures. Appl. Sci. **10**(15), 5130 (2020)
Hashimoto, S., et al: Hydrodynamic design and analysis of high speed catamaran with hydrofoils using CFD. In: Practical Design of Ships and Other Floating Structures: Proceedings of the 14th International Symposium, PRADS 2019, September 22–26, 2019, Yokohama, Japan-Volume I 14, pp. 508–518. Springer, Singapore (2021)
He, S., Chen, X., Ji, S.: Experimental Verification of Dynamic Ice Load Identification Method. POAC, 2022, Paper103 (2022)
Heinonen, J., Mikkola, E.: Modelling of Ice-Interaction with a Sea Channel Marker in the Bothnian Bay. POAC, 2023, Paper50 (2023)

Heinonen, J., Tikanmäki, M., MiA-kkola, E., Perälä, I., Shestov, A.: Scale-Model Ridges and Interaction with Narrow Structures, Part 3 Analysis of Ridge Keel Punch Tests. POAC21-091 (2021)

Helal, K.M., Fragasso, J., Moro, L.: Underwater noise characterization of a typical fishing vessel from Atlantic Canada. Ocean Eng. **299**, 117310 (2024) 14 p

Hendrikse, H., et al: Ice Basin Tests for Ice-Induced Vibrations of Offshore Structures in the SHIVER Project. OMAE2022-78507 (2022)

Heo, H., Choi, J., Choi, H.S., Oh, E.J., Park, S.: Dimensionality Reduction of Multivariate Sensor Data for Estimation of Ice Load on a Real Ship, p. 22110. IAHR Ice 2022 (2022)

Herrnring, H., Ehlers, S.: A finite element model for compressive ice loads based on a mohrcoulomb material and the node splitting technique. J. Offshore Mech. Arct. Eng. **144**(2) (2022)

Hong, S., McMorland, J., Zhang, H., Collu, M., Henning, H.K.: Floating offshore wind farm installation, challenges and opportunities: a comprehensive survey. Ocean Eng. **304** (2024). https://doi.org/10.1016/j.oceaneng.2024.117793

Hosseinzadeh, S., Tabri, K., Hirdaris, S., Sahk, T.: Slamming loads and responses on a non-prismatic stiffened aluminium wedge: part I. Experimental study. Ocean Eng. **279** (2023a). https://doi.org/10.1016/j.oceaneng.2023.114510

Hosseinzadeh, S., Tabri, K., Topa, A., Hirdaris, S.: Slamming loads and responses on a non-prismatic stiffened aluminium wedge: part II, numerical simulations. Ocean Eng. **279** (2023b). https://doi.org/10.1016/j.oceaneng.2023.114309

Høyland, K.V., et al: Fatigue damage from dynamic ice action – fatigue damage from dynamic ice action. The FATICE project (POAC21-026) (2021)

Hydar, V., Boote, D., Vergassola, G., Păcuraru, F.: Seakeeping analysis of a GRP fast patrol vessel. In: Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering – OMAE 2022, Hamburg (Germany) (2022)

Hydar, V.: Numerical dynamic analysis of a composite pleasure craft for comfort improvement. Int. Rev. Mech. Eng. **16**(8), 379–392 (2022)

Ibrahim, A.M., Judge, C.Q.: Investigations of hull girder slamming factor for a semi-displacement vessel using model testing. Appl. Ocean Res. **150**, 104084 (2024). https://doi.org/10.1016/j.apor.2024.104084

ISO: ISO 12215-9: Small Craft – Hull Construction and Scantlings. Part 9: Sailing Craft Appendages. International Organisation for Standardization (2012)

ISO: ISO 12215-5: Small Craft – Hull Construction and Scantlings. Part 5: Design Pressures for Monohulls, Design Stresses, Scantlings Determination. International Organisation for Standardization (2019)

ISO: ISO 12215-7:2020 Small Craft – Hull Construction and Scantlings – Part 7: Determination of Loads for Multihulls and of Their Local Scantlings Using ISO 12215-5. International Organization for Standardization, Geneva (2020a)

ISO: ISO 12215-10:2020 Small Craft – Hull Construction and Scantlings – Part 10: Rig Loads and Rig Attachment in Sailing Craft. International Organization for Standardization, Geneva (2020b)

ISO: ISO 22834: Large Yachts – Quality Assessment of Life Onboard – Stabilization and Seakeeping Guidelines. International Organization for Standardization, Geneva (2022)

Jacquet, L., Le Duigou, A., Kerbrat, O.: A systematic literature review on holistic lifecycle assessments as a basis to create a standard in maritime industry. Int. J. Life Cycle Assess. **2024**, 1–23 (2024)

Jagite, G., Bigot, F., Malenica, S., Derbanne, Q., Le Sourne, H., Cartraud, P.: Dynamic ultimate strength of a ultra-large container ship subjected to realistic loading scenarios. Mar. Struct. **84**, 103197 (2022). https://doi.org/10.1016/j.marstruc.2022.103197

Jang, J.W., Han, Z., Oh, D.: Light-weight optimum design of laminate structures of a GFRP fishing vessel. J. Ocean Eng. Technol. **33**(6), 495–503 (2019)

Javanmard, E., Mehr, J.A., Ali-Lavroff, J., Holloway, D.S., Davis, M.R.: An experimental investigation of the effect of ride control systems on the motions response of high-speed catamarans in irregular waves. Ocean Eng. **281**, 1–17 (2023). https://doi.org/10.1016/j.oceaneng.2023.114899

Javanmard, E., Mehr, A.J., Holloway, D.S., Davis, M.R., Ali-Lavroff, J.: Ride control system effects on motion, slam load, and passenger comfort of high-speed catamarans: an experimental study in irregular waves. In: Proceedings of the ASME 2024 43rd International Conference on Ocean, Offshore and Arctic Engineering, OMAE 2024, June 9–14, 2024 Singapore (2024). https://doi.org/10.1115/OMAE2024-126372

Jiang, Y.Y., Tang, W.Y.: Numerical study of section geometry of flexible bag of air cushion vehicle subjected to slamming loads. Ocean Eng. **227**, 108894 (2021)

Jiang, Y., Bai, J., Dong, Y., Sun, T., Sun, Z., Liu, S.: Investigations of air cushion effect on the slamming load acting on trimaran cross deck during water entry. Ocean Eng. **251**, 111161 (2022). https://doi.org/10.1016/j.oceaneng.2022.111161

Jiang, Y., Tang, W.: Numerical investigation on water entry of a three-dimensional flexible bag of an air cushion vehicle. Ocean Eng. **247**, 110653 (2022a)

Jiang, Y., Tang, W.: Numerical prediction of interaction between a flexible bag of an air cushion vehicle and solitary waves. Ocean Eng. **265**, 112583 (2022b). https://doi.org/10.1016/j.oceaneng.2022.112583

Jiang, Z.: Installation of offshore wind turbines: a technical review. Renew. Sust. Energ. Reviews **139**, 110576 (2021). https://doi.org/10.1016/j.rser.2020.110576

Jiang, Z., Heinonen, J., Tikanmäki, M., Mikkola, E., Perälä, I.: Scale-Model Ridges and Interaction with Narrow Structures, part 4 Global Loads and Failure Mechanisms. POAC21-031 (2021)

Jiao, J., Ren, H., Guedes Soares, C.: A review of large-scale model at-sea measurements for ship hydrodynamics and structural loads. Ocean Eng. **227**, 108863 (2021). https://doi.org/10.1016/j.oceaneng.2021.108863

Jeon, S., Kim, Y.: Fatigue damage estimation of icebreaker ARAON colliding with level ice. Ocean Eng. **257**, 111707 (2022). https://doi.org/10.1016/j.oceaneng.2022.111707

Kang, Y., Pei, Z., Ao, L., Wu, W.: Reliability-based design optimization of river-sea-going ship based on agent model technology. Mar. Struct. **94**, 103561 (2024)

Kashiro, R.: Innovative Ship Design with Less Ballast Water and Less Green House Gases. TSCF 2016 Shipbuilders Meeting (2016)

Khan, L., Macklin, J., Peck, B., Morton, O., Souppez, J.B.R.: A review of wind-assisted ship propulsion for sustainable commercial shipping: latest developments and future stakes. In: Wind Propulsion Conference. Royal Institution of Naval Architects (September 2021)

Kistner, G., Lal, K., Klüss, J., Kaeding, P.: Procedure for Torsional-Vibration Calculations in Ice. OMAE2022-80194 (2022)

Kjær, R.B., Shao, Y., Walther, J.H.: Experimental and CFD analysis of roll damping of a wind turbine installation vessel. Appl. Ocean Res. **143**, 103857 (2024)

Knudsen, S.S., Walther, J.H., Legarth, B.N., Shao, Y.: Towards dynamic velocity prediction of NACRA 17. J. Sail. Technol. **8**(01), 1–23 (2023)

Kong, S., Cui, H., Wu, G., Ji, S.: Full-scale identification of ice load on ship hull by least square support vector machine method. Appl. Ocean Res. **106**, 102439 (2021)

Koričan, M., Perčić, M., Vladimir, N., Alujević, N., Fan, A.: Alternative power options for improvement of the environmental friendliness of fishing trawlers. J. Mar. Sci. Eng. **10**(12), 1882, 26 p (2022)

Koričan, M., Vladimir, N., Fan, A.: Investigation of the energy efficiency of fishing vessels: case study of the fishing fleet in the Adriatic Sea. Ocean Eng. **286**(Part 2), 115734, 12 p (2023a)

Koričan, M., Frković, L., Vladimir, N.: Electrification of fishing vessels and their integration into isolated energy systems with a high share of renewables. J. Clean. Prod. **425**, 138997, 14p (2023b)

Kotinis, M., Parsons, M.G., Lamb, T., Sirviente, A.: Development and investigation of the ballast-free ship concept. Transactions SNAME. **112**, 206–240 (2004)

Kotinis, M., Parsons, M.G.: Hydrodynamic optimization testing of ballast-free ship design. Transactions SNAME. **115** (2007)

Kotinis, M., Parsons, M.G.: Hydrodynamics of the ballast-free ship. J. Sh. Prod. Des. **26**, 301–310 (2010)

Kramer, J.V., Steen, S.: Sail-induced resistance on a wind-powered cargo ship. Ocean Eng. **261**, 111688 (2022)

Kumar, V., Boote, D., Pais, T.: Development of a parametric model for analysing temperature effects of solar radiation on yachts. RINA Trans. Pt. B Int. J. Small Craft Technol. **158**., Part B1, pp. B-1,B-13, Jan-Jun 2016 (2016). https://doi.org/10.3940/rina.ijsct.2016.bl.l70

Larsson, L., Eliasson, R., Orych, M.: Principles of Yacht Design. Bloomsbury Publishing, London (2022)

Lau, C.-Y., Ali-Lavroff, J., Holloway, D.S., Shabani, B., AlaviMehr, J., Thomas, G.: Influence of an active T-foil on motions and passenger comfort of a large high-speed wave-piercing catamaran based on sea trials. J. Mar. Sci. Technol. **27**, 856–872 (2022a). https://doi.org/10.1007/s00773-022-00876-8

Lau, C.-Y., Ali-Lavroff, J., Holloway, D.S., AlaviMehr, J., Thomas, G.: Influence of an active T-foil on motions and passenger comfort of a wave-piercing catamaran based on sea trials in oblique seas. J. Eng. Maritime Environ., 1–13 (2022b). https://doi.org/10.1177/14750902221111122

Lazakis, I., Khan, S.: An optimization framework for daily route planning and scheduling of maintenance vessel activities in offshore wind farms. Ocean Eng. **225** (2021). https://doi.org/10.1016/j.oceaneng.2021.108752

Lee, E.J., et al: Experimental and computational fluid-structure interaction analysis and optimization of deep-V planing-hull grillage panels subject to slamming loads – part II: irregular waves. Ocean Eng. **292** (2024). https://doi.org/10.1016/j.oceaneng.2023.116346

Lemström, I., Polojarvi, A., Tuhkuri, J., Puolakka, O.: Model-Scale Tests on the Ice-Structure Interaction Process in Shallow Water, p. 22084. IAHR Ice (2022a)

Lemström, I., Polojarvi, A., Tuhkuri, J.: Model-scale tests on ice-structure interaction in shallo water – part I: global ice loads and the ice loading process. Mar. Struct. **81**, 103106 (2022b)

Li, H., Deng, B., Zou, J., Dong, C., Liu, C., Liu, P.: Experimental free-drop test investigation into wet-deck slamming loads on a generic trimaran section considering the influence of main hull profile. Ocean Eng. **242**, 110114., ISSN 0029-8018 (2021a). https://doi.org/10.1016/j.oceaneng.2021.110114

Li, H., Zou, J., Deng, B., Liu, R., Sun, S.: Experimental study of stern slamming and global response of a large cruise ship in regular waves. Mar. Struct. **86**, 103294 (2022a). https://doi.org/10.1016/j.marstruc.2023.103563

Li, F., Ding, S., Liu, R., Wang, A.: Stress-Strain Predictive Analysis of Ship Structure in Ice Area Based on Neural Network. OMAE2023-104315 (2023)

Li F., Khawar M.B., Sandru A., Lu L., Suominen M., Kujala P. (2021b) Full-scale measurement of ship performance and ice loads in Antarctic floe ice fields POAC21-038

Li, F., Liangliang, L.L., Suominen, M., Kujala, P.: Short-term statistics of ice loads on ship bow frames in floe ice fields: full-scale measurements in the Antarctic Ocean. Mar. Struct. **80**, 103049 (2021c)

Li, H., Zou, J., Peng, Y., Zhou, X., Lu, L., Sun, S.: Numerical study of slamming and whipping loads in moderate and large regular waves for different forward speeds. Mar. Struct. **94** (2024). https://doi.org/10.1016/j.marstruc.2023.103563

Li, B., Qiao, D., Zhao, W., Hu, Z., Li, S.: Operability analysis of SWATH as a service vessel for offshore wind turbine in the southeastern coast of China. Ocean Eng. **251**, 111017 (2022). https://doi.org/10.1016/j.oceaneng.2022.111017

Lin, B., Liang, C., Zhang, L., Qian, H.: Design of a convertible autonomous sailboat. In: In 2023 IEEE International Conference on Real-Time Computing and Robotics (RCAR), pp. 566–572. IEEE (2023)

Liu, C., Zhou, L., Ding, S., Liu, R., Wang, A.: Numerical Simulation of Ice-Propeller Milling Process with Cohesive Element Method. OMAE2023-104308 (2023)

Ljulj, A., Slapnicar, V., Smiljanic, D.: Proliferation of unmanned aerial and maritime vehicles in military operations. In: Degiuli, N., et al. (eds.) Theory and Practice of Shipbuilding. IOS Press (2024). https://doi.org/10.3233/PMST240043

Lloyd, T., Foeth, E.J., Lafeber, F.H., Bosschers, J.: Progress in the prediction and mitigation of propeller cavitation noise and vibrations. In: 26th International Virtual HISWA Symposium: On Yacht Design and Yacht Construction (2020)

Lowde, M.J., Peters, H.G.A., Geraghty, R., Graham-Jones, J., Pemberton, R., Summerscales, J.: The 100 m composite ship? J. Mar. Sci. Eng. **10**(3), 408 (2022)

Lorimer, T., Allen, T.: Concurrent multi-component optimization of stiffened-plate yacht structures. J. Sail. Technol. **7**(01), 203–227 (2022)

Lyons, D.: Expert Report, Sailing Vessel Showtime, Loss of Keel, 5 January 2020. Federal Court of Australia, NSD774/2020 (2021)

Lyons, D., Bird, A., Hinterhoeller, R., Hoffmeister, H., Loiselet, K., Souppez, J.-B.R.G.: Regulatory developments in structural keel design: A revised ISO 12215-9. In: 8th High Performance Yacht Design Conference, Auckland, New Zealand (21–22 March 2024)

Ma, S., et al: Experimental study on the drop test on wet deck slamming for a SWATH segment model. Ocean Eng. **285**(part 2), 115377, ISSN 0029-8018. (2023a). https://doi.org/10.1016/j.oceaneng.2023.115377

Ma, S., Zhu, M., Liu, D., Liu, J., Wang, W.: Experimental study of wet deck slamming for a SWATH in regular waves. Ocean Eng. **288**(part 1), 115996, ISSN 0029-8018 (2023b). https://doi.org/10.1016/j.oceaneng.2023.115996

MAIB: Report on the Investigation of the Loss of the Yacht Cheeki Rafiki and its Four Crew in the Atlantic Ocean, Approximately 720 Miles East-South-East of Nova Scotia, Canada on 16 May 2014. Marine Accident and Investigation Branch, Accident Report 08-2015, Southampton (2015)

Maksimova, P.V., Chernov, A.V., Likhomanov, V.A., Svistunov, I.A.: Ice Load Monitoring System for an Ice-Resistant Self-Propelled Drifting Platform "North Pole". POAC21-042 (2021)

Marimon Giovannetti, L., Farousi, A., Ebbesson, F., Thollot, A., Shiri, A., Eslamdoost, A.: Fluid-structure interaction of a foiling craft. J. Mar. Sci. Eng. **10**(3), 372 (2022)

Malchow, U.: Growth in Container Ship Sizes to Be Stopped. Maritime Business Review (2017). ISSN: 2397-3757

Marlantes, K.E., Maki, K.J.: A neural-corrector method for prediction of the vertical motions of a high-speed craft. Ocean Eng. **262** (2022). https://doi.org/10.1016/j.oceaneng.2022.112300

Miller, L.P., Quinton, B., Soper, J., Veitch, B.: Development of Ice-Load Algorithm for Real-Time Feedback During Simulator Training. OMAE2023-101443 (2023)

Minty, P., Gohari, S., Field, B., Burvill, C.: Analytical and experimental studies on dynamic response of a SES air cushion plenum experiencing forced oscillation. Ocean Eng. **289**, 116265 (2023). https://doi.org/10.1016/j.oceaneng.2023.116265

Mokhtari, M., Kim, E., Amdahl, J.: Numerical Simulation of an Aluminium Panel Subject to Ice Impact Load Using a Rate and Pressure Dependent Elastoplastic Material Model for Ice. OMAE2023-104771 (2023)

Montigneaux, R., Macdowall, A., Mower, M.: The business of yachting. Boat Int., 50–65 (2023). https://cdn.boatinternational.com/files/2023/01/9148ea90-9003-11ed-af00-9f6e2a9c4532-GOB_2019.pdf

Motok, M., Momčilović, N., Rudaković, S.: Reliability based structural design of river–sea tankers: still water loading effects. Mar. Struct. **83**, 103202 (2022)

Moupagitsoglou, K.: Structural glass in superyacht applications: overcoming challenges, design standards and analysis methods, challenging glass 7. In: Belis, Bos, Louter (eds.) Conference on Architectural and Structural Applications of Glass. Ghent University. ISBN 978-94-6366-296-3 (September 2020). https://doi.org/10.7480/cgc.7.4609

Mouton, L., Finkelstein, A.: Exploratory study on the flutter behavior of modern yacht keels and appendages. In: 5th High Performance Yacht Design Conference, Auckland, New Zealand (2015)

Mouton, L., Leroyer, A., Deng, G., Queutey, P., Soler, T., Ward, B.: Towards unsteady approach for future flutter calculations. J. Sail. Technol. **3**(1), 1–19 (2018)

Neves-Moreira, F., Veldman, J., Teunter, R.H.: Service operation vessels for offshore wind farm maintenance: optimal stock levels. Renew. Sust. Energ. Rev. **146**, 111158 (2021)

Nickerson, B.N., Laas, J., Bekker, A.: Verification of Inverse Propeller Moment Estimation Using a Scale Laboratory Rig: Further Results and Discussion. OMAE2023-104878 (2023)

Nickerson, B.N., Laas, J., Bekker, A.: Verification of Inverse Propeller Moment Estimation Using a Scale Laboratory Rig. OMAE2022-78787 (2022)

Nilva, V.: Detailed analysis of hull damages of river and river-sea cargo vessels. In: Proceedings of Fifteenth International Conference on Marine Sciences and Technologies (Black Sea' 2020), pp. 166–171, Varna (Bulgaria) (2020)

Ocera, M., Boote, D., Vergassola, G., Faloci, F.: Simplified analytical method for the evaluation of longitudinal strength of large sailing yachts. Ocean Eng. **133**, 182–196 (2017). https://doi.org/10.1016/j.oceaneng.2016.11.064

Oldford, D., Moakler, E., Bond, J.: Ice Class IA or Ice Class PC7 for Arctic Operations. ISOPE 2023, 2009 (2023)

Office for Product Safety and Standards: Recreational Craft Regulations 2017: Great Britain. Office for Product Safety and Standards – Department for Business, Energy and Industrial Strategy, Birmingham (2017)

Oh, D., Jang, J., Jee, J.H., Kwon, Y., Im, S., Han, Z.: Effects of fabric combinations on the quality of glass fiber reinforced polymer hull structures. Int. J. Nav. Archit. Ocean Eng. **14**, 100462 (2022)

Oh, E., Ha, J.S.: Estimating Missing Hull Strain Gauge Data of the ARAON Using Artificial Intelligence. POAC, 2022, Paper76 (2022)

Pan, J., Zhang, W.Z., Sun, Z.M., Qu, X., Xu, M.C.: Experimental study on the dynamical response of elastic trimaran model under slamming load. J. Mar. Sci. Technol. (2023). https://doi.org/10.1007/s00773-023-00969-y

Parunov, J., et al: Benchmark on the prediction of whipping response of a warship model in regular waves. Mar. Struct. **94**, 103549 (2024)

Patterson, N., Binns, J.: Development of a six degree of freedom velocity prediction program for the foiling America's cup vessels. J. Sail. Technol. **7**(01), 120–151 (2022)

Pei, Z., Ma, Z., Bo, Z., Wu, W.: Research on the bending efficiency of superstructure to hull girder strength of inland passenger ship. Ocean Eng. **195**, 106762 (2020)

Perälä, I., Tikanmaki, M., Heinonen, J.: Ice Impact Loads on Azimuthing Thrusters – Small-Scale Impact Tests and Analysis, p. 22075. IAHR Ice 2022 (2022)

Perčić, M., Vladimir, N., Koričan, M., Jovanović, I., Haramina, T.: Alternative fuels for the marine sector and their applicability for purse seiners in a life-cycle framework. Appl. Sci. **13**(24), 13068, 30 p (2023)

Perčić, M., Koričan, M., Jovanović, I., Vladimir, N.: Environmental and economic assessment of batteries for marine applications: case study of all-electric fishing vessels. Batteries. **10**(1) 2024., paper no. 7, 17 p (2024)

Petković, M., Zubčić, M., Krčum, M., Pavić, I.: Wind assisted ship propulsion technologies – can they help in emissions reduction? Naše More. **68**(2), 102–109 (2021)

Petry, A., Hammer, T.C., Polojärvi, A., Hendrikse, H., Puolakka, O.: Ice Basin Experiments on Mixed-Mode Failure on Ice Cones. POAC2022, paper 29 (2022)

Qu, X., Yu, W., Wenzhe, Z., Sun, Z.: Numerical study on the dynamic response and slamming pressure of trimarans. In: Paper Presented at the 33rd International Ocean and Polar Engineering Conference, Ottawa (June 2023)

Radojcic, D., Simic, A., Momcilovic, N., Motok, V., Friedhoff, B.: Design of Contemporary Inland Waterway Vessels (The Case of the Danube River). Springer (2022)

Rahman, S.M., Handler, R.M., Mayer, A.L.: Life cycle assessment of steel in the ship recycling industry in Bangladesh. J. Clean. Prod. **135**, 963–971 (2016). https://doi.org/10.1016/j.jclepro.2016.07.014

Raju, R., Prusty, B.G., Kelly, D.W., Lyons, D., Peng, G.D.: Top hat stiffeners: a study on keel failures. Ocean Eng. **37**(13), 1180–1192 (2010)

Ramsses: Realisation and demonstration of advanced material solutions for sustainable and efficient ships (2023). https://www.ramsses-project.eu/. Accessed 24 Nov 2023

Reche-Vilanova, M., Hansen, H., Bingham, H.B.: Performance prediction program for wind-assisted cargo ships. J. Sail. Technol. **6**(01), 91–117 (2021)

Ren, Z., Javaherian, J., Gilbert, C.M.: Kinematic and inertial hydroelastic effects caused by vertical slamming of a flexible V-shaped wedge. J. Fluids Struct. **103**, 103257 (2021a). https://doi.org/10.1016/j.jfluidstructs.2021.103257

Ren, Z., Skjetne, R., Verma, A.S., Jiang, Z., Gao, Z., Henning, H.K.: Active heave compensation of floating wind turbine installation using a catamaran construction vessel. Mar. Struct. **75**, 102868 (2021b)

Rinauro, B., Begovic, E., Mauro, F., Rosano, G.: Regression analysis for container ships in the early design stage. Ocean Eng. **292** (2024). https://doi.org/10.1016/j.oceaneng.2023.116499

Rosano, G., Begovic, E., Boccadamo, G., Míguez González, M., Rinauro, B., Santiago Caamaño, L.: On-board monitoring and estimation of lateral accelerations through extreme value theory. Ocean Eng. **284**, 115177, 12 p (2023)

Rosén, A., Garme, K., Razola, M., Begovic, E.: Numerical modelling of structure responses for high-speed planing craft in waves. Ocean Eng. **217** (2020). https://doi.org/10.1016/j.oceaneng.2020.107897

Russell, S., Vanhollebeke, G., Manganelli, P.: Insights from the Load Monitoring Program for the 2014–2015 Volvo Ocean Race. SNAME Chesapeake Sailing Yacht, Annapolis (2016)

Salganik, E., Ervik, A., Heinonen, J., Høyland, K.V., Perälä, I.: Scale-Model Ridges and Interaction with Narrow Structures, Part 2: Thermodynamics of Ethanol Ice. POAC21-067 (2021)

Santiago, C.L., Galeazzi, R., Nielsen, U.D., Míguez, G.M., Díaz, C.V.: Real-time detection of transverse stability changes in fishing vessels. Ocean Eng. **189**, 106369., ISSN 0029-8018 (2019). https://doi.org/10.1016/j.oceaneng.2019.106369

Santiago Caamaño, L., Míguez González, M., Galeazzi, R., Nielsen, U.D., Díaz Casás, V.: Application of real-time estimation techniques for stability monitoring of fishing vessels. In: Spyrou, K.J., Belenky, V.L., Katayama, T., Bačkalov, I., Francescutto, A. (eds.) Contemporary Ideas on Ship Stability. Fluid Mechanics and Its Applications, vol. 134. Springer, Cham (2023). https://doi.org/10.1007/978-3-031-16329-6_21

Santoso, B.R., Nasution, P.: Analysis strength structure fishing vessel of composite sandwich plate system using finite element method. IOP Conf. Ser.: Earth Environ. Sci. **695**(1), 012021 (2021)

Saral, D., Köse, E.: A non-dimensional offset table for the Black Sea type fishing vessels. Appl. Ocean Res. **139**, 103705 (2023). https://doi.org/10.1016/j.apor.2023.103705

Sawamura, J., Yamaguchi, H., Ushio, S., Mizuno, S.: Relationship Between Ship Structural Response and Ice Conditions in Antarctic Ocean. POAC, 2023, Paper 65 (2023)
Shabani, B., Ali-Lavroff, J., Holloway, D., Penev, S., Dessi, D., Thomas, G.: Using remote monitoring and machine learning to classify slam events of wave piercing catamarans. Int. J. Mar. Eng. **163**, A15–A30 (2021). https://doi.org/10.5750/ijme.v163iA3.797
Shabani, B., Ali-Lavroff, J., Holloway, D., Penev, S., Dessi, D., Thomas, G.: Intelligent monitoring of a large catamaran ferry. Int. J. Mar. Eng. **165**, A11–A22 (2023). https://doi.org/10.5750/ijme.v165ia1.791
Shamaei, F., Bergstrøm, M., Li, F., Taylor, R., Kujala, P.: Local pressures for ships in ice: probabilistic analysis of fullscale line load data. Mar. Struct. **74**, 102822 (2020)
Shao, W., Ma, S., Duan, W., Liu, J., Zhang, Y.: Vertical force prediction of planing craft in calm water based on variable section slamming model. Ocean Eng. **287**, 115693 (2023). https://doi.org/10.1016/j.oceaneng.2023.115693
Shenoi, A., et al: Committee V.8 Sailing Yacht Design, 17th International Ship and Offshore Structures Congress, 16–21 August 2009, Seoul, Korea (2009)
Shin, Y., Kim, Y.: Fatigue Damage Estimation of a Sloped Offshore Structure in Level Ice. POAC21-071 (Conical structure) (2021)
Silvestri, P., Pais, T., Vergassola, G.: On the experimental full scale vibrational response analysis of a large pleasure yacht. Appl. Ocean Res. **150**, 104141 (2024). https://doi.org/10.1016/j.apor.2024.104141
Souppez, J.B., Ridley, J.: The Revisions of the BS EN ISO 12215. Marine Sector Showcase-Composite UK (2017)
Souppez, J.B.R.: Structural design of high performance composite sailing yachts under the new BS EN ISO 12215-5. J. Sail. Technol. **3**(1), 1–18 (2018a)
Souppez, J.B.R.: Structural analysis of composite search and rescue vessels under the new BS EN ISO 12215-5. In: RINA Surveillance, Search and Rescue Craft Conference, London, (April 2018b)
Souppez, J.B.: Designing the next generation of small pleasure and commercial powerboats with the latest ISO 12215-5 for hull construction and scantlings. In: 1st SNAME/IBEX Symposium. Society of Naval Architects and Marine Engineers (2019)
Souppez, J.B., Dewavrin, J.M., Gohier, F., Labi, G.B.: Hydrofoil configurations for sailing superyachts: Hydrodynamics, stability and performance. In: Design & Construction of Super & Mega Yachts. Royal Institution of Naval Architects (2019a)
Souppez, J.B.R., Arredondo-Galeana, A., Viola, I.M.: Recent advances in numerical and experimental downwind sail aerodynamics. J. Sail. Technol. **4**(01), 45–65 (2019b)
Souppez, J.B.R., Begovic, E., Sensharma, P., Wang, F., Rosén, A.: Comparative assessment of rule-based design on the pressures and resulting scantlings of high speed powercrafts. In: HSMV 2020, pp. 263–275. IOS Press (2020)
Souppez, J.B.: Experimental testing of scarf joints and laminated timber for wooden boatbuilding applications. Int. J. Mar. Eng. **163**(A3) (2021). https://doi.org/10.5750/ijme.v163iA3.16
Souppez, J.B., Laci, J.: Ultimate strength of quasi-isotropic composites: ISO 12215-5: 2019 validation. Int. J. Mar. Eng. **164**(A2), 237–246 (2022)
Souppez, J.B.R.: Structural design of wooden boats. In: Historic Ships Conference 2023: Historic Vessels: Sustainable Futures. Royal Institution of Naval Architects (2023)
Souppez, J.-B.R.G., Viola, I.M.: Water tunnel testing of downwind yacht sails. Exp. Fluids. **65**, 15 (2024)
Su, S.J., Han, J., Xiong, Y.: Optimization of unmanned ship's parametric subdivision based on improved multi-objective PSO. Ocean Eng. **194**, 2019 (2019)
Su, S.J., Liu, C.B., Zhang, X., Wang, G.H.: Multi object optimization design of cargo hold structure of NOBS tanker based on RBF agent model. J. Wuhan Univ. Technol. **43**(11) (2021)

Su, S.J., Wang, G.H., Zhang, X.: Topology optimization of midship section of cargo hold of V-type non-ballast water tanker. Ship Eng. **44**(4), 58–63 (2022)

Sun, Z., et al: Characteristics of slamming pressure and force for trimaran hull. J. Mar. Sci. Eng. **9**(6), 564 (2021)

Sun, Z., Deng, Y.Z., Zou, L., Jiang, Y.C.: Investigation of trimaran slamming under different conditions. Appl. Ocean Res. **104**, 102316., ISSN 0141-1187 (2020). https://doi.org/10.1016/j.apor.2020.102316

Suominen, M., Toroody, A.B., Valdez, B.O.: Empirical Mode Decomposition for Noise Detection and Filtration of Ice-Induced Load Measurements. OMAE2023-102504 (2023)

Suominen, M., Lu, L., Kujala, P., Bekker, A.: Antarctic Sea Ice Properties on Zero Meridian Side During Austral Summers 2012–14 and 2018–19. POAC21-074 (2021)

Tabri, K., Tõns, T., Suominen, M., Kõrgesaar, M.: Ice-Induced Loads on Offshore Wind Turbines in the Baltic Sea. OMAE2022-79035 (2022)

Terui, C., Hino, T., Takagi, Y.: Numerical analysis of wake wash reduction for catamaran with hydrofoils. Appl. Ocean Res. **135**, 103556 (2023)

Thijssen, J., Fuglem, M., King, T., Paulin, M.: Evaluation of Floating Wind Turbine Platform Designs for Sea Ice Loads, p. 22111. IAHR Ice 2022 (2022)

Tillig, F., Ringsberg, J.W.: Design, operation and analysis of wind-assisted cargo ships. Ocean Eng. **211**, 107603 (2020)

TNO: Offshore Wind Access Report 2020. TNO' Internal R&D Instrument 'Kennis en Innovatie Project' – Programme 2020 (KIP), Pette, The Netherlands (2020) https://publications.tno.nl/publication/34637592/uSPDJu/TNO-2020-R11992.pdf

Truelock, D., et al: Committee V.5 special vessels. In: 21st International Ship and Offshore Structures Congress (ISSC 2022), September 11–15 2022, Vancouver, Canada (2022)

Truelock, D., et al: Committee V.5 special craft. In: 20th International Ship and Offshore Congress, Leige-Delft, September 2018 (2018). https://doi.org/10.3233/978-1-61499-864-8-279

Tusar, M.I.H., Sarker, B.R.: Developing the optimal vessel fleet size and mix model to minimize the transportation cost of offshore wind. Ocean Eng. **274** (2023). https://doi.org/10.1016/j.oceaneng.2023.114041

Uğurlu, F., Yıldız, S., Boran, M., Uğurlu, O., Wang, J.: Analysis of fishing vessel accidents with Bayesian network and Chi-square methods. **198**(2020), 106956 (2020). https://doi.org/10.1016/j.oceaneng.2020.106956

van Walree, F., Thomas, W.L.: Validation of simulation tools for a RHIB operating in heavy seas, in contemporary ideas on ship stability. In: Fluid Mechanics and Its Applications, vol. 134, pp. 690–707. Springer (2023)

van Walree, F., Sgariato, D.: Impulsive loads on and water ingress in a landing craft: model tests and simulations, contemporary ideas on ship stability. In: Fluid Mechanics and Its Applications, vol. 134, pp. 708–725. Springer (2023)

van der Kolk, N.J., Akkerman, I., Keuning, J.A., Huijsmans, R.H.M.: Low-aspect ratio appendages for wind-assisted ships. J. Mar. Sci. Technol. **26**, 1126–1143 (2021)

Valtonen, V., Bond, J., Hindley, R.: Improved method for non-linear FE analysis of polar class ship primary structures. Mar. Struct. **74**, 102825 (2020)

Veltheim, O., Suominen, M., Ikonen, T., Kujala, P.: Validation of an Inverse Model to Determine Ice Load Magnitude and Load Patch on a Ship Hull. IAHR Ice 2022 (2022)

Vergassola, G., Pais, T., Boote, D.: Numerical tools and experimental procedures for the prediction of noise propagation on board superyachts. RINA Trans. Pt. B Int. J. Small Craft Technol. **160(**Part B1), B-9, B-16, (Jan–Jun 2018) https://doi.org/10.3940/rina.ijsct.2018.b1.207.

Vergassola, G., Pais, T., Boote, D., Rasori, S., Tonelli, A.: On the structural assessment of tall ship rigs. Ships Offshore Struct. **2023** (2023). https://doi.org/10.1080/17445302.2023.2226506

Vergassola, G., Boote, D., Pais, T.: Hull–furniture interaction in the primary response to global loads of a carbon fibre sailing yacht. Ships Offshore Struct. **14**(3), 281–294 (2019a). https://doi.org/10.1080/17445302.2018.1498210

Vergassola, G., Pais, T., Boote, D.: Low-frequency analysis of super yacht free vibrations. Ocean Eng. **176** (2019b). https://doi.org/10.1016/j.oceaneng.2019.02.037

Vergassola, G.: The prediction of noise propagation onboard pleasure crafts in the early design stage. J. Ocean Eng. Mar. Energy. **6**(1), 15–301 (2020) https://link.springer.com/article/10.1007/s40722-019-00149-4

Vergassola, G., Boote, D.: A simplified approach to the dynamic effective thickness of laminated glass for ships and passenger yachts. Int. J. Interact. Des. Manuf. (IJIDeM). **14**, 123–135 (2020). https://doi.org/10.1007/s12008-019-00614-2

Wang, Q., Li, Z., Tan, B.: The Effects of Porosity on the Flexural and Uniaxial Compressive Strength of Sea Ice in the Summer Arctic. POAC, 2023, paper 67 (2023a)

Wang, J., Chen, X., Ji, S.: Analysis on the Influence of Measuring Point Failure in Ice Load Identification of Ship Structures. POAC, 2023, Paper106 (2023b)

Warren, M., Ali-Lavroff, J., McVicar, J., Magoga, T., Shabani, B., Holloway, D.: Fatigue estimation on a high-speed catamaran during normal operations. Int. J. Marit. Eng., A55–A67 (2022). https://doi.org/10.5750/ijme.v164i1.736

Warren, M., Ali-Lavroff, J., Holloway, D., Magoga, T.: Comparing linear damage hypothesis to linear elastic fracture mechanics in the estimation of fatigue life in a high speed light craft. Ocean Eng. **290**, 1116338 (2023). https://doi.org/10.1016/j.oceaneng.2023.116338

Wen, X., Del Buono, A., Liu, P., Qu, Q., Iafrati, A.: Acceleration effects in slamming and transition stages for the water entry of curved wedges with a varying speed. Appl. Ocean Res. **128** (2022). https://doi.org/10.1016/j.apor.2022.103294

Windyandari, A., Sulardjaka, K.O., Tauviqirrahman, M.: Bow structure damage analysis for hybrid coir-glass fiber composite fishing boat hull subjected to front collision load. Curved Layer. Struct. **9**, 236–257 (2022)

Wium, D., Lataire, E., Belis, J.: Considerations for the integration of glass in superyacht structures. In: Belis, J., Bos, F., Louter, C. (eds.) Challenging Glass Conference Proceedings, vol. 8, (2022). https://doi.org/10.47982/cgc.8.442

Wu, J., Sun, Z., Jiang, Y., Zhang, G., Sun, T.: Experimental and numerical study of slamming problem for a trimaran hull. Ships Offshore Struct. **16**(1), 46–53 (2021)

Xie, C., Zhou, L., Ding, S., Liu, R., Zheng, S.: Experimental and numerical investigation on self-propulsion performance of polar merchant ship in brash ice channel. Ocean Eng. **269** 113424 (2023)

Xin, J., Shi, F., Fan, S., Jin, Q.: A sharp interface multiphase flow model for two-dimensional water impact of a symmetric and asymmetric wedge. Appl. Ocean Res. **119**(2022), 102988 (2022). https://doi.org/10.1016/j.apor.2021.102988

Xu, S., Tang, Y., Chen, K., Zhang, Z., Ma, T., Tang, W.: Numerical investigation on pressure responsiveness properties of the skirt-cushion system of an air cushion vehicle international journal of naval architecture and ocean. Engineering. **12**(2020), 928–942 (2020). https://doi.org/10.1016/j.ijnaoe.2020.09.006

Yang, J., Sun, H., Li, X., Wu, D.: Experimental study on wave motion of partial air cushion supported catamaran. Int. J. Nav. Archit. Ocean Eng. **15**, 100525 (2023). https://doi.org/10.1016/j.ijnaoe.2023.100525

Yoon, S., Herrnring, H., Müller, F., von Bock und Polach F.: Numerical Analysis of Ice Blocks Impact on Stiffened Plates According to a Mohr-Coulomb Material and Node Splitting Technique. OMAE2023-102584 (2023)

Yu, Z., Lu, W., van Den Berg, M., Jørgen, A., Sveinung, L.: Glacial ice impacts: part ii: damage assessment and ice-structure interactions in accidental limit states (als). Mar. Struct. **75**, 102889 (2021)

Zambon, A., Moro, L., Biot, M.: Vibration analysis of super-yachts: validation of the Holden method and estimation of the structural damping. Mar. Struct. **75**, 102802., ISSN 0951-8339 (2021). https://doi.org/10.1016/j.marstruc.2020.102802

Zhang, Z., Shu, C., Khalid, M.S.U., Yuan, Z., Liu, W.: Investigations on the hydroelastic slamming of deformable wedges by using the smoothed particle element method. J. Fluids Struct. **114** (2022a). https://doi.org/10.1016/j.jfluidstructs.2022.103732

Zhang, G., Zhao, Y., Yang, B., Sun, Z.: Experimental and Numerical Investigation of the Hydrodynamic Effect during the Ice Floe-structure, p. 1325. ISOPE 2022 (2022b)

Zhao, W., et al: On the Structural Analysis of Icebreakers Due to Ramming of First-Year Ice Ridges. OMAE2022-79661 (2022a)

Zhao, W.H., Tian, Y., Yu, C., Gang, X., Lu, P.: Numerical Investigation on Center Loading on a Circular Plate of Model Ice. POAC, 2022, Paper36 (2022b)

Zhou, M., Jian, J., Wang, Q., Yang, M.: Ice-Pod Interaction Analysis for Ice-Classed Azimuth Propullsor. ISOPE2023, 1952 (2023)

Zhu, X., Liang, C., Qian, H.: Design and implementation of a novel adaptive multihull sailboat with liftable side hulls. In: 2023 IEEE International Conference on Robotics and Biomimetics (ROBIO), pp. 1–6. IEEE (2023)

Zhu, L., Cai, W., Chen, M.S., et al.: Experimental and numerical analyses of elastic-plastic responses of ship plates under ice floe impacts. Ocean Eng. **218**, 108174 (2020)