Benchmark Study of Evaluation of Methods for Ultimate Strength Analysis of Stiffened Plates

An initiative of the MARSTRUCT Virtual Institute

Contacts: Lars Brubak Lars.Brubak@dnv.com
Jonas Ringsberg jonas.ringsberg@chalmers.se
Carlos Guedes Soares c.guedes.soares@centec.tecnico.ulisboa.pt

Background

Stiffened plates are fundamental structural components in marine and offshore engineering, and these large steel structures are subjected to complex loading conditions. Accurate prediction of their ultimate strength is essential for ensuring structural integrity, safety, and compliance with classification society rules.

Over the years, various methods have been developed to assess the ultimate strength of stiffened plates. These range from advanced nonlinear finite element analyses (NLFEA) to simplified empirical formulas and semi-analytical tools. Each method offers different levels of accuracy, numerical model complexity, and applicability depending on the structural configuration and loading scenario. Common approaches include:

- Advanced nonlinear finite element analyses (NLFEA)
- Semi-analytical tools such as PULS and ISUM
- Empirical formulas
- Design rules and guidelines from classification societies, including ships and offshores structures
- Various methods developed by academia

Despite the availability of these methods, there are discrepancies in predictions and limitations in application. It is proposed to perform a benchmarking study that systematically evaluates and compares different approaches for regular stiffened plates. Such a study helps identify strengths and weaknesses and may promote harmonization across design standards and support the development of more reliable and efficient analysis tools. The proposal for the benchmark study was initiated and presented at MARSTRUCT conference in Lisbon in 2025.

Objective of the Benchmark Study

The primary objective of the MARSTRUCT Benchmark Study is to evaluate and compare the accuracy, reliability, and applicability of different methods for predicting the ultimate strength of stiffened plates used in marine and offshore structures.

A representative set of stiffened plate configurations and loading conditions will be analysed. The study will involve multiple participants and methodologies to provide a comprehensive understanding of the performance and reliability of current ultimate strength assessment techniques.

Nonlinear finite element analysis (NLFEA) will be used as the reference method in the benchmark study. To ensure consistency and provide a high-fidelity reference, a detailed modeling guidance for nonlinear finite element analysis based on best practices from classification societies is described in Annex B. This guidance describes how nonlinear finite element analysis of stiffened plates will be utilized in a rule context including mesh setup, boundary conditions, imperfection modeling, and material definitions. Based on the results received from the different participants, reference values for the ultimate strength will be established.

This benchmark may provide a structured basis for improving current methodologies and enhancing confidence in ultimate strength assessments across the industry.

Main Steps for the Benchmark Study
In the Benchmark study, comparisons will be performed for the three categories (A, B and C) defined in the following table:

Category	
A	**FE in a rule-based context:** NLFEA from participants following the procedure in Annex B. A reference value based on this procedure will be established by DNV.
B	**Design Capacity (non-FE based methods):** CSR (reference method for non-FE based methods), PULS, DNV-RP-C201, and other design standards (including safety factors if required). Expected outcome from the results of this comparison is to evaluate the difference between the design standards, etc.
C	**Extended study with additional results (free choice of method):** NLFEA with different assumptions, experimental tests, and other methods. This would require contributors to provide a brief description of their assumptions. These results could help to indicate the safety margins applied in design.

The main steps of the Benchmark Study can be summarized as follows:

1. *Selection of Evaluation Methods*
   Identify and select a diverse set of methods for assessing the ultimate strength of stiffened plates. The choice of methods will depend on the expertise and preferences of the participating organizations. These may include:
   - Nonlinear Finite Element Analysis (NLFEA)
   - Semi-analytical tools (e.g., PULS, ISUM)
   - Empirical formulas
   - Classification society rules and guidelines (e.g., CSR, DNV-CG-0128)
   - Academic or research-based approaches

Participants may submit results from one or more different approaches, including those obtained using finite element analysis following the procedure described in Annex B.

2. *Definition of Benchmark Cases*
   In Annex A, a set of representative stiffened plate configurations and loading scenarios to be used is presented. These reflect typical structural elements found in ships and offshore structures. The cases are selected to trigger different failure mechanisms:
   - Plate buckling: Thin plates under compressive loads
   - Stiffener buckling: Long stiffeners prone to lateral instability
   - Torsional stiffener buckling: High-aspect-ratio stiffeners susceptible to torsional failure

   If considered relevant, additional geometries and loading scenarios can be analysed (to be decided later).

3. *Application of Load Combinations*
   Apply in-plane loads in multiple directions to simulate realistic operational conditions. This will allow the generation of interaction curves and provide insight into the structural response under combined loading.

4. *Execution of Nonlinear Finite Element Analysis (NLFEA)*
   Perform detailed NLFEA simulations for each benchmark case. The analysis should follow a standardized procedure to ensure consistency across participants:
   - Model extent and boundary conditions
   - Mesh density and element types
   - Inclusion of initial imperfections (local and global)
   - Frame and support conditions

   To ensure consistency and provide a high-fidelity reference, detailed FE modeling guidance is presented in Annex B, based on best practices from classification societies.

5. *Comparison and Documentation of Results*
   Collect and compare results from all methods across the benchmark cases. Key parameters to be evaluated include:
   - Ultimate strength: Maximum load-carrying capacity before failure
   - Elastic buckling loads: Both local and global modes
   - Buckling and failure modes: Identification of dominant failure mechanisms (e.g., plate, stiffener, torsional), identified by sequence and load magnitude using the structure's force-displacement diagram

6. *Reporting and Harmonization*
   Document findings in a structured format, highlighting discrepancies, strengths, and limitations of each method. The results may contribute to harmonizing design practices and improving the reliability of strength assessments for stiffened plates.

Nonlinear Finite Element Analysis (NLFEA)

Nonlinear Finite Element Analysis (NLFEA) as described in Annex B will be used as the reference method in the benchmark study. It provides a detailed representation of the structural behavior of stiffened plates under in-plane loading, including buckling, post-buckling, and collapse.

To ensure consistency across participants, a standardized modeling approach will be followed, based on best practices from classification societies such as DNV (e.g., DNV-CG-0128). This includes:

- Mesh definition: Recommended element types and mesh density to capture local and global buckling modes.
- Boundary conditions: Representing that the stiffened plate is part of a larger structure.
- Imperfection modeling: Guidelines for introducing initial imperfections, both local and global imperfection.
- Material models: Elastic-plastic behavior with appropriate yield strength and material hardening.
- Load application: Procedures for applying in-plane loads in multiple directions to generate interaction curves.

To support participants, Annex B provided guidance including:

- Detailed modeling instructions
- Predefined FE models with geometry, mesh, and boundary conditions
- Material definitions and load cases
- Assumptions and validation references

Annex B will serve as a practical guide to ensure uniformity and facilitate comparison of results across different methods.

Experimental tests
If experimental data on the ultimate strength of stiffened plates are available, they can serve as a valuable extension to the benchmark study. Incorporating such data allows for a more comprehensive validation of the analytical and numerical methods under evaluation. Experimental results provide real-world insights into structural behavior, including:

- Initial imperfections and fabrication tolerances
- Material nonlinearities and residual stresses
- Actual buckling and failure modes under controlled loading

By comparing simulation results with experimental findings, the benchmark study can:

- Validate the accuracy and reliability of different methods
- Identify potential gaps or limitations in current modeling approaches
- Enhance confidence in the use of simplified or semi-analytical tools

Participants are encouraged to contribute relevant experimental datasets, and this will enrich the benchmark study.

Participant-Defined Nonlinear Finite Element Analysis (NLFEA)
In addition to the reference procedure for nonlinear finite element analysis (NLFEA) described in this proposal, participants will be given the opportunity to apply their own modeling strategies. This includes the freedom to define:

- Material models (e.g., hardening laws, strain-rate sensitivity)
- Imperfection modeling (e.g., magnitude, shape, and distribution of initial imperfections)
- Boundary conditions and load application techniques (should reflect that the panel is part of a larger structure with continuous plating around the entire plate)
- Mesh strategies and element formulations

The aim of this extended scope is to foster a broader discussion on the influence of modeling choices on ultimate strength predictions. By comparing results from both the reference procedure and participant-defined approaches, the benchmark study can:

- Highlight the sensitivity of results to modeling assumptions
- Identify best practices and potential pitfalls
- Encourage refinement of current methodologies

Participants are encouraged to document their modeling choices clearly. A dedicated section in the final report will be used to present and discuss these alternative approaches, contributing to a deeper understanding of nonlinear structural behavior and modeling robustness.

Goal and Timeframe

Outcome from the benchmark study:

- Intermediate results of the benchmark study are intended to be presented at MARSTRUCT 2027, University of Strathclyde, Glasgow.
- A joint journal paper will be submitted to a selected international journal (to be discussed)

Timeframe:

- Numerical results from all participating methods should be completed and submitted by November 2026
- Final documentation and comparative analysis should be ready by February 2027.
- Presentation materials will be prepared in time for the MARSTRUCT 2027 conference

References:

1. **DNV-CG-0128 – Buckling**
   This DNV class guideline defines methodologies for buckling and ultimate limit state (ULS) calculations.
2. **DNV-RP-C201**
   Recommended practice by DNV for buckling strength assessment of plated structures.
3. **PULS (Panel Ultimate Limit State)**
   A semi-analytical tool developed by DNV for evaluating buckling and ultimate

strength of stiffened plates. It is widely used in classification rule checks and integrated into the Nauticus Hull software.

4. **ISUM (Idealized Structural Unit Method)**
   A simplified method for progressive collapse analysis of ship structures. ISUM models structural units with idealized nonlinear behavior, offering computational efficiency compared to full FEA.
5. **Smith Method**
   A well-established approach for estimating the ultimate strength of ship hull girders. It simplifies the structure into stiffened panels and applies average stress-strain relationships to simulate collapse behavior.
6. **Nonlinear FE tools: Abaqus, Ansys, etc.**
   Commercial finite element software used extensively for nonlinear analysis of stiffened plates. It supports advanced buckling, post-buckling, and collapse simulations, including imperfection sensitivity and material nonlinearity.

ANNEX A

Panel and Load Definition for Benchmark Study

Introduction

Annex A presents the panels and load definition for the benchmark, and includes definition of geometry, material properties and load definition. It is assumed that 3 different stiffened plates will be included in the initial scope. To ensure a comprehensive evaluation of ultimate strength assessment methods, three representative stiffened panel configurations have been selected. Each panel is designed to trigger distinct failure mechanisms commonly observed in marine and offshore structures. These configurations will be analyzed under various in-plane loading conditions using multiple methodologies, with NLFEA serving as the reference approach.

Geometry

The geometry of three selected panels is described in Table 1:

Table 1: Panel dimesions for the benchmark study

Panel Id.	**Panel length L [mm]**	**Stiffener Spacing s [mm]**	**Plate thickness t [mm]**	**Total stiffener height h [mm]**	**Flange breadth b_f [mm]**	**Web thickness t_f [mm]**	**Flange thickness t_w [mm]**	**Number of stiffeners**	**Stiffener type**
Panel 1	3500	850	12	150	-	-	-	7	Flatbar
Panel 2	3500	850	18	350	100	12	18	5	Angle
Panel 3	4500	850	24	450	100	12	20	5	T-bar

The geometry of the plates for finite elements calculations will be provided as a mesh to each participant to reduce the uncertainties in the modelling.

Material properties

A bi-linear material model including strain hardening effect should be applied in the analysis. An example for a stress-strain curve is shown in Figure 1 and the material parameters to be used are:

Young's modulus, E [N/mm2]	206 000
Poisson ratio, υ	0.3
Yield stress [N/mm2]	315
Strain hardening parameter, E_T [N/mm2]	1000

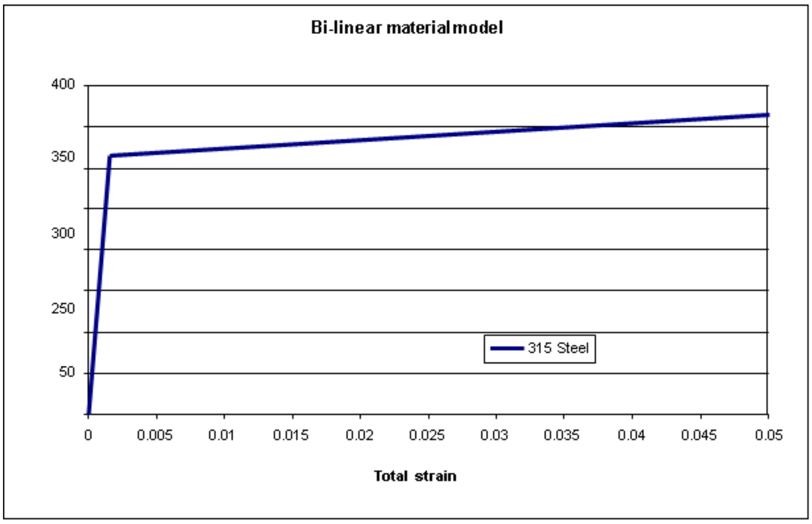

Figure 1: Bi-linear true stress-strain curve for 315 steel.

Loads

For each of the three plates, in-plane loads will be applied with combinations of axial and transverse loads with a 15 degrees interval between each load case as specified in Table 2. In the same table, the two last columns are results from calculated by each participant, which is the failure mode and the computed load proportionality factor (LPF).

Table 2: Compinations of in-plane loads for each load case

Load case	Applied S_x [MPa]	Applied S_y [MPa]	Computed failure mode	Computed LPF
Degree-0	315	0		
Degree-15	304	82		
Degree-30	273	158		
Degree-45	223	223		
Degree-60	158	273		
Degree-75	82	304		
Degree-90	0	315		

In the column with "Computed failure mode", it can be stated three different failure modes:

1. Plate buckling (i.e. dominant plate deformations at maximum load / LPF)
2. Stiffener buckling / GEB (i.e. dominant out-of-plane stiffener deformations at maximum load LPF, or global elastic stiffeners buckling (GEB) occurs before maximum load in nonlinear analysis)
3. Torsional buckling (i.e. sideways tripping of stiffener at maximum load / LPF)

The corresponding interaction curve for in-plane loads should be plotted as presented in the example below.

Example with reported results

For each of the three plates, the following should be presented:

Table 3: Example with reported results for one plate

Load case	Applied S_x [MPa]	Applied S_y [MPa]	Computed failure mode	Computed LPF
Degree-0	315	0	Plate buckling	0.56
Degree-15	304	82	Plate buckling	0.51
Degree-30	273	158	Plate buckling	0.40
Degree-45	223	223	Plate buckling	0.32
Degree-60	158	273	Stiffeners buckling/GEB	0.28
Degree-75	82	304	Stiffeners buckling/GEB	0.26
Degree-90	0	315	Stiffeners buckling/GEB	0.26

The LPFs and applied loads in Table 3 gives the interaction curve presented in the Figure 2.

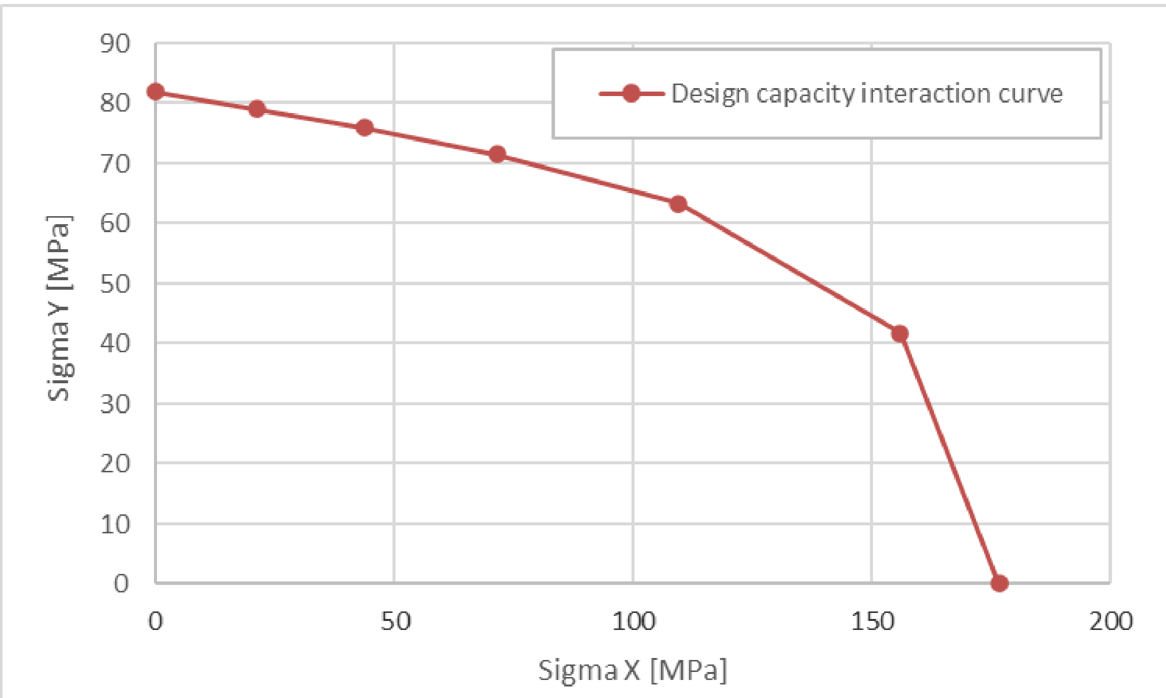

Figure 2: Example with interaction curve

ANNEX B

Non-linear finite element collapse analyses of stiffened panels
Procedure description

Introduction

Nonlinear Finite Element Analysis (NLFEA) will be used as the reference method in the benchmark study. It provides a detailed and accurate representation of the structural behaviour of stiffened plates under in-plane loading, including buckling, post-buckling, and collapse.

To ensure consistency across participants, a standardized modelling approach will be followed, based on best practices from classification societies such as DNV (e.g., DNV-CG-0128). This includes:

- Mesh definition: Recommended element types and mesh density to capture local and global buckling modes.
- Boundary conditions: Standardized supports and loading configurations.
- Imperfection modelling: Guidelines for introducing initial imperfections, both local and global.
- Material models: Elastic-plastic behaviour with appropriate yield criteria and hardening rules.
- Load application: Procedures for applying in-plane loads in multiple directions to generate interaction curves.

Annex B will serve as a practical guide to ensure uniformity and facilitate comparison of nonlinear finite element analysis results across participants. It describes a procedure for performing nonlinear finite element analyses of stiffened panels. The procedure includes a presentation of assumptions and simplifications made in the modelling process, as well as a detailed description of each work task necessary to perform the analyses.

Analyses are performed in two steps. First a linear eigenvalue analysis is performed in order to provide data for imperfection generation. This is used as input to a nonlinear analysis. The target of the analyses of the panel is to determine the ultimate capacity defined as the collapse load, i.e. the maximum load that the panel can carry.

Procedure Overview

This procedure describes the steps for performing nonlinear finite element analyses of stiffened panels. It includes the underlying assumptions and simplifications used in the modelling process, along with a detailed breakdown of each task required to complete the analysis. The methodology is applicable to finite element codes capable of capturing both geometric and material nonlinearities. The analysis is conducted in two main stages:

1. Linear Eigenvalue Analysis: Used to identify buckling modes and generate initial imperfections.

2. Nonlinear Collapse Analysis: Incorporates imperfections to simulate the structural response up to collapse.

The primary objective is to determine the ultimate capacity of the panel in accordance with rule-based design principles. In this context, global elastic buckling of stiffeners is not considered acceptable and must be assessed separately using eigenvalue analysis to ensure it does not occur. Consequently, the design capacity should be taken as the lesser of the capacity obtained from non-linear analysis and the global elastic buckling capacity of the stiffeners.

Model extent

To prevent the collapse of the panel to be initiated at the boundaries of the model, the model should represent three frame spans (½+1+1+½) in the direction of the stiffeners. In the transverse direction, the model should include five stiffeners, i.e. a total breadth of six stiffener spans. Transverse frames should not be explicitly modelled, but their presence must be reflected by the boundary conditions as described below.

Material properties

A bi-linear material model including strain hardening effect should be applied in the analysis. An example for a stress-strain curve is shown in Figure 1 and the material parameters to be used are:

Young's modulus, E [N/mm2]	206 000
Poisson ratio, υ	0.3
Yield stress [N/mm2]	315
Strain hardening parameter, E_T [N/mm2]	1000

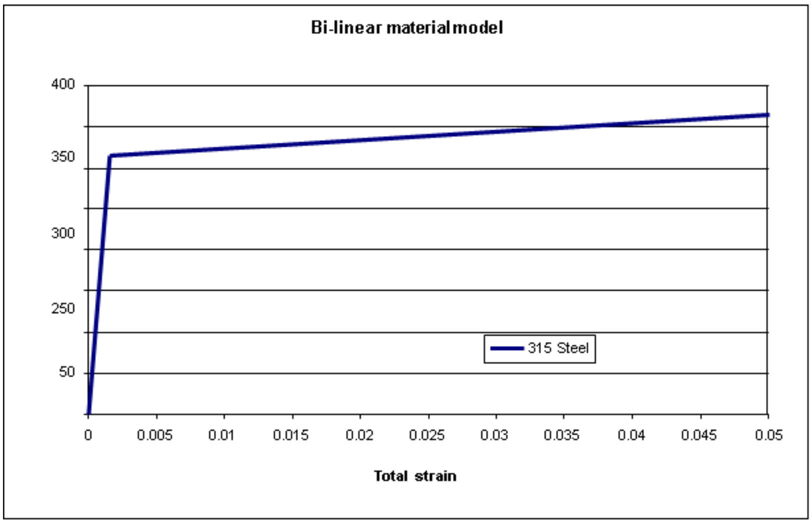

Figure 3: Bi-linear true stress-strain curve for 315 steel.

MESH

Element type

Plate, stiffeners web and flanges should all be modelled using shell elements. The analysis may be carried out using 4-node shell elements.

Mesh density

The mesh should be sufficiently fine to describe the localised deformations and stress patterns which develop during buckling. The requirements are therefore generally dependent on geometrical proportions, load combinations, and of course the type of element used.
The following mesh density should be applied:

- Plate: Six elements in the transverse directions between stiffeners. The number of elements in the axial direction should be selected so that the elements are nearly square, i.e. the typical element length for plate elements should be set to $s/6$, where s is the stiffener spacing.

- Stiffener web: Minimum four elements across the web height. The number of elements should be selected so that the elements are as close to square-shaped as possible.

- Stiffener flange: 1-2 element across the stiffener flange for angle- and bulb profiles and two elements for T profiles.

Modelling of panel using shell elements

The shell finite element models should be made in the mid-plane of plate and stiffeners as shown in Figure 4. This gives the following equivalent stiffener dimensions:

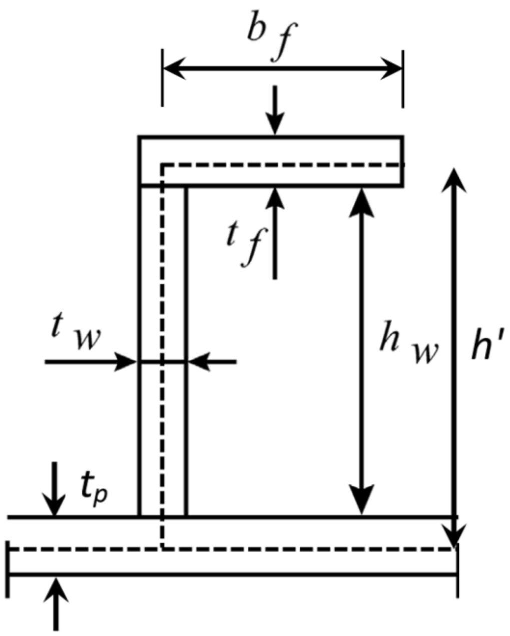

Figure 4: Equivalent stiffener dimensions using shell elements.

Boundary conditions

All edges in the model are forced to remain straight during the analysis. This is representing the support of adjacent panels in a larger structure. In a ship structure it is very likely that the neighbouring panels also will buckle and will therefore try to pull in with the same force. These forces will balance each other leaving the edge to remain straight.

Symmetry conditions are used at Edges B1 and B2 which are restrained from rotations about y- and z-axis. Edge B1 is fixed in *x*-direction and Edge B2 is free to move in this direction, but the edge is constrained to remain straight. Edges B3 and B4 are fixed in lateral direction and rotations about the *x*-axis are restrained to keep the panel from collapsing too early in one of the outermost plate fields.

At the frames (F1, F2 and F3), the plate and stiffeners are supported in vertical direction. In addition, the plate and stiffeners are free to move in-plane but sideways tripping of the stiffeners is prevented.

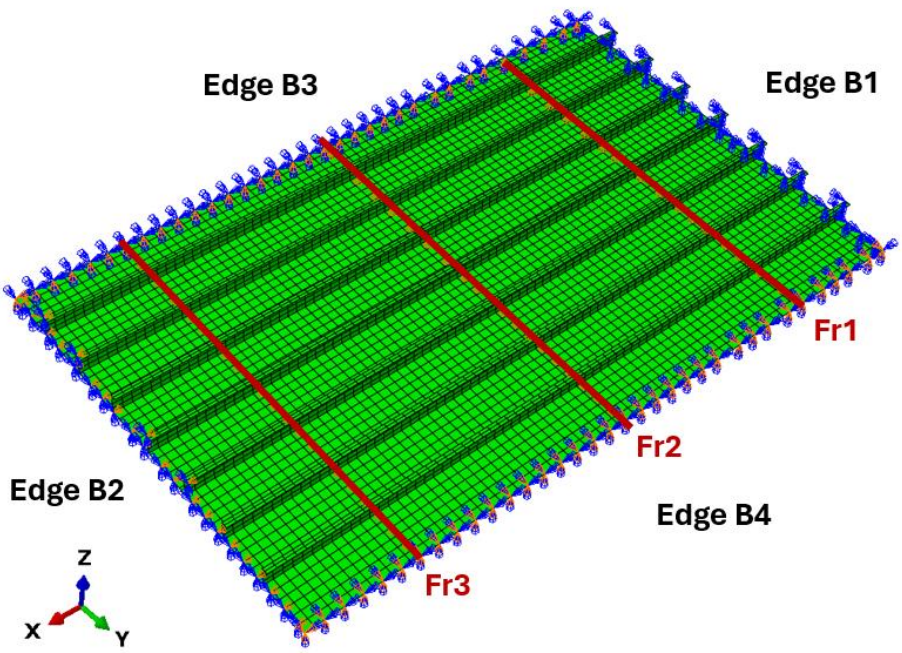

Figure 5: Boundary conditions in the panel model.

Loads and load application

In cases where the panel is loaded in a combination of in-plane loads and lateral pressure, the loads should be applied in two load steps. In the first load step the lateral pressure is incremented to the specified magnitude. In the second step, the in-plane loads are incremented proportionally with the lateral pressure kept fixed.

Imperfections

The first step of a nonlinear analysis is normally to define the shape of an initial imperfection. This is included to consider possible residual stresses and initial deformations from the fabrication of the vessel. Additionally geometrical imperfection will, in most cases be needed to trigger the nonlinear response in a stiffened panel and is normally required to be able to assess the buckling strength of the panel using nonlinear finite element method.
When an imperfection is applied, the structure may continue to deform in the prescribed shape as the loads increase. It may also snap over to a more preferred shape i.e. a shape requiring less energy (associated with less internal strain energy). Such mode snapping leads to unstable response and may give numerical instability and problems with convergence. In general, it is therefore desirable to prescribe an imperfection shape similar to the preferred (critical) collapse mode of the panel. However, it may be difficult to predict which mode requires the least amount of energy and for slender geometries this may also change throughout the deformation history.

When an imperfection is applied with a large magnitude more energy is required to change buckling mode. Thus, if the magnitude is large the structure may be forced into a non-preferred shape. A large imperfection combined with the preferred collapse mode may give unreasonably conservative prediction of the capacity. It is therefore important that the imperfection is carefully chosen both in terms of shape and amplitude. For buckling and ultimate strength analysis using nonlinear finite element method a small magnitude should be applied with a shape equal- or similar to the preferred collapse mode of the structure.

When working with imperfection modelling it is beneficial to think of the imperfection shape as being composed of a local and a global component. In this decomposition, the local component represents out of flatness of the component plates of the panel and sideways out of straightness of the stiffeners (plate between stiffeners, stiffener webs and stiffener flanges). The global imperfection refers to out of straightness of the stiffeners measured in the direction orthogonal to the panel. This is illustrated in Figure 6.

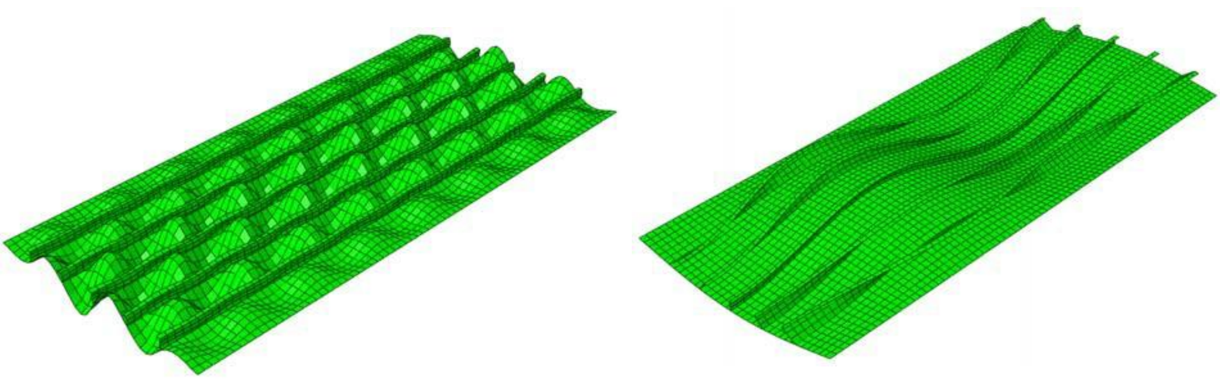

Figure 6: Example of typical local (left) and global (right) deformation modes.

Imperfections tolerances

The magnitude of the imperfections should be determined using the imperfection parameters defined in Figure 7 below. The tolerances should be as follows:

δ_{P0} = stiffener spacing / 200

δ_{S0} = stiffener length / 1000

δ_{T0} = stiffener length / 1000

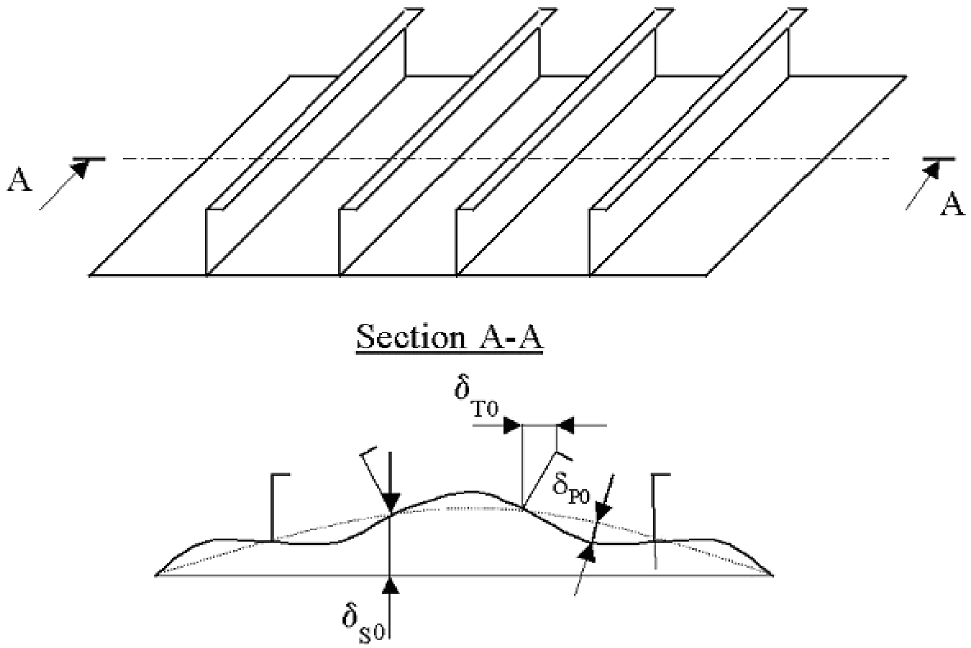

Figure 7: Definition of imperfection tolerances.

Global elastic buckling mode

In addition to conducting non-linear finite element analysis, it is essential to identify the global elastic buckling load. This is because global elastic buckling is not accepted within the rule framework. This buckling mode involves slender stiffeners deflecting in unison with the plate, compromising the structural redundancy intended by the stiffeners, which serve as a secondary barrier after plate buckling. When global elastic buckling occurs, the load must be redistributed to adjacent structural elements such as web frames and stringers. As a result, the surrounding structure must carry the additional load once the stiffened panel has buckled elastically. Therefore, in a rule-based context, the design capacity is taken as the lesser of the non-linear analysis capacity and the global elastic buckling capacity of the stiffeners. This concept is illustrated in Figure 8.

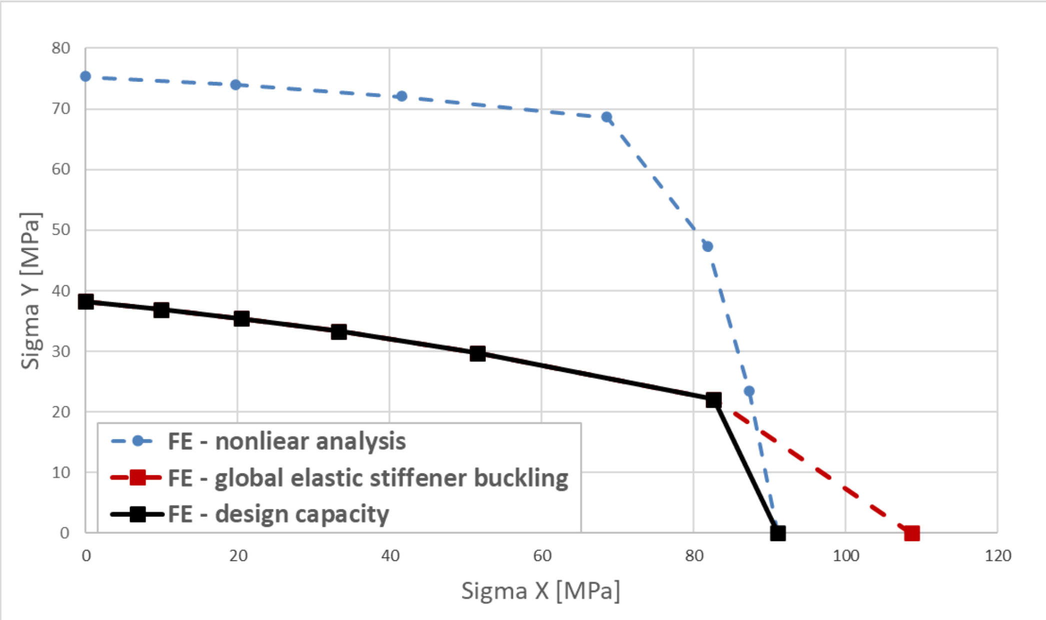

Figure 8: Interaction curves where the design capacity is taken lesser of the non-linear analysis capacity and the global elastic buckling capacity of the stiffeners.

A global elastic buckling mode is show in Figure 9. It can be mentioned that for most stiffened plates in ships and offshore structures, the stiffeners are strong enough to support the plates and global elastic buckling does not occur. For such cases, it may be difficult to identify the global elastic buckling load.

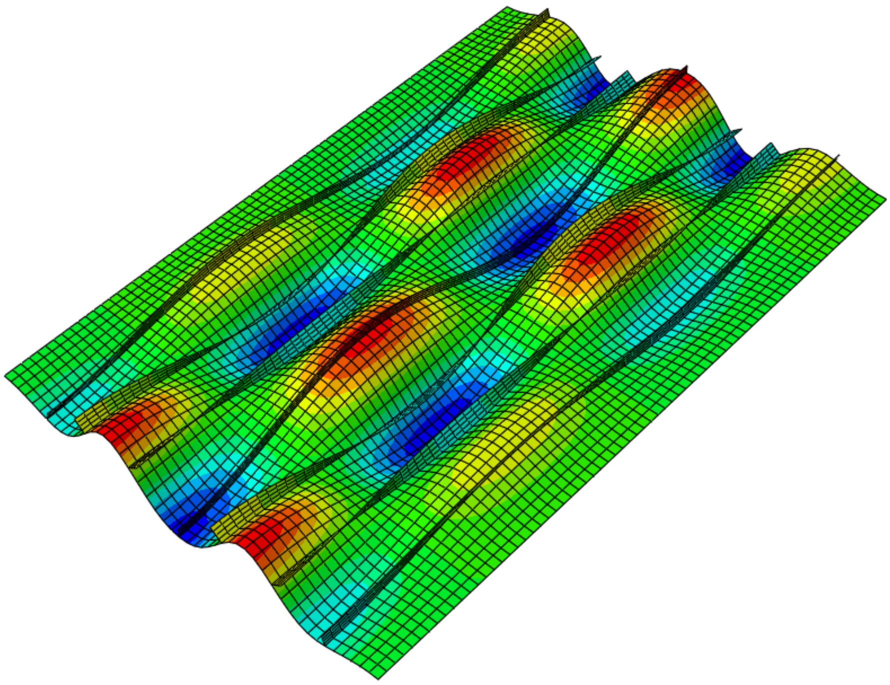

Figure 9: Global elastic buckling mode for a stiffened plate subjected to transverse loads.

Gross Yielding Criterion for Design capacity

Gross yielding in membrane stresses in one element in the stiffener flange is considered the upper limit for the design capacity. This criterion is particularly relevant for failure modes involving torsional buckling as shown in Figure 10 and global out-of-plane stiffener buckling.

In the case of torsional buckling, in-plane bending of the stiffener flange occurs. Since only two elements are used in the flange, fully integrated elements should be considered to accurately capture stress distribution and deformation behavior.

Gross yielding of the stiffener flange is not allowed in a rule context and must be avoided when determining the design capacity and should be taken as the upper limit (i.e. cut-off limit for the design capacity) as illustrated in Figure 11.

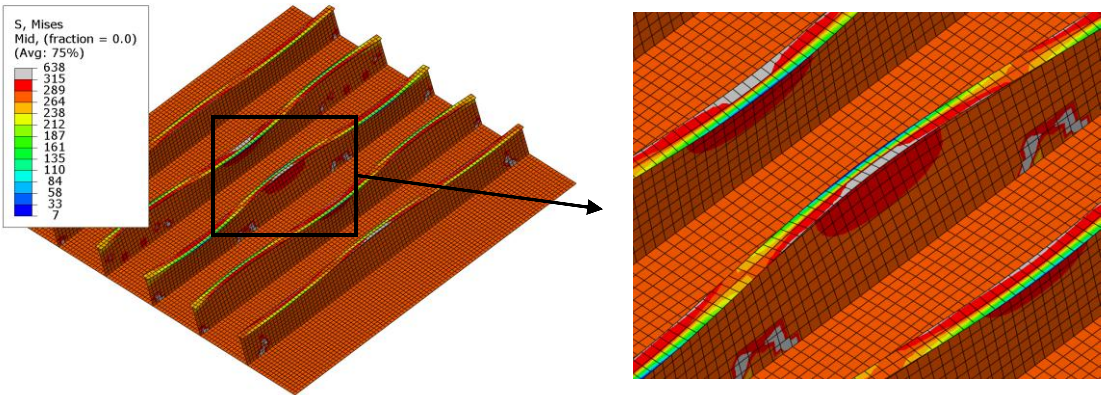

Figure 10: Gross yielding in membrane stresses in one element in the stiffener flange.

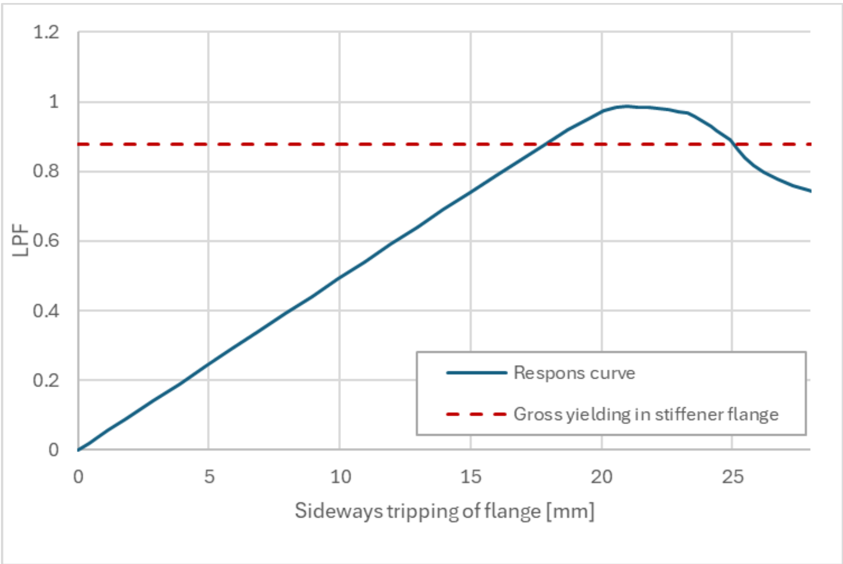

Figure 11: Gross yielding in the stiffener flange is the design capacity