Committee V.2: Experimental Methods

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Committee Mandate. Concern for advances in structural model testing and full-scale experimentation and in-service monitoring and their role in the design, construction, inspection and maintenance, structural health monitoring and digital twin of ship and offshore structures. This shall include new developments in: best practice and uncertainty analysis; experimental methods and techniques; full field imaging and sensor systems; data post processing and applications for ship and offshore structures; and correlation between model, full-scale and numerical datasets.

Keywords: Experimental methodologies · scale laws · hydrodynamic behavior of flexible structures · wave-in-deck phenomena · hybrid model evaluations · vibrational analysis · fatigue assessment · large-scale impact experiments · corrosion assessments · comprehensive iced load measurements · health monitoring frameworks · digital twin models · Digital Image Correlation (DIC)

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1 Introduction

Experimental methodologies are employed to assess the performance and responses of maritime vessels and offshore structures under diverse conditions. These experiments utilize sensor systems and numerical models to corroborate and substantiate design criteria, life cycle performance, accidental scenarios, and life cycle responses. This report embodies the expertise of the authors within their respective fields of research and disciplines, encapsulating the state of the art and identifying critical technologies and existing gaps in such fields.

The report encompasses sections on scaling laws, fluid-structure interaction, hybrid models, fire, friction, corrosion prognostics, large-scale subsea structures, large impact tests, full-scale ice loads, health monitoring, digital twins, and digital image correlation. It serves as a continuation of the 2021 report, incorporating a section with updates on the prior benchmark study. The report also provides a summary of findings and recommendations at the conclusion, emphasizing areas where further research is recommended.

The collaborative efforts of the diverse group of authors from various global regions are evident in the composition of this document. Overleaf served as the collaborative online platform to assemble the LaTeX content, facilitate version control, manage references, and resolve comments. Furthermore, its grammatical tool, Windscribe, was employed for editorial purposes. This tool utilizes language models and artificial intelligence capabilities to harmonize linguistic tone and standardize readability. It is crucial to highlight that the development of content was exclusively performed by the author, whereas the deployment of editorial tools was confined to grammatical and language standardization.

2 Scaling Laws

2.1 Introduction

Model-scale testing constitutes an important practice within the scientific domain. Compared to full-scale investigations, model-scale testing provides a controlled environment for studying phenomena, performance, and structural behavior, etc. Relative to other laboratory experiments, model-scale testing facilitates the examination of global phenomena and processes while integrating these with studies concentrating on local phenomena and processes. Furthermore, it presents a cost-effective approach to design analysis. This is particularly significant for industries characterized by limited production series or where prototypes serve as the definitive product, such as in shipbuilding. To effectively conduct model-scale testing and extrapolate observations to full-scale, it is imperative to comprehend the translation of these observations across varying scales, which can be accomplished via similitude methods or scaling laws.

This chapter offers a comprehensive examination of the applications and advancements of these theories. Recently, extensive reviews authored by Coutinho et al. (2016) and Casaburo et al. (2019) have been published, concentrating on similitude methods within structural engineering, while also encompassing publications external to the marine technology domain. These reviews have been significantly reflected in relevant sections of the most recent ISSC Experimental Committee reports (Ehlers S., 2022). Consequently, this review is dedicated to the exploration of studies not encompassed within those publications. The subsequent chapter presents an overview of various similitude methods, subsequently followed by recent developments and applications related to scaling laws.

2.2 Similitude Methods

Similitudes can be classified into three primary categories: geometric, kinematic, and dynamic similitude. Geometric similitude necessitates that geometric characteristics are scaled uniformly. Kinematic similarity asserts that velocities at corresponding points must be scaled by a constant factor. Dynamic similitude requires that all forces in the model be proportionally scaled by a constant factor relative to the corresponding forces in the prototype. An alternative method for classifying similitude is predicated on the fulfillment of similitude conditions (Casaburo et al., 2019), which pertains to the extent of similitude representation within the model: complete, adequate, or distorted. Complete similitude or true models satisfy all relevant conditions. Adequate similitude or first-order models fulfill the conditions related to the principal parameters. Distorted similitude or partial models do not satisfy at least one of the first-order conditions. These classifications must be considered and comprehended in the translation of observations across scales and during test preparations.

Similitude methods can be categorized into broader groups, which can be further subdivided into more specific subgroups based on the methodological approach. The literature exhibits a variety of divisions and terminologies that are somewhat contingent on the preferences of the respective authors. In general, these methods can be classified into dimensional analysis, application to governing equations, energy methods, and empirical similitude, as delineated in the ISSC Experimental Committee report (Ehlers S., 2022), consistent with the frameworks set forth by Coutinho et al. (2016) and Casaburo et al. (2019).

Dimensional analysis represents the conventional approach for establishing scaling laws (Coutinho et al., 2016), facilitating the identification of fundamental quantities that characterize the physical phenomenon or system (Ehlers S., 2022). This analysis involves defining a set of dimensionless parameters that govern the phenomenon under investigation. A physical phenomenon is expressed by an equation wherein both sides possess identical dimensions, known as dimensional homogeneity. These principles are encapsulated in Buckingham's theorem. In certain applications, this theorem is circumvented, and scaling laws are formulated by defining a scaling factor that represents the prototype/model ratio as a power law. The advantages of dimensional analysis include its simplicity and applicability even in the absence of known governing equations. However, a significant drawback lies in the necessity for an experienced analyst to select relevant parameters for the analysis. Furthermore, the resulting dimensionless terms, derived from the physical parameters when applying the theorem, may lack physical significance and uniqueness, often necessitating a trial-and-error approach (Casaburo et al., 2019).

An alternative prevalent method for deriving similitude conditions involves the direct application of similitude theory to the governing equations. This methodology entails the application of similitude theory directly to the fundamental equations of the system, encompassing boundary and initial conditions, which define the system with relevant variables and parameters. Given that analogous models are regulated by the same set of fundamental equations and conditions, similitude conditions can be deduced by establishing scale factors and juxtaposing the equations of the prototype with those of the model (Casaburo et al., 2019). This method connects the geometric, structural, excitation, and material attributes of the system with its response. The benefit of this approach lies in its ability to yield specific similitude conditions that possess physical significance. The primary limitation, however, is the necessity for the underlying equations to be known.

The energy method utilizes the principle of conservation of energy to establish similitude. Within this framework, the potential energy, exemplified as strain energy, is equivalent to the aggregate of kinetic energy and the work exerted by external forces. As the equation dictated by this principle incorporates the structural domain, applied loads, and boundary conditions, the system is analyzed in its entirety, thus negating the necessity to ascertain explicit and implicit scale factors (Casaburo et al., 2019).

The empirical similarity method entails the evaluation of two specimens. One specimen is fabricated via rapid prototyping using a simple geometric configuration, while the other is produced through the standard manufacturing process. The state transformation is ascertained by measuring the state vectors of these two specimens, in conjunction with the scaled structure derived from rapid prototyping.

2.3 Recent Developments in Ship and Offshore Structure Testing

Environment

Historically, model-scale testing in ice has concurrently employed Froude and Cauchy scaling methods. This combined scaling approach, along with the expertise of operational ice tanks, has demonstrated a strong correlation between scales concerning the performance in ice (such as resistance and maneuverability) of vessels with conventional hull designs, as noted by Riska et al. (1994) and Lau (2015). Nevertheless, this methodology results in relatively pliable model ice with increased plasticity, as discussed in A. Palmer & Dempsey (2009, R. U. F. von Bock und Polach & Molyneux (2017), von Bock und Polach et al., (2019), which may impede scale correlation when the testing parameters are adjusted. Consequently, novel scaling approaches for ice in model-scale testing have been proposed in recent studies.

To address the limitations associated with soft model ice, von Bock und Polach et al. (2021) proposed the use of Model Ice of Virtual Equivalent Thickness (MIVET). The fundamental aim of this method is to enhance the elastic modulus of ice to mitigate plasticity while preserving the ice stiffness number by reducing its thickness. The ice stiffness number serves as an equivalent to the ratio of the characteristic length to the ice thickness (F. Li et al., 2003). In order to ensure that the ice fractures under an external load comparable to that of conventionally scaled ice, the approach recommends an accurate scaling of the critical bending moment, which is determined via cantilever beam testing. To realize this, the method requires the ice's strength to be increased by the square of the factor k applied to modify the ice thickness h, denoted as MIVET = h/k (F. von Bock und Polach et al., 2021). The authors acknowledge that this technique modifies the ice's mass; however, the error introduced is deemed negligible for wave propagation within solid ice (Fox, 2001).

Challenges associated with soft model ice can considerably impede the accurate depiction of processes pertinent to structure-ice interactions. This is particularly true for investigations centered on the vibration of vertical structures where ice crushing predominantly influences the interaction. Following the recommendation by Palmer and Dempsey (2009), Hammer and Handrikse (2023) posited that ice strength remains invariant across scales. Within their methodology, the modal characteristics of structural models are adjusted through mass scaling, which corresponds to the ratio of mean brittle crushing load between model-scale and full-scale; however, the strength of the ice is not scaled (Hendrikse et al., 2022; Hammer & Hendrikse, 2023; Hammer et al., 2023). The outcomes indicate that this approach results in an enhanced representation of ice-induced vibrations compared to the conventional Froude-Cauchy scaling.

Merchant vessels operating in ice-covered maritime regions are typically engineered to function with the assistance of icebreakers. Consequently, these vessels are generally constructed to navigate through a broken ice channel, which serves as the design ice condition for merchant vessel construction in accordance with the Finnish-Swedish Ice Class Rules. According to Matala (2021), the soft model ice scaled using Froude-Cauchy scaling fails to accurately represent the natural behavior of brash ice, resulting in conservative performance estimates for vessels with hull forms optimized for open water (Matala & Suominen, 2022). This discrepancy is thought to be associated with an increased cohesion between brash ice fragments in the soft model ice compared to solid ice fragments in nature (Matala & Suominen, 2022). To address this issue, a new dimensionless parameter, termed brash ice similitude—which represents the relationship between cohesive and inertial forces—has been proposed for application in the scaling of brash ice properties to enhance the portrayal of brash ice behavior (Matala & Suominen, 2023). In practice, the new methodology suggests that the strength of brash ice fragments can be considered scale invariant, and that the cohesive forces between the ice fragments should be negligible at the model scale due to their minimal presence at the full scale. Fundamentally, this approach is consistent with the material strength-based scaling proposed by Høyland (2010) (Matala, 2021).

Structure Impact

Mazzariola and Alves (2019b) employed dimensional analysis, specifically the Buckingham theorem, to establish a scaling law for structural impact testing based on the VSM framework (comprising Initial Velocity, Yield Stress, and Structure Mass). This approach is capable of addressing thickness distortion, variations in density, and the mechanical properties of materials, such as yield stress, strain hardening, and strain-rate hardening. These distortions were mitigated through the development of a dimensionless parameter derived from the plastic bending moment. The methodology demonstrated substantial agreement between analytical and numerical analyses (Mazzariol & Alves, 2019b), and its validity was further substantiated through impact experiments involving various materials, scales, and applied loads (Mazzariol & Alves, 2019a).

Calle et al. (2020) employed an analogous methodology to assess structural impact, where a scaled-down model of a ship structure was fabricated using Additive Manufacturing techniques and subsequently subjected to collision tests. Nonetheless, it proved challenging to accurately scale the thicknesses of smaller structural components. It was observed that uniformly increasing the thickness across all structural elements did not yield an accurate representation of the model's response. Consequently, adjustments for thickness distortion in each structural element were made, taking into consideration the anticipated dominant structural collapse modes. In collision events involving large maritime structures, the predominant collapse mechanisms are associated with membrane tension and folding. This methodology was similarly employed and validated by Calle et al. (2020) through a large-scale raking experiment on a ship's bottom structure conducted by Kuroiwa et al. (1992).

Buckling

Wang et al. (2019) established a scaling law for the nonlinear buckling of stiffened orthotropic shallow spherical shells by employing an energy-based approach alongside Donnell's nonlinear shell theory. The total energy of the system was regarded as comprising both strain and potential energy components. The derivation of the strain energy took into account the constitutive equations pertinent to orthotropic shallow spherical shells. Concurrently, the potential energy resulting from external forces was derived under the assumption of external uniform pressure. Similitude factors, or scaling factors, which articulate the relationship between prototype and model parameters, were deduced by enforcing the requirement for complete geometric similitude of the skins of the two systems within the energy function. In the absence of empirical data, this scaling law was corroborated through numerical verification. Furthermore, the investigation included an analysis of partial similitude, or distorted models, concluding that a model with distortions in material properties and geometry is capable of forecasting the prototype's behavior. However, discrepancies in the Poisson's ratio may precipitate significant deviations in the behavior of the prototype.

Offshore Structure Vibrations

The interaction between ice and offshore structures presents distinct challenges, particularly for installations situated in regions characterized by seasonal ice cover. These challenges predominantly involve heightened loading and vibrational forces as a consequence of ice interaction. The phenomenon of frequency lock-in, wherein structural vibrations and movements are amplified due to ice interaction, poses significant risks for offshore infrastructures. Ziemer (2021) investigated the frequency lock-in phenomenon and ice-induced vibrations through model-scale experimentation with vertical structures embedded in ice. A recommendation was made to forgo Froude scaling since gravitational forces do not exert a substantial influence (A. Palmer et al., 2010). The crushing load scaling ratio was derived from the load equation pertinent to vertical structures, ensuring an accurate load level for rigid structures. However, the reliance of local pressure distribution on aspect ratio and ice thickness hinders complete similarity between the two geometrically scaled models. To accurately model the process associated with frequency lock-in, precise scaling of the amplification factor was deemed essential. Acknowledging that the local failure process dictating simultaneous load accumulation is independent of geometry, it was ascertained that time remains scale-independent. To maintain strain rate similarity, velocity must be scaled in accordance with geometric proportion, while the oscillator's mass must be adjusted by the square of the geometric scale. With this methodology, the crushing forces and the incidence of frequency lock-in are adequately scaled. Nonetheless, this approach necessitates large geometric scales due to stiffness considerations, whereupon the vibrations observed in model-scale evaluations may be insignificant enough to be reduced to mere noise.

A comparable scaling methodology has been employed in investigations concerning ice-induced vibrations on vertical-sided offshore structures (Hendrikse et al., 2022; Hammer & Hendrikse, 2023), and (Hammer et al., 2023). Hammer et al. (2024) proposed that the scaling of time should remain invariant, akin to the approach by Ziemer (Ziemer, 2021), while also ensuring the preservation of kinematics such that the amplitude of structural displacement remains consistent across different scales. Since the kinematics are not subjected to scaling, the properties of ice and the physical structure should exhibit uniformity across varying scales. For ice, the transition speed from ductile to brittle failure, as well as the impact of velocity, were regarded as critical for ice-induced vibrations impacting vertically-sided structures. To sustain these characteristics, the drift speed and strength of ice should remain unaltered. A more comprehensive exposition and discourse regarding the scaling has been discussed by Hammer et al. (2024). Aiming to achieve a structural response analogous to that observed in full-scale scenarios, a hardware-in-loop hybrid setup, encompassing both physical and numerical models, was implemented in model-scale testing. In the case of the physical model, the stiffness and material properties are maintained uniformly across different scales, i.e., they are not scaled. Nonetheless, mean pressure similarity, defined as the ratio between the measured model-scale and the estimated full-scale mean load, was employed to scale the structural properties (mass, damping, and stiffness) of the full-scale structure within the numerical domain during the model scale tests (Hammer et al., 2024; Hammer & Hendrikse, 2024). This scaling approach was corroborated through experimental validation, wherein the aspect ratio and shape of the structures were varied, and was qualitatively validated by replicating the structural vibrations observed in two full-scale structures, namely Molikpaq and Norströmsgrund lighthouse.

In the context of global ship vibrations, Froude scaling is employed due to the necessity for gravity wave similarity in experiments dominated by seakeeping considerations. It is demonstrable that geometric similarity with respect to the external configuration of the vessel, alongside dimensional analysis techniques for other aspects, can be effectively utilized (Bishop & Price, 1980). This approach relies on an idealized beam-like global dynamic behavior, which can be justifiably assumed in backbone models (refer to the subsequent section). To date, no comprehensive scaling theory has been established that encompasses both global and local scaling pertaining to ship structures. The typical method for assessing the effectiveness of the scaling process involves analyzing the resultant natural frequencies. While this approach may be adequate for vertical bending beam-like responses, it may rapidly lead to inaccuracies in the case of antisymmetric vibrations (Grammatikopoulos et al., 2021).

2.4 Summary and Conclusions

Model-scale testing has remained an important method for studying structures that requires understanding and development of scaling laws. Recently, the scaling laws developed for model-scale tests with structures have focused on structural failure in impact tests, vibrations, and buckling. In the case of model-scale testing in ice, the application of Froude-Cauchy scaling has been prevalent for several decades irrespective of the testing scope. Nevertheless, recent developments have shifted the emphasis towards scaling the response of ice in accordance with the specific testing scope. Consequently, various scaling methodologies tailored to distinct testing scenarios have been introduced. However, the validation of these newly proposed scaling methods is still in progress, and the current scaling approaches address only a limited range of testing scopes. Therefore, additional scaling strategies are necessary to adequately encompass the diverse scopes of different tests.

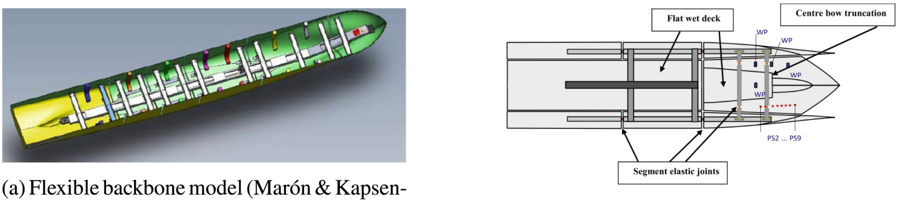
3 Fluid-Structure Interaction of Flexible Structures

3.1 Introduction

Ship and offshore structures frequently encounter conditions in which fluid-structure interactions are prevalent. Conducting experiments to assess global responses presents substantial challenges, as it necessitates the concurrent scaling of multiple aspects related to both structure and fluid (refer to the previous section). Predominantly, structural and wave-related aspects are scaled according to Froude's law, posing significant challenges; for wind turbines, Reynolds scaling may also be imperative, further increasing the complexity inherent in experimental design. This section elucidates the methodologies employed to develop flexible scaled models of ship and offshore structures for assessment within a towing tank, ocean basin, or analogous facility. The primary focus is on the scaling of the global responses of the structures. In this context, responses of individual components, such as foils, blades, sails, etc., are not considered. Consequently, the examined structural excitations are chiefly wave-induced. Aside from a singular instance presenting the response of a stiffened panel, this section exclusively addresses the global responses of ship hulls, floaters, and wind turbines. In the antecedent report by the Experimental Methods Committee, a section was dedicated to the hydrodynamics of flexible structures. This section seeks to augment that discourse by concentrating on the structural aspects of this interaction.

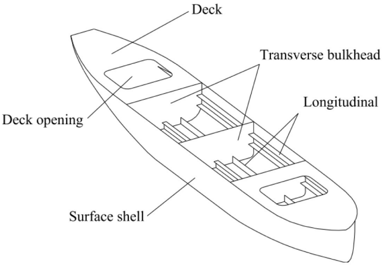
3.2 Types of Models

Models of ships and offshore structures intended for fluid-structure interaction experiments must possess the capability to undergo deformation in response to fluid excitation in a realistic manner. For Froude-scaled structures, this necessitates achieving identical strains at model-scale and full-scale. Irrespective of the structure type, flexible models are classified into distinct categories based on their manufacturing methods and the mode of introducing flexibility. In most cases, the external geometry, functioning as the fluid boundary, is composed of a series of rigid segments. Flexibility between these segments is provided through either a flexible backbone or a series of flexible joints. Less commonly, the structure is continuous, serving simultaneously as a source of stiffness and a fluid boundary. Illustrations of these categories for ships are presented in Fig. 1.



(a) Flexible backbone model (Marón & Kapsenberg, 2014)

(b) Flexible joint model (Davis et al., 2017)



(c) Elastic model (J. Jiao et al., 2021)

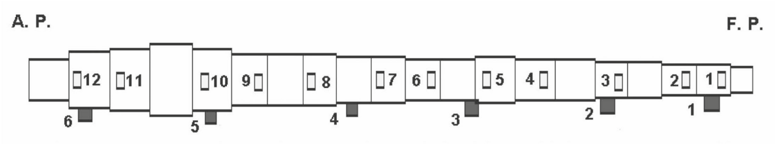
Fig. 1. Schematics of the three types of flexible models

The prevalence of experimental research utilizing flexible ship models surpasses that of floating structures. As a result, the nomenclature pertaining to various model types has predominantly developed within this domain of literature. This classification will be employed throughout the current section and will be extended to encompass models of other structural forms. The categorization is partially derived from the review conducted by Grammatikopoulos (Grammatikopoulos, 2023).

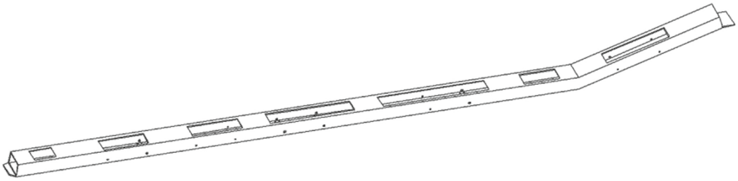
3.2.1 Flexible Backbone Models

Flexible backbone models integrate a backbone system to interconnect a sequence of rigid segments, as suggested by the nomenclature. Typically composed of aluminium or steel, this backbone may possess either a uniform or non-uniform cross-sectional profile along its length. The significance of the backbone's geometry is primarily related to its structural characteristics and its influence on the initial few natural frequencies, particularly the first one. Uniform backbones are often employed due to the simplicity of production and the focus on the first natural frequency. To accurately depict the 2-node bending mode, the assembly generally consists of a minimum of four segments. Deflection within the model is quantitatively assessed through the employment of strain gauges affixed along the backbone. For antisymmetric vibrations, shear strain gauges are utilized to measure shear strains along the backbone.

There are instances of non-uniform backbones in ship structures (refer to Fig. 2), particularly notable in vessels subjected to impulse loads (Dessi et al., 2007). In such scenarios, multiple flexible symmetric modes may be activated, necessitating a non-uniform stiffness distribution to achieve the scaling of natural frequencies. An alternative version of a non-uniform backbone is employed to scale the natural frequencies associated with antisymmetric modes. The prevalent method in this context involves introducing openings on the upper side of the backbone to approximate the shear centre location and distribution of torsional stiffness, thereby simulating deck openings typically found in container ships (Marón & Kapsenberg, 2014). Nonetheless, when a U-shaped backbone fabricated from steel or aluminum adheres to the stipulated scaling rules, it often fails to precisely align with the shear center location, resulting in diminished accuracy in the coupling level between horizontal bending and torsion (Grammatikopoulos, 2021). To mitigate this issue, materials characterized by a low Young's modulus, such as acrylonitrile butadiene styrene (ABS) resin, may be incorporated into the U-shaped backbone to concurrently simulate vertical vibration stiffness, horizontal vibration stiffness, and torsional vibration stiffness (Yang et al., 2021).



(a) Non-uniform backbone for symmetric modes (Dessi et al., 2007)



(b) Non-uniform backbone made of steel for antisymmetric modes (Marón & Kapsenberg, 2014)

Fig. 2. Schematics of non-uniform backbones

Backbone models are prevalently employed for ships due to the hull-girder's significant resemblance to beam-like dynamic behavior. Similarly, this principle applies to wind turbines, resulting in the increasing adoption of backbone models within this field. Robertson et al. conducted measurements of the global loads on various rigid wind turbine models as part of the DeepCwind project (Robertson et al., 2017). During the project's initial phase, three distinct 1/50 scale models of wind turbine concepts underwent testing. A direct consequence of the employed geometric scaling was the occurrence of unexpected behavior at low Reynolds numbers with respect to wind excitation. These rigid models were subsequently replaced by a flexible model of the same scale. Although the first natural frequency was accurately scaled, the diameter was significantly smaller than what the geometric scaling principles would suggest. As a result, the scaling of wind drag forces remained suboptimal. These experiments vividly illustrate the inherent challenges in simultaneously scaling the hydrodynamic and aeroelastic behavior of floating structures (Fig. 3).

Leroy et al. developed a 1/40 scale model of a 10 MW spar-type floating wind turbine (Leroy et al., 2022). The model's flexibility was incorporated via a flexible backbone, akin to those commonly employed in ship models. The structural geometry was represented by lightweight sections affixed to this backbone. The primary natural frequency, specifically the frequency corresponding to the 2-node bending mode, was scaled according to Froude's law. The experimental data obtained was subsequently utilized for the validation of numerical predictions (Ran et al., 2023).

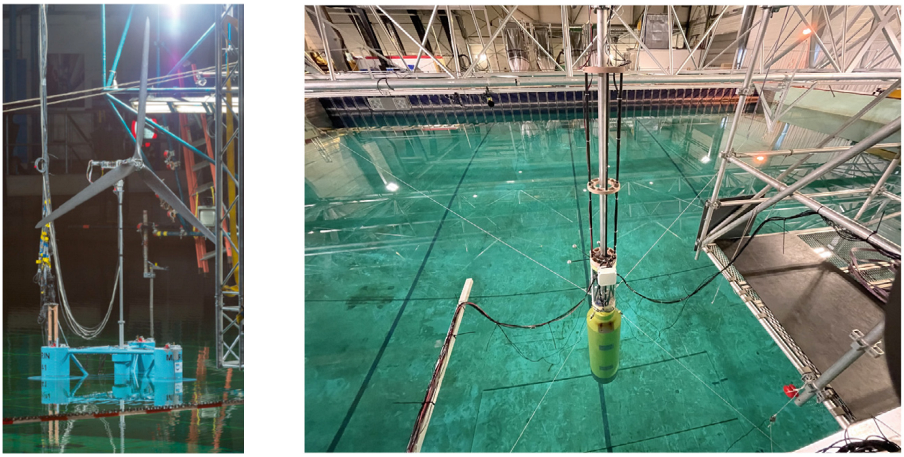


Fig. 3. On the left side, a flexible wind turbine model, achieving the correct first natural frequency by featuring a smaller diameter than what geometric scaling would dictate (Robertson et al., 2017). The example of a spar configuration on the right used light sections attached to the backbone to overcome this issue (Ran et al., 2023). (Color figure online)

3.2.2 Flexible Joint Models

The second category of segmented models, referred to as flexible joint models, enjoys considerable popularity. These models offer inherent adaptability, owing to the ability to adjust the stiffness of the flexible joints without necessitating replacement. Consequently, the same set of joints can simulate diverse stiffness levels as well as uniform or distributed stiffness (M. Wu et al., 2012), thus surpassing backbone models in adaptability. Deformations are measured through sensors incorporated within the joints, such as torsional springs (Thomas et al., 2003). The primary disadvantage of these systems is the absence of a continuous structure, which limits the model's capacity to account for cross-sectional characteristics, as previously described (e.g., effective shear area, location of shear centre).

Flexible joint models have not been applied within wind turbine models due to the simple cross-sectional geometry, which makes joint flexibility unnecessary. In contrast, these models have been employed to simulate floating solar installations and other Very Large Floating Structures (VLFS). Given that VLFS are frequently modular and employ flexible joints for inter-module connections in real-world scenarios, their use in scaled models is a logical extension. Ding et al. exemplified such experimentation, by constructing and evaluating an 8-module linear VLFS under varied wave conditions (Ding et al., 2021). A critical consideration for these extremely flexible structures is their dynamic interaction with seabed morphology, particularly in regions characterized by relatively shallow water depth.

3.2.3 Elastic Models

Elastic models are predominantly applicable to ships due to the relative complexity of ship structures compared to other offshore structures. These models present significant challenges in design and production, as the structure must also function as a boundary for fluid interactions. A notable advantage of these models is the capability to perform measurements at any location on the structure, with inherent scaling of factors such as distributed stiffness and the location of the shear center. Primary challenges involve the necessity for simultaneous scaling of both external dimensions and plate thicknesses, and the limitations posed by traditional manufacturing methods in the incorporation of complex structural details. Furthermore, the structural design must ensure watertight integrity.

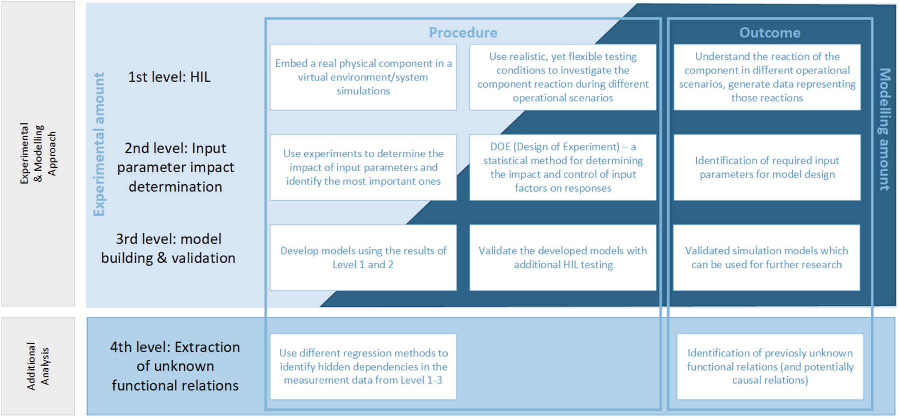
The aforementioned requirements considerably restrict the range of potential materials and manufacturing techniques. As a result, since the introduction of elastic models in academic literature, these models have incorporated only fundamental characteristics, such as deck openings and bulkheads (Y.-S. Wu et al., 2003), and have otherwise consisted of an external shell with transverse bulkheads. A more detailed version has been developed recently, featuring torsion boxes adjacent to the main deck, in a model constructed from acrylic sheets (Komoriyama et al., 2024).

In pursuit of a more precise structural response, certain research groups endeavor to develop models with increased structural detail, referred to as fully elastic models. These models generally incorporate most or all primary structural components. Chen et al. (2020) designed and fabricated elastic models utilizing sheets of Lexan$^{\text{TM}}$, a polycarbonate thermoplastic resin. Their initial model comprised a barge with three holds, featuring longitudinal, transverse, and bulkhead stiffeners. The authors identified a strain gauge stiffening effect on the local responses due to the material's high flexibility, which was considered during the calibration of the sensors. Subsequent work by the authors employed the same material and methodologies to construct a model of the S175 container ship, incorporating the cellular structure of the cross section.

Grammatikopoulos et al. (2021) proposed an innovative approach by utilizing additive manufacturing techniques to create fully elastic models. The initial demonstration featured a barge with a cellular cross section, which was similarly based on the S175. When using ABS as the printing material, discrepancies between the static and dynamic elastic moduli were identified, potentially exerting a significant impact on the dynamic responses of the final vessel, contingent upon the method of material property acquisition during design (Grammatikopoulos et al., 2020). Subsequently, an investigation was conducted involving a heavy-lifting catamaran model, comprising all primary structural elements, which was manufactured using PETG (Keser et al., 2023). Although the methodology shows promise, additional research is required to ascertain the transverse properties of additively manufactured structures, as these properties considerably influence the dynamic responses of multihull vessels.

As previously stated, the concept of elastic models is primarily applicable to ship structures. Nonetheless, in this subsection, it will be addressed in a broader context to encompass other models where the structural and fluid boundaries coincide. At the present time, this largely pertains to models of floating solar platforms. Otto et al. conducted tests on an inflatable mattress, intended to support solar panels, within a wave basin (Otto et al., 2022). In this instance, testing of the full-scale floater was feasible due to its manageable size, and it is anticipated that similar scaled tests may gain traction in the scholarly literature. Research involving membrane structures for floating solar platforms, both slack (Schreier & Jacobi, 2021) and pre-tensioned (Mukhlas et al., 2022), has begun to surface within the literature, and their prevalence is expected to increase. For slack membranes, a significant scaling challenge lies in the behavior of wrinkling; for pre-tensioned membranes, scaling primarily depends on the pre-tension load, as the membrane exhibits behavior analogous to a two-dimensional version of a string. Although these structures do not exhibit the geometric complexity challenges inherent in ship models, it is anticipated that distinctive types of issues will emerge as their utilization becomes more widespread.

In certain scenarios, only specific segments of a floating structure are modeled as flexible to facilitate the examination of localized responses. In such instances, the structural geometry is typically integrated into the scaled model, rendering the section concerning elastic models particularly pertinent. Ahani et al. conducted slamming assessments on 3D-printed panels, analogous to steel panels with stiffeners present in an offshore semi-submersible (Ahani et al., 2024). The work delineates a methodology wherein scaled models with intricate geometries, varying thickness, and stiffeners are employed in hydroelastic tests. In this study, the elastic properties of the material, influenced by strain rate, were quantified and applied in finite element simulations to ensure that the deflections upon impact corresponded with the Froude scale.



Experimental & Modelling Approach		Procedure		Outcome
	1st level: HIL	Embed a real physical component in a virtual environment/system simulations	Use realistic, yet flexible testing conditions to investigate the component reaction during different operational scenarios	Understand the reaction of the component in different operational scenarios, generate data representing those reactions
	2nd level: Input parameter impact determination	Use experiments to determine the impact of input parameters and identify the most important ones	DOE (Design of Experiment) – a statistical method for determining the impact and control of input factors on responses	Identification of required input parameters for model design
	3rd level: model building & validation	Develop models using the results of Level 1 and 2	Validate the developed models with additional HIL testing	Validated simulation models which can be used for further research
Additional Analysis	4th level: Extraction of unknown functional relations	Use different regression methods to identify hidden dependencies in the measurement data from Level 1-3		Identification of previosly unknown functional relations (and potentially causal relations)

Fig. 4. Hybrid model testing levels

3.3 Summary and Conclusions

Backbone models are demonstrably the predominant choice in the literature concerning the testing of flexible structures within fluid-structure interaction (FSI) studies. This popularity is particularly pronounced when a beam-like bending response can be assumed, and the first flexible mode is dominant. Accordingly, these models are frequently employed in the analysis of monohull ships and wind turbines. In contrast, for structures that deviate from a beam-like form, encompass complex mode interactions, exhibit torsional behavior, or necessitate consideration of local responses, elastic models have emerged as a progressive alternative. These models are typically produced through additive manufacturing, foam construction, or the shaping of plastic sheets. For two-dimensional structures, such as floating membranes, the prevailing method involves employing either scaled-down replicas of the real structures (e.g., inflatable mattresses) or direct scaled models of the membranes themselves. Within this categorization, these are considered more akin to elastic models, as both the source of stiffness and the hydrodynamic boundary coincide within the same structure. Notably, the application of elastic models to wind turbines has not been documented thus far; however, an impending increase in their use is anticipated, particularly in conjunction with the rising interest in floating wind technology.

4 Hybrid Model Testing

Hybrid model testing can be systematically classified into four distinct levels, each characterized by varying degrees of complexity and content (refer to Fig. 4): First-level basic hardware-in-the-loop (HiL) testing, as depicted in Fig. 4, facilitates the emulation of both the environment and ship systems through models that deliver realistic operational scenarios for the physical component undergoing testing. The response of this component to the scenarios can be directly evaluated. “Real-time hardware-in-the-loop simulation-based testing has been recognized as an advanced method for the analysis and testing of power system phenomena and components. Realistic, yet flexible testing conditions for de-risking equipment are its salient benefits.” (Kotsampopoulos et al., 2018). The accuracy of HiL test outcomes is inevitably contingent upon the precision with which the simulation models reflect the ship system and environment; as such, the component’s reactions will only be as accurate as the models that portray the scenarios.

The second tier pertains to the identification of input parameters necessary for the construction of precise and effective models. Experiments are instrumental in assessing the influence and regulation of input factors on responses. It is crucial to conduct an uncertainty evaluation of these experiments to ascertain their precision (Viswanathan et al., 2022).

The tertiary stage pertains to model validation and the advancement of software-driven functionalities for the component subject to evaluation. A Hardware-in-the-Loop (HiL) testbed serves as a technological development instrument that facilitates the assessment of simulation models devised to represent the component being examined. The HiL configuration permits a direct comparison between the behavior of the simulation model and the actual component, thereby enabling comprehensive model validation.

The fourth level pertains to the derivation of previously uncharted functional relationships, including potential causal associations, from empirical data. When the established physical interactions related to the observed behavior of the component under examination are formulated through differential equations, and the unfamiliar physical interactions are encapsulated within a system of equations by data-driven or machine learning models that have been trained using the available test data, regression techniques are accessible to discern functional dependencies concealed within the measurement data, thereby facilitating the augmentation of the existing system of equations. These functional relationships have the potential to reveal cause-and-effect dynamics underlying the unanticipated behavior of the component under scrutiny or to enhance existing models in order to augment the precision with which they characterize the behavior of the component in question (Safikou & Bollas, 2023; Man & Weil, 2023).

Within the scope of the EU-funded Project HELENUS (High Efficiency Low Emission Nautical SOFC - www.helenus.eu), coordinated by the DLR Institute of Maritime Energy Systems, Hardware-in-the-Loop (HiL) testing is employed to experimentally verify the dynamic operation of a Solid Oxide Fuel Cell (SOFC) module as an integral component of a ship's comprehensive energy system. Reference W. Shi et al. (2023) provides an extensive overview of real-time hybrid model tests conducted on floating offshore wind turbines, while Ha et al. (2023) successfully developed a hybrid model test technique for evaluating the performance of a floating offshore wind turbine under conditions of asymmetrical thrust. Concerning maritime applications, reference Wei et al. (2021) introduces a hybrid model for forecasting ship roll by utilizing full-scale measurements and analytical techniques. In addition, reference Jenssen et al. (2024) details the implementation of hybrid model testing to simulate the dynamic performance of Floating Wind Turbines (FWT) within hydrodynamic laboratories, as initially outlined in Fig. 5. Specifically, two distinct 15 MW FWT models were evaluated at SINTEF Ocean to demonstrate the effectiveness of this method. The findings illustrated that hybrid model testing proficiently controlled dynamic loads, maintaining minimal tracking errors.

Considerable utilization of Hardware-in-the-Loop (HiL) systems has been observed in testing the dynamic responses of marine risers. An innovative hybrid model test technology was developed by H. Ren et al. (2024) for the investigation of vortex-induced vibrations (VIV) in a bluff body. The general framework of this hybrid control method, depicted in Fig. 6, enables the precise real-time control of key physical parameters such as mass, damping ratio, and spring stiffness in VIV model tests. Furthermore, VIV tests at very high Reynolds numbers for a bluff body were conducted using this hybrid experimental technique, as documented in Fig. 7. These tests disclosed novel VIV behaviors, including the "Soar" and "Death" stages at critical Reynolds number ranges, as reported in

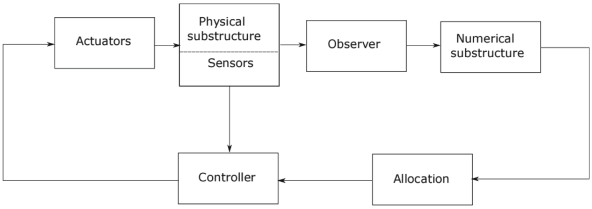


Fig. 5. Generic control loop of hybrid model testing

Fig. 8. Through these experiments, a database of hydrodynamic coefficients for VIV at high Reynolds numbers was established. This database, when used in conjunction with the non-iterative frequency-domain (Lu et al., 2018) and time-domain prediction method (Lu et al., 2019), facilitates accurate prediction of VIV for marine risers subject to high Reynolds numbers.

In summary, the integration of hybrid model testing and hardware-in-the-loop approaches persists in their application across various experimental methodologies. These approaches are utilized to mitigate risks in testing and to enhance the comprehension of intricate experimental settings. It is advocated that the continued application of these techniques be encouraged to further the integration of models with experimental data.

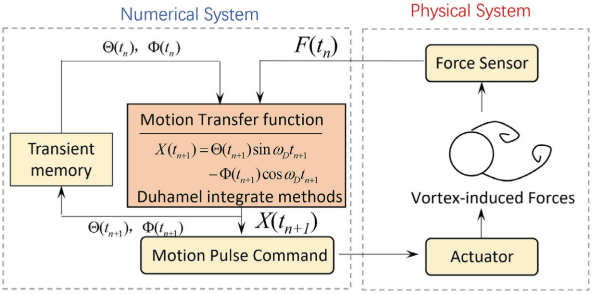


Fig. 6. A block diagram of the general framework of hybrid control methods

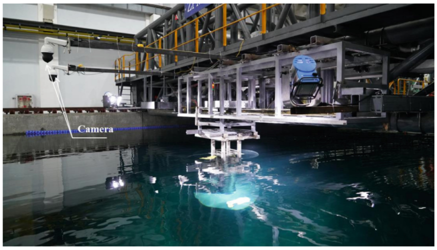


Fig. 7. Global diagram of the experimental apparatus, including the linear motion actuator, force sensor, and bluff cylinder model mounted under the towing carriage

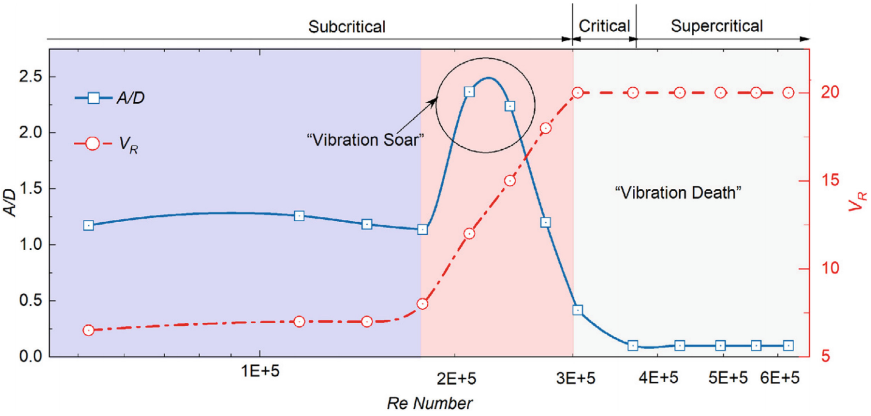


Fig. 8. Evolution of the non-dimensional maximum response amplitudes of VIV and the corresponding reduced velocity, with Re. The blue, red, and gray shaded regions denote the stable, tuning, and death stages for VIV response, respectively. (Color figure online)

5 Fire Test

This chapter gives an overview of the principles, rule, and standards applicable to design for fire accidental events for ships and offshore structures and the current state-of-the-art methods for fire testing.

5.1 Principles, Standards and Rules for Fire Test

The formulation of safety strategies aimed at mitigating fire hazards on board ships and offshore installations has traditionally been accomplished through adherence to prescriptive regulations set forth by regulatory authorities. The International Maritime Organization (IMO) has established fire safety regulations for international merchant vessels under the auspices of the International Convention for the Safety of Life at Sea (SOLAS). In July 1998, the IMO introduced the Fire Test Procedures Code (Organization & Committee, 2012), which encompasses fire test procedures for fire-resistant constructions and materials employed on ships. The FTP Code is founded upon International Standards Organization (ISO) fire tests, which encompass assessments of non-combustibility, fire resistance, flammability, flame spread, smoke production, and the toxicity of constructions and materials, as well as specific products such as textiles, upholstered furniture, and bedding. The tests, referenced tests, and analogous test methods are summarized in the table below (Table 1).

In the Oil & Gas industry, two primary fire testing scenarios are frequently employed: the hydrocarbon pool fire and the jet fire. A hydrocarbon pool fire involves the ignition of a pool of hydrocarbons in a furnace, with a crumple temperature that approximates 1100 °C and a heat flux of up to 150 kW/m$^{\mathbf{2}}$. The

Table 1. Fire test procedure code (IMO FTP Code, 2010) and test method

FTP Code	Type of test	Referred test method	Similar test Method
Part 1	Non-combustibility Test	ISO 1182	
Part 2	Smoke and Toxicity Test	ISO 5659-2	
Part 3	Fire Resistance Test for Fire Resistant Divisions	IMO A.754(18)	ISO 834-1 UL 1709 EN 1363-2:1999
Part 4	Fire Resistance Test for Fire Door Closing Mechanisms		
Part 5	Surface Flammability Test	IMO A.653(16) IMO A.687(17)	ISO 5658-2
Part 6	Test for Primary Deck Coverings	IMO A.653(16)	ISO 5658-2
Part 7	Flammability Tests for Curtains and Vertically Suspended Textiles and Films	IMO A.471(XII) IMO A.563(14)	ISO 6940/41 EN 1101/02
Part 8	Test for Upholstered Furniture	IMO A.652(16)	BS 5852-1 ISO 8191-1/-2 EN 1021-1/-2
Part 9	Test for Bedding Components	IMO A.688(17)	EN 597-1/-2
Part 11	Fire resistance test of load-bearing divisions of high-speed craft	-	-

test scenarios and methodologies for pool fires are generally prescribed in standards such as UL1709, BS476, IMO FTP Code 3, ISO 834-3, and ISO 1363-2. In contrast, a jet fire occurs because of the release of high-pressure hydrocarbons (gas) from a ruptured pipe or vessel. The jet fire test results in a higher temperature and increased heat flux, ranging from 250 kW/m^2 to between 350–500 kW/m^2, depending upon the test standards applied. The method for conducting a jet-fire test is defined within ISO 22899-1 and OTI95-634 standards.

It should be noted that these testing standards specifically address the evaluation of structural steel. The criteria of these tests involve measuring the time required to achieve the defined critical temperature of the steel, which is predominantly set at 400 °C. It is a standard procedure to apply the same testing conditions and critical temperature criteria to piping and other process equipment.

5.2 Fire Testing Methods

5.2.1 Fire Resistance Test

Fire resistance refers to the capability of a partition or boundary, typically a bulkhead or ceiling, to endure fire exposure, provide protection against fire, inhibit the propagation of fire to adjoining compartments, and preserve structural integrity when subjected to fire. Examples commonly used for fire resistance evaluations include pool fire tests, burner test, and furnace test with fire curves (see Fig. 9). Taking the furnace test as a specific instance, the structural specimens are evaluated in the form of panels, with the side within the furnace exposed to a temperature profile that adheres to one of the fire curves. Fire resistance is quantified by the duration required for the cooler surface of the panels to reach a temperature of 140 °C. The configuration of the selected fire curve is designed to reflect the characteristics of the particular fire hazard, acknowledging that there is significant variability among fires.

The fire resistance requirements for steel structures in oil and gas installations, specifically those involved in the transportation and production of hydrocarbons, such as tankers and offshore platforms, are examined. It is noteworthy

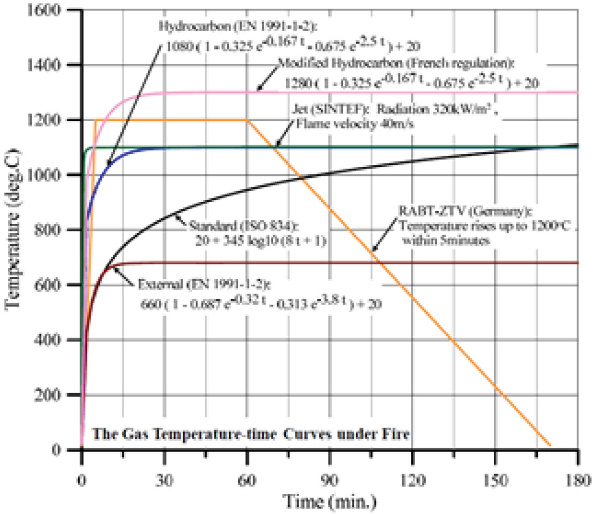


Fig. 9. Time-dependent temperatures curves

that the fire resistance values under hydrocarbon fire conditions, as contrasted with standard fire conditions, are specifically detailed for stationary offshore platforms (Gravit & Shabunina, 2022).

Fire doors are critical safety components designed to impede or halt the progression of fire and must be subjected to preventive testing and classification. Each door undergoes a specified time-temperature heating protocol based on its fire door classification, with both mechanical and thermal constraints employed to evaluate its functional performance. The design of conventional fire doors leverages well-established methodologies aimed at optimizing their thermal performance to satisfy fire resistance testing criteria. Nonetheless, thermal gradients can induce considerable deformations, as the door often bends away from its supporting frame due to uneven temperature distribution. This deformation can lead to the propagation of flames and smoke, thereby resulting in the failure of fire resistance tests (Kyaw Oo D'Amore et al., 2020).

Composite materials are increasingly utilized in various fire protection applications aboard ships and offshore installations. Figure 10 illustrates the fire resistance properties of several composite material types that have been evaluated for potential application in offshore installations. Despite the inherent combustibility of the composite's organic components, the materials analyzed exhibited notable fire-resistant properties. The fire behavior of thick composite laminates can be effectively modeled (Gibson et al., 1995; Dodds et al., 2000), facilitating the prediction of materials' integrity and fire performance given specific hot face temperature or heat flux levels. The predominant factor affecting the fire integrity of thick composite laminates is the endothermic nature of the resin degradation process, which acts to retard heat transfer through the laminate.

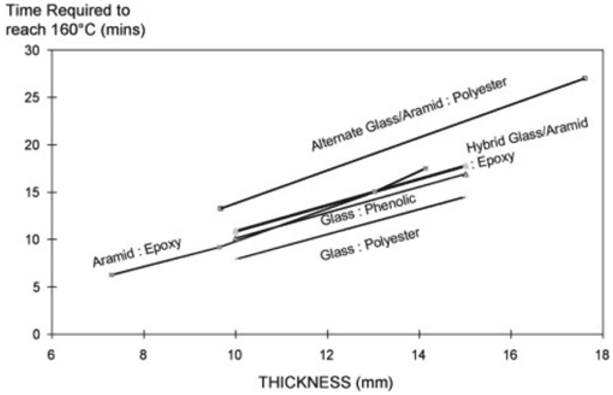


Fig. 10. Fire resistance values, measured as a function of thickness, for a range of different laminates, subject to the hydrocarbon fire curveÂă

A substantial amount of experimental research offers insights into fire integrity and performance metrics crucial for the design of fire-resistant ship compartment structures, primarily through standard fire resistance tests. Given that numerous companies often aim to attain specific classifications for their products, these tests are conducted with a designated fire load exposure and terminated when the predetermined objective is achieved. From a scientific perspective, such results are inadequate to comprehensively depict the performance of a product because (i) the continuation of the test might precipitate failure (such as collapse) shortly thereafter or after an extended period, and a similar uncertainty applies to the fire load. (ii) A minor increase in load could lead to failure before the required fire resistance duration is met. Consequently, it is always advisable to conduct fire resistance tests to the point of failure (e.g., structural failure due to collapse, significant deflection rate, or loss of integrity) to extract the maximum possible information from the test (Jones & Brischke, 2017).

5.2.2 Fire Test for Passive Fire Protection Systems

Passive Fire Protection (PFP) predominantly serves to maintain the structural integrity of steel frameworks, pipelines, including their valves and flanges, as well as other equipment that may contain hydrocarbons. The primary function of PFP is to facilitate a controlled shutdown and the safe evacuation of personnel during a fire incident. The evaluation of PFP should be performed in certified testing facilities, and these test results are utilized as a data set for designing PFP according to specific project requirements. Various thicknesses of PFP materials are assessed, and the duration required to reach the critical temperature is meticulously recorded. It is a widely acknowledged practice to interpolate, that is, to compute a theoretical line between two established points, from certified test results for optimizing the PFP layer thickness to fulfill the stipulated requirements (Paik et al., 2021a; Paik et al., 2021b). However, the extrapolation of results is generally not accepted.

5.2.3 Fire Test for Valve System

Fire protection is an essential aspect of safety design for industrial valves, particularly in environments where the occurrence of fire incidents is probable. Valves employed within the oil and gas, refining, chemical, and petrochemical sectors are required to ensure a dependable and secure shut-off during a fire. The concept underpinning fire testing is that a fire-safe valve must continue to function under pressurized conditions even after exposure to combustion at a predetermined high temperature for a specified duration, with post-burn leakage maintained within defined limits.

The standard methodology for the fire testing of valves, including fire-safe valves, entails the complete and uniform encapsulation of a water-filled, pressurized, closed valve in high-temperature flames ranging from approximately 750 °C to 1000 °C for a period of 30 min. During complete immersion of the valve in fire, which subjects the seat and sealing areas to elevated temperatures, the intensity of heat is closely monitored utilizing thermocouples and calorimeter cubes. Throughout this process, both the external and internal leakages from the valve are measured. Subsequently, upon cooling of the valve post-fire test, the pressure containment capability of the same valve seats, shell, and seals is evaluated.

5.2.4 Reaction to Fire Test

The concept of reaction to fire pertains to the extent to which a specific material contributes to a fire. Contrastingly, fire resistance pertains to a system's capability to withstand fire penetration and inhibit temperature escalation between the exposed and protected sides under a fully developed fire scenario. As the terminology implies, a material's reaction to fire refers to its behavior when subject to flame exposure. The assessment methodology evaluates the role of building materials in a fire, particularly during its nascent stages. Materials and products are classified into seven distinct Euro classes based on their fire reaction characteristics. In accordance with the European Standard EN 13501-1, products are categorized into one of seven principal classes, as detailed below, based on their combustibility level, and may also be assigned additional classes related to the volume of smoke emitted or the quantity of burning droplets or particles generated. Details regarding reaction to fire test methodologies are elucidated in Annex 1 of the IMO FTP Code. It is noteworthy that testing of a product or material may not always be necessary. Annex 2 of the FTP Code stipulates the conditions under which a material or product may be installed without undergoing testing or receiving approval. Furthermore, the provisions of the FTP Code exclude applications involving green or renewable energy in maritime contexts. Consequently, in alignment with the global trend towards eco-friendly shipping, the formulation of pertinent application guidelines will be essential when integrating green and renewable energy technologies into cargo and fuel shipping practices.

5.3 Recent Developments in Fire Experimental Methods

Fire resistance tests are formulated to assess the performance of building components concerning their load-bearing or fire-separating properties, commonly known as their fire resistance, in accordance with their regulated application in building structures. Given that fire resistance is predominantly necessitated in static structures such as buildings, which are subject to regulation by local jurisdictions and often by local building practices, a plethora of test specifications exist, and international consensus remains limited. Throughout Europe, the implementation of standardized testing is progressing via the Construction Products Directive.

In contrast to terrestrial structures, the transportation sector, encompassing aerospace, maritime, and offshore industries, represents an area where testing methodologies elucidate the principal requirements for fire resistance. Steel components within a ship's hull and the structures comprised of cargo tanks, decks, and bulkheads delineating industrial spaces are engineered according to specified fire resistance classifications, contingent upon parameters such as fire resistance limits and temperature exposure regimes, per the IMO FTP Code. Identical fire resistance classifications are prescribed for offshore platforms (ABS, 2021). Previous investigations into fire resistance have aimed to simulate experimental data to ascertain the fire resistance limits of various structural components and systems in ships of diverse classes. These investigations address several key issues, including the calculation of thermal insulation parameters, the prognostication of fire resistance limits (Zong et al., 2023), the computation of structural behavior under thermal loads (Seo et al., 2017), and the refinement of calculated coefficients of thermal conductivity and heat capacity pertinent to application within fire temperature ranges.

In the marine, offshore, and aerospace sectors, where the transition from metallic materials to polymer composites is underway, the employment of combustible composites in lieu of steel has the potential to significantly diminish weight. Conversely, this substitution may lead to an augmented risk of fire. Consequently, the development of novel testing methodologies is imperative to simultaneously address structural integrity and flammability. Evegren et al. executed fire tests to evaluate and ensure the safety of employing lightweight FRP composites within ship structures (Evegren et al., 2016). A non-load-bearing sandwich panel bulkhead concept, originally from the building sector, was identified to possess prospective utility for deckhouse structures (see Fig. 11). Two sets of tests were conducted with an emphasis on the fire performance of the exterior combustible FRP surfaces. Five series of tests were performed to assess the fire resistance, evaluating the structural fire integrity of various FRP composite structures. Three viable protective measures were identified to be suitable for safeguarding external FRP surfaces: a drencher system (3 mm/min), a fire-protective coating (LEO), and a certified balcony sprinkler. The fire resistance tests indicated that an insulated FRP composite bulkhead concept could be conservatively appraised by testing the bulkhead under the highest design load. Load-bearing double FRP composite bulkheads can provide adequate fire resistance in scenarios where traditional insulation is infeasible (e.g., for exterior surfaces).

Fig. 11. Fire resistance test of load bearing FRP composite bulkhead with design loads

The composites industry is experiencing an upsurge driven by heightened global environmental awareness. Innovative composite materials are being developed to mitigate their adverse environmental effects by employing cleaner manufacturing processes and, where feasible, substituting synthetic materials with more sustainable bio-based alternatives. Within this framework, natural fiber composites (NFC) are put forward as promising candidates to either replace or reduce the use of synthetic fibers for reinforcing polymers in various industrial sectors, such as the marine sector, where composite utilization has been extensively researched in recent years. A significant proportion of the research on the fire performance of natural fiber composites (NFCs) focuses on the response to fire parameters instead of fire resistance (Naughton et al., 2014). Moreover, the analytical techniques and prevailing theories pertinent to the residual mechanical properties of fiber reinforced polymer (FRP) composites exposed to fire are not applicable to NFCs.

A material or structural member attains a fire resistance classification through compliance with performance criteria established in a comprehensive fire resistance test. Such a test assesses the fire resistance capabilities of a building component within a configuration and scale comparable to practical applications.

The comprehensive fire test presents a challenge for the adoption of innovative materials, such as natural fibre composites (NFCs), due to its financial implications and the prescriptive nature of its pass/fail outcomes. Presently, no standardized tests exist specifically for NFCs. Nevertheless, contemporary UK standards acknowledge the incorporation of natural fibres as reinforcements within polymer composites, and much of the experimental testing of NFCs adheres to standards designed for conventional fibre-reinforced polymers (FRPs). A comprehensive test would be requisite to ascertain that an NFC adheres to building regulations and fire safety codes. Given that the fire resistance and reaction characteristics of NFCs remain largely unexplored, comprehensive testing remains the sole indicator of fire performance (Fan et al., 2017).

5.4 Summary and Recommendations

The field of fire testing is undergoing continuous evolution as standards undergo periodic revisions and updates. Nonetheless, the IMO FTP Code currently lacks applicability to green or renewable energy initiatives within the maritime domain. Composites are increasingly being employed in a range of fire protection applications on maritime vessels and offshore installations. Consequently, comprehensive full-scale testing and/or methodologies are requisite in order to develop and substantiate the compliance of novel composites, particularly those based on bio-based materials, with established marine standards and fire safety requirements.

6 Friction Tests

Friction constitutes a fundamental element in the interaction between solid surfaces, with objectives ranging from guaranteeing adhesion in components—such as bolts and rivets—to minimizing resistance in parts in motion. The discipline dedicated to the study of friction, referred to as tribology, concentrates on comprehending and regulating these interactions. Tribology encompasses the characterization and modification of surface properties, contact mechanics, and lubrication. Through the optimization of these elements, engineers can achieve specific design objectives, thereby ensuring durability, efficiency, and safety across diverse applications.

A review of the recent literature in marine and offshore publications reveals that a substantial portion of studies addressing contact mechanics depend predominantly on simplified models utilizing tabulated values for static and kinetic friction. Although such models establish a basis for fundamental calculations, they frequently fail to account for the intricate behaviors of materials in real-world scenarios. Variations in surface roughness, material degradation, and environmental factors, including moisture, temperature, and pressure, can considerably influence frictional properties. This issue is particularly pertinent to the interactions between sea ice and floating structures, where ice mechanics are considerably modified by environmental conditions.

The accelerated diminishment of polar sea ice attributed to climate change is resulting in the emergence of new maritime routes, notably the Northern Sea Route and the Northwest Passage. As these passages become increasingly accessible, a comprehensive understanding and mitigation of ice friction are imperative to ensure navigational safety. The implementation of friction-reducing coatings will enhance the operational efficiency of vessels traversing these nascent trade corridors. However, the environmental implications, particularly the release of micro-plastics and anti-fouling chemicals, warrant significant consideration due to the region's ecologically vulnerable wildlife (Qi, Li, Zhao, Zhang, & Zhou, 2024).

The prediction of friction between the hull and ice for vessels classified for ice conditions is crucial for calculating power requirements and optimizing ice-breaking performance. In experiments involving models tested in icy conditions, it is generally challenging to distinguish between forces attributable to friction and those arising from ice fracture and submersion. One study (Hisette & Myland, 2022) elaborates on a dynamic friction table setup, wherein model ice can be translated across various surfaces. Notable effects related to grain structure and speed were observed. During the initial 5–20 cycles, friction is maximized when the ice remains rough, with its granular surface layer exposed. Continued cycling reveals larger columnar grains, thereby resulting in a friction coefficient that stabilizes at less than half of the initial value. Subsequent tests will be conducted on abraded coatings.

Offshore wind turbines and wave energy converters employ submerged cables that facilitate the connection between energy-generating units and onshore power grids, where interlayer friction exerts a significant influence on torsional and bending stiffness, as well as on fatigue life (Qin et al., 2024). The prevailing industry practices, which utilize the Coulomb friction model incorporating an average of static and dynamic friction coefficients, are deemed conservative and fail to consider recent findings indicating that the interlayer friction coefficient undergoes temporal changes (Y. Yin et al., 2019). A friction and wear test apparatus, depicted in Fig. 12, was developed by Y. Yin et al. (2021), demonstrating that the evolution of the interlayer friction coefficient within an umbilical is correlated with the wear depth in the anti-wear nylon fiber tape.

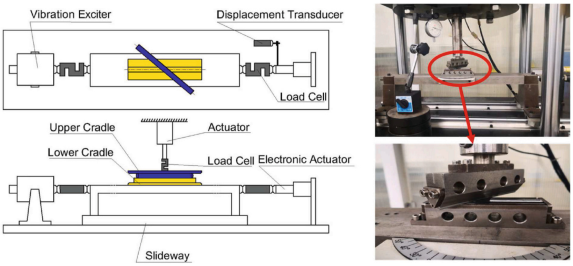


Fig. 12. Interlayer friction and wear test rig for umbilicals (Y. Yin et al., 2021).

In summary, investigations focusing on contact interactions frequently employ simplified friction models, utilizing tabulated values in lieu of conducting empirical friction tests under pertinent conditions. Validating these friction models through empirical testing and simulation becomes challenging, particularly when the measured responses encompass multiple physical domains. This challenge is notably evident in the context of sea ice interactions, as differentiating forces attributable to friction from those arising from ice fracture and submersion proves complex. Efforts are ongoing to characterize hull-ice friction concerning the crystallographic structure of ice and the properties of hull coatings. Similarly, the internal friction present within power cables and umbilicals has been examined through the use of specially designed test rigs. Moreover, comprehension of the external friction response of such structures is critical for accurately estimating installation loads under deep-water conditions. Friction within these structures significantly influences dynamic behavior and fatigue life. Therefore, friction testing is essential for enhancing the durability, efficiency, and safety of marine structures and equipment, and further research on tests conducted under relevant conditions is advocated.

7 Corrosion Prognostics Health Management

Corrosion represents a primary factor in the structural failure of ships and offshore structures, making expensive preventive maintenance a standard preventive measure, as documented in (Lin & Dong, 2023; Vieira et al., 2022). Consequently, corrosion prognostics within the realm of structural health monitoring emerges as a natural evolution and research domain aimed at enhancing structural reliability and reducing expenses. The intricacy of corrosion phenomena, notably pitting corrosion, presents considerable challenges in terms of characterization and prediction (Nugroho et al., 2021), even when utilizing laser scanners for surface capture. Laser scanning and digital image correlation demand a traceable surface, commonly necessitating the chemical cleaning of the surface to eliminate any loose subsurface corrosion deposits. Several probabilistic prediction models have been developed to address the complexity of corrosion wastage (Kim et al., 2022; Woloszyk & Garbatov, 2024). Reliable monitoring of corrosion degradation is crucial for producing meaningful predictions. Advanced monitoring systems now incorporate wave-based methodologies (Zima et al., 2022) and fibre Bragg grating-based sensing systems (Tan et al., 2017). For all approaches, the optimal placement of sensors is vital (Silionis & Anyfantis, 2024). The unpredictable nature of loading further complicates prediction efforts (Katsoudas et al., 2023a), necessitating provisions for instantaneous strength prediction (Y. Liu & Ren, 2023). Additionally, the concurrent monitoring of the impact of corrosion on the fatigue strength of welds, alongside efforts to mitigate coating failures, as summarized in Andresen-Paulsen et al. (2023), is essential.

To investigate the impact of seawater on the structural integrity of steel structures, fatigue experiments can be conducted within a seawater environment (Woitzik et al., 2023). Given the prevalence of welded structures, extending the study to include fillet and butt-welded specimens is a logical progression (Shojai et al., 2023). Digital Image Correlation (DIC) systems enable the measurement of geometry and surface parameters, such as pitting corrosion, which can subsequently be employed in numerical simulations to predict damage onset. Future research will involve comparing these findings with the fatigue life of larger specimens subjected to corrosion in artificial seawater (see Fig. 13). A critical area for analysis is determining whether the behavior of contemporary corrosion protection coatings, particularly around welds, is accurately represented by current advanced corrosion progression models. To further this analysis, employing a combination of 3D laser scanning and DIC to capture local geometries and strain configurations is recommended.

Fig. 13. Corroded specimen

8 Large-Scale Subsea Structures Test

8.1 Introduction

Comprehensive testing of subsea structures has been conducted since the 1970s, following the seminal publication by A. C. Palmer and Martin (1975) on buckle propagation in subsea pipelines. Due to the substantial costs associated with these tests, many experimental investigations utilize small-scale samples. However, to attain results that more accurately reflect the complexities of these structures, large-scale testing is occasionally necessary. This chapter will present recent studies focusing on large-scale testing of subsea equipment, emphasizing concerns related to structural integrity in components such as rigid or flexible pipes, cables, templates, and bases.

8.2 Flexible and Rigid Risers

Multiphase flow within pipes is prevalent in various engineering applications, particularly in offshore deep-water oil and gas transport. Flow-induced vibrations within the pipe can result in mechanical failure, potentially leading to the uncontrolled release of transported fluids. In subsea applications, flexible J-risers are commonly utilized to convey produced fluids from the seafloor to the host platform. Despite the significant risks associated with subsea hydrocarbon leaks, there is a notable paucity of investigations into how flow-induced vibrations in large-scale, pressurized flexible J-risers may compromise system integrity. Pickles et al. (2024) conducted an experimental study examining the response of a composite riser with a tensile armor helical structure subjected to various two-phase, water-nitrogen flows at a pressure of 10.8 barg and ambient temperature. High-speed cameras were employed to examine the flow structure at either end of the flexible riser, while synchronized surface-mounted strain gauges and accelerometers were used to analyze the pipe's response. Time-averaged data were captured to evaluate the general behavior of the pipe, while statistical analysis of fluctuations elucidated the pipe's movement. This phenomenon was primarily observed under multiphase flow conditions, specifically when the gas flow rate was increased at a constant water flow rate or under conditions of high gas flow rate. The strain gauges recorded increased average strain under these conditions, accompanied by a visually detectable whipping motion. The authors recommended future coupled analyses of fluid-structure interaction to assess the riser's structural integrity.

A combined hydraulic and power umbilical cable designed for deep-water applications, incorporating a 66 kV configuration, was subjected to an innovative testing approach as discussed in Y. Zhou et al. (2024). This approach integrated mechanical tests as outlined in API 17E and the type test consistent with IEC 63026 standards for high-voltage cables, aimed at validating the reliability of the umbilical system, including its repair joint and end termination. In addition to the standard electrical tests for power cables, the testing program encompassed a series of evaluations, including combined tensile and bending tests, end terminations strength assessments, torque trials, and fatigue as well as water penetration tests conducted under an external pressure of 15 MPa, as illustrated in Fig. 14. The proposed testing methodology serves as a potential benchmark for the qualification and assessment of such structures, particularly in the context of advancements in subsea electrification.

8.3 Rigid Pipes

Subsea rigid M-shaped jumpers provide dependable and adaptive connections to production systems by employing deflection to diminish the effects of internal flow and allow for installation tolerances. During their operational life, the gas-liquid mixed multiphase flow traversing these jumpers induces flow-induced vibration (FIV), thereby reducing their fatigue lifespan. G. Li et al. (2023) conducted an investigation into the air-water mixed two-phase flow within a rigid

Fig. 14. End termination strength test of 66 kV power and hydraulic combined umbilical.

M-shaped jumper at varying mixture velocities and water volume fractions, with the objective of analyzing the factors influencing flow patterns and determining the most vulnerable areas. Experimental procedures were undertaken to ascertain the flow patterns in each segment and the historical pressure variations. Air and tap water served as the gas-liquid two-phase media within the experimental setup. Under conditions of high-speed two-phase flow, significant equivalent stress was observed at the fixed supports at both ends of the M-shaped jumper. Concurrently, stress concentrations were identified at the elbows, with both the average and RMS of equivalent stress surpassing those in the horizontal or vertical segments attached on either side. The time-history stress response of each node on the developed structural model was obtained through one-way coupled fluid-structure analysis. The application of rain flow counting technology in conjunction with the S–N curve facilitates the performance of fatigue damage computations and the prediction of fatigue life as a subsequent analysis.

W. Li et al. (2022) conducted an investigation into gas-liquid flow and the consequent vibrations within a multi-plane jumper utilizing experimental methodologies (refer to Fig. 15). The investigation encompassed a detailed analysis of flow patterns at each characteristic section of a Z-shaped jumper with an internal diameter of 48 mm, encompassing diverse flow regimes such as dispersed bubbly, slug, churn, wavy, stratified, and annular flows. Displacement and pressure sensors were strategically installed adjacent to each elbow to effectively capture the vibrational and pressure responses of the jumper. The one-way transient fluid-structure analysis employed in this study is deemed adequate for predicting the dynamic response characteristics of the jumper. The time-averaged accelerations derived from the finite element method and the flow patterns forecasted by the volume of fluid method demonstrate a commendable agreement with the experimental observations. In addition to the internal two-phase flow phenomena, the jumper is also exposed to current flow, leading to external flow-induced vibrations within a subsea environment. Consequently, further research is warranted to explore the coupled vibrational characteristics of the jumper under the simultaneous influence of both internal and external flows.

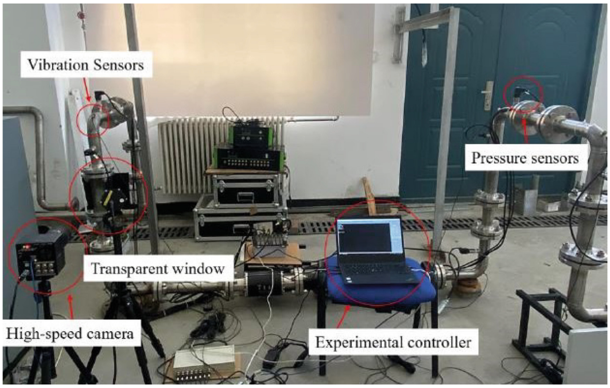


Fig. 15. Experimental setup to evaluate flow induced vibration.

The phenomenon of free spanning in subsea pipelines, resulting from localized seafloor scour, constitutes a significant operational concern. B. Zhou et al. (2024) conducted experimental analyses under clearwater scour conditions, examining the effects of impermeable, porous, and flexible spoilers on both fixed and self-burial configurations. The flow fields surrounding the pipeline were characterized utilizing the particle image velocimetry (PIV) technique (refer to Fig. 16). The results from the scour tests on a fixed subsea pipeline demonstrate that the presence of spoilers can significantly expedite the erosion rate.

Buckling damage constitutes a principal safety concern for subsea pipelines. Yu et al. (2021) undertook comprehensive full-scale experiments to investigate the buckling behavior of subsea pipelines equipped with integral buckle arrestors subjected to external pressure. The study presents pressure chamber tests of four full-sized pipelines characterized by uniform thickness but varying diameters. The tested samples, depicted in Fig. 17, encompass not only collapse and propagation tests but also crossover tests, which serve to assess the efficiency of buckle arrestors. This research was conducted to validate a finite element-based methodology employing thin shell elements for the calculation of collapse, buckle propagation, and crossover pressures in subsea pipelines. Despite demonstrating significant correlation with the experiments and other calculations, the authors acknowledge that this approach may benefit from refinement to accommodate thick-walled pipes.

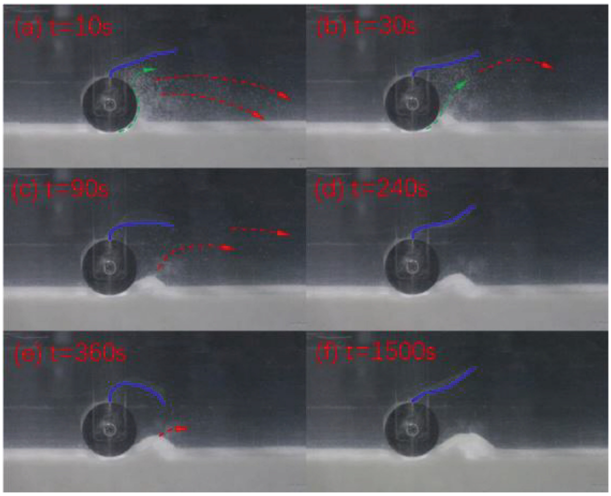


Fig. 16. Experimental snapshots on the scour process of pipeline attached with the flexible spoiler.

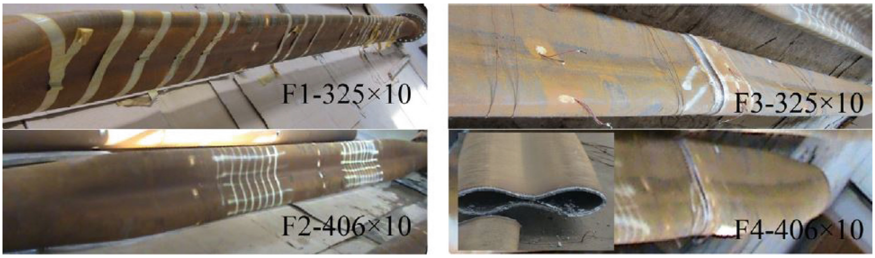


Fig. 17. Pipe morphology after tests. (a) Collapse and propagation tests, (b) Propagation and crossover tests.

8.4 Templates

During the process of elevating submerged marine modules, the most significant dynamic loads manifest within the splash zone. These forces exhibit substantial dynamism and their estimation with adequate precision proves challenging due to their irregular and complex geometrical configurations. An experimental investigation was undertaken by Zan et al. (2021) within a wave tank to examine the dynamics of a large subsea module in the splash zone under the influence of irregular wave conditions. The experiments utilized a 1:8 scale model of a subsea module, which was scrutinized at five distinct positions relative to the free surface, ranging from fully above the surface to entirely submerged. The ensuing data were subjected to analysis in both the time and frequency domains. Dynamic loads on the subsea module were examined through spectral analysis and a dynamic effect parameter. Furthermore, several time-domain numerical analyses were executed with varying peak periods to ascertain the tension in the sub-slings. The experimental findings pertaining to the relative forces and motions of the subsea module are presented.

8.5 Summary and Conclusion

In summary, numerous recent experimental investigations on large-scale subsea structures have primarily focused on fluid-structure interaction, with an aim to understand the responses concerning vibration, displacement, and stress. Although simulating two-phase fluid flow is relatively straightforward, challenges arise with the simulation of multiphase flow involving mineral oil. Additionally, the integration of internal and external fluid flows can result in costly experimental setups, which may undermine the feasibility of such experiments. This issue can be addressed by employing numerical models validated against simpler experimental setups, as these models are capable of coupling complex analytical scenarios.

9 Large-Scale Impact Tests

A fundamental aspect of research lies in the execution of experiments across varying scales, which offers profound insights into the behaviors under investigation. Experiments conducted at different scales elucidate observed behaviors, ranging from laboratory-scale models to specimens subjected to diverse scaling factors culminating in full-scale investigations. Scaling dependencies emerge when scale influences complexity and expenses, rendering some large-scale experiments more challenging and costly to perform. Nonetheless, such large-scale experiments are employed as they provide critical insights that are elusive at smaller scales. While other sections address health management systems or algorithms for monitoring large structures, this section concentrates specifically on large-scale impact testing, which is conducted infrequently.

9.1 Impact Tests

An instance of conducting a large impact test involved experiments with flexible guided anti-collision (FGAD) devices (F. Wang et al., 2023), where a series of 12 field tests were executed to assess the response of a vessel (weighing 250 t and operating at speeds of 2.5–3 m/s) upon impacting a pier at varying incidence angles (0 and 25°), with subsequent validation via numerical methods. The experiments entailed impact tests on piers equipped with these devices; the FGADs demonstrated the capability to alter the vessel's trajectory with minimal reduction in velocity, limited structural damage to the vessel over the course of 12 tests, and a reduction in forces exerted on the pier by up to 50.

A full-scale test may also transpire inadvertently, whereby unforeseen damage facilitates numerical analyses to elucidate the intrinsic behavior, as exemplified by the scenario in which wind turbine jacket foundations are impacted by ships

(X. Liu et al., 2022). In such an instance, the deformation observed on the foundation post-collision served as the foundation for numerical analyses concerning bulbous bows, wherein the evaluation of velocity and incident angles determined the positions of impact that engendered the maximal damage; localized deformation replicating the genuine damage was identified as the primary damage mode. Similarly, the impact on monopile structures that support wind turbines has been the subject of investigation, where adverse effects on the vessels have been documented. Studies derived from this data have prompted the recommendation to employ higher strength materials in the zones of impact where ruptures might occur, consequently diminishing the potential opening areas by up to 50.

Analogous to previously discussed anti-collision mechanisms, pneumatic rubber fenders serve to mitigate structural damage resulting from impacts. These fenders are implemented at piers during mooring processes and during interactions between tankers and offshore installations. Comprehensive full-scale experiments, alongside experimental evaluations, have been conducted to elucidate the intricate behavior of rubber, assess vessel damage through numerical means, and ascertain the optimal quantity of fenders required to maximally absorb impact energy between these two structures (Park et al., 2023). Additionally, solid fenders were subjected to full-scale experimental investigation to numerically assess the impact damage occurring between an offshore installation and a supply vessel, demonstrating a potential reduction in the applied energy on the impacted structure by up to 30.21.

The collision of structures is a significant concern, necessitating the execution of risk assessments, uncertainty analyses, and various other evaluations to prevent such occurrences (Sukma et al., 2022). These assessments are conducted concurrently with the advancements in technologies that support collision avoidance modeling and testing (Zhu et al., 2023).

The assessment of large-scale impact phenomena can be executed through underwater explosion (UNDEX) testing, as exemplified by the shock test conducted on a full-scale barge in conjunction with numerical simulations. The barge experiences irreversible structural damage as a result of the whipping effect induced by the shock and the initial collision, as well as from the generation of a subsequent jet impact due to the explosion. Although the test involves a barge rather than a full-sized vessel, it provides a fundamental insight into mechanisms that may elucidate the effects on larger vessels (Zhang et al., 2023).

Dedicated shock tests were carried out to calibrate numerical models by (Mannacio, Barbato, et al., 2022) and (Mannacio, Di Marzo, et al., 2022) on large scale specimens of composite laminates conceived on purpose. While the numerical model of the specimens was successfully validated using obtained experimental results, full scale shock trials of a composite hull block of a minehunter was not available for calibrating the hull model. Therefore, experimental data of a test carried out decades ago was used to validate the complete hull finite element model (Mannacio, Di Marzo, Gaiotti, Rizzo, & Venturini, 2023).

9.2 Full Ship Shock Trials: FSST

Naval vessels are susceptible to the risk of non-contact underwater explosions, a probability that arises from their operational environments. This consideration has compelled contemporary naval forces to adopt a comprehensive shock hardening testing protocol. While barge shock testing has been referenced as a method for evaluating smaller systems and components, it presents a challenge when attempting to conduct shock hardening assessments at the level of structural members or components of a vessel. This is necessary to accurately verify the behavior and error characteristics of related members and components within the entire ship system. Moreover, the scientific foundation underpinning the component testing methodologies is insufficient, and these procedures do not necessarily align with either the temporal progression of a shock impulse affecting a ship or the specific response of a component at its position on the vessel.

Full Ship Shock Trials (FSST) are undertaken to assess the resilience of hull structural integrity as well as the operational efficacy of systems and subsystems under shock conditions. Such trials are infrequent; the most recent FSST, conducted in 2021, served as a hardening evaluation of the United States Navy's latest nuclear aircraft carrier, the Gerald Ford, providing critical insights into the naval architecture and engineering systems of this platform (Fig. 18).

Fig. 18. FSST Test for Aircraft carrier USS Gerald R. Ford (2021)

The primary function of Full Ship Shock Trials (FSST) is to mitigate the risk of critical equipment failures that cannot be identified solely through component testing, to assess design and construction, and to validate shock hardening criteria. Nonetheless, FSST faces the challenge of being expensive and requiring extensive time for planning. Conversely, numerical modeling and simulation (M&S) offer insights into the intricate details of the structural and fluid models, dynamic characteristics of the ship hull, and its internal components. Within the context of the U.S. Navy, M&S is either replacing or being utilized alongside full ship trials test evaluations. Considering the swift advancements in M&S technology from a cost-effective perspective, various aspects of research and development are being pursued in applying M&S and FSST testing (Mair et al. 1997, Didoszak et al. 2004, Office of the Director 2022).

Currently, the mechanisms underlying vibration-damping in naval vessels subjected to underwater shock remain inadequately understood. Consequently, ship shock trials continue to be the most effective method for investigating issues related to ship vibration-damping. A strategy for modeling damping in naval ship systems was explored for the transient time-domain analysis of ship shock utilizing FSST (Fan et al., 2017). Madhusudhana et al. collected underwater acoustic data from FSST recordings to validate models of underwater acoustic propagation (Madhusudhana et al., 2023). A predictive approach for ship shock M&S has been developed, with predicted results compared to data from ship shock tests conducted during sea trials. These results are incorporated into an advanced M&S tool with significant modeling parameters replacing FSST (Grządziela, 2011).

Technology development is being carried out along with policy-based supplementation in related elements such as measurement-related monitoring technologies pertinent to the evaluation of FSST tests. Importantly, considerable efforts are being directed towards reducing costs associated with the application of FSST. Moreover, M&S and FSST are employed in a complementary manner for testing and evaluation, with concurrent advancement in technology development to ensure responsiveness to evolving threats from weapon systems.

It is necessary to recognize the specificity of these live ship shock tests being applied preferentially to specific nations and naval vessels. Nonetheless, it is anticipated that future maritime and offshore infrastructure will serve in the transportation and production of hazardous materials which have yet to be identified, or in the provision of energy and environmental advantages. The marine environment may be categorized into diverse accident scenarios, with extreme and accident-prone environments posing a more significant threat load than anthropogenic challenges. In light of FSST in naval ships, it is essential to examine measures for ensuring the integrity and safety of ships and marine structures within the commercial domain.

9.3 Summary and Conclusion

In summary, for this section, the execution of large-scale impact tests at full scale is constrained by their complexity and associated costs. In certain instances, unanticipated occurrences necessitate further inquiries through the integration of numerical simulation and laboratory-scale experimentation to replicate aspects of the impact conditions. The preparation of large-scale tests may extend over several years, encompassing numerical simulations, substantial financial outlay, meticulous instrumentation, platform planning, and the thorough execution of an intricate test event to capture the intended behavior.

10 Full-Scale Ice Load Measurements

10.1 Introduction

This chapter addresses methodologies for assessing ice-induced loads on ship hull structures at full scale. These methodologies are categorized into direct and indirect measurement techniques. The direct measurement methods entail the deployment of external devices affixed to, or integrated within, the structure to ascertain load parameters. Conversely, the indirect approach adopts inverse engineering principles, deducing external loadings from observed structural responses. While it is recognized that ice exerts considerable forces on ship propulsion systems and propellers, necessitating consideration in their design, the current review deliberately excludes measurement techniques pertaining to these components. In coherence with the committee's emphasis on Experimental Methods, this chapter concentrates on applicable methodologies. Any results and observations concerning measured loads have been delegated to respective loading committees. Furthermore, it is acknowledged that previous full-scale campaigns have been documented by antecedent committees, such as Committee V.6 Arctic Technology (2015). Accordingly, the purpose is not to compile an exhaustive list of measurement campaigns, but rather to highlight select instances where the methodologies have been effectively employed.

10.2 Direct Measurements

Various methodologies have been employed to directly quantify the loads induced by ice. Vuorio et al. (1979) devised a pressure gauge system that characterizes ice pressure by measuring the internal surface pressure of the hull within the confines of a rigidly structured area mounted internally. Glen and Blount (1984) implemented hull-mounted pressure gauges to measure pressure across the gauge area. Hoffmann (1985) utilized load sensors embedded in a specially constructed load panel affixed to the hull. The accuracy of the measurements attained through these systems is commendable. However, the limitation of these methods is their localized measurement scope, and the systems developed by Vuorio et al. (1979) necessitate extensive installation efforts. The load panel integrating load sensors within a specially constructed section of the outer hull (Hoffmann, 1985) demands even more comprehensive work and structural alterations. Additionally, a lack of published results from the load panel suggests its limited success.

In order to elucidate the effects of ice-induced external pressure, Riska et al. (1990) employed a PVDF film and a window on the outer hull to quantify local pressures and observe localized processes. Due to the interaction's extraordinarily high pressure and significant mechanical wear, the external gauge exhibited a brief operational lifespan, although the window facilitated qualitative observations. Gagnon (2008) and Gagnon et al. (2020) have engineered optics-based methodologies capable of enduring ice-induced pressures. These methods utilize acrylic beams and derive pressure measurements through analyzing beam deformation under load, categorizing them as indirect approaches. This technique has demonstrated the capability to deliver high-resolution pressure distributions at points of contact. However, a major limitation arises from the necessity of installing the system onto a ship, necessitating structural modifications. Moreover, by altering the structural stiffness, it remains uncertain how representatively the measured pressures reflect the actual structural conditions of the ship.

Recently, Gagnon et al. (2024) introduced a prototype of a relatively thin pressure sensor panel that employs an innovative application of fiber optics. In this configuration, the fibers feature specially engineered small indentations that enable light collection from the lateral direction, subsequently transmitting it along the fiber's length. These fibers reside between two acrylic plates, one of which is coated with a thin layer of Mylar film. When a pressure strip is applied to the suitably illuminated Mylar film, optical contact is established with the acrylic sheet, modifying the internal reflection of the side lighting, and consequently illuminating the white Mylar film within the contacted area. This configuration permits the estimation of both the area and magnitude of pressure. The outlined method has been validated under laboratory conditions but remains untested in full-scale implementations.

10.3 Indirect Measurements

Although direct methods have been employed, indirect approaches have predominated in the determination of local ice-induced loads. These methods ascertain the load acting on the structure by evaluating the structural response. Traditionally, this response has been gauged using strain gauges affixed to a frame or stiffener, although the potential of alternative methods has also been explored. The external load can be inferred from the load-strain relationship, typically determined through Finite Element Analysis (Ralph et al., 2003; Suominen, 2018). In these instances, the load-strain relationship is utilized to deduce the structural response, premised on assumed locations, shapes, and pressure distributions of the load, see e.g. Riska et al., (1983) and Ralph et al., (2003), which are generally considered constant during the measurement process. In scenarios where the instrumentation comprises multiple frames or stiffeners, the ice-induced load at a particular location can be deduced from the response of the entire instrumented structure by employing the response coefficient matrix. This matrix is derived using the unit load principle, whereby various locations are individually loaded, and the response at different instrumented locations is assessed.

The determination of hull responses is frequently derived from the measurement of shear strain differentiation between two positions on a frame, as exemplified by studies on MT Igrim (Korri & Varsta, 1979), IB Sisu (Kujala, 1989a), CANMAR Kigoriak (Ghoneim & Keinonen, 1983), MS Arcturus (Riska, 1982), MS Kemira (Kujala, 1989b), IB Oden (St. John et al., 1994), CCGS Louis S. St. Laurent (Ritch, 2008), MT Uikku (Kotisalo & Kujala, 1999), PM Teshio (Uto et al., 2006), USCGC Healy (Hänninen et al., 2001), CCGS Terry Fox (Ritch et al., 2008), PV Soya (Takimoto et al., 2006), KV Svalbard (Leira et al., 2009), PSRV S.A. Agulhas II (Suominen et al., 2013), and RV Polarstern (Kubiczek et al., 2022). This methodological approach is premised on the notion that ice-induced loads interact with the frame as shear forces. Consequently, the ice-induced loads between distinct locations, such as the upper and lower sections of transverse frames, can be ascertained by assessing the shear strain variation at these points. Occasionally, the focus has been on the compressive strain on the frame orthogonal to the shell, as observed in USCGC Polar Sea (St. John et al., 1984) and RV Nathanial B. Palmer (St. John & Minnick, 1995). This method targets the assessment of localized loads impacting the structure, given the rapid diminishment of strain normal to the hull plating beyond the contact area. Therefore, this technique facilitates the identification of loads with a direct impact at the strain gauge site. Furthermore, attempts to establish local loading through the measurement of bending strain at the frame's flange have been attempted; however, these measurements have presented interpretational challenges.

The magnitude, location, and dimensions of load patches induced by ice exhibit rapid variation in full-scale measurements (Kujala et al., 1994). The uncertainty inherent in these measurements is attributed to the presumed loading conditions. In scenarios involving load measurements on transverse frames, shear strain difference demonstrates reduced sensitivity to variations in loading conditions compared to compressive strain measurements normal to the hull; this reduced sensitivity pertains to alterations in the load patch height and its location on the frame, provided that the loading impacts occur between the gauges (Suominen, 2018). However, the shear strain difference-based methodology is susceptible to variations in the horizontal dimensions of the load, which are contingent upon the structural configuration. This vulnerability can be mitigated by extending instrumentation to adjacent frames (Suominen et al., 2017). Notwithstanding these uncertainties, measurements of ice-induced loads on transverse frames based on shear strain differences have been shown to produce magnitudes that are generally representative of the true loads involved (Suominen, 2018; Böhm et al., 2021). When an instrumented ship or structure is framed longitudinally, the variability in ice-induced load height and location exacerbates uncertainty, as the loading could affect either the spaces between frames or the location of sensors. In the former scenario, the structural response disparity is notably influenced by the local structural configuration. In the latter scenario, proximity to the load location may introduce a significant strain gradient, thereby impeding precise load determination.

More sophisticated inverse methodologies that do not presuppose known load locations or contact areas have been employed in historical full-scale assessments, as referenced in (Adams et al., 2019). Nevertheless, the variability in load position and contact area renders the inverse problem ill-posed, meaning disparate input values may produce identical outputs. Specifically, varying configurations of ice-induced loads can yield identical structural responses. To regulate the solution domain, such methods necessitate regularization to constrain the solutions (Adams et al., 2019; Y. H. Liu et al., 2016). Tikhonov regularization has been favored by Liu et al. (2016) and Adams et al. (2019) as the inverse technique to address the ill-posed nature of the problem and determine the ice-induced load on a ship's hull using full-scale measurement data. However, comparative analyses with controlled calibration pulls remain unpublished, rendering these methodologies principally verified through qualitative means.

In recent years, the rapid advancement of computational technology has facilitated the application of machine learning methodologies to the inversion of ice loads. To ascertain full-scale ice loads, Wu et al. (2021) executed an ice load measurement aboard the "Xue Long" during an Arctic expedition in August 2017. The least squares support vector machine algorithm was employed within the ice load identification model, and an experimental application was conducted to assess the feasibility of this model. Notwithstanding initial efforts and innovations in the domain of ice load inversion via machine learning, the current research is largely situated in the phase of method validation. These approaches predominantly operate within the scope of supervised learning, thereby requiring pre-existing stress and load datasets for model training. The training datasets are frequently virtual or derived from numerical simulations, which introduces uncertainties in assessing the error of inversion outcomes when applied to real-world ship data in practical engineering scenarios.

Efforts to assess ice-induced loads extending beyond instrumented regions have also been pursued. Kong et al. (2021) utilized the least square support vector machine approach to ascertain ice-induced loads acting outside the instrumented zone, based on the compressive strains measured on frames beyond the load influence area aboard RV Xue Long 2. Wang et al. (2023) employed a radial basis function neural network to the same dataset, thereby enhancing the outcomes. In addition, Wang et al. (2023) carried out model-scale tests to further investigate the method. On the whole, the numerical analyses and laboratory experiments were deemed to faithfully represent reality. Nonetheless, it should be noted that these far field measurements demonstrate susceptibility to noise. This sensitivity can be mitigated by introducing noise to the training data, although the noise level might become considerable when compared to the actual signal, particularly as strains outside the loading are negligible in full scale (Fig. 19).

10.4 Summary and Recommendations

The contact area and pressure distribution within the contact area of ice-induced loads exhibit significant spatial and temporal variability. Despite the uncertainties associated with these phenomena, measurement techniques based on hull response via shear strain gauges on transverse framing have demonstrated an ability to quantify the order of magnitude of ice-induced loads. In contrast, measurements for longitudinally framed vessels have proven more challenging, necessitating further refinement. Recently, more sophisticated inverse methodologies and machine learning techniques have been developed and implemented to enhance measurement accuracy and extract additional information, such as contact area dimensions. These advancements have been validated under laboratory conditions and qualitatively assessed in full-scale scenarios. Nonetheless, comprehensive validation and uncertainty analysis in full-scale conditions remain outstanding.

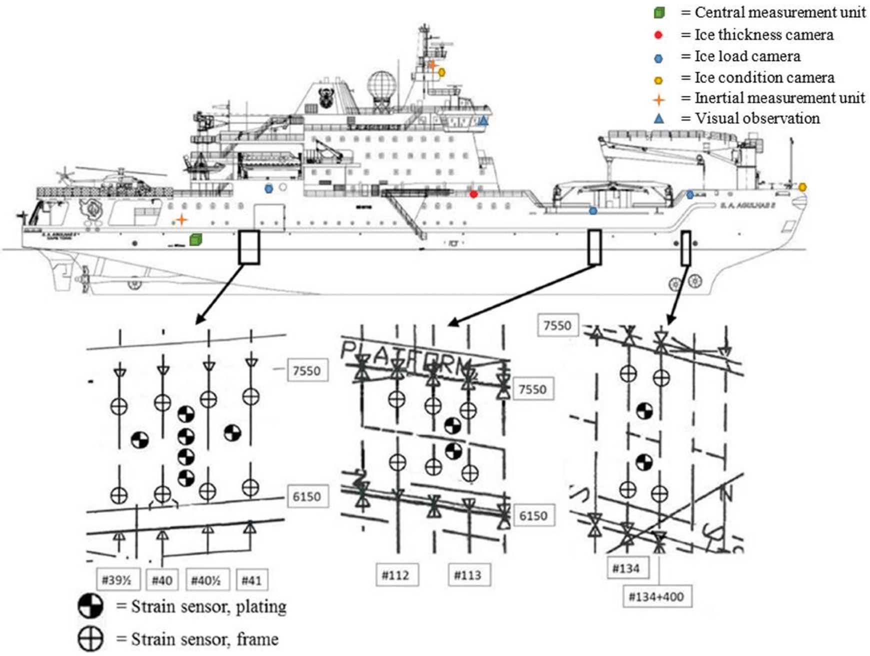


Fig. 19. Instrumentation of S.A. Agulhas II. The ship is instrumented with shear strain gauges at the starboard side on nine frames, including two at the bow, three at the bow shoulder and four at the stern shoulder. The measured shear strain can be converted to forces according to Suominen et al. (2015)

11 Health Monitoring and Digital Twin

This section delivers an exhaustive overview of two interrelated domains: Health Monitoring and Digital Twin Models, both of which are indispensable for the advanced structural analysis and operational efficiency of marine and offshore structures. These areas converge in their objective to harness real-time data to enhance the safety, reliability, and efficiency of maritime structures. Health monitoring methodologies concentrate on detecting and analyzing physical damage, whereas digital twin models expand upon this by offering a comprehensive virtual representation that not only monitors current conditions but also forecasts future performance, thereby providing a proactive approach to marine structure management. In the Health Monitoring subsection, we examine the latest approaches for overseeing the condition of ships and offshore structures, specifically the implementation of Acoustic Emission (AE) and strain sensors for real-time damage detection. Additionally, the integration of machine learning and other data-driven techniques in refining the accuracy and sensitivity of these monitoring systems is discussed, underscoring the crucial role of real-time data in preserving structural integrity.

The subsection on Digital Twin Models examines the implementation of digital twin technology within the maritime sector, wherein empirical data is harmonized with virtual simulations to optimize the lifecycle management of vessels and offshore installations. Digital twins offer essential insights into the operational efficiency and structural integrity of these assets, closely aligning with the objectives of health monitoring systems.

11.1 Health Monitoring

This subsection elucidates the advancements in Structural Health Monitoring (SHM) techniques and systems applicable to marine and offshore structures. A variety of health monitoring strategies have been devised for ship structures. Acoustic Emission (AE) constitutes an SHM method predicated on transient stress waves emanating as a result of damage initiation and progression in materials. Saccone and Pahlavan (2024) examined the effect of stiffeners situated between the damage source and AE sensors on the propagation of AE waves for ship structure surveillance through experimental and simulation approaches, aiming to enhance the sensitivity for fatigue crack detection by considering the presence of stiffeners. Monitoring strain induced by deformation is also advantageous, as excessive deformation may result in damage. Machine learning and additional data-driven processing methodologies have been developed and integrated into SHM. Katsoudas et al. (2023) utilized statistical pattern recognition and machine learning techniques to detect corrosion-induced thickness loss via strain sensors. Aravanis et al. (2023) proposed two distinct methodologies for damage detection in marine stiffened panels based on strain response data. The initial approach discriminates between healthy and damaged states employing a detection theory-based binary classifier, whereas the alternate method correlates strain to out-of-plane deflection utilizing a probabilistic regression model. These methodologies were assessed using simulation, and results demonstrated that they furnish uncertainty-informed forecasts of out-of-plane deflection levels within ship hull structures. In addition to hull structures, research concerning the SHM of rudders and propellers has been conducted. Jang et al. (2024) proposed sensor placements for effective fatigue failure monitoring of ship rudders by assessing the mode shapes derived from CFD and FEM analyses using the structural model, accounting for the structural complexity of ship rudders. Furthermore, Hamada et al. (2023) evaluated the vibration deformation of recreational boat propellers using piezoelectric line sensors integrated into the blades and determined that the amplitudes of the measured signals from damaged blades exceeded those from intact blades.

Fiber Bragg Grating (FBG) sensors possess several advantageous characteristics, including immunity to electromagnetic interference, resistance to chemical corrosion, compact size, and lightweight nature, making them highly effective for monitoring physical and chemical parameters in challenging environments such as marine settings. The foundational principles and theoretical underpinnings of their operation have been elaborated by Min et al. (2021), who also examined primary applications such as temperature, pressure, salinity, pH, heavy metal, and structural health monitoring, revealing the considerable potential of optical fiber distributed sensing technology for SHM. L. Ren et al. (2006) implemented FBG sensors for health monitoring of the offshore oil production platform CB271 situated in the Bohai Sea, East China, detailing the sensor installation process during platform construction and conducting model validation in a laboratory using a seismic simulation shaking table under various loading conditions. Additionally, L. Wu et al. (2018) evaluated the performance of FBG sensor packaging under conditions characteristic of the marine environment, including intense sunlight, heavy rainfall, and saline water, to ensure the sensors' repeatability and durability for long-term application (Fig. 20).

Fig. 20. The wind turbine model with FBG sensors fixed to the partially submerged (Min et al., 2021)

A variety of measurement and data processing methodologies for Structural Health Monitoring (SHM) of offshore structures, such as wind turbines and jacket platforms, have been introduced. Maetz et al. (2023) proposed a microwave SHM approach to detect damage in grouted connections between the monopile and the transition piece of wind turbines, demonstrating that the proposed methodology facilitates a preliminary localization of damage within these connections, based on experiments conducted with a scaled laboratory model. G. Wang (2024) presented a methodology for long-term offshore SHM utilizing a stand-alone Global Navigation Satellite System (GNSS), devoid of reference stations, to predict future structural submergence. This approach also assessed seafloor subsidence rates in the Gulf of Mexico's oil field area using data collected by a GNSS antenna mounted on a fixed platform. P. Jiao et al. (2024) developed a real-time SHM system for marine and offshore structures aimed at damage monitoring, identification, and early warning of underwater concrete structures through vision-based image processing conducted by highly controllable underwater robots. In support of this, P. Jiao et al. (2024) developed the YOLO-Underwater model, based on the YOLOv5 algorithm, to detect concrete damages underwater, including cracks, corrosion, and exposed reinforcement. Weil et al. (2022) implemented an unsupervised novelty detection pipeline, which combines an autoencoder with the Mahalanobis distance, to analyze SHM data from offshore wind turbines. Vieira et al. (2023) assessed the impact of implementing an SHM system for the support structures of bottom-fixed offshore wind turbines on overall energy production and the operational lifespan of wind farms using simulations based on economic models. The study demonstrated quantitative economic benefits, such as extended inspection intervals and potential prolongation of farm operation. Ye et al. (2022) designed an SHM system for an offshore platform under construction in the East China Sea and examined the characteristics and performance of the proposed system through numerical simulations across various scenarios.

The implementation of shape-sensing technology using the inverse Finite Element Method (iFEM) for the structural health monitoring of marine and offshore structures is presently under investigation. iFEM has been successfully utilized by Ghasemzadeh et al. (2022) to ascertain the locations of corrosion damage and pits within corroded offshore components and marine structures. Similarly, Miyashita et al. (2022) employed iFEM in the comprehensive modeling of a 6600 TEU container ship, successfully demonstrating that the bending and torsional deformations of the hull in waves can be accurately reconstructed from the strain data derived via fluid analysis and FEM. Furthermore, Miyashita et al. (2022) validated the feasibility of conducting real-time operational analyses with iFEM through the adoption of parallel computation techniques, thereby enhancing computational efficiency. Nevertheless, it must be noted that a significant portion of prior research remains simulation-based, with experimental assessments predominantly confined to plates and stiffened plates. On the contrary, (Riccioli, Huijer, Grasso, Rizzo, & Pahlavan, 2023) moved from the experimental side in the development of a novel sensor system intended for composite structures health monitoring: in that case, the numerical simulation is the mean for outlining and exploiting the measurements.

11.2 Digital Twin Models

In recent years, the marine industry has witnessed a marked increase in the implementation of sophisticated technologies, such as the Internet of Things (IoT), deep learning, cloud computing, and artificial intelligence (AI). These technologies, which have already transformed traditional sectors, are now poised to bring fundamental changes to the marine industry. Within this context, Digital Twin (DT) stands out as a notably promising instrument. DT constitutes a virtual representation of a physical object or system that operates as a digital mapping platform for pivotal and interconnected entities. It has found extensive application across various domains, including product design, manufacturing, mechanical analysis, construction, and engineering. By converting tangible physical data into virtual models, DT enables simulations, analysis, data accumulation, mining, and electronic application, thereby augmenting the performance, efficiency, and reliability of the physical system.

In the marine industry, digital twin technology plays a crucial role in delivering pertinent feedback throughout the entire lifecycle of marine products, encompassing design, production, operation, and maintenance. This feedback furnishes decision-makers or decision-making systems with essential insights, facilitating the optimization of product performance, cost reduction, and safety enhancement. Consequently, the application of digital twin technology serves as a practical benchmark for the intelligent and digital transformation of the marine industry. Given its potential for enhancing the efficiency, quality, and safety of marine industry products, research in this area is notably active and receives considerable support through grants specifically allocated for this purpose.

While the deployment of Digital Twin (DT) technologies in the maritime industry manifests promising applications, substantial research challenges persist. The comprehensive management of the life cycle of maritime assets via DT represents a prolonged challenge necessitating further scholarly inquiry and empirical case studies. Critical challenges to be addressed encompass:

- Achieving high-fidelity representation of physical entities through virtual models.
- Navigating the inherent complexity and uncertainties associated with ship systems and the dynamic marine environment.
- Overcoming limitations imposed by the current state of digitalization aboard vessels and the availability of shore-based communication infrastructure.
- Addressing the absence of standardization within the maritime industry, which hampers integration of disparate DT systems.
- Mitigating cybersecurity risks, as increased interconnectivity of ships and maritime systems renders them more susceptible to cyber-attacks.
- Upskilling and training of the maritime workforce in new technologies to enable the operation and maintenance of DT systems.
- Addressing the significant initial investments required for DT implementation, which may discourage some enterprises from adopting this technology.

Although digital twin (DT) technology in the maritime industry is still in its early stages, it possesses significant potential to advance the sustainable use of marine resources and contribute to environmental conservation. Ongoing research and development are imperative to address existing challenges and fully harness the advantages of DT within the maritime sector. The community's interest in the application of this technology is evident from the substantial number of review papers. For instance, Pang et al. (2021) provides an overview of the current state-of-the-art in digital twin technology, a crucial component of the Industry 4.0 digitalization process. Their research discusses the development of a novel framework that integrates the digital twin and digital thread to enhance data management, fostering innovation, improving production processes and performance, and ensuring continuity and traceability of information. The digital twin/thread framework incorporates behavior simulation and physical control elements, which depend on the connectivity between the twin and thread for effective information flow and exchange to drive innovation. The framework encompasses specifications related to organizational architecture layout, security, user access, databases, and hardware and software requirements. It is anticipated that the framework will be applicable to optimizing operational processes and information traceability in the physical realm, particularly in an Industry Shipyard 4.0. Lv et al. (2023) provides a review of the state-of-the-art DT applications across various segments of the maritime industry, including shipbuilding, offshore oil and gas, marine fisheries, and marine energy. The analysis indicates that DT significantly supports full lifecycle management within shipbuilding, including the product design phase, manufacturing, operations, and maintenance. Additionally, this work examines the challenges and opportunities associated with DT implementation in the maritime sector, aiming to offer a reference point for the development of intelligent systems and guide the sustainable use of marine resources in the future. Mauro and Kana (2023) presents a systematic review of DT applications in the maritime industry, focusing on the ship life cycle. It underscores that, unlike other industries, the shipping sector often misuses the term “Digital Twin,” mistaking it for basic virtual models that lack real-time data exchange. The review identifies gaps in current research, particularly in the design and decommissioning phases of the ship life cycle, where appropriate DT models remain underdeveloped. The paper also highlights that the ship industry is 2–3 years behind other sectors in adopting DT technologies, notably in manufacturing. A key contribution of the paper is the development of a systematic methodology for evaluating DT research, categorizing 58 relevant studies from 215 identified publications. The study recommends that future research should concentrate on developing DT-based procedures for ship design and retrofitting, with initiatives such as the “Digital Twin for Green Shipping” (DTGS) project offering potential solutions to address these research gaps (Fig. 21).

The focus of the Digital Twin (DT) application in the report by the Experimental Methods Committee centers on the integration of measurement and sensor equipment, alongside the processing of the collected data, Fujikubo et al. (2024) presents the outcomes of the Digital Twin for Ship Structures (DTSS) project, which was conducted through a collaborative effort between industry and academia in Japan. The primary objective of the DTSS is to offer a more comprehensive understanding and visualization of the real-time structural performance of ships during operation, thereby facilitating more optimal, data-driven ship design, construction, and operation. Key achievements of the project include the integration of monitoring systems with numerical simulations via data assimilation methods, specifically the wave spectrum method, Kalman filter method, and iFEM. These methods were validated through measurements at both model-scale and full-scale ship levels. The DTSS system proficiently captures stress responses across the entire ship structure when encountering waves, thereby enabling more precise predictions of short-term extreme responses and long-term fatigue damage. Compared to conventional methods, DTSS offers sig-

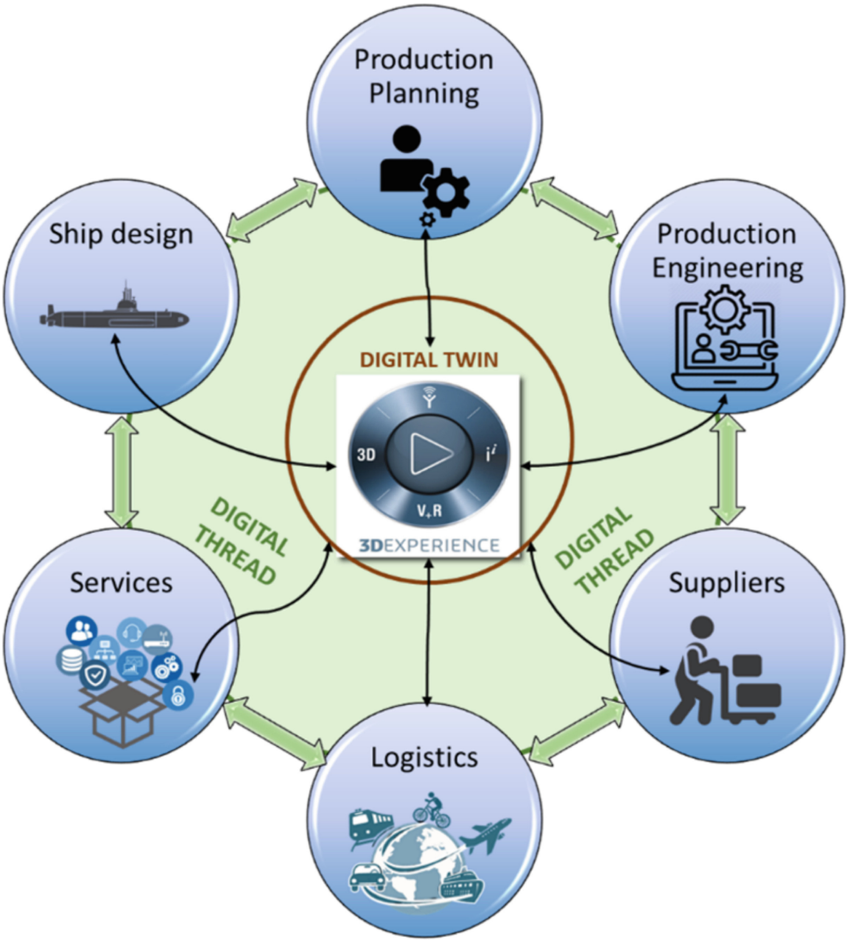


Fig. 21. Digital Twin and thread implementation scheme for a shipyard (Pang et al., 2021)

nificantly enhanced response predictions by utilizing real-time data from encountered wave conditions. The DTSS project introduced an open platform, i-SAS, which enables the application of DT technology for navigation support, maintenance planning, regulatory improvements, and product value enhancement. Furthermore, future research requirements were identified, including extending DTSS to address nonlinear responses and localized stress for fatigue assessments, as well as reducing uncertainties inherent within the DTSS system itself. The results of this project confirmed the technical feasibility of DTSS through comprehensive numerical simulations and real-world experiments, demonstrating its capability to mitigate uncertainties in load and strength estimations, thus contributing to safer and more efficient ship operations. The project underscores the broad potential for DTSS in predicting diverse ship responses, making it applicable beyond ships to marine structures such as floating wind turbines. Future endeavors aim to extend DTSS capabilities, further integrate it into the maritime industry, and explore cost-effective implementation strategies.

Hasan et al. (2024) delineates a rigorous methodology for fault diagnosis in autonomous maritime vessels, capitalizing on the capabilities of digital twin (DT) technology. The principal feature of this investigation lies in the incorporation of the Adaptive Extended Kalman Filter (AEKF) algorithm within the DT framework. This integration successfully illustrates the algorithm's ability to estimate fault parameters, particularly within the propulsion systems of ships. Digital twins function as virtual analogs of physical systems, with the AEKF algorithm performing a critical function by supplying accurate estimations of fault magnitudes. The proposed methodology received validation through extensive numerical simulations, which demonstrated the algorithm's proficiency in delivering accurate and reliable fault diagnoses. These findings highlight the algorithm's effectiveness and capability in detecting and estimating system anomalies. Additional validation was obtained via real-world experiments, substantiating the practical applicability of the proposed approach. The experiments underscored the capacity of digital twins to facilitate real-time health monitoring of ships, thereby allowing timely identification and remediation of faults. Oka et al. (2025) research endorses the 2D-AIS method, which employs two-dimensional wave spectra to more precisely estimate long-term hull stress as compared to conventional approaches. By integrating actual wave data from hindcast sources, the 2D-AIS method enhances the accuracy of predictions, reducing errors from approximately 35.

11.3 Summary and Conclusions on Health Monitoring and Digital Twin

This section delineates the critical technologies of Health Monitoring (HM) and Digital Twin (DT), both intended to augment the safety, efficiency, and resilience of marine structures through the employment of real-time data. Health monitoring techniques concentrate on damage detection by employing sensors and data-driven methodologies, whereas digital twins furnish virtual models to forecast future performance and refine lifecycle management.

Notable advancements have been realized in both domains. Health Monitoring has experienced the integration of Acoustic Emission, strain sensors, and machine learning to identify structural damages. Concurrently, DT technology has progressed through the utilization of empirical data and sophisticated algorithms, such as Kalman filters, to enhance structural assessments and operational decisions.

Nevertheless, several gaps persist. In the domain of health monitoring, a significant portion of research depends on simulations with limited empirical data, and the integration of real-time monitoring for intricate structures such as rudders and propellers remains a formidable challenge. Concerning digital twins, principal challenges encompass high-fidelity modeling, constraints in digitalization, cybersecurity issues, and substantial implementation costs. Furthermore, the maritime industry is comparatively slower in the adoption of these technologies when juxtaposed with other sectors.

12 Applications of Digital Image Correlation (DIC)

12.1 Introduction

Digital Image Correlation (DIC) represents a relatively novel measurement technique predicated upon the acquisition of extensive datasets through digital imaging. In recent years, DIC has been introduced to the market, with the advent of open-source software being developed by researchers, subsequently made accessible online and applied in selected cases. Commercial software and equipment were also developed in parallel by a few start-up firms. These methodologies signify a paradigmatic shift in the experimental analysis of structures; traditionally, displacement and strain measurements are conducted at a limited number of specific points with commendable accuracy. Conversely, emerging digital methods facilitate the acquisition of an extensive pattern of displacement and strains distribution over a surface. This, however, comes at the expense of accuracy, albeit temporarily with anticipated improvements on the horizon, and of some difficulties in the practical use of the measurement system, which is still rather complicate to deploy in the field for the time being. Significantly, such innovative methodologies enable more meaningful comparisons with numerical analyses like Finite Element Analysis (FEA), consequently fostering a robust experimental-numerical integrated approach in structural design and analysis of ships and offshore structures, possibly integrating also environmental action analysis. As a matter of facts, image processing based techniques are also applied in the assessment of hydrodynamic phenomena, both in laboratories and in the field. The 2021 Committee provided an introduction to DIC through a literature review of this emergent experimental technique and executed a benchmark study aimed at evaluating its uncertainties, with an emphasis on human factors in the application of DIC alongside other measurement techniques. The 2025 Committee undertook a review of recent applications of DIC, focusing on a detailed examination of its utilization within the domain of ships and offshore structures. Purposefully, other fields of application were excluded from this review, unless explicit connections or indications relevant to the marine industry were discerned. The fundamental objective is to offer motivating exemplars and specialized application practices, potentially contributing to the exploitation of DIC's capabilities in maritime and offshore structural contexts. Indeed, the advent of novel materials and a goal-based design strategy necessitate enhanced experimental validation of increasingly complex and elaborate numerical simulations, which are increasingly integral to project development and mandated by regulatory requirements.

12.2 Potential of DIC

In this section, the literature review is organized to underscore various aspects of the potential applications of DIC in the context of ships and offshore structures. Although the literature contains numerous studies detailing DIC applications, there is a scarcity concerning our particular areas of interest. Consequently, the objective of this review is to delineate the benefits and limitations within the ship and offshore structure sectors. It is acknowledged that DIC holds significant potential; however, the breadth of its applications remains limited due to certain anticipated challenges to be resolved in the future. An exemplary application of DIC is observed in the case of hybrid joints: for instance, to determine the optimal geometry of a joint, a structural adhesive cohesive zone model Finite Element Analysis (FEA) simulation was executed to minimize Von Mises stresses, subsequent to its validation through DIC measurements obtained from a destructive laboratory test in the adhesive-bonded area. The failure modes of fracture and debonding were throughly examined, which conventional techniques struggle to capture with adequate detail. Comprehensive descriptions are provided by (de Vicente et al., 2022). The modeling and analysis of thin-walled aluminum/steel explosion welded transition joints for shipbuilding purposes have been documented in (Boroński et al., 2020), where a successful integration of Finite Element Analysis (FEA) and DIC results has been achieved, as also noted in (Corigliano et al., 2018), which includes comparisons with infrared thermography measurements as well. Furthermore, a three-dimensional Digital Image Correlation (3D-DIC) method was utilized on a composite underwater structure specimen to evaluate its pressure-bearing capability, employing both conventional strain gauges and numerical simulations. Experimental and numerical evidence indicates that strain gauges exhibit limited accuracy and produce erratic measurements due to the substantial size discrepancy between the strain gauges and the small structural components, coupled with a restricted number of measurement points. In contrast, the 3D-DIC system features a minimal measurement unit that is smaller than the size of these small structural components, enabling precise stress-strain evaluation over an expansive measurement area, and provides a detailed illustration of the strain surface distribution. Additionally, a protective shield was engineered for the cameras to secure optimal functionality within the experimental setting, thereby presenting the feasibility of employing DIC underwater, albeit presently confined to laboratory conditions (Luo et al., 2023). The investigation of fluid–structure interaction effects was satisfactorily conducted using DIC, demonstrating its efficacy in measuring structural deformations associated with unsteady cavitating flows around both flexible and rigid NACA hydrofoils composed of polyvinyl chloride (PVC), brass, and aluminum, as reported by (Yuxing Lin & Schellin, 2022). Reference is made to the limited comparable applications available in the open literature, directing interested readers to this publication for its comprehensive literature review. An analogous application, which boasts the advantage of measuring the response without affecting model properties or altering the flow field, unlike conventional experimental methods and in situ measurements, is elucidated in

(Tödter et al., 2021). This represents a significant benefit of optical measurement techniques not attainable with traditional sensors, which are generally intrusive. The stereo digital image correlation (stereo-DIC) technique demonstrates significant potential in the comprehensive three-dimensional (3D) deformation measurement of marine propeller blades, utilizing stroboscopic lighting to characterize 3D dynamic deformation underwater in a windowed cavitation tunnel. Although enhanced calibration techniques were necessary, the feasibility of monitoring the full-field 3D dynamic response and structural health of underwater rotating structures has now been established (Su et al., 2022). Savio (2015) and Savio et al. (2024) satisfactorily employed stereo DIC to measure the deflection of resin propeller blades solving the problem caused by windows distortion. To evaluate the applicability of DIC for vortex-induced vibration (VIV) investigations, results were compared with those obtained from conventional methods utilizing triaxial accelerometers, possibly intrusive as strain sensors. For small motion amplitudes, the speckle pattern required refinement, while it was adequate for medium and large amplitudes. The influence of the DIC processing techniques was found to be negligibly small under the tested conditions, although different speckle patterns displayed varying accuracy. The repeatability of DIC measurements could not be assessed cost-effectively due to the excessive acquisition duration at high frame rates, as the memory capacity of the cameras posed a limiting factor (Tödter et al., 2021). The role of curvature in the response of air-backed composite plates within the design of naval systems has been successfully studied by Ulbricht, Han, & Porfiri (2024), who used both DIC and planar particle image velocimetry (PIV) to allow for the study of the flow physics and structural response. An impulsive loading was generated from the side of the plate in contact with the fluid, mirroring the loading conditions associated with underwater explosions. An application of DIC for analyzing rapid dynamic events is documented in Gargano et al. (2022), focusing on the response of sandwich structures to explosive blasts in naval ships. The reverse side of the specimen sandwich panels was coated with a speckle pattern comprising dots to enable DIC measurement of out-of-plane displacements and surface strains induced by explosive forces. The dots measured approximately 2 mm in diameter and were spaced roughly 1 mm apart, establishing the spatial resolution for the DIC assessments. The Aramis DIC system was effectively utilized with dual high-speed Photron SA5 cameras operating at a frame rate of

$$7000\,\mathrm{s}^{-1}$$

and offset at an angle of

$$22.5^\circ$$

from the panel surface.

The assessment of service conditions for ships and offshore structures presents a significant avenue for investigation. For instance, corrosion assessments have been conducted and documented, as seen in Qvale et al. (2021) and Shojai et al. (2023), with respect to fatigue failures. Typically, corrosion and fatigue are evaluated independently within standard testing and measurement practices.

However, DIC facilitates the identification of interactions, particularly in differentiating between crack initiation and propagation sites at pre-existing weld notches and those arising from corrosion. It was observed that both, individual pits and uniform corrosion at the weld toe, contribute to fatigue, aligning with expectations; yet, surprisingly, residual stresses induced by clean blasting were partially mitigated by corrosion, thus influencing fatigue strength. More recently, Hu, Hua, Liu, Wang, & Wu, (2025) investigated the multiple pit corrosion interactions and their effect on fatigue crack initiation by methodically establishing a sensitive crack initiation detection scheme by combining high-frequency testing and DIC. DIC finds particularly notable applications in the analysis of highly flexible structures, such as composite foils, and fabrics, such as sails, as well as in fluid-structure interaction problems more broadly. In these contexts, conventional deformation measurement techniques may be intrusive and fail to yield reliable outcomes. Banks et al. (2015) evaluates the use of DIC in these scenarios, focusing on the examination of a curved daggerboard of a racing catamaran with complex geometry within a wind tunnel setting. Additionally, they furnish a comprehensive review of analogous applications. Of particular interest is their discussion on the generation of speckle patterns, whether manually or through a stochastic digital image creation software, which may influence measurement outcomes. Furthermore, they address the issue of image blurring due to vibrations at elevated wind speeds, advocating for the encapsulation of cameras within purpose-designed fairings, which only marginally mitigates the problem, reducing the DIC system error by 57 An interesting application of DIC together with traditional strain gauges is described by G.-J. Shi, Ji, Xu, Wang, & Xu, (2024): the ultimate strength of a scaled GFRP hull girder with hat stiffeners and foams under bending load was experimentally assessed. The strain variation is recorded by the digital image correlation (DIC) system on deck upper surface while critical locations are locally monitored by strain gauges and displacement sensors. Videos allowed recording deformed shapes as well as strain field to validate FEA. The ISSC 2025 Technical Committee III.2 on Ultimate Strength has conducted a benchmark study focusing on the buckling and ultimate strength of a transversely loaded thin plated stiffened structure. A full-scale experiment conducted at the Marine Structures Testing Lab of the University of Genoa served as the experimental target for this benchmark, (Barsotti et al., 2025). Data on applied load versus displacement was provided, alongside 3D scans of the panel's geometry prior to testing for the assessment of initial deformations, and measurements from approximately 40 strain gauge channels and potentiometer displacement gauges were also available. Interested readers are referred to the pertinent ISSC report and associated literature for detailed information. Data from collapse tests were also compiled, complemented by high-definition videos of the shell plating captured from various angles suitable for 3D reconstruction. Acquired DIC data were not utilized in the aforementioned benchmark. Presented here are some images illustrating preliminary analyses of such DIC data currently under review and available for future benchmarks. In addition to the displacements of the central zone of the panel, which is the target area of the tested specimen (being the panel ends specifically engineered to impose appropriate boundary conditions), it was feasible to obtain the temporal evolution of the strain tensor maps on the plating. Traditional gauging techniques, which offer only point measurements, cannot provide such information (see Fig. 22). Consequently, strain gradients can be estimated within the 2D domain, facilitating a comprehensive insight into the buckling behavior of elementary plate panels enclosed by stiffeners. It is pertinent to mention that, as of now, current buckling evaluations recently consolidated in IACS Rec. URS-35 (IACS, 2024) endorse local elastic plate buckling, given that a stiffened plate has reserve strength exceeding the elastic buckling of elementary plate panels. The benchmark conducted by the aforementioned ISSC Technical Committee III.2 on Ultimate Strength identified conservative results in CSR formulations, underscoring the critical importance of validating nonlinear finite element analyses for the shipbuilding industry, especially considering that CSR guidelines apply to at least 90.

12.3 Updates on the Benchmark of ISSC 2021 Committee

In an effort to supplement the ISSC 2021 benchmark, a Committee member who did not participate in the prior study was enlisted. The identical composite specimens utilized in the previous benchmark were supplied to this new participant, with instructions to meticulously adhere to the benchmark guidelines and to document the measurement techniques and their practical application. This consideration arises from the understanding, based on prior experiences, that the application of DIC techniques necessitates a distinct perspective and specific skills for successful implementation. Consequently, the ensuing description serves as a guidance document to underscore the challenges and application strategies as discussed among the current committee members. The primary objective of the 2021 benchmark was, and remains, to estimate the first natural frequency of small cantilever beams composed of fiberglass sandwich laminate. These specimens were originally cut from a sandwich panel for the prior benchmark investigation. The characteristics and properties of the specimens have been detailed in the preceding Experimental Methods Committee of the ISSC 2021 report (Ehlers S., 2022) as follows:

- The sandwich core is a 10 mm thick PVC (75 kg/m^3)
- E PVC 2.60E+09 [N/m^2], PVC 0.32 [-]
- The skins' stacking sequence includes one biax layer (±45°; 600 g/m^2) and one twill layer (0°/90°; 200 g/m^2) on each skin.
- Nominal dimensions of the cut sample are (length/width/thickness): 560/30/12 mm
- Measured dimensions: 563 × 30.7 × 11.8 mm/70 g (Sample A)
- Material properties:
  - E glass 7.00E+10 [N/m^2], glass 0.25 [-], G glass 3.00E+10 [N/m^2]
  - E epoxy 3.00E+09 [N/m^2], epoxy 0.35 [-], G epoxy 1.50E+09 [N/m^2]

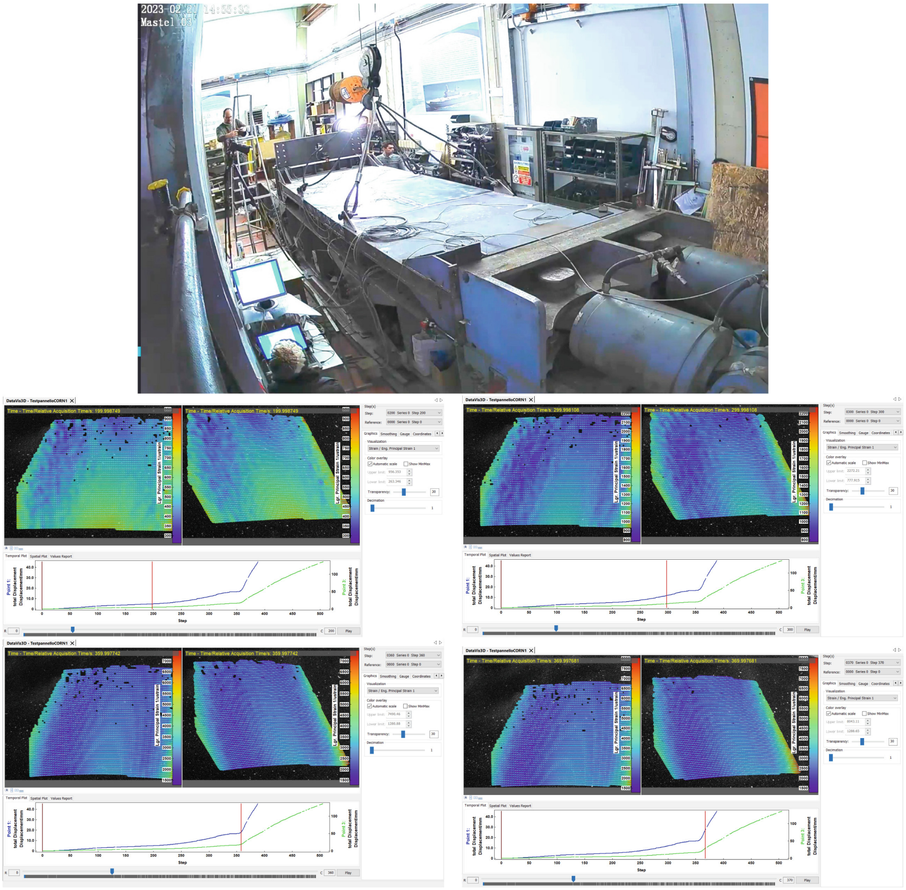


Fig. 22. examples of DIC results obtained from the experimental target of the benchmark test of the ISSC TC III.2 on Ultimate Strength, strain pattern of the plating at certain points in time

Figure 23 illustrates the specimen subjected to testing and its measurement conducted using a basic measuring tape. It is worth noting that nowadays even such trivial measurements are more and more carried out and reported in everyday practice using the aid of digital pictures. To ensure a secure and rigid clamping arrangement, the specimen was secured using a hydraulic wedge grip MTS 647.10A, maintaining a 500 mm length of unsupported span. To mitigate potential damage to the specimen due to excessive clamping force, aluminum spacers with a thickness of 11.55 mm were fabricated, thereby averting the risk of deformation under high pressure. The DIC system utilized for measurement comprised two cameras and two illumination sources.

- Cameras: Basler boost boA5328 - 100 cm
- Lenses: Schneider Kreuznach, JADE 2.8/35 C (focal length 35 mm)

- Lights: Blue-X-Focus v3

The data acquisition was performed using the Vic-Snap commercial software, and the subsequent analysis was conducted within the Vic-3D environment.

A speckle pattern was applied to the tip of the specimen. The cameras and lighting sources were mounted on a tripod. The cameras were configured at an approximately 20-degree stereo angle, such that the sample was centrally positioned within the camera views, maintaining a distance of 55 cm from the cameras to the sample, as illustrated in Fig. 23. Following the alignment of the cameras, the lighting sources were oriented and adjusted accordingly. The focus of the cameras was manually adjusted directly from the lenses and subsequently locked after achieving the sharpest image at an aperture of F/4. To facilitate an increased sampling frequency, the image was cropped to the area of interest, specifically an approximately 40 × 40 mm, plane at the location of the speckle (refer to Fig. 24). The frame rate was then configured to 500 Hz, with the exposure time set at 86 ms. Subsequent to these configurations, calibration was performed using a 14 mm-10-dot calibration frame, adhering to the standard calibration procedure in which the calibration table is rotated and translated within the field of view of the cameras, approximately at the distance of the sample. Polarizing lenses were affixed to the cameras prior to measurements to mitigate local overexposure during the data acquisition process.

Calibration images and measurements were acquired utilizing Vic-snap software. The sample underwent excitation through horizontal force applied via an Allen key at its lowest corner, followed by its release to facilitate free vibration. Measurements spanning approximately 20 s were recorded. Subsequent to recording the vibrations, the gathered data underwent analysis using the Frequency Analyzer tool integrated into Vic-3D software. A calibration routine was executed within the program to generate a calibrated database. To minimize projection error, the 'Auto Correct Calibration' function was employed, successfully reducing the error to 0.05 mm. During data analysis, initial displacements were excluded from consideration. To determine the first eigenmode, horizontal displacements were calculated from the images, both as an average over the defined area of interest and from a specific point, as illustrated in Fig. 24. Figure 25 displays a three-second excerpt from the measured time history, wherein the phase of average displacement over the area and displacement at the point closely corresponds. Consequently, the Fast Fourier Transform (FFT) was applied exclusively to the average area using the tool. The FFT results indicated the highest amplitude, identifying the first natural frequency as 28 ± 0.2 Hz, which is approximately 10% higher but consistent with the DIC results reported in the 2021 ISSC benchmark Fig. 25.

The preceding detailed description elucidates that multiple instrumentation parameters require appropriate configuration by the user, while numerous other parameters remain unreported due to their integration within the proprietary software employed in this instance. Nevertheless, the measurements align with those documented in the prior term of the Committee.

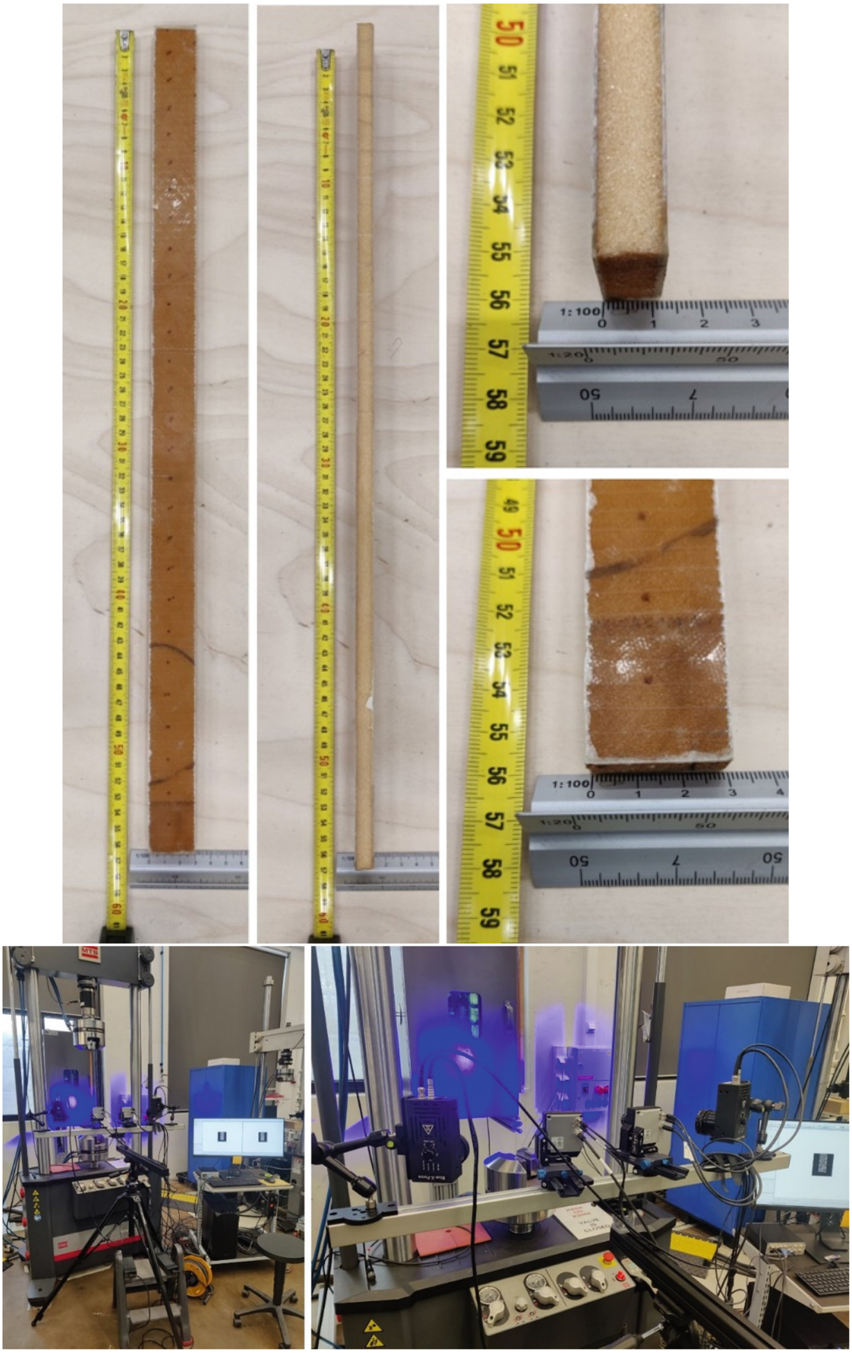


Fig. 23. Specimen and testing setup

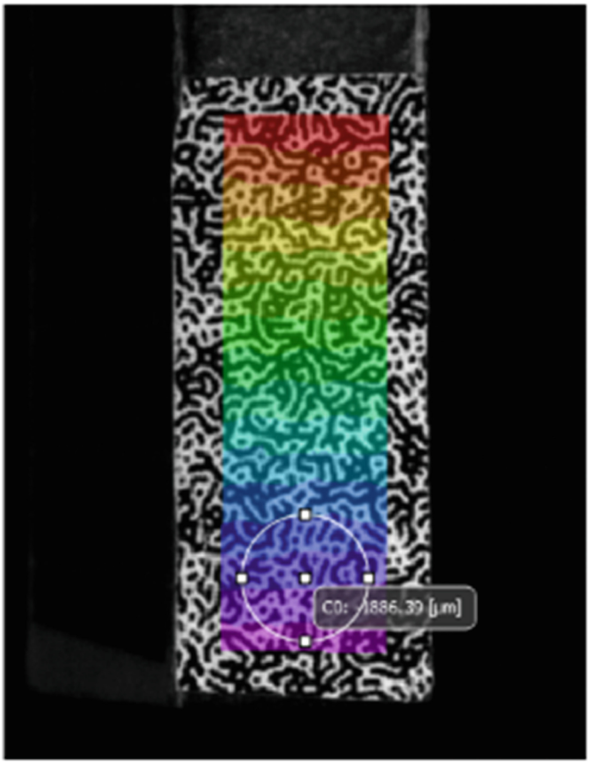


Fig. 24. Screenshot from the build-in Frequency Analysis tool. The colored area over the speckle shows the area of interest, and the white circle with markers a secondary area of interest.

12.4 DIC Application Issues

Applications of DIC have been acknowledged in scientific literature for several years, with the 2021 ISSC Committee introducing a benchmark to probe this emerging experimental technique. The current Committee is focused on assessing DIC applications pertinent to maritime vessels and offshore structures. Supplementary benchmarking tests have been conducted to enhance previously established findings. The succeeding discussion delineates the obstacles encountered in applying DIC, particularly considering specific and in situ applications. Primarily, during the benchmarking process, researchers faced significant challenges in producing a dependable speckled pattern for the measurement of extensive structural areas, in contrast to specimen measurements. For the purposes of the benchmark, the measurement area approximated $0.1\,\mathrm{m}^2$, where conventional techniques for speckle pattern generation, such as the indiscriminate application via a spray can, proved inadequate at this scale. Some participants succeeded in pattern creation through random splattering, yet subsequently encountered complications in accurately calibrating the DIC system. This was ostensibly due

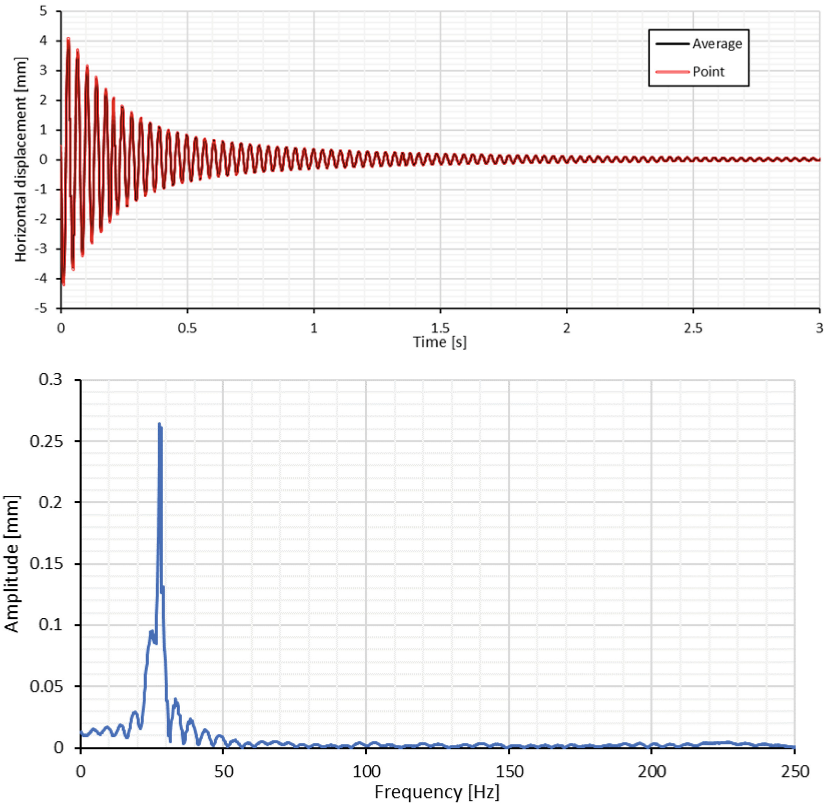


Fig. 25. Measured time history of horizontal displacement and corresponding FFT

to utilizing a calibration pattern of substantial size compared to the dots produced on the specimen's surface. Several alternative methods were proposed and experimentally evaluated: • The application of a printed speckled pattern on the surface of the structure did not result in significant measurements, suggesting suboptimal adhesion. • The employment of a plastic "stamp" failed to generate distinctly defined spots, although this method had previously proven effective for softer, rubber-like structures. The fabrication of a rubber stamp remains a potential solution under consideration. • The manual creation of a quasi-random speckled pattern yielded comparatively improved results (see Fig. 26), yet the signal-to-noise ratio in conditions involving vibrations was found to be inadequately low.

A significant issue identified in the benchmark investigation as well as in other referenced experimentation was the loss of camera focus. The structure in general exhibits both rigid body motions and vibrations: when the magnitude of these motions increases, there is a greater likelihood that portions of the surface would be outside the camera's field of view and the remaining visible surface would be at an incorrect distance for the lenses to accurately capture the

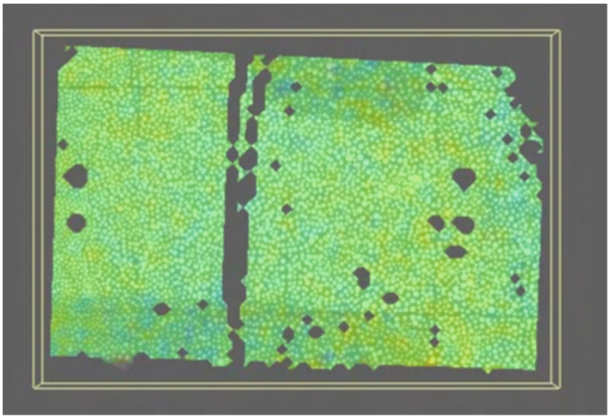


Fig. 26. the manually generated (using a marker) speckled pattern was captured by the cameras in the areas without cables and holes. Nevertheless, vibration measurements were not possible due to low signal-to-noise ratio

responses. Overall, individuals utilizing DIC techniques encountered challenges in preparing the surface for measurement, even within a laboratory setting. Such challenges are exacerbated during large or full scale tests, as demonstrated in the previously referenced panel collapse test (Barsotti et al., 2025). Figure 27 presents images from a large scale test also conducted at the Marine Structures Testing Lab of the University of Genoa on an actual propeller blade, which underscore these issues, highlighting that they are further compounded in situ.

In addition to the challenges associated with pattern preparation and system calibration, users frequently encounter difficulties related to the positioning of the system and the management of cabling components (see again Fig. 27). The abundance and fragility of power and data cables/connectors further complicate operations in environments that are not conducive to delicate equipment. While utilizing custom-developed software can enhance comprehension and offer flexible application options, employing a commercial hardware and software measurement setup provides the benefit of producing reliable results within a reasonable timeframe. This approach mitigates the need for adjusting numerous parameters and instrumentation variables, which are often complex to fine-tune accurately. Nonetheless, it is important to note that even relatively straightforward tests conducted in controlled laboratory environments with a well developed commercial system and software pose significant measurement challenges. Attention is specifically directed to the speckle pattern illustrated in Fig. 24, which differs notably from those generated by random applications of spray cans.

Admittedly, Digital Image Correlation (DIC) is still in its nascent stages, with a novel experimental data paradigm emerging, transitioning from one-dimensional point measurement to two-dimensional surface measurements as previously mentioned. Consequently, when test data are employed for the val-

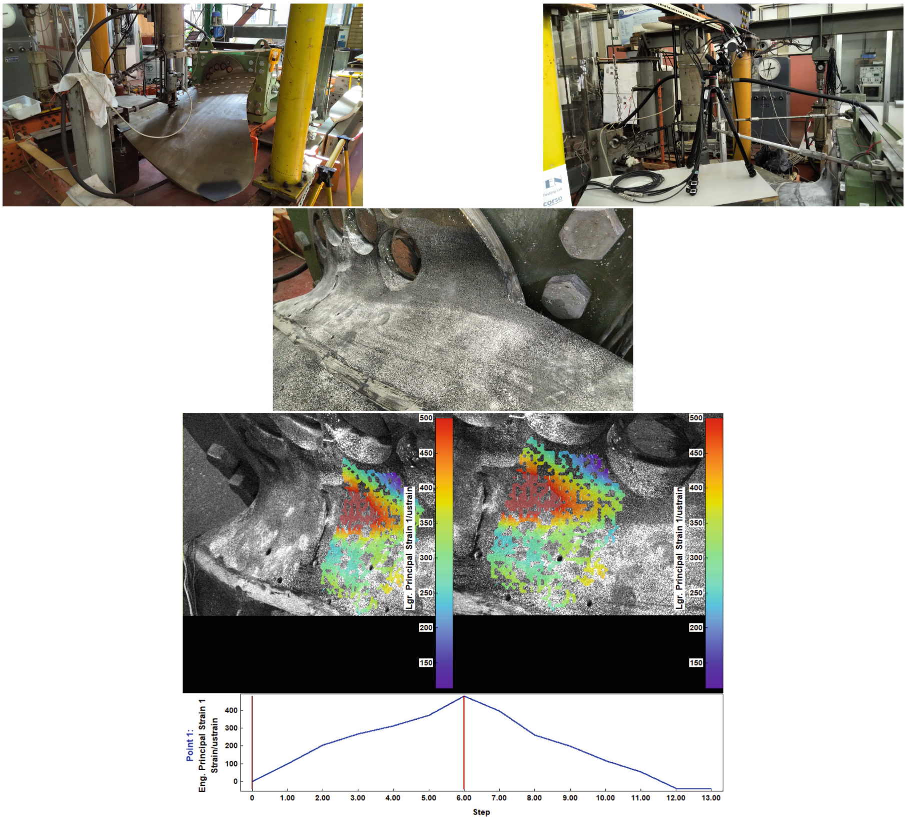
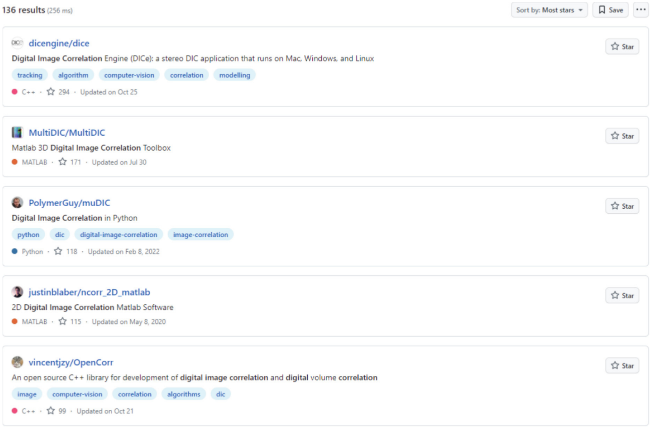


Fig. 27. issues in setting up the DIC measurements in a large scale test in the Marine Structures Testing Lab of the University of Genoa, Italy: "holes" in the strain measurements onto the blade surface are evident

idation of numerical models, as is frequently the case, contemporary literature underscores the advantageous integration of these two methodologies. Notably, commercial DIC software now provides the capability to interface with results from key Finite Element Analysis (FEA) packages. As an additional perspective, a concise account of a DIC challenge documented in the open literature further demonstrates the dynamism within this field (Reu et al., 2017). This initiative evaluates the precision and dependability of various DIC software and methodologies. Participants engage in the analysis of standardized images of a test object subjected to predetermined deformations, utilizing either commercial or open-source software. The challenge evaluates the performance of these tools based on criteria of accuracy, efficiency, and the capability to process complex datasets. This undertaking not only sets a benchmark for existing DIC software but also cultivates a collaborative environment, promoting the exchange of techniques and insights. Open-source tools are frequently emphasized for their adaptability, which facilitates the swift integration of community-driven innovations. The DIC Challenge 2.0 (https://idics.org/challenge/), a progression from the initial DIC Challenge cited in 2021 report of this committee (Ehlers S., 2022), sought to advance the comprehension and evaluation of two-dimensional DIC algorithms. The primary goal was to improve the quantification of the spatial resolution of these algorithms. An essential component of this challenge was the development of novel images specifically tailored for assessing and enhancing the execution of 2D-DIC. The findings elucidated the trade-off between displacement and strain signals noise (or measurement noise) and spatial resolution across a spectrum of DIC algorithms. The results revealed that, while the performance of 2D algorithms generally conformed with theoretical predictions, particularly concerning displacement measurement, the determination of strain spatial resolution exhibited significant variability among the different algorithms. A notable conclusion drawn from the study is that, with appropriate adjustment of solution parameters, the performance of each of the 10 codes can be more closely aligned. This suggests that the quality of outcomes for 2D-DIC is more significantly influenced by the choice of analysis software settings rather than the code's implementation itself, at least among those who participated in this challenge. Consequently, adequate training is essential for the effective adoption of DIC as a primary measurement technique in laboratory and in situ. While obtaining results through DIC is a relatively straightforward process, ensuring the accuracy and reliability of those results presents greater challenges. Moreover, it is crucial to note that, in many experimental contexts, the quality of results is predominantly affected by experimental conditions rather than by deficiencies in the DIC software itself. Commercial DIC software solutions such as Correlated Solutions' VIC-2D/3D, GOM Correlate, LaVision's DaVis, and Dantec's Istra4D provide an array of comprehensive features, including intuitive user interfaces, extensive support, and advanced processing capabilities, though their substantial cost may be a barrier for some users. This potential impediment can be mitigated by open-source alternatives available on platforms like GitHub. Software such as Ncorr and DICe are accessible and modifiable without cost. Ncorr, which operates within MATLAB, and DICe, suitable for both 2D and stereo-DIC applications, offer viable platforms for conducting DIC analysis, though they often necessitate increased user input and customization. Open source DIC software hosted at GitHub were sorted by number of (discord) stars:

- Digital Image Correlation Engine (DICe)
- MultiDIC
- μDIC
- Ncorr
- OpenCorr, (see also W. Yin et al. (2024))

to assess the practicality of various software options. An endeavor was undertaken to evaluate open-source software endowed with stereo-DIC capabilities. Software reliant on MATLAB was excluded from the investigation due to the relatively high cost associated with acquiring a MATLAB license, as the primary objective was to explore entirely cost-free alternatives. Contrary to initial expectations, the undertaking proved to be considerably more challenging, and consequently, the current ISSC report does not include comprehensive findings since the investigation remains ongoing. Nonetheless, a promising software adaptation is in development and is anticipated to be presented, if not sooner, at the forthcoming ISSC Congress. Open-source DIC software generally presents a steep learning curve and necessitates a high degree of expertise in both DIC techniques and programming. Although certain platforms provide 3D DIC functionalities, applying them to practical applications poses significant challenges. Difficulties frequently encountered include inadequate documentation, the absence of intuitive or effective graphical interfaces for process management, the requirement for Python or C++ programming to set up particular measurements, algorithmic inefficiencies resulting in untenable analysis durations, and a deficiency in post-processing tools. A prevalent issue is the inconsistency or cessation of developer engagement within many open-source initiatives. Consequently, post-initial release, the software may cease receiving updates, bug resolutions, or feature enhancements, thus undermining its reliability for long-term usage. In some instances, development is entirely abandoned, leaving users with obsolete or partial tools. Moreover, diminished or intermittent community contributions can result in prolonged periods during which even critical issues remain unresolved, thereby complicating efforts to address these challenges or adapt the software to meet evolving requirements (Fig. 28).



136 results (256 ms)

dicengine/dice
Digital Image Correlation Engine (DICe): a stereo DIC application that runs on Mac, Windows, and Linux
tracking · algorithm · computer-vision · correlation · modelling
C++ · ☆ 294 · Updated on Oct 25

MultiDIC/MultiDIC
Matlab 3D Digital Image Correlation Toolbox
MATLAB · ☆ 171 · Updated on Jul 30

PolymerGuy/muDIC
Digital Image Correlation in Python
python · dic · digital-image-correlation · image-correlation
Python · ☆ 118 · Updated on Feb 8, 2022

justinblaber/ncorr_2D_matlab
2D Digital Image Correlation Matlab Software
MATLAB · ☆ 115 · Updated on May 8, 2020

vincentjzy/OpenCorr
An open source C++ library for development of digital image correlation and digital volume correlation
image · computer-vision · correlation · algorithms · dic
C++ · ☆ 99 · Updated on Oct 21

Fig. 28. Open source DIC software hosted at GitHub sorted by number of (discord) stars

12.5 Summary on DIC Applications in Ship and Offshore Structures

The literature and internet survey, along with the applications detailed in this section and the experiences documented in the 2021 ISSC Committee report, suggests that DIC is a promising experimental technique. However, its primary limitation is its applicability in challenging environments such as marine settings. Although commercial equipment permits applications with acceptable but considerable effort, leveraging open-source software, standard cameras, and other readily available market devices, to develop DIC instrumentation remains currently beyond the typical skill set of naval architects and marine engineers. The predominant challenges involve system calibration and the creation of an appropriate pattern on the specimen's surface, as well as the selection of suitable instrumentation components and their appropriate integration when not using ready-to-use equipment available from relatively few vendors. Conversely, laboratory applications provide valuable opportunities for validating numerical simulations, which conventional gauging techniques cannot achieve, offering a comprehensive view of structural deformations as evidenced by literature and direct applications by members of this ISSC Committee.

13 Summary and Conclusions

Various experimental methodologies are employed to assess the performance and responses of ships and offshore structures under diverse conditions. These methodologies utilize sensor systems and numerical simulations to verify and validate design specifications, lifecycle performance, accidental scenarios, and lifecycle responses. The report encapsulates the expertise of the authors in their specific research domains, articulating the current state of the art and identifying critical technologies and existing gaps. Summaries of each section are provided, with more comprehensive details available within each respective section.

Within the Scaling Laws section, the validation process for the newly proposed scaling method remains in progress, and the current scaling approaches address only a limited portion of the testing scopes. Therefore, additional scaling methodologies are requisite to encompass the scopes of various tests.

In the section on the Fluid Structure Interaction of Flexible Structures, it is observed that elastic models are increasingly being employed for non-beam-like structures, scenarios where multiple modes are significant, torsion, and local responses, among others. These models are fabricated utilizing additive manufacturing, foam, or shaped plastic sheets.

Within the section dedicated to Hybrid model testing, a comprehensive summary of models is presented across various categories, with particular emphasis placed on hardware-in-the-loop methodologies, which are increasingly prevalent within the domain.

Within the fire test section, it is acknowledged that fire testing methodologies are continuously advancing. Consequently, the implementation of a comprehensive full-scale testing protocol is essential to develop and confirm that novel composites, specifically bio-based materials, adhere to marine standards and fire safety prerequisites.

Within the section dedicated to friction testing, the intricacies associated with interactions involving sea ice are highlighted, particularly the challenges in differentiating forces attributed to friction from those related to ice fracture and submersion. In a similar vein, the investigation of internal friction in power cables and umbilicals is explored. The necessity of friction testing is underscored, and further research conducted under pertinent conditions is advocated.

The section on corrosion prognostics elaborates on corrosion as a principal contributor to the structural failure of maritime vessels and offshore structures. Corrosion prognostics are being integrated with structural health monitoring techniques to effectively manage life cycles and minimize costs.

Within the domain of large-scale subsea structures, numerous recent experimental investigations have been focused on the fluid-structure interaction, aiming to understand the response concerning vibration, displacement, and stress.

In the section concerning large impact tests, it is observed that the planning of large-scale tests may require several years. This includes numerical simulations, substantial financial resources, instrumentation, platform planning, as well as the meticulous execution of a complex testing event to accurately observe the desired behavior.

Within the section on full-scale ice load measurements, it is observed that the contact area and the pressure distribution within this area exhibit significant spatial and temporal variability. Measurements of ice-induced loads on ships with longitudinal framing present further complexities, necessitating additional advancement in this area.

Within the section on health monitoring and digital twins, the field of health monitoring heavily depends on simulations, which are constrained by the availability of experimental data. The integration of real-time monitoring for intricate structures, such as rudders and propellers, continues to pose significant difficulties. Digital twins are confronted with fundamental challenges including the need for high-fidelity modeling, limitations of digitalization, issues related to cybersecurity, and substantial implementation costs. Furthermore, the maritime industry is notably behind other sectors in embracing these technologies.

The section on the application of Digital Image Correlation (DIC) indicates that DIC is a promising experimental method. However, its primary limitation lies in its application challenges in harsh environments, such as marine settings. Furthermore, although commercial equipment facilitates applications with considerable but manageable effort, the potential for utilizing open-source software, standard cameras, and other widely available devices to develop DIC instrumentation exceeds the current average proficiency of naval architects and marine engineers.

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