# 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.

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# 1 Discussion

## 1.1 Official Discussion by Jeom-Kee Paik

### 1.1.1 Introduction

I would like to express my sincere appreciation to the members of Committee V.2 for producing such a comprehensive and forward-looking report. The breadth of topics covered—from scaling laws and hybrid testing to corrosion prognostics, large-scale impact tests, and the integration of health monitoring with digital twins—clearly reflects the committee's deep expertise and strong global collaboration.

This report serves as a valuable resource that will undoubtedly guide ongoing research and best practices in ship and offshore structural experimentation. I would especially like to acknowledge the committee's dedication to advancing experimental methods that support safer and more resilient ships and offshore structures. In my official discussion, I intend to raise some critical questions and offer forward-looking recommendations for future committee activities.

### 1.1.2 General Points of the Report

Role of Experimental Methods in Nonlinear Structural Response Assessment:

The report effectively underscores the indispensable role of experimental methods in validating computational simulations, particularly for assessing nonlinear structural responses under extreme conditions and accidental scenarios. While computational techniques can yield highly accurate results for linear elastic problems, they become considerably less reliable under nonlinear or accident-driven conditions due to inherent modeling uncertainties.

The report correctly highlights that, unlike hydrodynamic problems, structural responses lack well-established scaling laws, thereby necessitating full-scale or at least large-scale experimental testing to ensure the fidelity and reliability of simulation outcomes. This point is well presented and emphasizes the essential role of experimental validation in structural mechanics.

Fluid-Structure Interaction (FSI) for Flexible Structures:

The discussion of fluid-structure interaction is another notable strength. Although FSI effects are often neglected in many practical scenarios of ships and offshore structures, the report provides a balanced and nuanced treatment by acknowledging instances where FSI becomes significant for specific types of flexible structures. It supports this with valuable model test studies that illustrate when and how FSI effects can impact structural responses. This balanced perspective enhances the report's contribution.

Hybrid Model Testing:

The concept of hybrid model testing—integrating physical experiments with numerical simulations—is an innovative and forward-looking development. The report presents several illustrative case studies that demonstrate both the feasibility and the practical benefits of this approach. This reflects ongoing methodological advancements in structural testing.

Fire Testing and Passive Fire Protection:

The report also offers a focused examination of fire hazards, particularly hydrocarbon fires, which represent some of the most catastrophic risks in maritime operations. The inclusion of case studies on fire testing and passive fire protection systems is both timely and highly relevant to the safety design of ships and offshore structures.

Frictional Effects in Collision Scenarios:

The role of frictional resistance in energy dissipation during ship-ship and ship-iceberg collisions is effectively addressed. In ship-ship collision scenarios, computational models commonly assume a friction coefficient of 0.3, while for ship-iceberg collisions, it is typically assumed to be zero. However, these values are uncertain, and more effort is needed to validate them. The report provides a valuable survey of experimental studies that examine frictional effects, offering important insights into collision dynamics and structural crashworthiness assessments.

Corrosion Testing for Aging Structures:

Recognizing corrosion as a predominant form of in-service degradation, the report provides an up-to-date review of recent corrosion tests and explores various methods for assessment and mitigation. This represents an important contribution to long-term asset integrity management.

Because natural corrosion testing requires significant time and cost, most laboratory corrosion studies are conducted using accelerated corrosion techniques. While naturally corroded tests of marine steels are available in the literature, this report does not delve into them.

The primary purpose of corrosion testing is to determine the corrosion rate, which indicates how quickly corrosion damage (such as pitting depth or uniform thickness reduction) progresses. Another critical issue is whether corrosion alters the chemical composition of structural steels. As long as the chemical composition remains unchanged, the mechanical properties should also remain unaffected. Thus, the impact of corrosion damage on steel strength results solely from geometric reduction, with mechanical properties playing no role. For more details, refer to A. Rajput and J.K. Paik (2021), *Effect of naturally-progressed corrosion on the chemical and mechanical properties of structural steels*, Structures, 29: 2120–2139.

Experimental Studies on Subsea Systems:

For deepwater resource development, the performance and integrity of subsea structures such as risers and pipelines are critical. The report documents several recent test campaigns focused on these systems, offering practical insights into their design and behavior in deepwater environments.

Large-Scale Impact Testing for Structural Crashworthiness:

The report provides an overview of large-scale impact tests relevant to structural crashworthiness. This includes scenarios such as ship-bridge pier collisions, iceberg

impacts on stiffened panels, supply vessel impacts on jacket-type offshore wind turbines, collision tests on fender-equipped structures, and underwater explosion tests. The discussion effectively highlights the importance of understanding shock loading on ship hull integrity.

However, it is essential to emphasize that structural crashworthiness involves complex crushing and fracturing behaviors that are influenced by many factors (Paik, 2020), including:

- Buckling
- Plastic deformation
- Crushing (folding)
- Fracture (brittle, ductile, rupture)
- Welding-induced initial imperfections
- Age-related degradation (corrosion, fatigue cracking, localized denting)
- Impact loading rates (collisions, dropped objects)
- Low temperatures during Arctic operations
- Cryogenic conditions from accidental LNG or hydrogen leaks
- Elevated temperatures from onboard fires
- Friction at contact surfaces
- Effects of surrounding water
- Interactions between the striking and struck bodies

Detailed investigations of these factors should be a focus of future committee activities.

Ice Load Measurements in Arctic Operations:

Defining ice loads is a critical aspect of structural design for Arctic environments. The report provides a valuable summary of full-scale ice load measurements and offers practical recommendations that support safer Arctic operations.

However, for trading ships operating in Arctic regions, icebergs are generally treated as the struck body, while the ship is considered the striking body. During a collision, the kinetic energy of the striking ship is dissipated through:

- Structural deformation (buckling, plasticity, crushing, fracturing)
- Local and global damage to both bodies
- Motion of both bodies
- Hydrodynamic effects (added mass, wave radiation, fluid resistance)
- Energy absorption by internal damping and contact friction

This implies that icebergs can be modeled as structures composed of ice materials whose mechanical properties vary by location and age. It is therefore recommended that further investigations and tests be conducted to characterize the mechanical properties of "ice materials" from different regions and of different ages.

Health Monitoring and Digital Twin Technologies:

The report concludes with a comprehensive review of structural health monitoring and digital twin technologies. These are becoming increasingly vital for enhancing the safety, sustainability, and operational efficiency of aging ships and offshore assets operating under harsh environmental conditions. The coverage is thorough and up to date, reinforcing the report's relevance to both current and future challenges.

However, since the present committee is focused on experimental methods, future committee activities should prioritize investigating techniques for physical tests to monitor and measure health parameters that can be implemented into digital twin-based simulations.

### 1.1.3 Areas of Improvement

Report Presentation and Structural Coherence:

- The report would benefit from a more consistent and coherent editorial style. At present, different chapters appear to have been authored independently by various members of the committee and then compiled with limited editorial integration. This results in noticeable inconsistencies in terminology, writing style, and structural flow, which can make the document harder to navigate and diminish its overall readability.
- The impact of the report could be significantly enhanced by adopting a systematic structure across chapters. For example, each topic could consistently address: (i) test facilities and setups, (ii) experimental programs and case studies, (iii) key findings and engineering implications, and (iv) unresolved technical issues alongside recommendations for future work.

Alignment with Committee Mandate and Methodological Rigor:

- While the report covers many relevant topics, some sections treat critical areas superficially, lacking in-depth technical explanations or robust methodological grounding. A more rigorous approach would involve clear documentation of how literature was surveyed, how case studies were selected, and how conclusions were drawn, thereby strengthening the report's authority and alignment with the committee mandate.
- Ideally, the report should begin with a systematic review of recent (past 3–5 years) publications from high-impact journals, identifying key trends, knowledge gaps, and emerging technologies that set the stage for the presented experimental work.

Depth and Comparative Analysis of Technical Content:

- The level of technical analysis varies considerably across sections. In some places, discussions are largely descriptive or anecdotal, lacking rigorous interpretation or quantitative insights. The report would benefit from deeper analyses, drawing more explicitly on data to support conclusions.
- Inclusion of comparative studies—such as between different experimental methods, or between experimental and computational (numerical) results—would greatly enrich the technical value of the document. Such comparisons help identify strengths, limitations, and applicability boundaries of various approaches, offering meaningful guidance for industry and future research.

Treatment of Digital Twin and Health Monitoring Topics:

- The section on structural health monitoring and digital twins is particularly timely. However, since this topic is broad and often crosses into areas beyond experimental methods (such as data analytics and IoT-driven digital solutions), it would be beneficial to focus explicitly on experimental techniques supporting these systems—such

as real-time monitoring of corrosion, fatigue cracking, mechanical denting, or environmental loads using sensor technologies, and the physical validation of digital twin models.

Critical Analysis, Discussions, and Forward-Looking Recommendations:

- One of the more noticeable shortcomings of the report is the limited critical discussion of test results and their broader engineering implications. While many test cases are presented, the report does not sufficiently explore what these findings mean for current design practices, where significant knowledge gaps remain, or how methodologies might evolve.
- The concluding sections would be stronger if they synthesized the report's key insights into generalizable lessons, clearly articulated the merits and limitations of current experimental practices, and proposed a forward-looking research agenda aligned with emerging technological trends.

### 1.1.4 Additional Review Comments and Forward-Looking Recommendations

#### 1.1.4.1 Extreme and Accidental Events in Ships and Offshore Structures

Greater emphasis should be placed on experimental studies and test campaigns that specifically investigate nonlinear structural responses under extreme and accidental events, such as collisions, groundings, fire, explosion, and ice impacts. These scenarios often dictate the ultimate limit states of ships and offshore structures, directly influencing design safety margins and regulatory compliance (Fig. 1).

To advance this field, the committee could:

- Encourage the development of large-scale or full-scale experiments that replicate realistic accidental scenarios, including ship-ship collisions, grounding events on varied seabed profiles, and ice impacts under controlled Arctic-like conditions.
- Promote the integration of coupled hydro-structure experiments to better capture combined hydrodynamic and structural effects during accidents (e.g., progressive flooding following collisions).
- Systematically document and compare the residual structural strength and progressive damage patterns under sequential accidental loads (for instance, ice loading followed by collision or fire-induced weakening), thereby supporting more robust risk-informed design.

Such efforts would not only fill critical knowledge gaps but also improve the calibration of computational models used for accident simulation, ultimately leading to safer and more cost-effective structural designs.

#### 1.1.4.2 Key Parameters Influencing Nonlinear Structural Responses

Future committee work should aim to systematically identify, categorize, and quantify the key parameters that govern nonlinear structural responses under extreme and accidental scenarios, such as collisions, groundings, fires, explosions, and ice impacts. A robust understanding of these parameters, along with their inherent uncertainties, is essential to ensure the credibility of computational models, the design of meaningful experiments, and the reliable interpretation of test outcomes.

$$f(X) = f(X_1, X_2, X_3, X_4, X_5, X_6, X_7, X_8, X_9)$$




**Fig. 1.** Various types of extreme condition accidents in ships and offshore structures (J.K. Paik (2020). *Advanced Structural Safety Studies with Extreme Conditions and Accidents.* Springer Nature, Singapore)

where,

$X_1$ = Geometric properties
$X_2$ = Material properties
$X_3$ = Fabrication-related initial imperfections
$X_4$ = Load types
$X_5$ = Loading speed (strain rate effects)
$X_6$ = Temperature (elevated and cryogenic)
$X_7$ = Age-related degradation (corrosion, fatigue cracking, mechanical denting)
$X_8$ = Accident-induced damage (collision, grounding, fire, explosion)
$X_9$ = Human error

Specifically, future studies should:

- Distinguish between global and local parameters influencing structural response, such as overall hull girder flexibility versus local plate and stiffener characteristics, and understand how they interact under nonlinear loading regimes.
- Investigate material nonlinearity, including strain-rate effects, thermal softening during fire, and fracture propagation in ductile and brittle failure modes.
- Examine geometric imperfections and residual stresses, which can have pronounced effects on buckling and post-buckling behavior, especially in large thin-walled marine structures.
- Characterize contact and friction parameters in collision and grounding scenarios, noting how variations in friction coefficients or contact stiffness alter energy dissipation and failure modes.
- Account for dynamic amplification effects where loading rates significantly exceed quasi-static assumptions, as in explosion or ice impact scenarios.
- Explore environmental influences, such as corrosion wastage or ice accretion, that modify baseline structural capacities and alter nonlinear response thresholds.
- Quantify interaction effects, such as combined hydrostatic pressure and impact loading, or simultaneous thermal and mechanical demands during fire and explosion.

In parallel, probabilistic frameworks should be encouraged to capture the uncertainties in these key parameters, facilitating risk-informed design and more robust reliability assessments. By developing a standardized methodology for parameter identification, experimental calibration, and uncertainty quantification, future committee work can greatly enhance the predictive accuracy of nonlinear structural analyses. This would directly support safer and more cost-effective design solutions for ships and offshore structures exposed to accidental and extreme events.

#### 1.1.4.3 Review Process of Experimental Methods

A more structured and systematically documented presentation of experimental methods is strongly recommended to enhance the clarity, comparability, and long-term value of committee outputs. This should aim not only to catalogue existing approaches but also to create a foundation for standardized reporting and collaborative benchmarking across the international maritime and offshore community.

#### 1.1.4.3(a) Test Facilities

An updated and well-classified inventory of available international test facilities is proposed, detailing their capabilities to support large-scale, high-fidelity, or specialized experiments. This should include:

- Capacities in terms of scale (e.g., full-scale ship shock tests, large ice basins, high-capacity fire laboratories).
- Technical specializations, such as multi-axial loading rigs, wave-current tanks with ice-making capability, and high-rate impact or blast chambers.
- Notable past or ongoing projects demonstrating facility strengths.

Such a compendium would serve as a strategic reference for researchers, classification societies, and industry stakeholders when planning complex experimental campaigns. It could also identify opportunities for multi-institutional collaborations, leveraging unique facility strengths to conduct ambitious hybrid or multi-physics tests that are otherwise beyond the reach of single institutions (Fig. 2).




**Fig. 2.** Test facilities at KOSORI (Korea Ship and Offshore Research Institute at Pusan National University, South Korea), enabling full-scale and large-scale model testing (www.kosori.org)

### 1.1.4.3(B) Matrix of Test Targets and Loading Conditions

To complement the facility overview, it is recommended to develop a comprehensive matrix that systematically maps experimental objectives to specific structural targets and loading conditions. For example:

- Levels/types of structures: S1 = Material (steel/Al./composite/ice), S2 = Beams/columns/beam-columns, S3 = Plates, S4 = Stiffened panels, S5 = Stiffened plate structures, S6 = Plate assemblies (plate girders), S7 = Hull structures, S8 = Tubular structures, S9 = Risers, S10 = Pipelines, S11 = Others
- Loading conditions: cyclic fatigue, ultimate static loading, dynamic impact, explosion overpressure, hydrocarbon fire, ice crushing, combined thermal-mechanical scenarios.

| Class | P1 | P2 | P3 | P4 | P5 | P6 | P7 | P8 | P9 | P10 | P11 | P12 | P13 | P14 | P15 | P16 | P17 | P18 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S1 | | | | | | | | | | | | | | | | | | |
| S2 | | | | | | | | | | | | | | | | | | |
| S3 | | | | | | | | | | | | | | | | | | |
| S4 | | | | | | | | | | | | | | | | | | |
| S5 | | | | | | | | | | | | | | | | | | |
| S6 | | | | | | | | | | | | | | | | | | |
| S7 | | | | | | | | | | | | | | | | | | |
| S8 | | | | | | | | | | | | | | | | | | |
| S9 | | | | | | | | | | | | | | | | | | |
| S10 | | | | | | | | | | | | | | | | | | |
| S11 | | | | | | | | | | | | | | | | | | |

P1 = Material properties
P2 = Initial distortions
P3 = Welding residual stress
P4 = Static loading
P5 = Repeated/fatigue loading
P6 = Extreme cyclic loading
P7 = Dynamic/impact loading
P8 = Corrosion
P9 = Fatigue cracking
P10 = Denting
P11 = Elevated temperature
P12 = Low/cryogenic temperature
P13 = Collisions
P14 = Grounding
P15 = Hydrocarbon fire (jet, pool)
P16 = Hydrocarbon explosion
P17 = Underwater explosion
P18 = Others

This matrix approach would help:

- Standardize reporting: ensuring consistent documentation of test goals, specimen types, instrumentation layouts, and data outputs across different studies.
- Facilitate benchmarking: by enabling clearer comparisons of test results for similar targets under equivalent loading regimes, thereby accelerating design rule evolution and validation of advanced numerical models.
- Identify gaps: revealing under-studied combinations of structural systems and extreme loads that could become priorities for future research campaigns.

#### 1.1.4.3(C) Recommendations for Data Sharing and International Benchmarking

To maximize the impact of individual experiments and support broader digital twin and AI-driven predictive frameworks, it is further recommended to:

- Establish protocols for curated data sharing (while respecting confidentiality constraints), potentially hosted under ISSC or aligned with open-access maritime research platforms.
- Encourage comparative studies where identical or similar structural targets are tested under agreed protocols across different facilities, fostering rigorous international benchmarking and mutual learning.

### 1.1.5 Full-Scale Tests not Addressed in the Current Report

The current report does not sufficiently address recent full-scale tests that hold significant relevance for advancing the understanding, modelling, and practical design of ship and offshore structures. Such full-scale experiments are indispensable for validating numerical predictions, assessing construction-induced imperfections, and informing class rules and design standards. To strengthen future reviews, it is recommended to incorporate dedicated sections on major full-scale test programs that offer insights into structural behavior under realistic fabrication and operational conditions. Three specific examples are proposed here.

#### 1.1.5.1 Full-Scale Tests of Welding-Induced Initial Distortions and Residual Stresses in Ship Stiffened Plate Structures

Welding remains the primary fabrication method for ship and offshore structures, but it

inherently introduces initial geometric distortions and residual stresses, which can significantly influence the nonlinear structural response—particularly buckling and ultimate strength. Recent large-scale or full-scale experiments have sought to quantify:

- The magnitude and distribution of welding-induced initial imperfections across typical stiffened panel configurations (including longitudinal and transverse stiffeners, openings for access or piping, and attached brackets).
- Residual stress profiles resulting from different welding processes and sequences, and their stabilization or redistribution under cyclic loading (Fig. 3).



**Fig. 3.** Full-scale testing of initial distortions and welding-induced residual stresses in steel stiffened plate structures

Such full-scale tests provide critical data to calibrate imperfection amplitude models (e.g., based on DNV, IACS or ISSC recommended distributions) and to validate advanced finite element simulations that incorporate welding-induced residual stresses. The accurate representation of these fabrication effects is essential, as they often dominate the safety margins in ultimate strength assessments for ship hulls and offshore topside modules.

Future committee reviews should document and synthesize outcomes from these test campaigns, highlighting:

- Comparisons of measured distortion and residual stress patterns against industry design assumptions.
- Their influence on the compressive and shear strength of stiffened plate structures under combined loads (e.g., axial + lateral pressure).
- Recommendations for design practices that mitigate detrimental welding effects, such as optimized weld sequences, heat input control, and post-weld treatments.

By doing so, the committee can directly support improved rule development and foster more reliable and cost-effective designs.

References:

1. MS Yi et al. (2020). Direct measurements and numerical predictions of welding-induced initial deformation in a full-scale steel stiffened plate structure, Thin-Walled Structures, 153: 106786.
2. MS Yi et al. (2021). Direct measurements, numerical predictions and simple formula estimations of welding-induced biaxial residual stresses in a full-scale steel stiffened plate structure, Structures, 29: 2094–2105.

### 1.1.5.2 Full-Scale Tests of Ship Stiffened Plate Structures Under Axial Compression at Cryogenic Temperatures

These recent full-scale experiments are particularly motivated by safety scenarios involving accidental LNG leakage and containment failures, which expose structural components to cryogenic environments (down to −80 °C). Under such extreme temperatures, conventional steel exhibits a marked reduction in toughness, making structures highly susceptible to brittle fracture, even under stresses well below room-temperature yield strengths (Fig. 4).

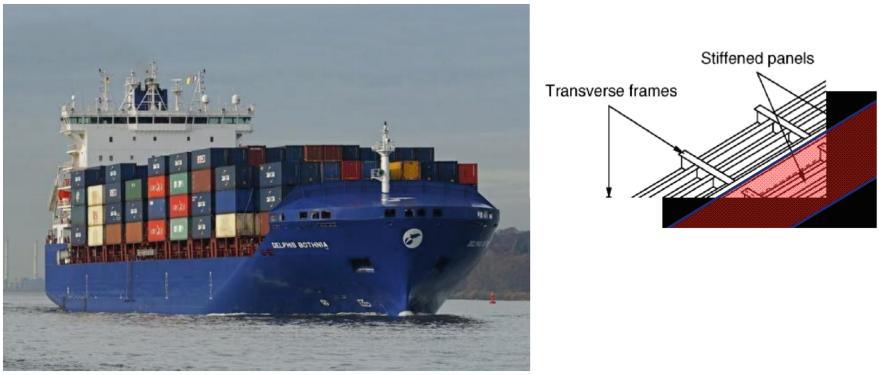



**Fig. 4.** Full-scale stiffened plate structures from an 1,800 TEU containership

Full-scale collapse tests have therefore been conducted to directly investigate:

- Buckling collapse behavior and post-buckling residual strength of stiffened plate structures subjected to axial-compressive loads at cryogenic temperatures, representative of conditions following LNG leakage in fuel tanks or containment systems.
- The onset and propagation of brittle fracture, and how it couples with global and local buckling modes, providing crucial insights into the ultimate safety margins of LNG-fueled ships and offshore processing units.

These tests also explored cyclic loading effects, which simulate dynamic ship motions superimposed on cryogenic cooling—a realistic operational hazard scenario.

Strategic significance:

Such full-scale investigations are essential because:

- They directly validate or challenge traditional design assumptions on the adequacy of current buckling and fracture criteria under cryogenic exposures.
- They reveal combined instability mechanisms (interaction of local plate buckling, stiffener tripping, and brittle cracking) that are difficult to capture with small-scale or ambient-temperature tests.
- Data from these experiments are indispensable for calibrating finite element models incorporating temperature-dependent material constitutive laws and fracture mechanics criteria, thereby supporting enhanced predictive design tools (Fig. 5).

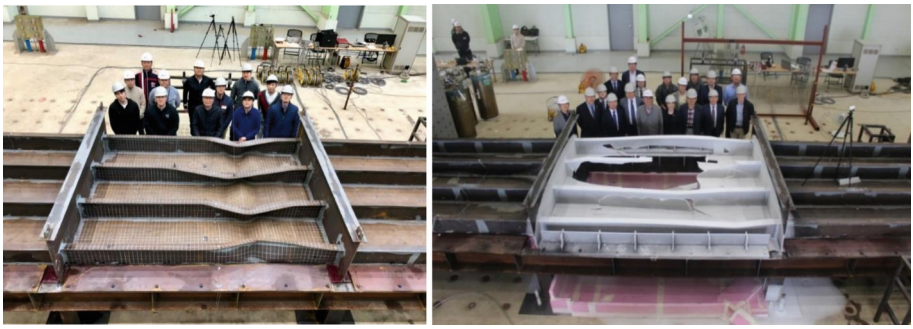


**Fig. 5.** Left: Typical ductile buckling collapse failure mode at 20 °C; Right: brittle fracture at − 160 °C.

Key publications:

Recent landmark studies in this area include:

1. JK Paik et al. (2020) *Full-scale collapse testing of a steel stiffened plate structure under axial-compressive loading, triggered by brittle fracture at cryogenic condition*, Ships and Offshore Structures, 15(sup1), S29–S45. → Investigates static axial loading to failure at cryogenic conditions, with detailed fracture tracking.
2. JK Paik et al. (2020) *Full-scale collapse testing of a steel stiffened plate structure under cyclic axial-compressive loading, triggered by brittle fracture at cryogenic condition*, Structures, 26, 996–1009. → Extends analysis to cyclic load conditions, revealing accelerated crack initiation.
3. JK Paik et al. (2021) *Full-scale collapse testing of a steel stiffened plate structure under axial-compressive loading at a temperature of − 80 °C*, Ships and Offshore Structures, 16(3), 255–270. → Explores progressive collapse under sustained extreme cryogenic exposure.

Recommendation for future committee reviews:

It is strongly recommended that future committee reports systematically review such full-scale cryogenic tests. This would:

- Integrate critical safety considerations for LNG-fueled ships and emerging ammonia or hydrogen carriers, which also involve low-temperature containment systems.
- Provide foundational datasets for class societies to refine fracture control plans and inspection regimes.
- Highlight experimental evidence that can inform robust combined buckling-fracture models, advancing both the reliability and economic efficiency of ship structural designs in the age of alternative fuels.

#### 1.1.5.3 Full-Scale Tests of Stiffened Plate Structures Without and with Passive Fire Protection (PFP) Under Fire Conditions

Comparative full-scale testing of fire-exposed stiffened plate structures—representative of topside modules on VLCC-class FPSOs—has provided critical data on the structural performance of steel under severe hydrocarbon fire conditions, both with and without passive fire protection (PFP) systems. These tests are directly motivated by catastrophic offshore accidents involving hydrocarbon leaks and fires, which continue to represent some of the most hazardous scenarios in shipboard and offshore operations (Fig. 6).



**Fig. 6.** Full-scale fire testing to collapse of steel stiffened plate structures under lateral patch loading: without and with passive fire protection

Strategic experimental objectives:
These recent large-scale experiments have been designed to:

- Quantify the reduction in load-carrying capacity, ductility, and stiffness of stiffened plate structures subjected to sustained elevated temperatures typical of hydrocarbon pool fires.
- Examine the onset and propagation of local plate buckling, stiffener tripping, and global collapse under lateral patch loading—a critical load case for topside modules containing process piping and equipment.

- Evaluate the effectiveness of modern PFP systems in preserving structural integrity during fire exposure, by directly comparing collapse loads, deformation patterns, and failure modes in protected versus unprotected structures.

Key technical findings:
The comparative studies revealed:

- Without PFP, stiffened plates experienced rapid temperature rise, leading to accelerated material strength degradation, premature local buckling, and significantly reduced ultimate load capacity.
- PFP systems markedly delayed temperature escalation, maintaining steel temperatures within tolerable ranges over the critical exposure window. This substantially increased the time to collapse and preserved much of the original load-bearing capability.
- Differences in failure modes were documented, with unprotected structures typically failing through combined local buckling and gross yielding, while PFP-protected structures sustained loading longer and showed delayed instability.

References:
Recent foundational publications in this domain include:

1. J.K. Paik et al. (2021) *Full-scale fire testing to collapse of steel stiffened plate structures under lateral patch loading (part 1) – without passive fire protection*, Ships and Offshore Structures, 16(3): 227–242. → Detailed thermal-structural measurements and collapse observations for unprotected panels.
2. J.K. Paik et al. (2021) *Full-scale fire testing to collapse of steel stiffened plate structures under lateral patch loading (part 2) – with passive fire protection*, Ships and Offshore Structures, 16(3): 243–254. → Comparative tests showing enhanced performance of PFP-coated structures.

Recommendations for future committee work:
Inclusion of these full-scale fire test results in future technical committee reports would:

- Provide robust experimental evidence to calibrate design fire curves, structural resistance models, and inspection/maintenance intervals for topside structures.
- Support optimization of PFP system specifications, balancing weight, cost, and fire endurance.
- Offer critical insights for updating offshore safety case methodologies and risk-based design frameworks, particularly as the industry moves towards larger integrated FPSOs and complex offshore production hubs.

#### 1.1.5.4 Real-Time Monitoring and AI-Enhanced Digital Healthcare Engineering Systems

There are significant limitations associated with the use of strain-gauge methods for structural health monitoring (SHM) of ship hulls. The disadvantages of strain-gauge-based SHM systems include the following:

1. Restricted to linear elastic behavior: Strain gauges are primarily effective for monitoring structures within the linear elastic regime. They do not reliably capture nonlinear phenomena such as local or global buckling, plastic deformation, or progressive collapse. As a result, critical failure mechanisms that occur beyond the elastic range cannot be precisely assessed using this method.
2. Extensive instrumentation requirements: To obtain a comprehensive understanding of strain distributions across a ship's hull, a large number of strain gauges must be strategically installed throughout the entire structure. This presents substantial challenges in terms of installation complexity, calibration, data acquisition, and long-term maintenance—particularly in harsh marine environments where sensors are exposed to corrosion, fouling, and mechanical damage.
3. Limited load component detection: Conventional strain-gauge configurations are typically designed to infer only the vertical bending moment component of the hull girder loads. They are generally inadequate for directly capturing other important load effects such as horizontal bending, torsion, or shear, which are critical for assessing the full multi-axial stress state of the hull, especially under complex loading scenarios encountered during heavy seas or accidental events (Fig. 7).

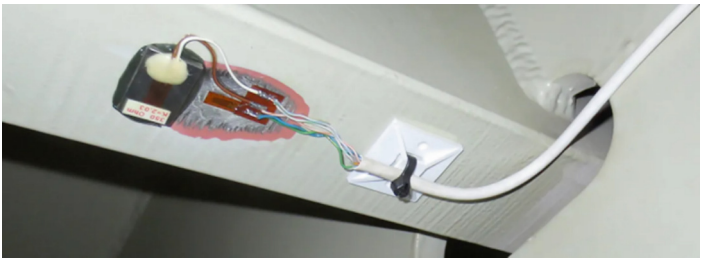


**Fig. 7.** Onboard strain gauge for monitoring ship hull structural strains

Because of these limitations, there is a growing interest in developing more advanced structural health monitoring approaches—such as full-field optical measurement systems, distributed fiber-optic sensing, and digital twin models integrated with real-time sensor data—which can overcome many of the constraints inherent in traditional strain-gauge-based methods.

Real-time monitoring coupled with AI-enhanced Digital Healthcare Engineering (DHE) systems, introduced by J.K. Paik (2024), represents a transformative approach to the continuous assessment of structural integrity, machinery performance, and crew well-being in both maritime and offshore operations. By leveraging advanced sensor technologies, IoT frameworks, AI-driven diagnostic tools, and digital twin platforms, these systems enable a shift from reactive to predictive maintenance and support comprehensive safety management strategies.

Strategic engineering context and benefits:

These emerging systems are designed to:

- Continuously capture multi-parameter data, including wave profiles, wind speeds, hull girder strains, local corrosion wastage, fatigue crack propagation, and machinery vibrations, using distributed IoT-enabled sensors.
- Integrate real-time health data streams with digital twin models that simulate evolving structural and machinery states under operational and extreme conditions. This allows near-instantaneous comparison between expected and measured performance.
- Employ AI and machine learning algorithms to detect early anomalies, classify degradation patterns, and recommend targeted maintenance actions before failures propagate, thereby extending the service life of assets.
- Monitor crew health and environmental conditions (e.g., noise, temperature, vibration), supporting occupational safety and well-being on board aging ships and offshore platforms.

Such systems align closely with IMO's 2050 objectives for enhancing both safety and sustainability, offering pathways to significantly reduce downtime, avoid catastrophic failures, and optimize inspection intervals based on actual asset health (Fig. 8).

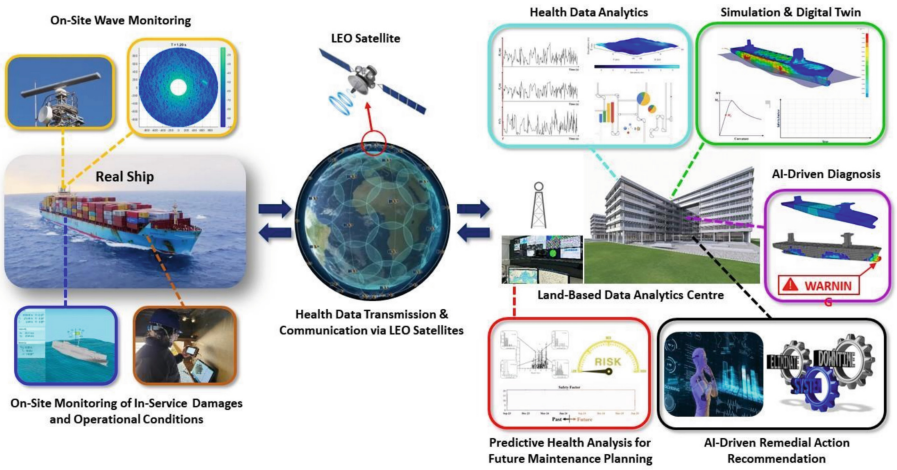



**Fig. 8.** Framework of a real-time monitoring and AI/digital twin–driven digital healthcare engineering system for aging ships, introduced by J.K. Paik (2024)

Integration with broader experimental and operational frameworks:
Future committee work should explore:

- The coupling of these digital systems with controlled physical experiments (for example, impact, fatigue, or fire tests instrumented with identical sensor arrays), to directly validate sensor performance and AI models under known loading and damage scenarios.
- The deployment of low Earth orbit (LEO) satellite communication networks for robust data transfer between offshore assets and shore-based analytics centres, crucial for remote operations in the Arctic or deep-sea mining contexts.

- The formulation of standardized protocols for data fusion and interpretation, ensuring that insights are consistent and actionable across different platforms and operators.

Key recent publications underpinning this field:

A growing body of recent work lays the technical foundation for these advancements, including:

1. J.K. Paik (2024). *Enhancing safety and sustainability through digital healthcare engineering*, Marine Technology, The Society of Naval Architects and Marine Engineers, April, 34–40. → Conceptual framework for DHE systems in maritime contexts.
2. Sindi et al. (2024). Advancing digital healthcare engineering for aging ships and offshore structures: an in-depth review and feasibility analysis, Data-Centric Engineering, 5: e18. → Comprehensive review of technologies and practical barriers.
3. N.M. Fadzil et al. (2024). *Digital healthcare engineering for aging offshore pipelines: a state-of-the-art review*, Ships and Offshore Structures, doi.org/10.1080/17445302.2024.2424320. → Focused on subsea pipelines, integrating corrosion and fatigue monitoring.
4. W. Duan et al. (2024). *Enhancing safety and resilience of aging land-based LNG Tank structures through digital healthcare engineering: a feasibility assessment in seismic environments*, Ships and Offshore Structures, doi.org/10.1080/17445302.2024.2428229. → Extends the concept to seismic risk environments.
5. Y. Xie et al. (2025). *Enhancing the safety and sustainability of aging jacket-type offshore wind turbines in extreme weather conditions through digital healthcare engineering: a literature review*, Ships and Offshore Structures, doi.org/10.1080/17445302.2025.2502868. → Adapts DHE principles to offshore renewable installations.
6. H.J. Kim, J.K. Paik (2025). *A digital twin model within the framework of a digital healthcare engineering system for aging containership hull structures*, Ships and Offshore Structures, accepted for publication. → Application of digital twin methodologies to large hull structures.

Recommendations for future committee consideration:

Future committee reports should:

- Include systematic surveys of field trials and pilot implementations of DHE systems on ships and offshore structures, highlighting lessons learned and quantifiable benefits.
- Encourage comparative studies that integrate physical experiments with AI-driven monitoring, building robust confidence in automated diagnostic systems.
- Propose a roadmap for standardizing digital health data structures and AI interpretability frameworks, ensuring industry-wide interoperability and regulatory acceptance.

By doing so, the committee would play a pivotal role in guiding the maritime sector towards next-generation safe, sustainable, and digitally enabled operations.

### 1.1.6 Forward-Looking Experiments

#### 1.1.6.1. Hybrid Testing and Multi-Physics Coupling

The hybrid model testing approach highlighted in the report represents a forward-looking methodology. However, there is considerable scope to extend this to more advanced multi-physics problems, such as:

- Fire-structure-fluid interactions in hydrocarbon spill scenarios.
- Simultaneous thermal and mechanical loading to simulate explosion-induced damage.
- Hybrid coupling of physical impact tests with CFD-driven fluid forces to replicate real sea conditions.

Establishing best practices for such complex hybrid experiments—including sensor placement, synchronization of data streams, and integration with numerical solvers—would set a new benchmark in experimental ship and offshore structural research.

#### 1.1.6.2 Climate-Driven and Next-Generation Operational Scenarios

Future experimental programs should increasingly reflect emerging operational challenges, such as:

- Testing under climate-change-driven conditions, for example higher sea states, increased frequency of ice-infested waters, or combined wave-current effects on offshore platforms.
- Investigating how next-generation fuels (like ammonia or hydrogen) affect fire and explosion behavior in ship machinery spaces, requiring new fire testing standards.
- Exploring the performance of structures intended for ultra-long service lives (e.g., 50+ years), with accelerated corrosion-fatigue testing to validate extended design assumptions.

Such forward-looking experimental agendas would position the committee's work at the forefront of maritime and offshore innovation, addressing both environmental imperatives and evolving operational risks.

### 1.1.7 Recommendations for Enhanced Collaboration and Knowledge Transfer

Finally, to amplify the impact of future reports and ensure alignment with industry needs:

- The committee could facilitate collaborative international benchmark test programs, pooling resources to conduct large-scale tests beyond the capacity of individual institutions.
- Establishing open-access experimental databases, with standardized data formats, would accelerate model validation efforts across academia and industry.
- Periodic synthesis papers that distil lessons learned from multiple ISSC cycles could serve as authoritative references for practitioners, class societies, and regulatory bodies.

### 1.1.8 Recommendations for Future ISSC Committee Focus

Future committee work could achieve even greater impact by:

- Advancing Multi-Hazard Experimental Programs: Addressing coupled scenarios like ice impact with subsequent collision, or corrosion combined with cyclic fatigue.
- Integration of Digital and Experimental Pathways: Developing standardized protocols for embedding sensor networks in laboratory and field tests to directly support AI-driven diagnostics.
- Benchmarking and Global Data Sharing: Facilitating multi-institutional campaigns and creating accessible databases to enable international benchmarking of experimental data and advanced nonlinear simulations.
- Lifecycle and Sustainability-Driven Experiments: Exploring long-term performance of novel or lightweight structures under accelerated environmental conditions to support extended service life and decarbonization targets.
- Cross-Disciplinary Linkages: Engaging with offshore renewables, subsea mining, and Arctic logistics sectors to transfer lessons learned from ship and offshore oil & gas applications.

Moreover, by identifying and prioritizing unresolved technical challenges—spanning from fabrication-induced imperfections and cryogenic fracture to coupled fire and impact scenarios—the committee can help set a forward-looking research agenda that directly addresses emerging industry needs. This would strengthen the foundation for future revisions of design rules and classification standards, while fostering innovation in both experimental and computational frameworks.

### 1.1.9 Final Remarks

The reviewed report offers a broad and valuable survey of experimental methods and developments relevant to the design, safety, and lifecycle management of ships and offshore structures. It successfully highlights many state-of-the-art techniques and showcases important case studies across scaling laws, fluid-structure interactions, hybrid testing, fire and impact assessments, corrosion prognostics, and emerging digital twin applications.

Looking ahead, more systematic presentation, rigorous literature-grounded methodologies, and deeper integration of advanced experimental and digital approaches will be crucial. By prioritizing unresolved technical challenges—from fabrication-induced imperfections to multi-hazard scenarios—the committee can set a clear agenda that strengthens future design rules, classification standards, and ultimately fosters innovation across the maritime and offshore industries.

In conclusion, the committee's continued leadership in mapping the evolving landscape of experimental methods is indispensable for guiding the global maritime and offshore community toward safer, more resilient, and technologically advanced operations. Future reports that build on these recommendations will not only reinforce the relevance of the ISSC community but also serve as essential references for practitioners, regulators, and researchers striving to meet the complex challenges of next-generation marine and offshore structures.

## 1.2 Floor and Written Discussions

### 1.2.1 Floor Question 1

What is the reliability of film pressure sensors for ice load test?

Suggestion: I think the spatial distribution is a good reference but the exact value of the measured ice pressure might not be reliable.

### 1.2.2 Floor Question 2

Regarding the testing for FSI, I see the advantages of elastic models but what about the challenges? What is the progress in that respect.

To mention 2 examples:

1. Using 3D printed polymer models, primary members can be printed, but thickness challenges pop up. Appropriate scaling will induce buckling induced failures, which is not realistic.
2. What about scaling of the polymer material properties, which are typically non-linear. 'Globally' near elastic properties can be achieved but in higher shear region (e.g. corner), not and those are critical for the local response (which was supposed to be the added value of elastic models).

### 1.2.3 Floor Question 3

This is regarding fluid structure interaction of flexible structures, as we know, this type oof structure has an infinite number of models of oscillations, unlike the case of a rigid structure.

Then my question is that how do you consider this flexibility to track the displacement of this kind of structure?

Question: in your hybrid model tests, at what stage these phenomena you implement.

### 1.2.4 Floor Question 4

The presentation of the committee's report highlighted that its primary focus was on experimental research. By definition, empirical research relies on real, observable data, while experimental research is a specific type of empirical study that involves manipulating variables in a controlled environment to test a hypothesis. Numerical methods, which involve calculations to generate approximate solutions, can be used to analyze or predict actual occurrences. Typically, some researchers aim to calibrate their numerical findings using experimental data, even if this calibration was not explicitly mentioned in the committee report presentation.

My question is: How can we compare numerical and experimental findings with empirical data if we lack complete confidence in them? The nature of these outcomes differs, raising concerns about how to establish reasonable trust, correlation, and acceptance among the various types of data?

# 2 Reply by Committee

## 2.1 Reply to Official Discusser

The committee wishes to commence by expressing gratitude to Professor Paik for consenting to serve as our discusser and for delivering a comprehensive review of the experimental methods committee report. Throughout the preceding ISSC cycle, the committee engaged in intensive collaboration to formulate this report, which evaluates the current state of the art across various domains and formulates recommendations for advancing future research. The subsequent sections contain responses to the official discusser.

### 2.1.1 Official Discusser Recommended Investigations by Future Committees

The official discusser identified two primary domains for future committee research: quantifying ice loads and implementing health-monitoring and digital twin technologies.

Ice Load Measurements in Arctic Operations:

The official discusser underscores the complexities inherent in the interaction between ice and structures, emphasizing the necessity to characterize ice material from diverse regions and of varying ages. The committee's experts focused on ongoing research on ice-structure interaction, using both direct and indirect measurement methodologies in laboratory and alternative environments. Additionally, they emphasized the importance of investigating contact area and pressure distribution to adequately capture the temporal and spatial variability inherent in ice loads. The official discusser's recommendation is consistent with the committee's endorsement that these advancements have been validated in laboratory settings and through qualitative assessment in full-scale scenarios. However, a comprehensive validation and uncertainty analysis under full-scale conditions remains an outstanding requirement. Upon conclusion of the recent congress, an Arctic Technology committee was established for the next cycle. Hence, the Experimental Method committee should mainly complement and integrate the work done in that committee. In the previous cycle, we covered the topic as there was no dedicated committee and because we had several experts in the ice loading field.

Health Monitoring and Digital Twin Technologies:

The official discusser highlights the necessity for future committee endeavors to prioritize the exploration of methodologies for physical testing aimed at monitoring and quantifying health monitoring parameters, which can subsequently be integrated into digital twin-based simulations. This observation is consistent with the committee's findings, which indicate that, within the realm of health monitoring, a considerable proportion of research relies heavily on simulations, accompanied by a dearth of empirical data. Moreover, integrating real-time tracking for complex structures, such as rudders and propellers, remains a substantial challenge. In relation to digital twins, the primary challenges include the need for high-fidelity modeling, constraints imposed by digitalization processes, cybersecurity issues, and significant implementation costs. Additionally, the maritime industry exhibits a slower pace of adoption of these technologies than other industries.

**Full-Scale Fire Test**

The official discusser emphasizes that including full-scale fire test results in future committee reports can make a substantial contribution to establishing fire design criteria, optimizing PFP systems, and improving offshore safety and risk-based design frameworks. The committee acknowledges and supports the official discusser's recommendation concerning the necessity of extensive or full-scale fire testing.

Historically, the "Experimental Methods" Committee has not explicitly addressed fire experiments within its scope. Although fire-related topics such as thermal loads, fire incidents, and heat transfer responses have been partially explored by other committees, this marks the first time this committee has formally considered fire testing. In response, the committee conducted an initial review of prevailing regulations, guidelines, and classification rules pertinent to fire testing in marine and offshore structural applications. This review pinpointed current limitations and delineated prospective directions for future research and standardization endeavors. Additionally, recent advancements and emerging trends in fire testing methodologies have been documented.

Based on these insights, the committee acknowledges the need for future investigations to focus on the development of performance-based design standards, fire mitigation and prevention systems, and risk-informed design frameworks—particularly those bolstered by data from large- or full-scale fire experiments involving structural components. These facets merit further scrutiny by subsequent committees. Notably, two pivotal publications on fire testing, as accentuated by the official discusser, have been included in the current committee's report.

**Full-Scale Tests Not Addressed in the Current Report**

The official discusser advises that forthcoming committee reports should systematically review comprehensive cryogenic test outcomes. Such reviews have the potential to augment the safety of LNG and emerging low-temperature fuel carriers, whilst concurrently advancing the reliability and cost-effectiveness of structural design methodologies.

Specific subjects articulated herein have been previously examined by ISSC 2022 Committee V.1: Accidental Limit States, wherein the principal publications cited were also subjected to scrutiny. Consequently, the present committee deemed it unnecessary to revisit these topics with extensive detail.

In line with the official discusser's remarks, we recognize the imperative for continued dialogue from an experimental methodology perspective, with a specific focus on cryogenic conditions, residual stresses, and associated variables.

The analysis of safety considerations for LNG and next-generation low-temperature fuel carriers, the enhancement of fracture-control and inspection standards by classification societies, and the establishment of experimental bases for the formulation of coupled buckling-fracture models constitute an extensive and intricate domain. Such matters cannot be adequately addressed by merely including selected publications in the current report.

It is therefore recommended that these subjects be examined not only by this committee but also in concert with other pertinent committees, or, if necessary, through the formation of a new, dedicated committee. Furthermore, the ISSC should consider

sustained deliberation on these themes and the feasibility of establishing a new specialist committee to thoroughly address them, especially given ongoing global events surrounding the use and impact of LNG carriers.

Accordingly, we recommend that such topics be explored not only by this committee but also in collaboration with other relevant committees, or through the establishment of a dedicated new committee. Alternatively, ISSC should consider continued discussion of these specific themes and the possibility of forming a new specialist committee to address them in depth.

### 2.1.2 Official Discusser Highlighted Areas of Improvement

The official discusser provided the following generalized areas for consideration by the committee:

Report Presentation and Structural Coherence:

- Recommendation: The report would benefit from a more consistent and coherent editorial style. The impact of the report could be significantly enhanced by adopting a systematic structure across chapters.
- Response: This report encapsulates the insights of eleven members who voluntarily contribute their time and expertise to the ISSC in developing this document. Each member brings specialized knowledge from distinct domain areas and diverse cultural backgrounds, resulting in varied writing styles. Independent peer reviews were conducted for each section to enhance congruence and readability. Overleaf was employed as the collaborative online platform to assemble the LaTeX content, facilitate version control, manage references, and address comments. Additionally, its grammatical tool, Windscribe, was utilized for editorial purposes following the official discussion review. This tool employs language models and artificial intelligence technologies to harmonize linguistic tone and optimize readability. It is important to emphasize that the content development was carried out solely by the authors, while the use of editorial tools was limited to grammatical and language standardization. The committee also initiated work on a standardized structure for each chapter via Overleaf; however, the expertise and content provided by the committee often necessitated deviations from a formalized structure, thereby allowing adaptations to accommodate the content better as advised by the expert contributors to this report.

Alignment with Committee Mandate and Methodological Rigor:

- Recommendation: A more rigorous approach would involve clear documentation of how literature was surveyed, how case studies were selected, and how conclusions were drawn, thereby strengthening the report's authority and alignment with the committee mandate. Ideally, the report should begin with a systematic review of recent publications (the past 3–5 years) from high-impact journals, identifying key trends, knowledge gaps, and emerging technologies that set the stage for the presented experimental work.
- Response: The committee, comprising 11 members, employed a systematic methodology in compiling this report. Initially, the members delineated their areas of expertise and research focus, thereby selecting the report sections that most appropriately

aligned with their respective technological domain contributions. Subsequently, the committee members conducted a comprehensive review of journals to identify materials pertinent for inclusion in the report, thereby fulfilling the committee's mandate. The search strategy was not restricted to high-impact journals, allowing for a diverse range of sources. After thorough evaluation, members selected relevant and citable sources, which were incorporated into the report. This process was supplemented by an assessment of materials from previous iterations of the experimental methods report to prevent redundancy by avoiding previously cited sources. This approach facilitated a comprehensive canvassing of available sources for pertinent material.

- Furthermore, members would submit sources discovered during their searches that were thematically compatible with different chapters, allowing the chapter leads to assess their relevance. Additionally, several committee members are actively involved in various professional societies and attend conferences throughout the report cycle, thus acquiring supplementary sources that could apply to the report. During our monthly meetings dedicated to the report's development, members would present and discuss their findings and make requests to other members for additional research in the assessed categories.

Depth and Comparative Analysis of Technical Content:

- Recommendation: The level of technical analysis varies considerably across sections. The report would benefit from deeper analyses, drawing more explicitly on data to support conclusions. Inclusion of comparative studies—such as between different experimental methods, or between experimental and computational (numerical) results—would greatly enrich the technical value of the document.
- Response: The official discusser emphasizes the significance of comparative studies to enhance the document's value. However, given the impracticality of conducting such studies for every topic in this report, the committee has elected to dedicate a comprehensive section to digital image correlation. This section commences with an elucidation of digital image correlation, followed by a discourse on technological applications. It includes an update on findings from the preceding report and demonstrates the technology's application across various experiments. The section concludes with a comprehensive summary of the technology's current state, recommendations for practitioners, and identification of gaps for future research. The selection of DIC as a benchmark study should be regarded as a paradigm of the current shift from analogic to digital approaches in all fields and therefore also in experimental methods. In fact, in the concluding summary of the relevant chapter, it was highlighted that experimental analysis of structural behaviour can now consider the stress/strain distributions rather than values in selected points for the structural assessment. This was unconceivable even a few years ago. Hence, DIC is a specific application highlighting a general trend. Despite the committee's intention to cover all topics, there are constraints on report size and the scope of work that investigators can feasibly address. Our strategy was to balance advancements across technology areas while monitoring new developments and best practices, as we did during our evaluation.

Treatment of Digital Twin and Health Monitoring Topics:

- Recommendation: The section on structural health monitoring and digital twins is particularly timely. However, since this topic is broad and often crosses into areas beyond experimental methods (such as data analytics and IoT-driven digital solutions), it would be beneficial to focus explicitly on experimental techniques supporting these systems—such as real-time monitoring of corrosion, fatigue cracking, mechanical denting, or environmental loads using sensor technologies, and the physical validation of digital twin models.
- Response: The committee agrees with the official discusser regarding the significance of digital twins, which are indeed incorporated into this report as a chapter. The report observes that Health Monitoring has integrated Acoustic Emission, strain sensors, and machine learning to detect structural damage. Simultaneously, Digital Twin (DT) technology has advanced by leveraging empirical data and sophisticated algorithms, such as Kalman filters, to improve structural evaluations and operational decisions. Regarding digital twins, the primary challenges include high-fidelity modeling, limitations in digitalization, cybersecurity concerns, and significant implementation costs. Additionally, the maritime industry is slower to adopt these technologies than other sectors. The report also comprises sections on corrosion prognostics, specifically tailored to address their contribution to Structural Health Monitoring (SHM), their large-scale impacts, and hybrid model testing related to structural health monitoring and digital twins. The principal focus of this report is on experimental methods and includes examples of digital twins and health monitoring; it is not exclusively focused on health monitoring. (DT is the integration of many technologies, not necessary to address specific items)

Critical Analysis, Discussions, and Forward-Looking Recommendations:

- Comment: One of the more noticeable shortcomings of the report is the limited critical discussion of test results and their broader engineering implications. While many test cases are presented, the report does not sufficiently explore what these findings mean for current design practices, where significant knowledge gaps remain, or how methodologies might evolve. The concluding sections would be stronger if they synthesized the report's key insights into generalizable lessons, clearly articulated the merits and limitations of current experimental practices, and proposed a forward-looking research agenda aligned with emerging technological trends.
- Response: The authors of this report undertook a comprehensive evaluation of the current state of the art, formulated recommendations, and highlighted significant findings derived from the collected source material. This content underwent a peer review process to ensure the consistency of the presented material and to build upon the findings from previous reports. As an illustration, the section on hybrid model testing delineates these methodologies, introduces hardware-in-the-loop systems used for vortex-induced vibrations, emphasizes their advantages, and suggests prospective technological pathways. Similarly, the section on digital image correlation adopts a comparable approach, identifying significant gaps in its application and outlining a future trajectory for its use. Additionally, the committee reconvened to conduct a subsequent review of the report, addressing the comments provided by the discusser following the feedback.

### 2.1.3 Official Discusser Forward-Looking Recommendations

The official discusser also included several areas for future inclusion in the committee work:

- Advancing Multi-Hazard Experimental Programs.
- Integration of Digital and Experimental Pathways.
- Benchmarking and Global Data Sharing.
- Lifecycle and Sustainability-Driven Experiments.
- Cross-Disciplinary Linkages.

These domains exhibit numerous gaps and continue to evolve as we explore their application in experimental methodologies, including AI/ML, data sharing, and alternative strategies. As the subsequent committee is constituted, it will be imperative to assess the expertise of its members to address the critical areas identified by the official discusser.

## 2.2 Reply to Written and Floor Discussion

### 2.2.1 Floor Question 1

What is the reliability of film pressure sensors for ice load test?

Suggestion: I think the spatial distribution is a good reference but the exact value of the measured ice pressure might not be reliable.

**Response:** We agree. The consensus is that the film pressure sensors give a good understanding of the spatial distribution. However, the accuracy of the measured pressure, the magnitude, has been questioned and discussed. This discussion has been highly dependent on the type of film. The accuracy of capacitance-based sensors has often been questioned, as they have been claimed not to be able to record highly dynamic events. Debate on the accuracy of piezoelectric films has not been as extensive. Recently developed fiber-optics-based sensors close to the film thickness [3] are still in the laboratory testing phase, and their accuracy has yet to be confirmed at full scale.

### 2.2.2 Floor Question 2

Regarding the testing for FSI, I see the advantages of elastic models but what about the challenges? What is the progress in that respect.

To mention 2 examples:

1. Using 3D printed polymer models, primary members can be printed, but thickness challenges pop up. Appropriate scaling will induce buckling induced failures, which is not realistic.
1. What about scaling of the polymer material properties, which are typically nonlinear. ‘Globally’ near elastic properties can be achieved but in higher shear region (e.g. corner), not and those are critical for the local response (which was supposed to be the added value of elastic models).

**Response:** Limitations in thickness are certainly one of the significant challenges with 3D printed models. Even if the specified thickness can be achieved, as the question suggests, local buckling can occur due to the considerable unsupported length and residual stresses from the manufacturing process. This should be accounted for when selecting the scale and deciding which structural members to include. Perhaps it is inevitable to include some local stiffeners to avoid these issues.

Polymer properties are, indeed, nonlinear. Using an elastomer would cause significant issues in this manner, so hard plastics are recommended for scaled models. For the latter, the nonlinearity is less pronounced and, assuming small deflections, can be ignored without significant loss of accuracy. The above has been observed qualitatively, but quantifying these nonlinearities should be a key development to allow these techniques to be used more widely and confidently. The behavior near shear regions is yet to be investigated. We agree that this should be investigated further, but there are further limitations to measuring local responses before this issue is tackled, for instance, the scaling of mass distribution.

### 2.2.3 Floor Question 3

This is regarding fluid structure interaction of flexible structures, as we know, this type oof structure has an infinite number of models of oscillations, unlike the case of a rigid structure.

Then my question is that how do you consider this flexibility to track the displacement of this kind of structure?

Question: in your hybrid model tests, at what stage these phenomena you implement.

**Response:** Infinite modes are not limited to elastic models; they are also present in backbone models, where the beam providing flexibility is continuous. In practice, only a few modes (usually 1–4) are excited, so we can use modal truncation to reduce the problem size. For segmented models, a uniform backbone can accurately approximate the 2-node bending mode shape (and associated natural frequency), but this accuracy deteriorates already for the 3-node bending mode. Non-uniform backbone models were introduced precisely to tackle this problem and achieve accurate emulation of several mode shapes. Elastic models have this property inherently. For flexible models, rigid body motions and flexible displacements are treated separately: the former are measured either via a tow post or via optical measurements, whereas the latter are typically captured using strain gauges. In most cases, flexible displacements are sufficiently small compared to rigid body motions not to cause any issues with the measurements of the latter.

We are not aware of any examples of experiments combining a flexible structure with hybrid (software-in-the-loop) methods. We are not certain how this would be incorporated on the software side. However, we anticipate such developments in the literature in the near future.

### 2.2.4 Floor Question 4

The presentation of the committee's report highlighted that its primary focus was on experimental research. By definition, empirical research relies on real, observable data,

while experimental research is a specific type of empirical study that involves manipulating variables in a controlled environment to test a hypothesis. Numerical methods, which involve calculations to generate approximate solutions, can be used to analyze or predict actual occurrences. Typically, some researchers aim to calibrate their numerical findings using experimental data, even if this calibration was not explicitly mentioned in the committee report presentation.

My question is: How can we compare numerical and experimental findings with empirical data if we lack complete confidence in them? The nature of these outcomes differs, raising concerns about how to establish reasonable trust, correlation, and acceptance among the various types of data?

**Response:** This is a good question about the nature of experimental findings based on empirical data and the lack of confidence in them. It is important to note that when measurements are conducted, researchers consider the uncertainty associated with both observations from nature and the measurement tools used. One example is ice loading, where there is considerable uncertainty in ice behavior dynamics; nonetheless, researchers continue to press forward while examining and expanding the bounds of the knowledge gained via experimental methods.

Empirical data itself must undergo a rigorous process to understand the data quality, assess any existing biases, and account for any hidden variables or confounding factors that are not well known or understood. Similarly, experimental findings must account for systemic behavior and errors, take into consideration statistical uncertainty, and, of course, report a confidence interval for the captured results. Associated numerical models should be validated to understand their limitations, assumptions, and errors, and to conduct sensitivity analyses and uncertainty quantification to bound the model's predictive uncertainty.

As we capture data on phenomena through different means, it is vital to understand the nature of these observations, apply statistical methods, quantify and bound uncertainties, and conduct reliability analyses.

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