Committee III.1: Ultimate Strength

Citation for the original published paper (version of record):

Ringsberg, J., Brubak, L., Chen, X. et al (2026). Committee III.1: Ultimate Strength. Lecture Notes in Mechanical Engineering, 3(III:1): 88-116. http://dx.doi.org/10.1007/978-981-95-2782-3_5

Committee III.1: Ultimate Strength

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Committee Mandate. Concern for the collapse behaviour of ships and offshore structures and their structural components under ultimate conditions. Uncertainties in strength assessment shall be highlighted. Attention shall be given to the influence of load combinations, fabrication-induced imperfections, life-cycle effects, damage, and user approach. Consideration shall be given to the practical application of methods.

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W. Wu and J. Ding (Eds.): ISSC 2025, LNME, pp. 88–116, 2026.
https://doi.org/10.1007/978-981-95-2782-3_5

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1 Discussion

1.1 Official Discussion by Emmanuel Samuelides

1.1.1 Introduction

I am deeply honoured with the invitation of the organizers and the standing committee to act as an official discusser to the report of Committee III.1 "Ultimate strength" and I am pleased to provide my comments for a discussion.

The committee has 20 members. Twelve of the members did not participate in the respective previous Committee, so the report includes a fresh view on the work that has been performed in the field of ultimate strength of ships and offshore structures.

The report contains approximately 295 references. Of those, 182 were published during the reporting period (2022–2024), and 77 were published in 2020 and 2021. Thus, the committee's work focuses primarily on recent publications. Interestingly, the oldest cited reference is Douglas Faulkner's 1975 article, "On effective plating for use in the analysis of stiffened plating in bending and compression".

I read the report with great interest and found that most sections include useful information on published work and address the issues defined in the mandate. I would like my comments to address the following questions:

a. Does the committee identify major advances achieved during the reporting period?
b. Are there emerging areas of research?
c. Is there useful information on the research reported in the literature?
d. Are there research needs?
e. Are there advances in codes and regulations?

1.1.2 Remarks

My discussion follows the same structure as the report, and the headings correspond to those in the report.

Chapter 2: FUNDAMENTALS

The introductory part of Chapter 2 FUNDAMENTALS, refers to the ultimate strength as *"the maximum resistance that a material, structural element or largest structure can carry when exposed to external loading"*. When discussing "ultimate strength", it is appropriate to distinguish between ultimate strength under static loading conditions and ultimate strength under dynamic loading condition. When referring to ultimate strength under static loading conditions a more precise and clearer definition of the ultimate strength of a structure or structural element is **the maximum load carrying capacity for a particular loading pattern, under which the structure concerned may achieve static equilibrium**.

When referring to the material level, the ultimate strength is the maximum stress developed in the material. In relation to the strength of a ship girder under static condition, the ultimate bending moment is the maximum internal moment that may be carried by a cross section of the hull girder, which equals the applied moment. However, this is not the case when the girder is loaded dynamically since the difference between the external and the internal moments equals the inertia. This point is clearly described in Jagite *et al.* (2022) – the publication is discussed in Sect. 4.1.1 of the report – where it is stated *"Firstly, the inertia of the structure affects the structural response, and mainly the amplitude of the internal load, which can be higher or lower than the applied external load."* The maximum bending moment that a girder can carry under dynamic loading conditions depends on the temporal variation of the applied action, which can be either moment or curvature. Since the response of a structure under dynamic loading conditions depends heavily on the load history of the applied actions (load or displacement), I suggest providing a clear definition of "dynamic ultimate strength" whenever the term is used.

2.1 Definitions, Assumptions and Uncertainties

In a section including definitions, it is useful to make clear that: a) the ultimate strength under static conditions is determined for a particular pattern of action (it may be either load or deformation), b) when the structure is loaded dynamically, the issue is either to calculate the maximum internal loads that may be developed under dynamic conditions or the response of the structure under ultimate dynamic actions, c) that ultimate strength may be determined either using i) nominal values of the properties of the structure ii) actual values which also include the particulars of a damaged structure after a serious accident, iii) anticipated values of parameters to determine the future ultimate strength or the residual strength after an accident.

The last paragraph of Sect. 2.1 refers to i) the initial and tangent stiffness of the curves and ii) the area below the load deformation relationships. It could be added that the initial tangent stiffness should be the linear elastic stiffness, and this observation may be used to check the results. For example, in a load - end shortening curve in terms of stress-strain, it should be the Young's modulus, and in a moment-curvature curve under, it should coincide with the bending stiffness. The area below the load deformation curve may be employed in the determination of the response under "quasi-static" response, i.e. ignoring inertia effects when the structure is loaded dynamically, by equating the energy input to the structure with the structural energy absorption.

2.1.1 Assumptions

The section distinguishes the ultimate strength under nominal conditions and the ultimate strength under actual conditions, which varies during the lifetime of the structure. The section also refers to the use of digital twin for the latter. The committee observes that *"... in practice, this is a very difficult and expensive endeavour for most ships and offshore structures."* I agree with the statement, but since digital twins are mentioned recently very often, I would like to ask the committee to elaborate as to the practical difficulties when using them.

The last paragraph of that section makes reference to recent publications, most of them within the reporting period, which address aspects of particular interest and which deserve further attention, as they may open areas for future research. The work reported in that paragraph could had been further elaborated. The points of interest are:

- The transfer of knowledge from the aerospace industry *"allowing two-way coupling between material properties and structural behaviour"*. My understanding from that statement is that the platform provides for the update of the material properties with the structural behaviour. The aspect deserves further discussion.
- Addressing the degradation of the structure due to combined environmental effects, which subsequently has an impact on the ultimate strength. Structural degradation is an area of interest and it will be useful to provide some more information of the main findings of the cited publication of Peng *et al.* (2022).
- The *"Carrera unified formulation (CUR)"* to determine or the systematic selection of the kinematics of a structural element as a function of its thickness coordinate, and *"Best Theory Diagrams"*. Further information is required for the reader of the report to understand how useful these publications are for the determination of the ultimate strength.

2.1.2 Uncertainties

The section refers to four types of uncertainties: *"systematic, epistemic, stochastic and aleatoric"*. The clear definition of the four "types" would provide guidance to the reader, since the state of the art usually refers either to **epistemic uncertainties**, i.e. uncertainties due to incomplete knowledge, and **aleatoric uncertainties**, i.e. uncertainties due to inherent randomness. Epistemic uncertainties may be reduced by obtaining additional information of the phenomenon (e.g. modelling of material) or the input variables (e.g. material strength), whereas aleatoric uncertainties will always introduce an uncertainty level to the results (e.g. wave load, corrosion randomness). Although, in theory epistemic uncertainties could be addressed by improved knowledge, in practice the elimination of epistemic uncertainties is not possible, since the deterministic definition of parameters that in theory could be precisely known, for example the thicknesses of a corroded structure, in practice they are not.

Uncertainties are discussed in Sect. 2.1.2 and in Chapter 3. The committee claims that epistemic uncertainties are discussed in Sect. 2.1.2 and aleatoric in Chapter 3.

However, it is not clear to me why all aspects addressed in Sect. 2.1.1 are under epistemic uncertainties.

When referring to uncertainties, I believe that there is a need to distinguish the uncertainties that refer to the current state of the structure (current geometry, thicknesses, material properties, residual stresses) and the uncertainties that are related to the prediction of the ultimate strength in the future, such as uncertainties related to corrosion or dents. I would consider the former epistemic and the latter aleatoric, noting that the same variable may introduce an epistemic uncertainties when addressing the issue of the current ultimate strength and aleatoric uncertainties for the prediction of the ultimate strength during the lifetime of the structure. This applies also in the case of the residual strength, such as the residual strength of a ship after collision or grounding: before the accident there is an inherent uncertainty in the description of the damage but when the structure has suffered the accident, the description of the damage could be accurately described, at least in theory.

The last three paragraphs of that section discuss the selection of solvers, types of elements, application of actions. These aspects are essential, and the information provided valuable, but I found it confusing when they are discussed in the context of uncertainties. I would consider at least some of these aspects, i.e. selection of solver and type of element, as simplifications and the related issue is to make the most appropriate selection.

The following comments on Sect. 2.1.2 refer to particular uncertainties that are presented:

Initial imperfections may be addressed either by Artificial Neural Networks (ANNs) or Bayesian statistical inference. It is important to understand the differences of the two procedures. A neural network is trained by a dataset to determine the weights, so as to provide results to arbitrary input. Applying Bayesian statistical interference provides for the update of the parameters of the probability density functions of either an input or output variable, based on a number of observations.

The report points to finding of the prior art that stiffener misalignment should be also considered, when addressing initial imperfections. An issue that is related to misalignment (although it is not the same), is the tilting of the stiffeners that the committee observed in the specimens that were discussed in the benchmark study (Chapter 6). Did the committee identify the effect of the tilting on the results?

The paragraphs dedicated to the description of the geometry of the structure provide useful information on addressing corrosion and defects in FE, the influence of residual stresses, the effect of fabrication on the load-end shortening curves.

In the discussion of Wang *et al.* (2022b), it is re-iterated that *"Therefore, they recommended using the dynamic solver, as the inclusion of inertia effects improves numerical stability, thus avoiding severe overprediction of the ultimate load."* I expect that, if an FE model will reach a static equilibrium at a particular load level, the same model (mesh, material, boundary condition) may find a state of dynamic equilibrium at a higher level of external load, because the internal load may be lower. How can a static solution provide an overprediction of the ultimate strength in comparison with a dynamic solver, which includes inertia?

2.2.1 Numerical Methods

The simulation of the response of the structure under repeated loading requires an adequate material model not restricted to monotonic loading paths. The report notes that Chaboche model provides the most stable accumulation of plastic strain. The discussion of that aspect is of particular interest. Although not directly derived by the mandate, the report would provide an added value, if it briefly discussed how to determine the parameters of the Chaboche model for material used in shipping and offshore industries. A further point that could be discussed is the definition of loading patterns that could be used for the definition of the ultimate strength for classification purposes. Relevant publications are:

- Houbiao Ma, Yang Yang, Zheng He, Ziyue Jia, Yahui Zhang (2018). Experimental study on constitutive relation of the high performance marine structural steel under extreme cyclic loads. Ocean Engineering 168, 204–215.
- Gang Shi, Meng Wang, Yuanqing Wang and Fei Wang (2013). Cyclic Behavior of 460 MPa High Strength Structural Steel and Welded Connection under Earthquake Loading. Advances in Structural Engineering Vol. 16 No. 3.
- Preventas, M., Fanourgakis, S., Samuelides, M.(2021). Effect of low cycle/high amplitude loads on the moment carrying capacity of a ship's hull. MARSTRUCT 2021 8th International Conference on Marine Structures, Trondheim, Norway.

The discussion of the influence of HAZ, residual stresses and imperfections is definitely useful, but it is not clear why they are reporter under "Numerical methods".

The report discusses in the Sects. 2.1.1, 2.2.1 and 2.2.2 the *"Carrera unified formulation"*. It would be preferable and clearer to merge the discussion of the aspect in one section.

The relevance of the article cited in the last paragraph on insulated glass units is not clear.

2.2.2 Reduced-Order and Analytical Models.

The section focuses on two important aspects: a) the ultimate strength of stiffened panels under combined loads and b) the implementation of neural networks for ultimate strength prediction.

It appears that Putranto extended the application of **E**quivalent **Si**ngle-**L**ayer within the reporting period to box girders (Putranto 2024). As the efficiency of computers increase, I would welcome the opinion of the committee on simplified numerical procedures, such as ESL, ISUM or ISFEM for non-linear structural analysis: are these procedures promising for the future, considering the simplifications and the effort to define the properties of the simplified elements? Along the same line, I would like to have the opinion of the committee on which of the alternatives is preferable: modelling stiffeners with beam or shell elements? (This comment is also related to the 6^{th} bullet of Sect. 7.2 *Recommendations.*)

The committee discusses the application of Physics-informed neural networks (PINNs) and physics-guided deep neural networks (PGDNN) for structural analysis. I suggest that the authors present the fundamentals of the incorporation of laws of physics in NN to address issues related to structural strength and structural response, if it considers that PINNs provide a promising platform to address these aspects.

I could not find any reference to Bayesian linear regression in Ishibashi *et al.* (2024). Please check.

I would suggest to the committee to summarize at the end of the first paragraph the Machine Learning methods that have been developed in the last 3 years for ultimate strength prediction (e.g. ANNs, Kriging method, etc.).

Chapter 3: Construction, In-servce, and Life-Cycle Effects

Chapter 3 is well structured and balanced. My comments on Chapter 3 follow.

Replace *"Aspects such as material properties, fabrication techniques, environmental effects, and structural maintenance all contribute to the accuracy of ultimate strength prediction, which has further implications for design optimisation, service management, and potential life extension. However, uncertainties exist in all of these aspects and are often difficult to quantify across structural scales."* by *"Aspects such as material properties, fabrication techniques, environmental effects, and structural maintenance all contribute to the ultimate strength prediction, which has further implications for design optimisation, service management, and potential life extension. Because there are uncertainties in all of these aspects, which are often difficult to quantify across structural scales, there is an uncertainty in the ultimate strength prediction."*

The statement *"Research shows that a 10% uncertainty in the ultimate strength of plating may translate to a 20% variation in the ultimate strength capacity of a ship hull (Li et al., 2021b)."* deserves further discussion, if the committee is of the opinion that is based in solid grounds.

3.1 Material Uncertainties

The finding that *"it may be possible to confidently estimate the magnitude of the ultimate strength magnitude, it may be difficult to precisely predict the location of damage"* requires further consideration. If the prediction of the location of the damage and possibly the mode of failure is not correct, the prediction of ultimate strength would be doubtful, even if it is close to the value that is measured during a corresponding test.

Uncertainties that are linked to the variation of the material behaviour that is expressed through the stress-strain curve imply that uncertainties depend on the type and grade of steel that it is used. A steel with more pronounced variations in the stress-strain curve would inevitably lead to higher uncertainties.

It is useful to identify the point on the stress-strain curve of the material that corresponds to the end point of the load-deformation curve of the structure under investigation. The accuracy of the stress-strain curve is important for the estimation of the ultimate strength (and the post ultimate strength) as long as the stress-strain relationship is used for the calculations. The portion of the stress-strain curve that is beyond that end point, does not affect the results.

I suggest to elaborate on the findings related to hard corners, since it appears that the use of the material stress-strain curve to simulate the compression of such elements requires revision. Addressing hard corners in a "Smith-type" as an uncertainty may be an alternative.

3.2 Fabrication Uncertainties

In the introductory paragraph, it is mentioned that *"Within the context of FE analysis, efforts generally focus on direct or implicit simulation of distortions and residual stresses* *through imperfection generations in either a deterministic or statistical manner."* I would add that **stochastic** representation of initial distortions has been also considered to reflect their randomness.

3.3 In Service Degradation and Damage

The committee correctly distinguishes the in-service degradation and mechanical damage on one hand and accidental damage on the other. Is there any reliable tool for the prediction of crack initiation?

3.3.1 Corrosion and Metallic Degradation

Degradation of metallics.

In relation to Piscopo and Scamardella (2021), the committee refers to "transverse structural members". Which elements are implied?

Geogiadis *et al.* (2021b) concluded that the spatial variation of thickness due to corrosion need not to be modelled and the effect of corrosion could be addressed by using a average value. However, this conclusion cannot be a priori extrapolated in case of pitting corrosion in areas with pronounced stress concentrations.

I cannot understand the distinction between "corrosion allowance" and *"future corrosion allowance"*. My understanding is that corrosion allowance is to anticipate future corrosion wastage. Please explain.

Chapter 4: Ships

Considering the issues related to the ultimate strength of container ships, the next committee my consider addressing any particular issues related thereto.

4.1.3 Other Load Effects and Load Combinations

It is stated that "Various methods, including empirical models, finite element analysis, and AI, have been developed to improve the accuracy of strength predictions under complex loading conditions." This is doubtful for AI: AI is used to increase the cases analysed and in some cases to provide results to cases that are difficult to simulate. The methodology does not necessarily improve accuracy, which is highly dependent on the dataset used for training and whether the set of parameters of the problem to be solved constitute an interpolation or extrapolation vis-à-vis the range covered by the training dataset. A recommendation for the next committee is to include a section addressing **M**achine **L**earning methods in ultimate strength prediction.

Georgiadis *et al.* (2023b) concluded that the findings show that a significant **increase** rather than decrease in the failure probability of container ships was due to the double-bottom effect in hogging conditions. The publication is more relevant to Sect. 4.3.1.

4.2.1 Stiffened panels

The discussion of each reference is in general informative and strives to summarize the key points. What, I think is missing, are observations or conclusions of the committee that are based in the numerous pieces of work which address the same issue. For example, there are numerous publications on the treatment of initial imperfections. Is there any teaching that may be drawn when considering them all, as to which initial imperfections provide appropriate predictions of the ultimate capacity of a stiffened plate during the design phase of the structure?

I note the following statement of the committee *"Zhang et al. (2023a) … provided a basis for an ultimate strength evaluation formula suitable for different failure modes.*" Could you please provide some info on the formula suitable for different failure modes?

If my understanding is correct Chujutalli *et al.* (2020) addresses the response under tension. Is this correct?

A further publication that deserves attention is Seyffert et al. (2019).

4.3.1 Intact Hull Girder

It appears that Tatsumi and Fujikubo (2020) and Georgiadis *et al.* (2023b) address the issue of double-bottom effect. It would be advantageous, if the two publications are discussed in one place.

4.3.2 Residual Strength of Damaged Hull Structures

Kuznecovs *et al.* (2021; 2022) applied a methodology to determine the residual strength to a case of an intact and a damaged oil tanker under both non-corroded and corroded structural conditions across various sea states. Which are the differences between the results of the corroded and the non-corroded cases?

The committee discusses an article, Komoriyama *et al.* (2023), suggesting an empirical formula for rapid estimation of the ultimate strength reduction. In view of the context of the work, i.e. to decide an appropriate remedial action, it is appropriate to discuss and provide some opinion on the required level of accuracy of such a formula on one hand and on the available input data to perform the calculations on the other.

4.3.4 Progression Sequence of Failure

In the discussion of Deng et al. (2022), it is pointed that *"While these results [on the effect of repeated loading] demonstrate the capabilities of numerical simulations, the question remains of how to integrate these relatively costly simulations into ship structure analysis and rule development."* In an earlier publication Preventas et al. (2021) has defined the ultimate strength after n repeated loads at a certain level of initial ultimate strength expressed in terms of curvature at ultimate load.

4.4.1 Development of Rules and Regulations

4.4.2 Class Requirements: Ultimate Hull Girder Strength Assessment for Ships

Sub-Sects. 4.4.1 and 4.4.2, which go beyond the determination of ultimate strength and address the assessment of the structure under ultimate state limit, i.e. the assessment of the structure vis-à-vis the ultimate loads, are welcomed.

The committee discusses the wave scatter diagram and IACS rec. No 34. The formulation that is used for the assessment of safety using partial safety factors enable to address the demand and the capacity separately, but at the end the safety margin, that is expressed through the reliability level, depends on the pdfs of both variables. It is therefore suggested to investigate the impact of the change of the demand on the reliability level of a ship structure under ultimate limit state, when the reliability is calculated for the nominal life of a ship.

4.4.5 Recent updates to the CSR.

The last Section of Chapter 4 provides a useful overview of the amendments to UR S35.

Chapter 5. Offshore Structures

5.1 Loads

The information Sect. 5.1.1 is interesting and valuable to the reader, but for some references (see for example those that are cited in paragraphs 5 and 8 (last paragraph)), I cannot see their relationship with ultimate strength. The section refers and discusses loads on offshore structures, but it is not always evident, which is the most critical load pattern that would cause collapse.

Similarly, Sect. 5.1.2 does not make clear, which load pattern related to ice load is critical for the ultimate limit state assessment of an offshore structure. I would like to ask the committee to provide some information on that issue.

5.2 Structural Elements.

The committee presents the publications and their relation to the ultimate strength.

The comment related to (Energy Watch, 2023) that *"the incident [detached of a rotor with three blades from the nacelle] was attributed to a production fault in the affected rotor"* should be considered when assessing a structure in ULS, since it introduces an uncertainty related to production, which may considerably lower the capacity of the structure. The next committee should focus on uncertainties that are inserted in production or operation.

Figure 28 reflects the need to consider experiments, analytical methods and discrete models as well as observations from actual cases to develop a reliable procedure for the assessment of a structure in ULS and ALS. The Figure as such does not add any valuable information on how to combine the information from the various sources.

One issue that should be always distinguished, when referring to an extreme loading condition, is whether it causes damage to a structure, which reduces the ultimate strength, or it is considered for the assessment in ULS or ALS.

Chapter 6: Benchmark Study

Sixteen participants were involved in the benchmark study and the results are adequate to reach useful conclusion for our community. Below my comments that are related to the conclusions of that study:

> *"The results from Phase 1 were rather scattered despite little freedom for an analyst to make assumptions related to the geometry, boundary conditions, load, or material modelling."*

I do not agree that there was little freedom for the analyst. The analyst was free to decide on the modelling of the material and the imperfections. In the first phase, I would prefer to test purely the parameters that affect the numerical solution, i.e. FE solver, mesh size, and element type.

In fact, these parameters are mentioned in the 1st bullet of the conclusions related to the benchmark study on page 85 of the report. If only these were left open to decision by the analysts, the results should had been very close.

There is also another reason that I would limit the freedom to the above mentioned parameters: in the early phases of designing a structure, the designer relies on nominal models and parameters for the material and the imperfections which are usually provided by the applicable rules and regulations, because the actual values are not available.

As for the boundary conditions, I understand that for the benchmark study the analysts had to model the supports, but that could be left for the following phase of the study.

> *"This underscores the crucial need for such guidelines in our community."*

Have the participants considered the existing guidelines?

ABS (2021) GUIDANCE NOTES ON NONLINEAR FINITE ELEMENT ANALYSIS OF MARINE AND OFFSHORE STRUCTURES.

DNV (2019). Determination of structural capacity by non-linear FE analysis methods. Recommended Practice No. DNV-RP-C208, Det Norske Veritas GL AS, Oslo.

> *"The modelling of geometrical imperfections greatly influenced the panel's stiffness in the initial loading phase, affecting load redistribution among the various structural components, as well as the failure sequence and post-collapse behaviour."*

During the assessment of a structure in the design phase, I believe that the prevailing issue is to anticipate a "nominal model" and the question to be addressed, is which model represents in the most appropriate manner the imperfections of the panels that will be used. This unknown parameter, i.e. imperfections, introduces an inherent aleatoric uncertainty that will always exist. When the structure is known, the issue is, to model in the most appropriate manner, the existing imperfect geometry, which still carries some uncertainty. This is an epistemic uncertainty. In a benchmark study the questions that, in my opinion, should be addressed are a) which is the level of uncertainty of the results that are attributed to the modelling of imperfections, b) which imperfection models are to be used in the design phase.

I note that the report suggests the modelling of the imperfections *"including the first three modal shapes"* but refrain from providing guidance as to the amplitude magnitudes.

A further question related to imperfections of the model: have the analysts considered in the modelling of imperfections, the initial tilting of the stiffeners?

> *"The diverse selection of material models (such as yield plateau and work hardening) led to even greater variability than observed in Phase 1."*

To investigate the effect of material modelling, I would suggest performing phase 1 as above, i.e. addressing only parameters that influence the numerical solution, and subsequently providing freedom in the modelling of the material.

A point of interest is the portion of the stress strain curve that is relevant for the analysis. It would be possible to identify the portion of the stress-strain curve that is used in the analysis, by detecting the maximum strain that appears during the simulation.

> *"Unfortunately, the designed boundary conditions were not consistently maintained during testing, while numerical models in Phases 1 and 2 adhered to the original boundary conditions as planned."*

This highlights the difficulties of a modelling of an actual structure, where the boundaries are not maintained constant during her life. When analysing a stiffened panel of a ship the designer needs guidance on how large the model should be to avoid uncertainties related to the boundary conditions.

Further, the following questions relevant to the benchmark study, are addressed to the committee:

- Which equations were used to calculate the ultimate stress of the stiffened panel (Sect. 6.6, 45 MPa)
- Which deviations would be considered as acceptable and satisfactory?
- Is the committee in a position to provide guidance to designers, based on the findings of the study, regarding solver, element, mesh size, extend of a model of a stiffened panel?

Chapter 7: Conclusions, Trends and Recommendations

"The use of machine learning (ML) and physics-informed neural network (PINN) methods is increasing, especially in studies related to a large number of uncertainties, such as structural health monitoring and diagnostics of aged ships and offshore structures where the ultimate strength capacity is reduced due to, e.g., corrosion and accumulated plastic deformation." My understanding from the statement is that the committee concludes that ML is employed to produce results for a vast combination of input parameters, which are uncertain.

"Hydrodynamic loads caused by breaking waves can significantly contribute to the overall loading of the structure, impacting the ultimate limit state." Does the statement imply that the breaking waves load the structure up to the ultimate limit or that breaking waves cause damage that compromises the ultimate strength of the structure?

The committee has reached a conclusion that *"A holistic research approach, which considers technical, economic, societal and environmental aspects, is crucial for the large-scale deployment of offshore wind farms."* The statement is very general and does not refer to ultimate strength.

In relation to structures for renewable energy exploration m the committee concludes *"One evident observation regarding guidelines and regulations is that, while well-established for the oil and gas industry—despite occasional improvements or adjustments—they remain limited for offshore renewable energy exploration."* Are there any particular aspects that the anticipated guidelines should address?

In relation to the first phase of the benchmark study the committee concludes that there is a need of guidelines for NLFE to reduce the uncertainties introduced by the analysts. This is true, but to me understanding the analysts involved in the benchmark study did not make use of existing guidelines. Why?

In phase 3 of the benchmark study, the committee notes that the experimental data were significantly influenced by uncertainties related to the intended boundary conditions for the panel. This finding relates to the test. What about the boundary conditions of a stiffened panel that is supported by girders and web-frames? Should the boundaries considered as uncertain or in a deterministic manner. What is the opinion of the committee?

In the recommendations for future work, the committee points to the need of development of *User-friendly practical tools … to minimise uncertainty as a result of the skill level of the analyst*. How do "user friendly practical tools" will minimize the skill level of the analysts? Does the committee anticipate that the practical tools would remove uncertainties by suggesting deterministic values?

In a further recommendation the committee suggests *"When quantifying epistemic uncertainties in numerical modelling via experimental/numerical comparison, it is recommended to consider not only the ultimate strength value but also the failure modes and overall collapse behaviour to ensure comprehensive validation."* I agree that failure modes should be always considered but I do not understand why this need is related to epistemic uncertainties. In my opinion if there is a more or less accurate prediction of the ultimate load but for a different failure mode, something must be wrong with the analysis.

7.2. Recommendations

The committee presented 12 recommendations (there are 11 bullet point and the last paragraph which I understand was the last recommendation rather than the concluding remark). My comments to the recommendations are as below:

> *"Future studies conducted by academia, research institutes, and the industry should focus on developing more advanced machine learning models for strength assessment, integrating traditional inspection as well as LiDAR/3D geospatial data into FE models, and exploring the application of data-driven approaches in ship and offshore structural design to reduce reliance on expensive numerical simulations."*

Inspection and geospatial data relate to the modelling and representation of geometry and ML are employed to avoid numerical simulations. The issue with ML techniques is to define a reliable training data set for the appropriate training of the model. Usually, such datasets are obtained from numerical simulations. Once, a procedure that employs ML technique is in place, the benefit will be the increased possibility to generate results for a large number of input parameters in limited time.

> *"Distortions resulting from fabrication processes should be incorporated into structural analysis to improve the accuracy of strength predictions. These can be included from actual measurements, idealised distortions, or from modal analysis, where several modes are mapped on the geometry."*

I believe that the issues raised in this recommendation should be distinguished:

a. there are uncertainties that are attributed to the fabrication processes, and which include distortions and misalignments.
b. At the early stage of the design, when not all details and parameters of the structure are known, or when the objective is to anticipate the future strength of a structure, the engineer should foresee the future distortions, dents or other minor damages. The objective is to use as input geometry and parameters that will provide results with an acceptable level of uncertainty.

> *"This report emphasises the importance of utilising advanced monitoring and inspection techniques to update FE models and create digital twins that reflect the*

actual state of the structure. User-friendly practical tools and interfaces need to be developed to minimise uncertainty as a result of the skill level of the analyst."

How do *"user friendly practical tools"* will minimize the skill level of the analysts? Does the committee anticipate that the practical tools would remove uncertainties by suggesting deterministic values?

"When quantifying epistemic uncertainties in numerical modelling via experimental/numerical comparison, it is recommended to consider not only the ultimate strength value but also the failure modes and overall collapse behaviour to ensure comprehensive validation."

"Numerical predictions should support multiple failure modes and their interactions while providing precise predictions of the collapse and post-collapse behaviour of the structural members and assemblies involved. Structural elements should be modelled at a level that allows for developing a proper buckling/collapse shape, particularly for the compression zone."

These recommendations were raised in the respective committee of 2022. Has the committee observed any progress?

"Shell elements currently provide a well-balanced approach for modelling large structures. Future advances in computational power could make large-scale models using solid elements more feasible. The development of ESL (Equivalent Single Layer), ISUM (Idealised Structural Unit Method), and ISFEM (Incremental Structural Finite Element Method) should also be pursued for large-scale applications. Reduced-order models are increasingly proposed in the literature but often lack direct comparisons with new or established models. The next committee is advised to include these comparisons in a benchmark study to assess the strengths and limitations of each model."

This is point that was raised in the respective committee of 2022. Does the committee of the opinion that in view of increased CPU power on one hand the development of ML techniques of the other, the future of the simplified NLFEM is promising?

"Multi-scale and multi-physics frameworks, such as the NASMAT software originally designed for aerospace applications hold significant promise for transforming design methodologies for ships and offshore structures, promoting sustainability throughout their service lives. Although this may extend beyond the current committee's direct focus, it is highly pertinent to the ISSC and aligns with the committee's mandate, as it intersects with ultimate strength, life-cycle management, and life-cycle engineering principles."

The transfer of knowledge from other industries, is welcomed.

"*Future research is needed to better predict/quantify the material degradation processes (e.g., corrosion, repeated plastic deformation, development of cracks), especially when new materials are increasingly used for ship and offshore constructions, and to better incorporate the human element (from fabrication to operation) into the analysis.*"

This is point that was raised in the respective committee of 2022. I would like to second on the need to investigate the behaviour of new materials.

"The committee did not find any specific studies on the ultimate strength of wind assisted propulsion systems (WAPS), or indeed vessels with WAPS installed. However, the WAPS technology is becoming increasing popular driven by the IMO net zero target set for 2050 in the shipping sector. As these systems, such as Flettner rotors and wingsails, can be quite large (currently up to 50 m tall and 200 tonnes per unit), the structural failure of WAPS or WAPS-ship interface may significantly affect the integrity/ultimate strength of hulls. Therefore, the committee recommends future research into the structural integrity of these systems and their hull-supporting structures."

I would like to add that it is essential to investigate the most critical failure modes for structures other than ship-like structures.

"Standards and guidelines specifically for offshore renewable energy structures, such as floating wind turbines, should be developed and consolidated, as current regulations are still largely based on oil and gas structures."

The committee has pointed in the report to the need of issuing Guidelines for NLFE. As I had mentioned above such Guidelines do exist.

"There should be stronger collaboration between research institutions and industry to ensure that innovations in predicting and improving ultimate strength are applied practically in the design and maintenance of offshore structures."

This point was elaborated in the 2022 report. In my opinion it is important to address the issue of the level of uncertainty that is considered acceptable, in a ULS analysis.

"Continued research into the effects of the corrosive marine environment on the ultimate strength of structures throughout their operational lifespan is essential. Investigating advanced materials, such as composites, along with effective strengthening and retrofitting techniques, will be critical for extending the service life and resilience of these structure[s].

An editorial comment. I understand that this is the last bullet of the list rather than a general concluding remark. I would like to add that the operation of a structure may be the source of uncertainties, when addressing the ultimate strength.

1.1.3 Conclusion of Official Discussion

The committee addressed all issues defined in the mandate and provide useful information for the designed and the user. Comments related to the mandate follow below.

- Since the mandate refer to behaviour *"under ultimate conditions"*, it may be useful to define when ultimate conditions occur for the various structures – for example in terms of probability.
- The report includes a comprehensive discussion on uncertainties, as required by the mandate. It would be useful to clearly distinguish epistemic and aleatoric uncertainties, since the latter exist by definition, whereas the former may be reduced by a better knowledge of the condition of the structure.
- The mandate refers to fabrication-induced imperfections. I would suggest broadening the scope by referring to fabrication-induced defects.
- The consideration of practical approaches is essential, and in my opinion the next committee should address this issue, by mentioning the most reliable and well-established approaches to address ultimate strength as well as to investigate the behaviour of structures under ultimate limit state conditions.

The report is well drafted and easy to follow, and the committee should be congratulated for the effort and the produced result. In the Introduction to my Discussion, I listed 5 questions, whose answers may be retrieved from the Conclusion of the committee's, report. As reviewer, I need to provide comments and information that I hope may assist the next committee that will address ultimate strength for the next three years.

1.2 Floor and Written Discussions

1.2.1 Henk den Besten

Considering the benchmark as an illustrative example, does the committee think that it is a general trend that when providing/incorporating more information improves the precision but reduces the accuracy? Since if so, when we take both reliability and confidence into account (e.g., for design), will the estimate be different with and without taking the additional information into account? In my opinion, there is an optimum that has to be defined, and it holds in general (so it is a trend).

1.2.2 Irving David Hernández Fontes

The benchmark study concluded despite being provided with additional input the individual analysts' modelling choices led to significant results scatter, and unforeseen experimental scatter like shifting boundary conditions ultimately governed the physical response. Given these powerful sources of uncertainty, what tangible actions can the committee take to develop standardized, verified procedures for non-linear FE analysis and to ensure experimental benchmarks are designed to minimize and quantify such "real-world" uncertainties?

1.2.3 No Name

The benchmark study shows that the axial stiffness of the tested stiffened panel estimated FE analysis is higher than the experiment in Phase 2. The Phase 3 study shows that the reason for this is the boundary condition. I completely agree with this because the displacement measured by the testing actuator includes not only the shortening of the stiffened panel but also the shortening of the fixtures, the gap between the fixture and the stiffened panel, and so on. This is one of the epistemic uncertainties in the experiment, which should be reduced as much as possible on the experiment side. For example, the inter-frame displacement should be measured by some displacement transducers. The uncertainty factors that should be reduced on the FE analysis side and those that should be reduced on the experiment side should be defined.

2 Reply by Committee

2.1 Reply to Official Discusser

2.1.1 Introduction

The Committee would like to thank the official Discusser, Professor Emmanuel Samuelides, for his effort and kind contribution to the assessment of the Committee's Report. The Committee appreciates Professor Samuelides' (hereafter referred to as the "Discusser") valuable and inspiring comments which we reply to in the following.

2.1.2 Reply to Remarks

The Committee thanks the Discusser for valuable and thoughtful feedback on the Committee's work. The Committee's replies to the remarks follow the structure of the Discusser's headings. Compared to previous ISSC mandate periods, the committees of ISSC2025 were instructed to revise their reports submitted to the Discussers in accordance with the Discussers' recommendations. The Committee has followed the instructions, and the following outlines the revisions considered in the final report based on the Discusser's recommendations.

Chapter 2: Fundamentals

- The report has been updated with a definition of ultimate strength that distinguishes between ultimate strength under static loading conditions and ultimate strength under dynamic loading condition.
- The report has not been updated with a clear definition of dynamic ultimate strength whenever the term is used since the Committee feels that it is discussed as a term in multiple places of the report in the contexts when a clear definition was needed.

2.1 Definitions, Assumptions and Uncertainties

- The Discusser suggested the Committee to clarify various terms and definitions. The Committee agrees with the suggestions. The text has been updated in some places in the report.

2.1.1 Assumptions

- The Committee has updated the text in the report to elaborate on the practical difficulties using digital twins for ultimate strength assessments.
- The Discusser pointed out three areas that could be further elaborated in the report. The Committee agrees with the Discusser and has revised the text in this section of the report.

2.1.2 Uncertainties

- Thank you for the remarks regarding uncertainties and how they are presented and discussed in various parts of the report. It should only read epistemic and aleatoric uncertainties. The Committee has made the requested changes in the report and wants to clarify that Chapter 2 focuses on fundamentals related to modelling while Chapter 3 focuses on life-cycle effects.
- The Committee has revised the text in the report and clarified the difference between the two procedures Artificial Neural Networks (ANNs) and Bayesian statistical inference.
- Regarding the remark on initial imperfections and stiffener misalignment, the Discusser raised a similar question in Chapter 6. The Committee's reply in Chapter 6 is more extensive, and the short reply, here, is that no significant differences were observed in the results between those who used the stiffeners' tilt and those who ignored it in the imperfection model. The text has been updated in Sect. 6.3.1 of the report.
- The Committee's reply to the remark related to the Wang *et al.* (2022b) discussion is that this is due to the time steps over which stability is reached. The text in the report has been revised.

2.2.1 Numerical Methods

- The Committee thanks the Discusser for the recommendation to add the references Ma et al. (2018) and Shi et al. (2013). Additional text has been added in the report to give examples of how the Chaboche model material parameters can be experimentally determined.
- The Committee thanks the Discusser for the recommendation to add the reference Preventas *et al.* (2013). Additional text has been added in the report to give an example of how the Chaboche material parameters can affect the ultimate strength of the hull girder.
- The text in the report has been updated with regard to the remark on the influence of HAZ, residual stresses and imperfections.
- The Committee's reply to the remark referring to the Sects. 2.1.1, 2.2.1 and 2.2.2 and the *"Carrera* unified *formulation"* is that the main idea is presented in Sect. 2.1.1, the application to composite materials in Sect. 2.2.1, and use of these within the ML context in Sect. 2.2.2, all of which are connected. The Committee feels that it is important to discuss in several places in the report to understand the links between different approaches taken, this way making the big picture clearer for the reader. No changes have been made to the report.

- Regarding the remark related to the insulated glass unit article, the Committee has revised the text in the report.

2.2.2 Reduced-Order and Analytical Models

- The text in the report has been revised. The computational efficiency is not going to increase to the levels where we could efficiently run parametric investigations with large complex structures with standard FE analysis. The Committee believes the same reasoning has been behind the development of NASMAT model. With regard to simplified numerical procedures, the advantage of ESL is that it is embedded in commercial simulation software (such as Abaqus) and offers considerable time savings compared with full field 3D numerical simulations. However, as the Discusser correctly points out, it requires generation of structural stiffness (K) matrices under different loading configurations using unit cell (UC) simulations, which is cumbersome and time consuming. One way to overcome this limitation is to replace these UC simulations with surrogate models and developments in this direction are already ongoing. Further work is also needed on validating the 2D ESL response. This could be achieved by reconstruction of a full 3D response from 2D ESL response, which would provide insight to the local structural response of stiffeners (non-linear buckling) as part of the 2D ESL model, and thus would provide an additional layer of validation on top of force-displacement curves. Such reconstruction is possible for linear problems (Miao et al., 2024), but not for non-linear problems.
- The Committee presented PINNs and PGDNNs for structural analysis as emerging methods and field of research. The Committee's literature study found few published contributions related to marine structures during the Committee's mandate period. It is recommended that the next Committee continues the discussion and follows the progress of these methods related to the Committee's mandate.
- The Committee has presented a review of Ishibashi *et al.* (2024) in Sect. 2.2.2. No changes have been made to the report.
- The Committee thanks the Discusser for the suggestion to add a summary at the end of the first paragraph which includes Machine Learning methods that have been developed in the last three years for ultimate strength prediction. A summary has not been added here, but additional text as a comment regarding the future use of these methods has been added. It is recommended that the next Committee follows the development and applicability of these methods during the next mandate period.

Chapter 3: Construction, In-service, and Life-Cycle Effects

- The Committee has modified the sentence in the report according to the Discusser's suggestion.
- The intention of the other sentence identified by the Discusser is to provide some quantified context to emphasize the importance of studying uncertainties. However, this does not mean the Committee firmly believes that 10% uncertainties always lead to 20% variation in hull capacity; and hence the wording "may" is used. As this is a short introduction, we preferred not to elaborate extensively on a single paper in this paragraph. No changes have been made to the report.

3.1 Material Uncertainties

- Remark related to the prediction of the location of failure modes: The sentence does not imply that the predicted failure mode is "incorrect", but rather "insufficiently precise". The Committee has modified the sentence in the report to enhance clarity: "*This implies that even though it may be possible to confidently estimate the magnitude of the ultimate strength magnitude with a small error, it is difficult to precisely predict the location of damage. Note that failure mode validation is more challenging than validating the ultimate strength value, as in most large-scale experiments in the literature, the failure mode is typically measured by strain gauges at discrete locations rather than through a full-field measurement. It is challenging to identify any onset of plasticity that can be compared with FE results.*".
- Remark related to material properties and hard corners: The Committee thanks the Discusser for the suggestion. The paragraph has been revised as follows: "... *increased accuracy of the hull girder ultimate strength assessment. Therefore, it may be beneficial to assign more realistic material properties to hard corner elements in reduced-order/analytical methods, such as the Smith method.*".

3.2 Fabrication Uncertainties

- The Committee thanks the Discusser for the suggestion. The sentence has been revised as follows: "*Within the context of FE analysis, efforts generally focus on direct or implicit simulation of distortions and residual stresses through imperfection generations in a deterministic, statistical, or stochastic manner.*".

3.3 In Service Degradation and Damage

- The Committee considers the topic of crack initiation to be outside the scope of this report. The focus here is on how existing cracks affect the structural ultimate strength, with minimal overlap with the ISSC Fatigue & Fracture Committee, which focuses more on crack initiation and propagation. No changes have been made to the report.

3.3.1 Corrosion and Metallic Degradation

Degradation of metallics.

- The Committee apologizes for the confusion. The authors studied cross sections of a bulk carrier. The sentence has been revised as follows: "*A more general framework for assessment of the ultimate strength of a bulk carrier subject to pitting corrosion was developed by Piscopo and Scamardella (2021).*".
- Remark related to the reference Georgiadis *et al.* (2021b): The following text has been added to the discussion of the paper: "*Their findings indicated that thickness data collected from inspections could be used to inform spatial variations in the material, enabling more reliable vessel-specific predictions of ultimate strength. However, this conclusion cannot be a priori extrapolated in the case of pitting corrosion in areas with pronounced stress concentrations.*".
- The Discusser has a remark related to the distinction between "corrosion allowance" and "*future corrosion allowance*". The Committee decided to remove "future corrosion allowance" from the text in the report.

Chapter 4: Ships

4.1.3 Other Load Effects and Load Combinations

- The Committee is grateful for the Discusser's good remark. The introductory sentence has been modified to: "*Empirical models, finite element analysis, and machine learning based approaches have been employed to improve the accuracy of strength predictions under complex loading conditions.*". The Committee also agrees with the Discusser that ML-based models should have more emphasis in the next committee's report.
- The reference Georgiadis *et al.* (2023b) has been moved to Sect. 4.3.1, and the Discusser's suggested correction was also considered.

4.2.1 Stiffened Panels

- Thank you for the remark. The references and text discussing imperfections have been reordered and updated. Since the paper by Li *et al.* (2022d) provided recommendations, this was discussed lastly and the recommendations provided have been summarized in the report.
- Reply to the remark regarding different failure modes: The Committee has revised the text in the report to clarify how Zhang *et al.* (2023a) extended previous fitting equations (two references were added: Paik 1997, and Zhang 2009) and what failure modes are covered. Also, a figure was added comparing the new results with the results obtained with previous fitting equations.
- Reply to the remark related to the reference Chujutalli *et al.* (2020): The original text in the report was actually reflecting one earlier study by Chujutalli. The text in the report has therefore been revised as follows: "*One approach to account for mechanical damage to a stiffened panel is to consider the damaged geometry as a form or type of imperfection. Chujutalli et al. (2020) investigated the ultimate strength reduction of stiffened panels under compression due to indentation damage. The ultimate strength, failure mode, and deformation field were measured experimentally for selected scaled stiffened panels, which were used to validate the simulation model. The validated FE model was subsequently used for parametric study to gauge the effects of indentation dent depth, indenter diameter, indentation location and stiffener slenderness. It was found that depending on the stiffener type used (flat bar or T-stiffener), the indentation parameters have a different effect on the response.*".
- The publication Seyffert et al. (2019) has been reviewed and the following text has been added to Sect. 4.1.3 instead to keep the balance between the length of different sub-sections: "Seyffert et al. (2019) *presented an interesting approach that employs the non-linear Design Loads Generator (NL-DLG) process to efficiently estimate the lifetime performance of stiffened panels under combined loading. The approach allows for a direct comparison between panel options and highlights critical panel parameters that are strongly related to design robustness. The approach was used to compare the failure probabilities of six different stiffened panel designs for a specific vessel in a long exposure to harsh ocean excitation. The comparison was especially interesting since some class society had previously vetted all designs. It was demonstrated that the NL-DLG process yields similar statistical characteristics*

to those of brute-force Monte Carlo simulations, while reducing simulation time by a factor of 87,000.".

4.3.1 Intact Hull Girder

- Thank you for the suggestion. The Committee has moved the reference Georgiadis *et al.* (2023b) from Sect. 4.1.3 Other loads effects to Sect. 4.3.1 Intact hull girder to keep the two references together.

4.3.2 Residual Strength of Damaged Hull Structures

- Thank you for the remark. New text has been added to the report: "*Corroded structures resulted in larger damage opening and penetration depth of the striking bow, but the damage was limited to the same internal compartments. Consequently, this resulted in similar floodwater volumes and distributions, with the corroded tanker reaching the steady state faster due to the larger damage opening area.*".
- Reply to the remark regarding the reference Komoriyama *et al.* (2023): The committee argues that no such suggestion was made in the article nor was it implied in the Committee's discussion in the report, unless the Discusser considers Smith's method as empirical formula. Namely, the report states that "Komoriyama *et al.* (2023) investigated the collapse behaviour and ultimate longitudinal bending strength of damaged box girders in upright and inclined conditions through experimental and numerical analyses. These experiments involved applying four-point bending loads to box girders with elongated holes. The authors concluded that the Smith method can estimate the ultimate strength of damaged box girders similarly to the FE model. They suggested further research to investigate different hole sizes, shapes, and locations, as well as real ship structures.". No changes have been made to the report, except for the reference year that was corrected to 2024 to correspond with the publication year of the proceedings.

4.3.4 Progression Sequence of Failure

- The reference Preventas et al. (2021) has been added to the discussion in accordance with the Discusser's suggestion.

4.4.1 Development of Rules and Regulations

4.4.2 Class Requirements: Ultimate Hull Girder Strength Assessment for Ships.

- The Committee thanks the Discusser for the suggestion related to the Sects. 4.4.1 and 4.4.2. However, the Committee thinks it is beyond the scope of the present committee's mandate. A separate study is needed to meet the Discusser's proposal which the next Committee may consider doing.

Chapter 5: Offshore Structures

5.1 Loads

- The Committee thanks the Discusser for his observation regarding the relevance of some references in Sect. 5.1.1 to ultimate strength. In response, the Committee has carefully reviewed the referenced literature and removed four references that were not directly related to the ultimate strength assessment. The revised chapter now focuses more clearly on studies that contribute to identifying critical load scenarios relevant to ULS evaluation.
- Reply to the remark referring to Sect. 5.1.2: The Committee acknowledges that Sects. 5.1.1 and 5.1.2 could benefit from clearer articulation of the most critical load patterns in relation to ultimate strength. The Committee has revised these sections to explicitly identify the load scenarios that are most likely to govern the ultimate limit state (ULS) for offshore wind turbines and Arctic offshore structures. The revision includes: (1) highlighting the role of extreme wave and wind combinations and tendon failure in floating wind turbines as critical to ULS, and (2) emphasizing ice-induced crushing and bending loads on structural elements near the waterline as governing ULS in Arctic conditions.

5.2 Structural elements

- The Committee appreciates the comment regarding the Energy Watch (2023) reference. While the incident was not caused by an external load, it underscores the role of production-related uncertainties in reducing structural capacity. The Committee has clarified this point in the revised report text and emphasized the need for future committees to address such uncertainties in ULS assessments.
- Reply to the remark related to Fig. 28: The Committee agrees with the Discusser that the figure, in its current form, does not provide sufficient guidance on how to integrate information from experiments, analytical methods, discrete models, and real-world observations. It has therefore been removed from the report to maintain clarity and focus.
- Reply to the remark related to ULS and ALS: The Committee appreciates the insightful comment on the distinction between extreme loading causing damage and its role in ULS or ALS assessment. The Committee has revised the text in Sect. 5.2.2 to explicitly clarify this distinction and emphasize its importance in structural evaluations.

Chapter 6: Benchmark Study

- Reply to the remark related to freedom for the analyst: In the first phase of the benchmark study, the differences in the interpretations on the material model were minimal, and the result comparisons show differences between perfectly plastic and work hardening models in the post-ultimate stage only (Fig. 34). As for the interpretation of the initial imperfections, the Committee did not expect such a varied scenario: having provided the complete 3D scan of the model, we assumed that the real geometry would be used for geometric modelling by all participants. Indeed, some participants opted for different strategies ignoring the real imperfection and choosing alternatives such as eigen mode or sinusoidal. No changes have been made to the report.

- Reply to the remark on FE solver, element size, etc.: In reality, the Committee found that the results suggest a different scenario: comparing for example the results of teams #8 and #11, they have opted for almost identical modelling parameters using the same software, yet a difference on the ultimate strength higher than 4% is observed. The same for participants #19 and #22 that, apart from a difference in mesh size (15 × 15 vs. 20 × 20) and imperfection amplitude, opting for similar modelling parameters show variations on the ultimate strength close to 20%. No changes have been made to the report.
- Reply to the remark on early phases of designing a structure: During the first phase of the benchmark study, the 3D reconstruction of the model by laser scanning was already available, consequently the participants' task was not to hypothesize the geometric imperfection of the model, but to represent such imperfection in the own FE model. In this phase, in fact, important considerations emerged that concern the interpretation of the real imperfection by the researchers within their own geometric model.
- Reply to the remark related to boundary conditions and guidelines: Unfortunately, not much is reported in the existing guidelines that can be used practically in defining a FE model for this purpose. For example, DNV (2019) only reports the following sentence when it comes to the definition of boundary conditions: "The selected model boundary condition needs to represent the real condition in a way that will lead to results that are accurate or to the safe side. Often it is difficult to decide what the most "correct" or a conservative boundary condition is. In such cases sensitivity studies should be performed.". ABS (2021) emphasizes the crucial role of accurately modelling boundary conditions in Nonlinear Finite Element Analysis (NLFEA), more so than in linear analyses. It warns against uncritically applying assumptions valid for linear models since these can lead to inaccuracies when nonlinear effects come into play. The text also notes that these assumptions might still be used if areas of interest are distant from structural boundaries. Examples of appropriate boundary conditions for various structural elements and scenarios are referenced in the supplementary materials. Nevertheless, the examples given in the appendix show very idealized boundary conditions. No changes have been made to the report.
- Reply to the remark related to geometrical imperfections: The Committee agrees with the Discusser's statement. However, it was not the purpose of this benchmark to make considerations about the hypotheses concerning the best strategy to introduce geometrical imperfections in the model that approach the actual imperfections of naval structures. In fact, it was expressly decided to skip this important phase, present instead in the previous committee's ISSC2022 benchmark, providing already in the first phase the real geometry of the specimen to limit the potential choices in the modelling phase. No changes have been made to the report.
- Reply to the remark related to the number of mode shapes: The analysis on the amplitude of imperfections to be used for eigenmode imperfections is reported in Sect. 6.3.1. It is stated that models using a mode-one eigenmode imperfection with an amplitude of at least to 2.0 mm exhibit a behaviour closer to models with actual

measured imperfections, though they remain slightly stiffer. No changes have been made to the report.

- Reply to the remark related to the initial tilting of the stiffeners: The tilts of the reinforcements were provided to the participants, although not in the form of a complete 3D reconstruction. In particular, detailed reconstructions of three parts for each common stiffener (at the two ends and at the mid-span) were provided, from which it was possible to extract the tilt angle at these three points. However, many participants chose to ignore this information. It was noted that in the current study, no significant differences were observed in the results between those who used the stiffeners' tilt and those who ignored it in the imperfection model. The text has been revised in Sect. 6.3.1 of the report.
- Reply to the remark related to material modelling: Focusing only on material modelling is not easy in a benchmark where different FEM analysis software are used. In this regard, it would be easier to identify a subset of participants using the same software, fix all the modelling parameters and leave only the interpretation of the material model free. In the planning of phase 3, this possibility was discussed, but due to time and resource limitations it was decided to focus the last phase on other aspects. No changes have been made to the report.
- Reply to the remark related to the portion of the stress-strain curve relevant for the analysis: Thank you for the interesting suggestion. The Committee presents an example of results at the ultimate capacity point from one of the FE simulations. The plastic equivalent strain is plotted in the figure at the ultimate capacity which occurs at the displacement of 6.79 mm. At this point, the plate buckles and the stresses are redistributed from the interior of the plate to the stiff edges. Both the maximum equivalent plastic strain according to von Mises (PEEQ) at the surface and the mid-plane of the elements were extracted to 1.6% and 2.4%, respectively. No text has been added to the report.
- Replies to the remarks related to Sect. 6.6. No changes have been made to the report.

  – The current formulas for buckling in CSR and UR-S35 (IACS, 2024) are the same formulas. In these rule sets, there are equations both for the plate check and the stiffener check, and the computed ultimate capacity equal to 45 MPa is taken equal to the least of the capacity from the plate and the stiffener. In this case, stiffener buckling was the critical failure mode and global elastic stiffener buckling is the upper limit.
  – This committee did not work on defining an acceptable level of uncertainty, but limited itself to photographing the current situation, which still shows significant deviations in the results, even when working with a rather limited number of input parameters. New text has been added to Sect. 7.1.
  – The committee is not able to provide guidance to designers, based on the findings of the study, regarding solver, element, mesh size, extend of a model of a stiffened panel. Apart from clear indications that emerged in the first phase regarding the initial geometric imperfection model, no trends emerged regarding solver, element or mesh size. Instead, a non-negligible effect due to the introduction of residual stresses was shown and some critical issues related to the strategy of introducing such stresses emerged, here the self-equilibrium at the level of the single panel was

not verified by all participants, leading to an overestimation of the ultimate capacity of the specimen. Furthermore, it emerges that the correct strategy of modelling the constraint conditions is by far the most influential parameter on the results. It is therefore recommended by this committee that experiments should acquire the axial displacements at intermediate frames as well as panel ends as well as monitor all degrees of freedom at the panel ends to be able to more effectively reconstruct the exact boundary conditions.

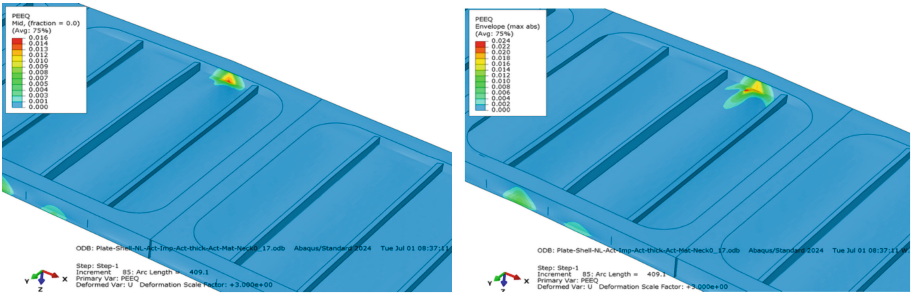

Fig. 1. Maximum PEEQ (-) at the ultimate capacity point (6.79 mm displacement) (left) at plotted at the elements' surface, and (right) plotted at the elements' mid-plane.

Chapter 7: Conclusions, Trends and Recommendations

- Reply to the remark related to machine learning (ML): The Committee confirms that the Discusser's understanding is correct. The sentence has been modified to enhance clarity: "*The use of machine learning (ML) and physics-informed neural network (PINN) methods is increasing, especially in studies related to a large number of input parameters with uncertainties, such as structural health monitoring and diagnostics of aged ships …*".
- Reply to the remark related to hydrodynamic loads caused by breaking waves: The Committee has revised the sentence to clarify that breaking waves do not necessarily cause damage but can significantly increase structural demand, potentially contributing to conditions approaching the ultimate limit state.
- Reply to the remark related to the conclusion on holistic research approach: The Committee agrees with the Discusser that the original statement was formulated too broadly. The text has been revised to clarify how a holistic research approach also encompasses structural aspects, including ultimate strength, fatigue, and degradation mechanisms, which are essential for the safe and reliable deployment of offshore wind farms.
- Reply to the remark related to structures for renewable energy exploration: Thank you for the good remark. The Committee has revised the text to specify the key aspects that future guidelines for offshore renewable energy structures should address, including environmental loading, fatigue and ultimate strength criteria, material degradation, and design for maintenance and decommissioning.

- Reply to the remark related to the first phase of the benchmark study: The Committee and the participants of the benchmark study found that existing guidelines provide limited practical advice on defining NLFE. DNV (2019) highlights the importance of representing real conditions accurately or conservatively, suggesting sensitivity studies when uncertainty exists. ABS (2021) stress the critical role of boundary conditions in nonlinear analyses and cautions against relying on assumptions from linear models. While supplementary materials offer examples, these are often highly idealized. The text in the report has been revised.
- Reply to the remark related to the third phase of the benchmark study: The benchmark study did not investigate the actual characteristics of the boundary conditions of the stiffened panels present inside the test specimen, but concentrated on the effect related to the partial loss of stiffness (and consequent load redistribution on frames) of these panels due to the elastic buckling caused by transverse loads. However, in Sect. 6.6 in which the results are compared with UR-S35, the study highlighted how a simple support constraint hypothesis is extremely cautious. At the moment, based on the benchmark results, the Committee has no information to establish whether the boundary conditions can be idealized and in what way, but the stiffness ratios between the structural elements examined seem, in this case, to confirm a fully clamped condition, at least until the global buckling of the specimen occurs. No revision has been made to the report.
- Reply to the remark related to user-friendly practical tools: The sentence in the report specifically addresses uncertainties stemming from the analyst, e.g., modelling skill variations. If the numerical tools were simpler, there are less chances of making mistakes for the analyst. No changes have been made to the report.
- Reply to the remark related to failure modes. Thank you for this remark. The committee has reformulated this item to clarify its message.

7.2. Recommendations

- The Committee agrees with the Discusser's remark related to ML. The generation of data for ML with high-fidelity models was also mentioned in Sect. 7.1 in the report. No changes have been made to the report.
- The Committee agrees with the Discusser's remark related to distortions from fabrication processes. The last sentence in the text highlighted by the Discusser has been revised as follows: "*Depending on the stage of the design/assessment, these can be included from actual measurements, idealised distortions, or from modal analysis, where several modes are mapped on the geometry.*".
- Reply to the remark related to "user friendly practical tools": The sentence has been revised as follows: "*User-friendly practical tools and interfaces need to be developed to minimise uncertainty as a result of the skill level of the analyst.*".
- Reply to the remarks related to "epistemic uncertainties" and "multiple failure modes": In the current benchmark study, no detailed information was provided to the participants regarding the failure modes that could be potentially predicted by the numerical models. However, all participants correctly estimated both the collapse mode and the location where it would occur. We can therefore establish that, at present, all the analysts employed in this study were able to use numerical techniques capable of correctly estimating the different nonlinear effects observed experimentally,

with particular reference to plasticization, local buckling and global buckling. The state-of-the-art shows that researchers can capture multiple failure modes and their interactions in NLFEA. The Committee decided to delete this point in the conclusions to avoid misunderstandings.

- Reply to the remark related to CPU power, ML techniques, and the future of the simplified NLFEM: The Committee confirms that yes, there is a future. There are two types of surrogate models: (1) reduced-order models, and (2) data driven models. The problem with the first one is that they are still inaccurate. The problem with the second is that it is extremely costly to generate data for large structural models. If the latter could be circumvented somehow, for instance by high-fidelity, but fast FE models (i.e., ESL), this data generation process for ML could be streamlined. So even if the ML takes over, these reduced-order models could be an important stepping stone for developing ML models.
- Reply to the remark related to the editorial comment: The Committee has revised the formatting to ensure that the statement is presented as part of the bullet list, rather than as a separate concluding remark. Additionally, the Committee has incorporated the point that operational conditions can introduce uncertainties affecting the assessment of ultimate strength.

2.1.3 Reply to Conclusion of Official Discussion

The Committee thanks the Discusser for valuable and thoughtful feedback on the Committee's work.

2.2 Reply to Written and Floor Discussion

2.2.1 Henk Den Besten

Based on the benchmark study results presented by the Committee in the 2022 and 2025 reports, it is reasonable to conclude that more information improves accuracy but results in higher dispersion (scatter). Both benchmark studies show that providing more information to the analysts in Phase 2 resulted in a larger dispersion in predictions, due to increased epistemic uncertainty related to the constitutive material models used by the analysts. More straightforward, unified modelling guidelines, defined and agreed upon by classification societies, can ensure accuracy and help reduce dispersion.

2.2.2 Irving David Hernández Fontes

Considering the current guidelines for the definition of a nonlinear finite element model—specifically DNV (2019) and ABS (2021)—the committee observed that they are extremely vague and provide little practical guidance for defining precise modelling strategies, particularly with regard to boundary conditions.

The Committee agrees with the comment and has written in Chapter 7.1 of the report that guidelines for experiments and nonlinear FE analysis need to be developed. It is suggested that classification societies initiate and lead a joint industry project to agree on unified guidelines that are consistent across all classification societies.

2.2.3 No Name

The Committee thanks for the comment and agrees that it is important to measure displacements at several positions of the frame and on the transducers. It was done in the current experiment. The measured data were used to re-simulate the experiment in Phase 3, using FE analysis, by three participants.

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