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Nordic Master in Maritime Engineering

Buckling Screening Analysis of Ship Plate Structures

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Master's thesis
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Abstract

Sufficient strength of the ship's structure is a significant factor to ensure safe shipping. Thus, it is important to study the failure modes of the structure, such as buckling. However, there are limited methods to perform buckling check efficiently, and it is often still conducted manually.

The aim of the study was to create a new buckling check tool, making buckling analysis efficient and saving time for other work. This has solved by implementing a script that calculates the buckling of the unstiffened rectangular plate fields of the ship. The script is based on a screening method that is used to find critical plate fields. The criteria for the method are buckling guidelines by DNV.

The functionality of the study method was tested by a case study for a generic global model part. The analysis was performed twice with a coarse mesh by subjecting a global load combination of still water bending moment and ice shear force to the model. The buckling capacity of the plate fields was estimated by examining their transversal and longitudinal compressive and shear stress. The initial model was strengthened according to the initial results, and then the analysis was carried out again.

The main findings of the case study were the effect of the framing system selection and plate field size on buckling capacity. The location of the plate field in the ship was also found to influence the buckling resistance.

The results of the case study were validated using manual calculation and a local model. Manual calculation proved the functionality of the study method and the validity of the results. In turn, the local model analysis ensured the result accuracy with a coarse mesh and the applicability of the study method to different models. The results obtained from the case study are reasonable.

Although the development of the method is still necessary, the study method proves to be an effective and functional approach to buckling check analysis with potential for the future.

Keywords Buckling check, ship design, screening method

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Tiivistelmä

Laivan rakenteen riittävä lujuus on merkittävä tekijä turvallisen merenkulun varmistamiseksi. Siksi on tärkeää tutkia rakenteen vikatiloja, kuten lommahdusta. Tehokkaita tapoja suorittaa lommahdustarkastus on kuitenkin rajallisesti, ja se tehdään usein edelleen manuaalisesti.

Tutkimuksen tavoitteena oli luoda uusi lommahduksen tarkistustyökalu, joka tekee lommahdusanalyysista tehokkaan säästäen aikaa muuhun työhön. Tämä on ratkaistu implementoimalla skripti, joka laskee laivan jäykistämättömien suorakulmaisten levykenttien lommahduksen automaattisesti. Skripti perustuu seulontamenetelmään, jonka avulla kriittiset levykentät löydetään. Menetelmän kriteerinä toimivat DNV:n lommahdussäännöt.

Tutkimusmenetelmän toiminnallisuutta kokeiltiin tapaustutkimuksena geneeriselle globaalimalliosalle. Analyysi suoritettiin kaksi kertaa karkealla verkotuksella kohdistamalla malliin globaali tyynen veden taivutusmomentin ja jääleikkausvoiman kuormakombinaatio. Levykenttien lommahduskapasiteettia arvioitiin tarkastelemalla niiden poikittaista ja pitkittäistä puristavaa jännitystä sekä leikkausjännitystä. Alkuperäistä mallia vahvistettiin ensimmäisten tulosten perusteella, ja analyysi suoritettiin uudelleen.

Tapaustutkimuksen päähavaintoja olivat kaarijärjestelmän valinnan ja levykentän koon vaikutus lommahduskapasiteettiin. Myös levykentän sijainnilla laivassa huomattiin olevan vaikutusta lommahdusvastukseen.

Tapaustutkimuksen tulokset validoitiin manuaalisen laskennan ja lokaalimallin avulla. Manuaalinen laskenta osoitti tutkimusmenetelmän toiminnallisuuden ja tulosten pätevyyden. Lokaalimallin analysointi varmisti puolestaan tulosten tarkkuuden karkealla verkotuksella ja tutkimusmenetelmän soveltuvuuden eri malleihin. Tapaustutkimusmallista saadut tulokset ovat perusteltuja.

Vaikka metodin kehitys on edelleen tarpeen, tutkimusmenetelmä osoittautuu tehokkaaksi ja toimivaksi lähestymistavaksi lommahdustarkastelulle, jolla on potentiaalia tulevaisuuden kannalta.

Avainsanat Lommahdustarkastus, laivasuunnittelu, seulontamenetelmä

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Symbols and Abbreviations

Symbols

β	Parameter that affects method stability
γ	Parameter that affects damping properties
δ	Plate deflection surface function
η, η_x, η_y	Stability usage factor
$\sigma_a, \sigma_{ax}, \sigma_{ay}$	Calculated actual compressive stress
$\sigma_c, \sigma_{cx}, \sigma_{cy}$	Critical compressive buckling stress
τ_a	Calculated actual shear stress
τ_c	Critical shear stress
h	Time interval
k	Spring constant
n	Factor dependent on plate dimensions
q	Factor dependent on relation between actual and critical shear stresses
t	Thickness of a plate
w	Intensity of a continuously distributed load
x, y, z	Rectangular coordinates
D	Flexural rigidity of a plate
E	Modulus of elasticity
F	Stress function
I	Area moment of inertia
K	Factor dependent on plate dimensions and material properties
L	Length of a column
P	Buckling force
$[C]$	Damping matrix
$[K]$	Stiffness matrix
$[M]$	Mass matrix
$\{a\}$	Vector of accelerations
$\{u\}$	Vector of displacements
$\{v\}$	Vector of velocities
$\{F\}$	Vector of external loads

Abbreviations

ABS	American Bureau of Shipping
BV	Bureau Veritas
DNV	Det Norske Veritas
FE	Finite element
FEM	Finite element method
IACS	International Association of Classification Societies
LR	Lloyd's Register

1 Introduction

1.1 Background

Ships are essential for the effective international trade, as over 80% of it is carried out by sea (UNCTAD, 2025). In order to guarantee safe shipping, they must be carefully designed. One essential part of the design is to ensure that the ship's structures can withstand loads subjected to it. This is done by examining possible failure modes of the structure, which include yielding, fracture, and buckling.

To guarantee the structural integrity of the ship and prevent possible failures, strength assessments against failure modes must be carried out (Lamb, 2003). A detailed direct analysis that considers the actual conditions of the ship such as material properties, load cases and operational environment are often used. The analysis usually applies finite element method (FEM). (Hudghes & Paik, 2010)

Analysing the yield strength is straightforward as the global model stresses are checked against criteria (DNV, 2021a). In turn, fracture is studied by performing a fatigue analysis. Fatigue is an essential issue with long ships, such as container ships, and it need to be carefully considered during various design phases (Ringsberg, et al., 2015). The assessment should be done for all stress critical locations (Lamb, 2003). To identify these, an efficient screening method is applied in accordance with the guidelines given by the regulations (DNV, 2025).

In contrary, buckling is a general problem for all types of ships due to their thin and relatively large plates, which are prone to bend and buckle under compressive load before the material strength limit is met (Jerath, 2021). Additionally, buckling capacity needs to be reviewed on a large scale, as the analysis should be conducted individually for all structural members (DNV, 2021a).

The importance of the buckling check is emphasized nowadays, as the aim is to use high-strength materials in ships to reduce the thickness and weight of the structures. However, despite the increase in strength, the stiffness of the material remains the same. (Gaiotti, et al., 2024)

1.2 Research Problem

According to previous projects of ship design, the occurrence of buckling capacity check is inevitable (Shama, 2013). Additionally, the projects have tight schedules without flexibility. However, the buckling function of ship’s plate fields is complex and calculating them manually is time-consuming and challenging. Thus, it predisposes to errors that may appear in the calculations.

Ways to efficiently evaluate buckling capacity against classification society regulations is needed. For this purpose, the screening method seems suitable. The thesis

presents a new buckling check evaluation using this approach. It is applied to review the buckling stress results calculated by using FEM.

The purpose of the work was to implement a script for screening of buckling. The script was used to examine buckling of ship plates and find the critical areas resulted from global loads. It is an additional feature to a 3D viewer. The screening method ensures that the strength of the ship's plate fields meet the criteria of the classification society regulations. Additionally, the aim of the thesis was to find out how the used method affects the reliability and efficiency of ship buckling analysis.

1.3 Scope of Research

The methodology presented in the thesis consists of three phases. The pre-processing is done using the FEM software Ansys 2023R2 (Ansys 2023R2, 2025). For the simplicity and computational efficiency, only a global ship model part having a coarse mesh is considered in the work. Moreover, the longitudinal and transversal compressive stresses as well as shear stresses acting on plates resulted from a linear analysis of global ship loads are studied. Thus, lateral pressure and tension criteria were not analysed. Further, the creation of the global model or the definition of the global loads and load combinations were not in the scope of the thesis.

The focus of the work was on the in-processing phase, where the application of the screening method and new procedure takes place. The use of screening method is limited as it is used to investigate user selected plate fields, such as a deck or a bulkhead, from a global ship model part. Additionally, the method is applied only to identify locations of the selected plate structures which do not comply with the regulations. Thus, local models of the critical structures are done only for validation purposes. Not accepted structural solutions revealed by screening method are modified directly in the global ship model and rechecked using the method.

The post-processing phase includes the result visualization in an in-house 3D viewer, which development was not in the scope of the thesis. The study does not provide a solution on how the buckling capacity of the plate fields would meet the criterion, but only presents the current state. Thus, it does not take a stand for example on structural weight changes, and the analysis on this must be carried out by the user.

Research focused on buckling of the ship structures, and it is the only failure mode considered in the thesis. Further, the study was limited only to elastic buckling of plate fields. Only rectangular, planar and unstiffened plates without cutouts were considered. Defined plate type is illustrated in Figure 1.

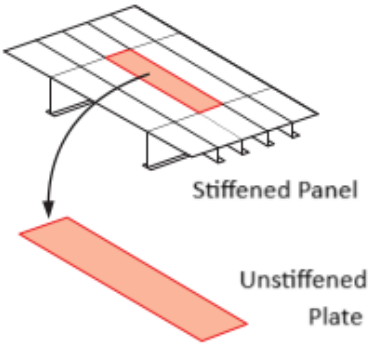

Figure 1. Plate type considered in the work (Zhang, 2016).

Buckling calculation of the plate fields in the thesis is based on elasticity theory. Its basic principle is the relation between displacement and stresses. However, buckling capacity in the study was measured according to classification society, DNV, regulations. The standard applies for ships with length of 100 metres or above. (DNV, 2016a)

First, the relevant background for the study related to the buckling, applied methods and ship global loads are discussed in the thesis. The methodology is presented, which is then applied to a case study. The results of the case study are validated, analysed and discussed. Finally, conclusions of the thesis are made.

2 State of Art

This Chapter covers the basic concept of buckling of the ship plates and introduces its history and regulations. Additionally, the development of FE analysis and the possibilities of applying the screening method are discussed. Lastly, the ship global loads are shortly presented.

2.1 Buckling of Ship Plates

The plates between the stiffeners examined in this study encounter a wide range of loads during the ship's life cycle. When a critical value is reached, structure under thrust bends and the structural stability is lost (Yao & Fujikubo, 2016). This event is called buckling. Example of a buckled plate structure is presented in Figure 2.

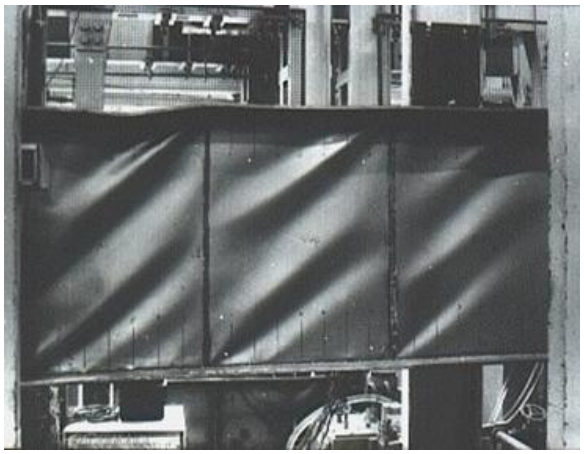

Figure 2. Buckled plate structure (ESDEP, 2010a).

The load type affects the behaviour of the plate, which can be as shown in Figure 3. In Figure 3a, an in-plane compressive load is mainly acting on the plate. In turn, the plate in Figure 3b is loaded with shear force, which results into more complex deformation. In addition to these, it can be affected by lateral pressure (Lamb, 2003). However, it was not considered in the study, as lateral pressure is used to estimate plate yielding (DNV, 2010).

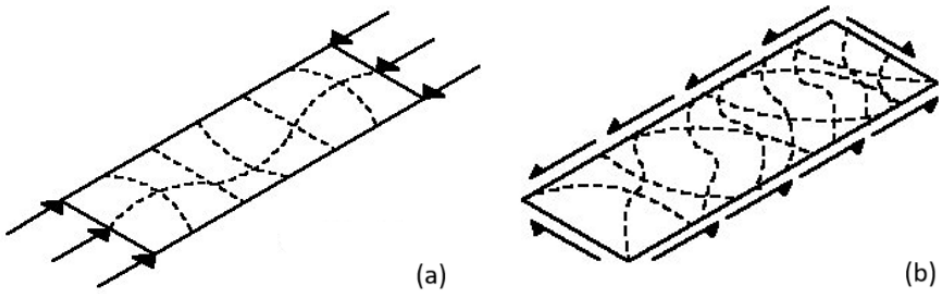

Figure 3. Buckling behaviour resulted from (a) in-plane compressive stress (b) shear stress (ESDEP, 2010b).

The buckling magnitude depends, for example, on the loading of the plate structure (Kubiak, 2013). Thus, it is important to know all the possible loads subjected to it (Yao & Fujikubo, 2016). However, the plate thickness in respect to other dimensions, i.e. the slenderness ratio, is the main factor affecting on the magnitude (Timoshenko & Woinowsky-Krieger, 1959).

The slenderness also affects the type of buckling. For thick plates, the material yield limit is reached before buckling occurs resulting into irreversible deformation meaning that the buckling is plastic. The buckling of thin plates, such as ship plates, occurs before yielding, and the event is called elastic buckling. (Betten & Shin, 2000) If the loading continues, the material strength limit is met, and the buckling becomes plastic. This limit is the ultimate strength of the plate (Lamb, 2003). Thus, it is not in the scope of the buckling study.

The structural stability of the plate can be maintained even though elastic buckling occurs (Lamb, 2003). Occurrence of elastic buckling is also accepted according to the regulations within the limits, as it is proven to be non-critical (DNV, 2010). Buckling regulations are discussed more in Chapter 2.1.2.

2.1.1 Historical Background

The strength of iron ships has been investigated since the mid-1800s, but the first studies based on post buckling of ship structures date back to the early 1900s, when Schnadel developed a solution to consider the buckling of the hull structures (Lehmann, 2014). In general, however, the history of buckling research dates back as early as the mid-1700s to Euler's (1744) theoretical solution of the column subjected to compressive load. The formulation based on the solution he later formed is still applied (Oldfather, et al., 1933) (Euler, 1759):

$$P = \pi^2 \frac{Ek^2}{L^2} \leftrightarrow P = \pi^2 \frac{EI}{L^2}, \qquad [1]$$

where

k = Spring constant,
P = Buckling force,
L = Length of a column,
E = Modulus of elasticity and
I = Area moment of inertia.

The ship structures can be considered to be primarily rectangular plates supported by primary members such as webs and girders, and secondary stiffeners reducing buckling. Thus, the history of the buckling theory of ship plates is strongly linked to the development of plate buckling study in general (Bleich, 1952). The first study on it was published by Bryan (1890), who analysed a simply supported rectangular plate under a compressive load. He applied Kirchhoff's (1850) elasticity theory of the energy method (Bleich, 1952).

The ship structural plates are relatively thin, which means that their thickness in respect to width is small and thus slenderness ratio is high. This affects the failure limit or ultimate strength of the structure, and it is greater than the buckling limit. The investigation of ultimate strength brings a new problem to the buckling behaviour study, as it cannot be examined according to linear strength theory. The nonlinear differential equations describing the relation between stresses and displacement were implemented in the early 1900s by studying the large deflection of a thin plate. The theory was first developed by Föppl and later expanded by Von Kármán. (Bleich, 1952) The following nonlinear differential equations were formed (Timoshenko & Woinowsky-Krieger, 1959):

$$\frac{\partial^4 F}{\partial x^4} + 2\frac{\partial^4 F}{\partial x^2 y^2} + \frac{\partial^4 F}{\partial y^4} = E\left[\left(\frac{\partial^2 \delta}{\partial x \partial y}\right)^2 - \frac{\partial^2 \delta}{\partial x^2}\frac{\partial^2 \delta}{\partial y^2}\right] \text{ and}$$

$$\frac{\partial^4 \delta}{\partial x^4} + 2\frac{\partial^4 \delta}{\partial x^2 y^2} + \frac{\partial^4 \delta}{\partial y^4} = \frac{t}{D}\left(\frac{w}{t} + \frac{\partial^2 F}{\partial y^2}\frac{\partial^2 \delta}{\partial x^2} + \frac{\partial^2 F}{\partial x^2}\frac{\partial^2 \delta}{\partial y^2} - 2\frac{\partial^2 F}{\partial x \partial y}\frac{\partial^2 \delta}{\partial x \partial y}\right), \quad [2]$$

where

t	=	Thickness of a plate,
w	=	Intensity of a continuously distributed load,
x, y, z	=	Rectangular coordinates,
δ	=	Plate deflection surface function,
D	=	Flexural rigidity of a plate,
E	=	Modulus of elasticity and
F	=	Stress function.

The nonlinear equations have been applied to several methods. For example, a study by Von Kármán (1932) uses the energy method based on it, presenting the concept of effective width. Levy (1942), in turn, solves Von Kármán equations by using the Fourier series for representing deflections and normal pressures for a rectangular plate subjected to a combined compression and lateral edge load. Also, in experiment by Stein (1959), the unknown functional fields are expanded in a power series to simplify Von Kármán equations to infinite linear equations.

The theory of plates with large deflection was further developed by Timosheko, who defined the strain energy of the plate (Bleich, 1952). The publications by Timosheko and Woinowsky-Krieger (1959) and Timosheko and Gere (1961) generally present approximations for analysing the buckling of several structures under variable loads and boundary conditions.

Initially, buckling behaviour was studied mainly against static loads. In reality, however, the loads are dynamic. (Kubiak, 2013) Dynamic loads subjected on the ship, such as wave-induced hydrodynamic loads and slamming, have a significant impact on the strength. Therefore, considering them in buckling analysis is important. The first and significant dynamic buckling studies on plates have been carried out, for example, by Budiansky (1966) and Hutchinson and Budiansky (1966), who present

a critical value for a dynamic load. In the latter, the imperfection of the structure has also been considered (Hutchinson & Budiansky, 1966).

The ship hull is subjected to a normal pressure under longitudinal compression. Therefore, longitudinal strength and hull girders are important factors in the ship ultimate strength study. Their failure can cause total collapse of the ship, which is dangerous to people and the environment (Zhang, 2016). One of the first papers of this presents a study performed by Caldwell (1965) of a simplified calculation of the ultimate bending moments in the midship cross-section. However, only static loading was considered in the analysis. The ultimate longitudinal strength evaluation of the entire ship, considering also the dynamic loads, were first carried out by Smith (1977) and Dow et.al. (1981) using the incremental finite element method.

2.1.2 Regulations Overview

For the design, construction and maintenance of a ship to be consistent, certain criteria are defined for the ship (Lamb, 2003). The criteria are defined by flag state and international requirements, ship owner requirements and classification societies. Classification societies are the marine industry's own regulations that ensure the safety and operability of the ships. (Hirdaris, 2021) Therefore, each ship must be certified according to one classification society (Lamb, 2003).

The buckling assessment requirements of different classification societies include the same basic principles. According to them, buckling check should be performed for different structural elements: plates, stiffeners, primary supporting members and other structures (DNV, 2024). There are specific general calculation methods for each structural member.

In the regulations, the plate buckling check is based on a buckling criterion that the structure strength must fulfil. It is presented by the utilization factor, which purpose is to compare the actual with the allowable buckling. The magnitude of the allowable limit depends on the structural member type and location as well as the load scenario. The actual buckling of plates, however, is achieved with the calculation of interaction functions. (IACS, 2024) The function formulation depends on the primary loads subjected on the plate, which are shown in Figure 4.

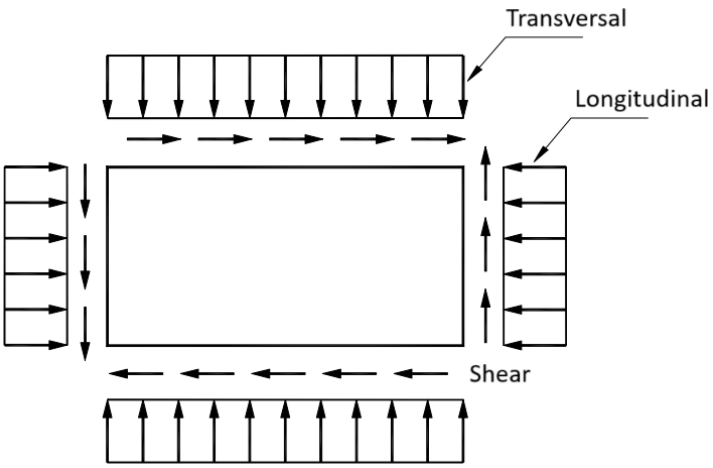

Figure 4. Primary loads on a plate (DNV, 2010).

The interaction functions are also affected by material properties and geometry depending ultimate buckling stresses, and applied stresses. In plate buckling criterion calculation, the type of plate, as illustrated in Figure 5, and model boundary conditions must also be considered. The location of the structure in the ship defines which regulations of the plate type and boundary conditions must be applied. (IACS, 2024) The study focused on the plates between the stiffeners.

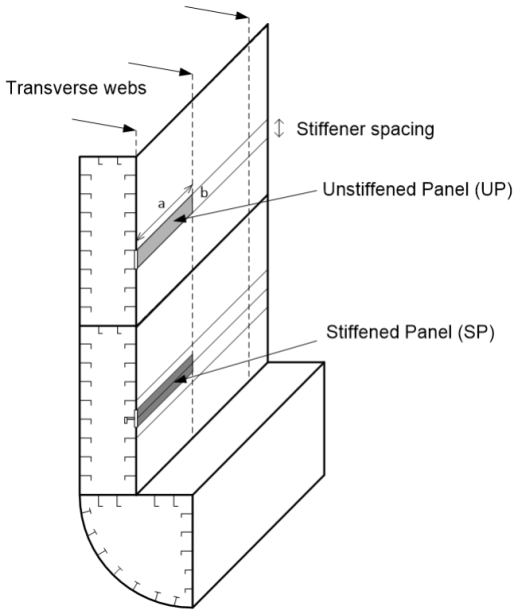

Figure 5. Stiffened panel and unstiffened plate panel (Lloyd's Register, 2021a).

When performing buckling check of the plates, it is important to ensure sufficient thickness. Some of the regulations define a slenderness requirement that specifies the minimum thickness of the plate (DNV, 2024). However, in some rules, the problem has been solved by defining a slenderness ratio, which depends on the material properties and dimensions (ABS, 2018). If the ratio is too small, the buckling

criterion is not met. In addition, the average thickness of the plate elements may be used if the plate field thickness is not constant (DNV, 2024).

General analysis methods for plates apply only to rectangular planar plates. Therefore, the rules define specific procedures for example for curved plates and plates with holes. In addition, there are rules for certain ship types. However, these were not considered in this work. Regulations applied in the study are presented more in detail in Chapter 3.2.1.

2.2 Finite Element Analysis

Finite element method (FEM) is a numerical approach which is used to study structural strength of systems (Cook, et al., 1989). The development of the method has offered the possibility to solve even challenging problems precisely, as it can solve material and geometric nonlinearities and calculate several algebraic equations simultaneously, which cannot be evaluated by classical analysis methods with sufficient accuracy (Cook, et al., 1989).

The basic principle of FEM is to analyse the model under consideration by dividing it into smaller elements and their connection points are nodes. These together form a model entity called mesh. (Kurowski, 2004) Example mesh of a plate model is illustrated in Figure 6.

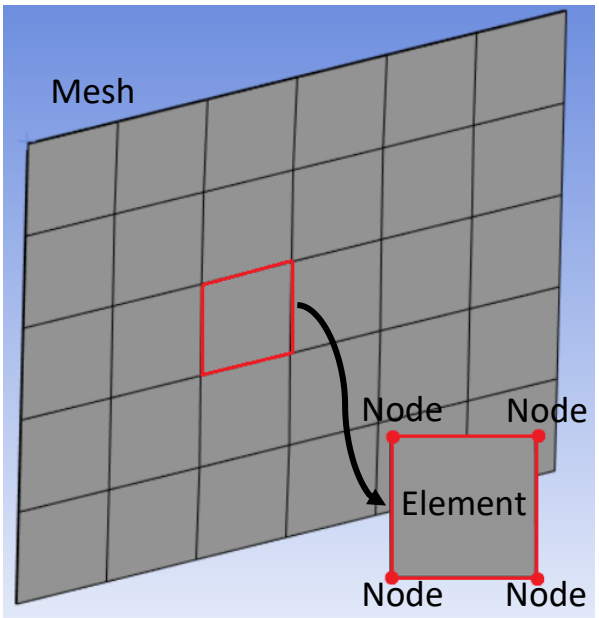

Figure 6. Mesh of a plate model.

2.2.1 Historical Background

The concept of FE analysis dates back to the mid-1800s, when Schellbach (1851) presented the surface of an area inside a closed curve in space as smaller elements (Sabat & Kundu, 2021). However, actual development of the method did not begin until the 1900s, when one of the pioneers, Hrennikoff (1941), studied the problem of plate bending and plane elasticity. He suggests dividing the structure into elements using a lattice analogy (Hrennikoff, 1941). FEM still used today was first introduced in the publication by Courant (1943), who proposes to discretize the structure into triangular elements. Already then, the theory has been based on the matrix method of structural analysis (Kubiak, 2013).

The first paper on the application of FEM was published in 1956, when Turner et.al. studied the stiffness of a simple truss, a flat plate and a box beam. A derivation of the static analysis foundation based on Hooke's law is also presented in their paper according to which the nodal displacements are to be determined. (Turner, et al., 1956) Displacements depend on the force boundary conditions, which are expressed by the load vector, as well as the geometry of the model, material properties and the boundary conditions of displacement, which are expressed by the stiffness matrix (Kurowski, 2004):

$$\{F\} = [K]\{u\}, \qquad [3]$$

where
$\{F\}$ = Vector of external loads,
$[K]$ = Stiffness matrix and
$\{u\}$ = Vector of displacements.

In 1960, the method was named *finite element method* and the first FEM-based computer programs, such as Ansys, were founded (Cook, et al., 1989). Research on the method increased and many approaches were implemented. One of the most used approaches in dynamic analysis, presented in a paper on structural dynamics by Newmark (1959), was also developed. Newmark method can be applied to both linear elastic and plastic analysis. It is used to evaluate the relationship between force and displacement. (Newmark, 1959) The method is based on the following equations with a time step $n + 1$ (Newmark, 1959) (Bajer & Dyniewicz, 2012):

$$\{v\}_{n+1} = \{v\}_n + (1-\gamma)\{a\}_n h + \gamma\{a\}_{n+1} h,$$
$$\{u\}_{n+1} = \{u\}_n + \{v\}_n h + \left(\frac{1}{2} - \beta\right)\{a\}_n h^2 + \beta\{a\}_{n+1} h^2 \text{ and}$$
$$\{F\}_{n+1} = [M]\{a\}_{n+1} + [C]\{v\}_{n+1} + [K]\{u\}_{n+1}, \qquad [4]$$

where
$\{F\}$ = Vector of external loads,
$[K]$ = Stiffness matrix,
$[C]$ = Damping matrix,
$[M]$ = Mass matrix,

$\{u\}$ = Vector of displacements,
$\{v\}$ = Vector of velocities,
$\{a\}$ = Vector of accelerations,
γ = Parameter that affects damping properties,
β = Parameter that affects method stability and
h = Time interval.

2.2.2 FEM in Buckling Analysis

In the late 1900s, FEM started to be applied to the study of buckling behaviour (Kubiak, 2013). The first considerations of FEM implementation to the plate buckling are presented in paper by Kapur and Hartz (1966). In their study, the plate buckling in various load cases is examined, and the stability coefficient and stiffness matrices are used together (Kapur & Hartz, 1966).

First, the application of FEM to the plate buckling only considered the unstiffened plates. The first study on the buckling of stiffened plates is presented in paper by Dawe (1969), who examined the plates under membrane loading. Also, Shastry et.al. (1976) researched the topic. They performed a high precision FE analysis on stiffened plates under arbitrary membrane loading (Shastry, et al., 1976). In turn, Mukhopadhyay and Mukherjee (1990) investigated the use of an isoparametric bending element of stiffened plates for buckling analysis.

Nowadays, FEM is one of the most significant tools for buckling behaviour analysing. The buckling assessment results obtained using FEM have been compared with other methods in several publications, such as in papers by Paik et.al. (2008) and Özgüç (2020). They have proved the accuracy of FEM. The method is also considered in the classification society rules, and specific procedures have been developed for it (DNV, 2021b).

In the study, FEM is applied by using Ansys 2023R2 for the buckling check analysis. Ansys is a versatile software as it can be applied for many purposes, such as design and product development. Multiple analyses can be performed using Ansys, including structural, thermal and modal analysis. (Ansys 2023R2, 2025) Calculation procedure of the software is based on Newmark method (Kubiak, 2013). The use of FEM in the study is discussed more in Chapter 3.1.

2.3 Screening Method

A screening method is a systematic process, which is used to identify items that meet specific criterion from a large dataset. It is a method used in different research in most scientific fields. It is also used in ship design and regulations related to its application can be found in various classification society guidelines. In ship design, the screening method is mainly applied for fatigue assessment of the structures.

According to BV, the screening approach can used to identify hotspot stresses. Based on the method results, more detailed analysis is needed for found hotspot stress

regions. (BV, 2020) ABS also recommends applying the method to recognize fatigue-sensitive areas from a simple coarse FE model that needs refined analysis in sensitive areas (ABS, 2020).

LR applies the screening method not only to fatigue assessment, but also to sloshing analysis, which evaluates probable fluid motion locations (Lloyd's Register, 2022). In turn, IACS utilizes the screening method to calculate the strength of structural details (IACS, 2024). These are structural discontinuity points, where peak stresses often occur.

DNV determines the need for a fine mesh analysis of the structure based on the results of the screening analysis in the global model fatigue assessment. However, according to DNV, the screening method can also be applied to a partial ship model and thus is suitable for local structural strength analysis and fine mesh analysis. (DNV, 2021b) DNV has also considered using the screening method to detect global buckles of submarine pipelines (DNV, 2021c). Apart from that, the screening method is not yet used for buckling assessment in the rules.

The reason for not using screening method for buckling assessment is due to lack of sufficient tools and the expensive licences. Also, the global FEM models are not required for all ships by the classification societies (DNV, 2016a). Thus, the screening for buckling is not mandatory. Regulations rely on scantling calculations, which include structural design and buckling requirements (Gaspar, et al., 2011). However, they do not cover the discontinuities of structures or structural arrangement in details (Drężek & Augustyniak, 2024). Thus, some critical areas might be left uncovered and may cause buckling issues during ship operation.

However, the use of the screening method for buckling analysis has been studied earlier. For example, Tõns (2009) presents a procedure that analyses rectangular flat plates without holes between stiffeners. The procedure includes both the calculation of a larger model for finding critical areas and the calculation of a more detailed model of these areas. (Tõns, 2009) Blackwell (2022) applies the screening method to buckling check but only to analyse the global FE model. The ship weight according to the results is also estimated in her work (Blackwell, 2022).

2.4 Ship Global Loads

To assess the longitudinal strength of the ship, global loads should be defined. Global loads include bending moments and shear forces (DNV, 2016a). They are calculated based on the sum of the upward force caused by the water, the buoyancy, and the weight distribution along the ship length (Shama, 2013). The sum forms load distribution along the ship length and it varies depending on the considered loading condition (DNV, 2016a).

The shear force is obtained by integrating the load distribution over the length. In turn, bending moment is an integral of calculated shear force over the length. (Shama, 2013) Thus, the maximum bending moment occurs when shear force is zero,

which takes place around midship. Maximum shear forces occur in the between of amidship and ends of the ship. (Hirdaris, 2021) General behaviour of the shear force and bending moment along the ship length is presented in Figure 7.

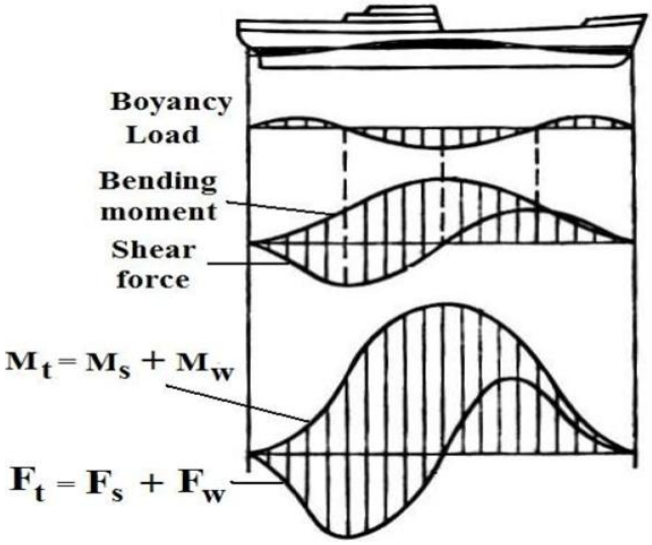

Figure 7. Bending moment and shear force behaviour along the ship length (Shama, 2013).

The total global loads consist of static still water loads M_s and F_s and dynamic wave loads M_w and F_w as indicated in Figure 7. They should be analysed in two conditions: hogging and sagging. (DNV, 2016a) Hogging describes the condition where the wave crest occurs in amidship and thus bends the midship section upwards as shown in Figure 8. Sagging, in turn, occurs when the wave crest is in both ends of the ship bending the midship section downwards as illustrated in Figure 8. (Shama, 2013) Sagging results into negative bending moments whereas hogging into positive values.

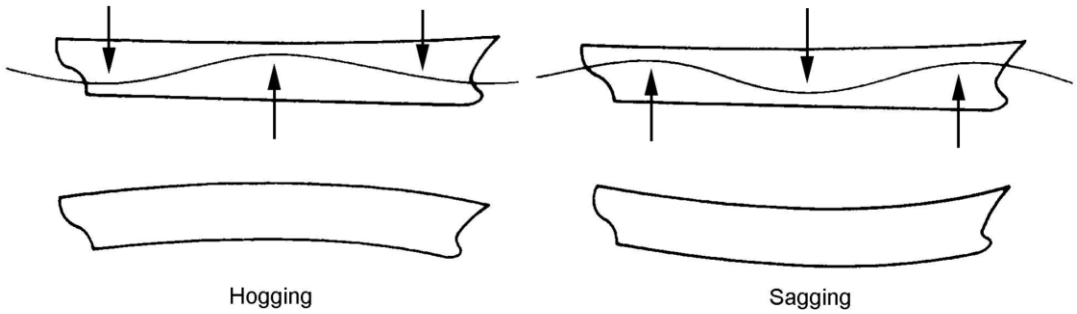

Figure 8. Behaviour of a ship in hogging and sagging condition (Fagerberg, 2003).

Loading conditions are defined individually to each ship but classification societies might also require calculating some loading cases (DNV, 2016a). Additionally, if the ship has an icebreaking capability, the loads due ice, such as ramming, must also be considered (DNV, 2016b).

3 Methodology

The work procedure is presented in the diagram in Figure 9, in which the different steps of the in-processing procedure are numbered. The starting point of the study is an analysis performed by FEM software Ansys. The stress results obtained from the software are analysed by an implemented script, which screens through the results. The script compares the obtained buckling stresses with the allowable criterion based to DNV (DNV, 2016a). According to the script results, 3D viewer highlights the locations of the structures which stresses exceed the allowable limit.

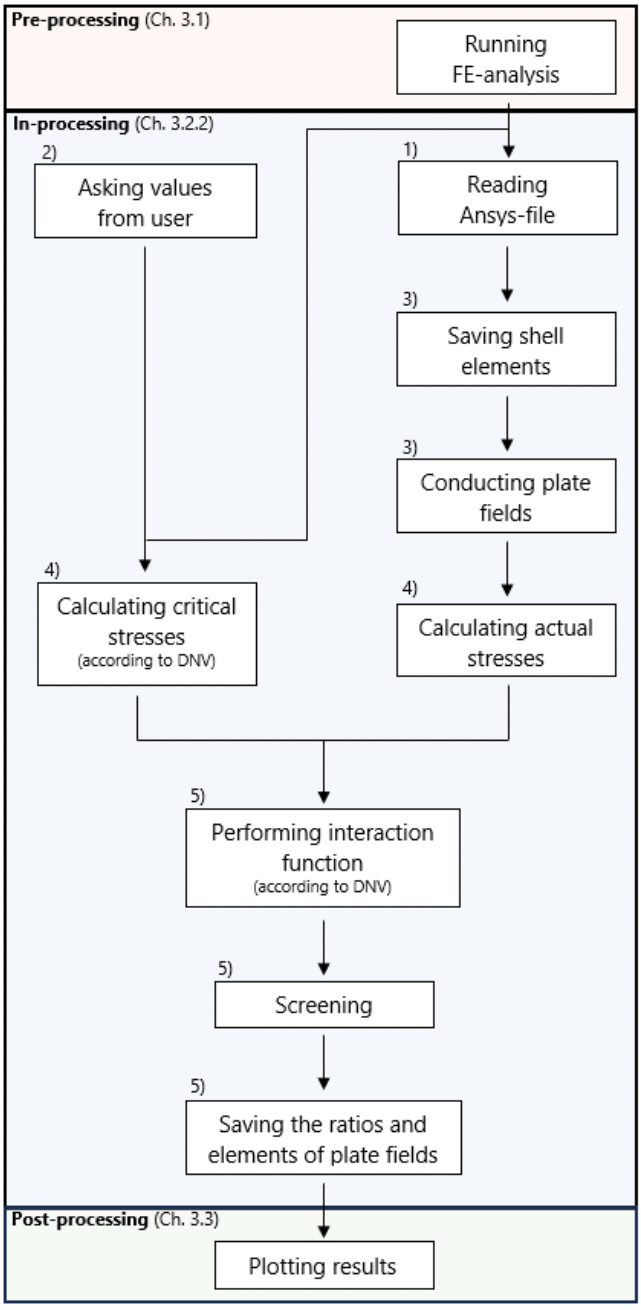

Figure 9. The steps of the study method.

3.1 Pre-Processing

FE analysis can be considered as the pre-processing phase of the study, as illustrated in Figure 9. The method has generic aspects to be considered each time it is applied. However, the study also has certain prerequisites that should be accomplished when performing the analysis.

3.1.1 Model Creation

In order to ensure accurate results in the method application, a suitable model creation as well as element type and boundary condition selection should be considered carefully. Classification societies have requirements for defining the element types. For example, DNV specifies that the plates, such as decks and bulkheads, and the girders and transverse webs should be shell elements in the global analysis. Stiffeners and girder flanges, in turn, should be modelled as beam elements. (DNV, 2021b)

Discretization of the structure should also be observed (Kubiak, 2013). Mesh should be fine enough to achieve accurate results, but finer mesh increases the computational time. After a certain point, a finer mesh may not give more accurate results, but only reduces the efficiency of the analysis. However, finer mesh might be created in certain areas of the model, such as around openings and stress concentrations, as shown in example in Figure 10.

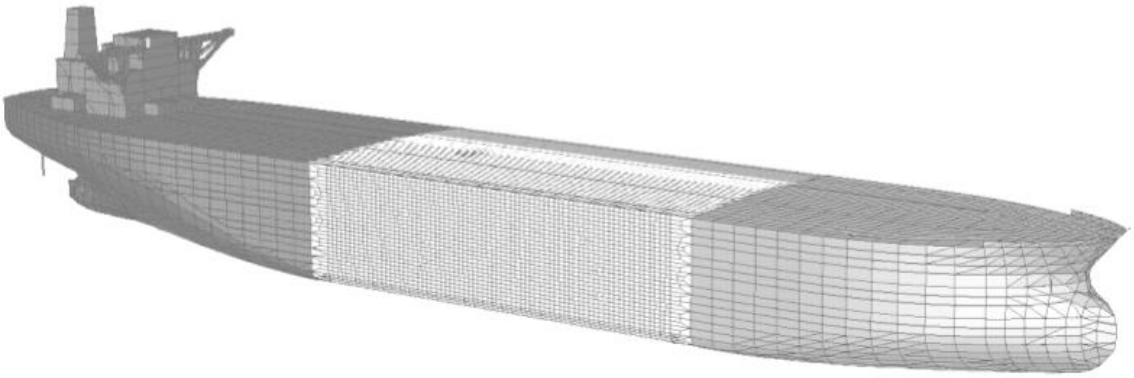

Figure 10. Global model of an example ship with finer mesh in midship region (DNV, 2021b).

When forming a mesh, it is important to ensure that the different bodies of the model are connected to each other as desired. Meshing forms nodes and elements with unique identifiers. With these, the location of the model in the global coordinate system is known, which also simplifies modifications to the model.

Suitable boundary conditions must be defined separately in each case. They should be relatively simple, and they should mainly prevent the rigid body motions. Further, fixation points should be located far from the region of interest so they would not affect the results. Commonly, boundary conditions are placed close to both ends of the ship on the centre line. (DNV, 2021b)

3.1.2 Prerequisites

In order to carry out the process successfully, there are certain prerequisites in running the FE analysis. Firstly, as discussed more detailed in Chapter 3.2.2, the method is only applicable to rectangular planar plates. Thus, the analysis should only be done for the global ship model part, where the interest is in such parts.

3D model should be done according to general arrangement, tank capacity plan and pre-defined scantlings. Thus, the designed material, beam types and plate thicknesses should be used. It should be noted that corrosion deduction is not considered in the script. Thus, the thicknesses of the model plates should be defined with net values, as DNV requires considering the corrosion deduction for the FE analysis when performing buckling check (DNV, 2021b).

When analysing a ship or its parts, the mesh should be defined to have rectangular elements (DNV, 2021a). This is also desired for the script as discussed in Chapter 3.2.3. Therefore, meshing type should be set as quadrilaterals.

When defining the boundary conditions of a ship model, it must be considered that the stress results obtained in their vicinity are not necessarily accurate due to differences in mesh sizes and interpolated nodal values from the global model to a local model. Thus, if the user can estimate critical point locations before running the analysis, the boundary conditions should be placed relatively far from them.

In the study, a global ship model part is subjected to global loads, such as still water and wave bending moments. In Ansys, the displacements resulted from these must be inserted in the analysis of the ship model part under consideration from the global model analysis. Different load combinations can be defined by the user. The script assumes that each time step has one user-defined global load.

Buckling behaviour in longitudinal and transversal direction as well as buckling resulted from shear stress are investigated in the study. The actual stresses are not needed to be calculated in the FE analysis, as it is done in the script. However, the mesh, boundary conditions and loading must be defined in the analysis.

3.2 In-Processing

As shown in Figure 9, once the FE analysis in Ansys has been completed, the actual in-processing starts. The stress results are calculated based on the FE analysis specifications, and they are compared to the allowable buckling stresses according to the regulations. This is accomplished with a script that reviews the stress distribution of each structural plate of the ship or a selected region of the ship.

Ansys and Python have created libraries that can be used to process Ansys data in Python interface. Utilizing the tools in the libraries, the script for buckling analysis is developed using Python. (PyAnsys, 2025) This ensures the compatibility between

the script and FE analysis. The script development is done using Python version 3.11 (Python, 2025).

The script consists of several steps as shown in Figure 9. Buckling check regulations applied in the script are introduced in the following. Then, the script procedure is discussed and related assumptions and simplifications are explained.

3.2.1 Buckling Check Regulations

In the study, buckling check regulations have been incorporated into the in-processing phase to ensure that the buckling critical areas are detected. The application steps of the rules are indicated in Figure 9 and presented in Chapter 3.2.2. The buckling check is performed by applying DNV regulations. Despite the most recent rules, the study applies DNV Pt.3 Ch.1 (2016a) procedures to conduct buckling check. The practice has still remained the same in different rule versions.

The study focuses on calculating the buckling of the ship plates. This is done by analysing the plate fields between the stiffeners. They can be subjected to uniaxial or biaxial compressive stress either without or combined with shear stress (DNV, 2016a). The buckling check of a plate field under a uniaxial load is based on the ratio of the calculated actual compressive stress σ_a or shear stress τ_a to the critical stress σ_c or τ_c (DNV, 2016a):

$$\eta \geq \frac{\sigma_a}{\sigma_c} \text{ or } \eta \geq \frac{\tau_a}{\tau_c}, \quad [5]$$

where actual stresses are obtained according to the initial conditions defined in FE analysis. The stability usage factor η depends on the location, such as side or bottom plating, or load level of the considered plate. The usage factor is generally defined to be less than 1 (DNV, 2016a). Thus, it also acts as a safety factor, ensuring that the actual stress is less than the critical stress.

The buckling check of a plate field under biaxial compression, however, is evaluated by the interaction between the longitudinal and transversal buckling strength. The interaction function mentioned in Figure 9 refers to the following (DNV, 2016a):

$$\frac{\sigma_{ax}}{\eta_x \sigma_{cx}} - K\frac{\sigma_{ax}\sigma_{ay}}{\eta_x \eta_y \sigma_{cx}\sigma_{cy}} + \left(\frac{\sigma_{ay}}{\eta_y \sigma_{cy}}\right)^n \leq 1. \quad [6]$$

In turn, the buckling check of a plate field under the combined load of biaxial compression and shear force is calculated by interaction between biaxial compression and shear stress. The interaction function mentioned in Figure 9 refers to the following (DNV, 2016a):

$$\frac{\sigma_{ax}}{\eta_x \sigma_{cx} q} - K\frac{\sigma_{ax}\sigma_{ay}}{\eta_x \eta_y \sigma_{cx}\sigma_{cy} q} + \left(\frac{\sigma_{ay}}{\eta_y \sigma_{cy} q}\right)^n \leq 1,$$

[7]

where $\eta_x = \eta_y = 1.0$ when considering global loads. K depends on the material properties, the thickness and size of the plate field and the ratio between the plate field side lengths. The ratio also affects to factor n. In turn, q depends on calculated actual shear stress τ_a and critical shear stress τ_c. Critical buckling stress depends on the ratio between ideal compressive strength σ_{el} and minimum upper yield stress σ_f or the ratio between ideal shear strength τ_{el} and yield stress in shear τ_f as follows (DNV, 2016a):

$$\begin{aligned}
&\sigma_c = \sigma_{el} && when\ \sigma_{el} < \frac{\sigma_f}{2},\\
&\sigma_c = \sigma_f\left(1 - \frac{\sigma_f}{4\sigma_{el}}\right) && when\ \sigma_{el} > \frac{\sigma_f}{2},\\
&\tau_c = \tau_{el} && when\ \tau_{el} < \frac{\tau_f}{2}\ and\\
&\tau_c = \tau_f\left(1 - \frac{\tau_f}{4\tau_{el}}\right) && when\ \tau_{el} > \frac{\tau_f}{2}.
\end{aligned}$$

[8]

The ideal elastic buckling stresses σ_{el} and τ_{el} is influenced by the size and the stress distribution of the plate field under consideration, the type and orientation of the stiffeners, the corrosion addition and the elastic modulus of the material. (DNV, 2016a)

The application of the rules in the script is presented in Chapter 3.2.2. It should be noted that the presented rules apply only to plates within the scope of the work. For more complex plate structures and other structures, separate regulations are defined that must be applied to them.

3.2.2 Procedure

1) Reading the FE analysis file

An important starting point for the script is to define the model under consideration, which is done by reading a file obtained from the pre-processing phase discussed in Chapter 3.1. The file provides element and node information generated in the meshing, which allows the script to form a corresponding model as in Ansys. Mesh metadata is used to obtain element ids, types, surface areas and material information, as well as node ids and coordinates. The elements of each geometry body can also be specified using the generated file.

With the data processing tools in Python, it is possible to access simulation data including the normal force vectors, which allow defining the stress results in the script. However, it should be noted that the script does not perform the FE analysis itself, and the boundary conditions and loads must be defined in Ansys.

2) User defined values

The buckling check can be performed for the entire model or a limited region. In the study, analysis is conducted on a plane direction chosen by the user. This makes the script running efficient, as analysing the entire model at once can be relatively time-consuming. In turn, this limitation ensures that no critical points are left outside the area restricted by the user. However, if the user is only interested in a specific region, they can trim the model in Ansys and perform the FE analysis only for the trimmed part. Thus, in the scope of the study, the script asks the user to choose the desired plane direction, *xy*, *xz*, or *yz*, to be analysed. In addition, the user is asked to specify the material yield strength.

The user is also prompted to enter the desired load or load combination to be considered. There are no options, but the user defines the values themselves. Each value corresponds to one loading which are defined in Ansys as a time step. At least one valid value must be inserted for the script to run successfully. Example of correspondence between input values and loads is shown in Table 1. The user interface of the script is shown in Figure 11.

Table 1. Input values corresponding on the global load conditions.

Input value	Global Load Condition
1	Wave Bending Moment in Maximum Hogging
2	Still Water Bending Moment in Minimum Hogging
3	Wave Bending Moment in Maximum Sagging
4	Still Water Bending Moment in Maximum Hogging
5	Ice Shear Force
6	Ice Bending Moment

```
[?] Choose the yield strength of the material [MPa]:
 > 235
   265
   315
   355
   390

[?] Choose the considered plane direction:
 > xy
   xz
   yz

(If you want to consider multiple load cases, put a space between the values)
Input the time step value(s) depending on which load case(s) you want to consider:
```

Figure 11. The user interface of the script.

3) Saving shell elements and creating plate fields

The script goes through all the elements and saves the elements which type is shell, and which are parallel to the selected plane direction. This is done by using the node coordinates. It should be noted that the list may include elements that are not of interest, such as flanges modelled as a shell element. These are filtered out by the script.

After saving the needed elements, the plate field creation begins. Plate fields are mainly formed by two different element types. First limiting body is beam, which is defined as line elements. These are identified and located by going through all the nodes. If the node is included in a list of saved elements but also in some line element, the node and the line coordinates formed from them are saved. This acts as a boundary line separating the plate fields. Saved nodes and formed lines are illustrated in Figure 12, where each formed plate field is numbered.

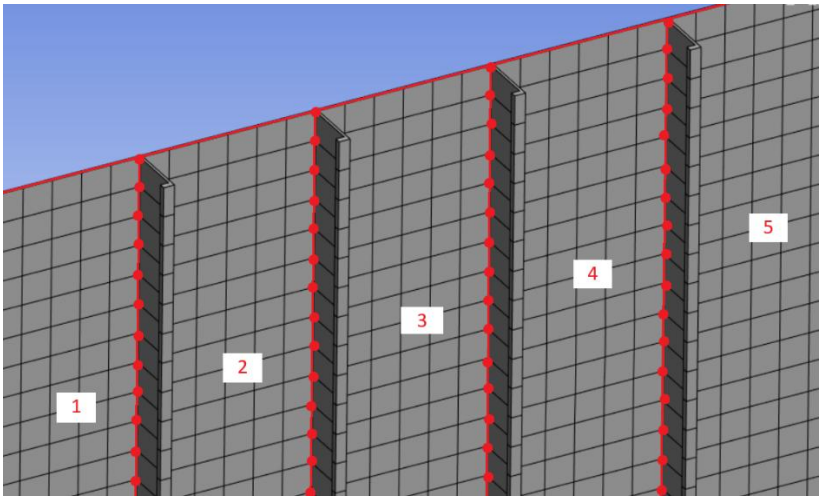

Figure 12. Forming boundaries with beam element bodies for the plate field creation. Formed plate fields are located within the red lines.

Second limiting structures are modelled as shell elements, such as a girder or a bulkhead. Here, the shell elements that are not included in a list of saved elements are gone through. From this set, the elements that share two nodes with the saved elements are searched and saved. The shared nodes form a line that acts as a boundary line separating the plate fields. Saved nodes and formed lines are illustrated in Figure 13, where each formed plate field is numbered.

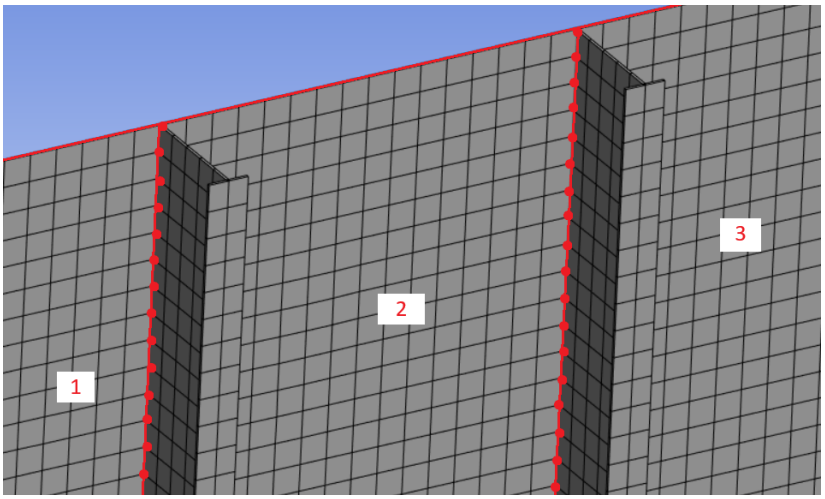

Figure 13. Forming boundaries with shell element bodies for the plate field creation. Formed plate fields are located within the red lines.

The formed lines are saved as lines located in the model's global coordinate system. If the lines cross with each other and form a closed region, the nodes and elements located in this region are saved. A plate field is created. An example of the plate field division is shown in Figure 14, where each plate field is numbered.

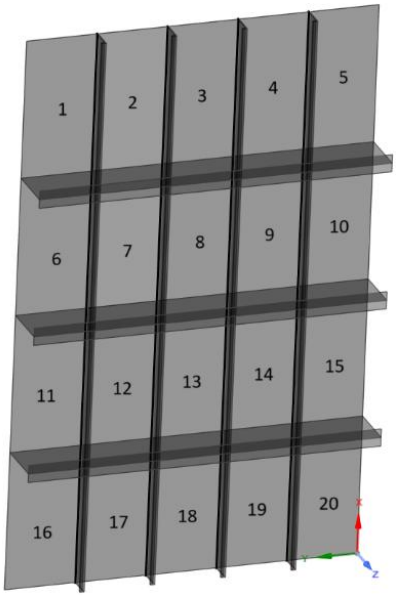

Figure 14. Plate field division example.

As script regulations are applicable only for plates described in Chapter 1.3, the formed plate fields are reviewed to filter out those to which different regulations should be applied. Firstly, the surface area calculated with the shortest and longest plate field sides is compared to the surface area calculated with the elements included in the plate field. If the element surface area is smaller, it indicates that plate field has a cutout. Thus, this plate field is filtered out. Secondly, there are some factors in the interaction functions that are affected by the ratio between the plate field side

lengths. However, these factors can only be calculated according to the rules if the ratio is between 1.0 and 8.0 (DNV, 2016a). Thus, if the ratio is outside the limits, the plate field is filtered out and not considered further in the analysis. These plate fields need other methods to calculate their buckling.

4) Calculating actual and critical buckling stresses

The actual compressive and shear stresses are calculated for each plate field. The stresses are evaluated from the element stresses. Elemental stresses are calculated as elemental mean values (DNV, 2021b). This means that each element is assumed to have a uniform stress distribution, and the stress value is the average of the stresses calculated at the element points (Ansys, 2024). In addition, the position setting is defined as middle, i.e. the stress results are taken from the middle surface (DNV, 2021b).

The stresses of plate fields can be estimated simply by taking the highest value of the element stresses. In the study, however, the actual stresses have been calculated using the ratio of elemental stress σ_{ai} or τ_{ai} to surface area A_i applying DNV Classification Notes No. 34.1 (DNV, 2013). The stress of a plate field with *n* elements is calculated as follows:

$$\sigma_a = \frac{\sum_{i=1}^{n} \sigma_{ai} A_i}{\sum_{i=1}^{n} A_i} \text{ and } \tau_a = \frac{\sum_{i=1}^{n} \tau_{ai} A_i}{\sum_{i=1}^{n} A_i} \quad [9]$$

As the interest in the calculation of actual stresses is only in compressive and shear stresses, as normal tension does not cause buckling, normal tension values are neglected and set to zero. Compressive stresses have negative values whereas shear stresses can be both negative and positive. (DNV, 1995)

The size of the plate field affects the critical stress, and it is calculated using the plate field limiting boundaries. The thickness of the plate field also affects the critical stress, and it is calculated using element thicknesses. Critical buckling stresses are applied in the script as defined in Equation 8.

5) Performing interaction functions, screening and saving elements

When the actual and critical stresses of plate fields are estimated, the interaction functions for each plate field can be calculated. In terms of design, interest is in the worst-case scenario, meaning the combined load of biaxial compressive stress and shear stress. Thus, the screening in the script is done only according to the results of Equation 7.

If the interaction function is calculated for the plate field, its element ids are saved with a ratio between the obtained result and the allowable criterion. In turn, elements that are not included in any plate fields and thus are not considered in the interaction

function are saved with factor *0*. A file is created where the data is saved for the visualization.

3.2.3 Assumptions

Method and the use of the script include certain assumptions and simplifications. However, they have been defined according to the factor giving the worst result, making the assumptions safe and conservative. For example, a user can select only one yield strength value. However, the model may consist of structures with different materials. Thus, the user must choose the yield strength of the weakest material.

The type of supporting structure affects to the ideal elastic buckling stress. However, to simplify the script, the type has not been considered, and the lowest possible value that is affected by it, the factor corresponding to flat bars, has been used to ensure conservative results. The plate field location on the ship has also not been considered, i.e. whether the plate is part of a double bottom or a double side.

The normal stress distribution on the plate field can be assumed to be linearly variable (DNV, 2016a). However, the study has assumed that the distribution is constant, meaning that the stress is assumed to be maximum at all points.

When the script treats shell elements, they are assumed to have four nodes. Thus, when forming plate fields, all the necessary elements may not be considered if the elements share more than two or only one element with the considered planar plate elements.

3.3 Post-Processing

Visualization and the result analyzation of the study method are part of the post-processing phase. Visualization is executed in a 3D viewer, which is used to clearly present the stress results of FE analysis and operates as a communication tool with the customer. In connection with the study method, 3D viewer presents the results with the obtained ratios instead of stresses.

In 3D viewer, the user can select the result files that are linked to the software. It has several tools including for example measurement and photo capturing. In addition, viewing angle can be changed and the visibility of the model can be cut or cropped. The user can see the ratio values and thicknesses of each plate field by selecting a certain element as shown in Figure 15, in which the reviewed plate field has a ratio of 1.06.

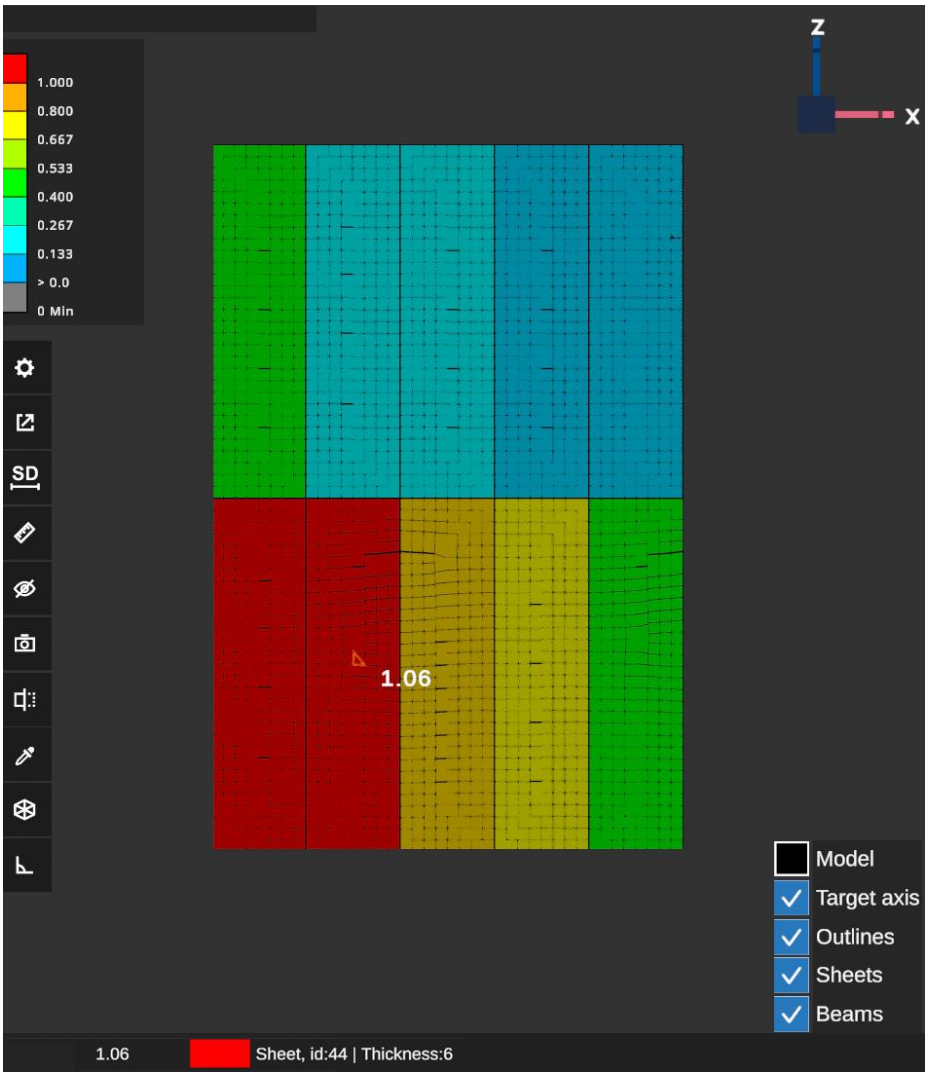

Figure 15. 3D viewer user interface.

The file created in the script and the model file from Ansys are exported to the 3D viewer. The viewer forms the model, and the results are presented visually with the contour plot. The elements with factor *0* are shown in grey. In turn, the elements of the plate fields that have been identified to have stresses above requirements according to the created file are indicated in red. Thus, it is quick to detect locations that need additional reinforcement. After making possible modifications on the model, a new analysis can be performed using the same method procedures.

4 Application

To ensure the correct functionality of the new method, it should be applied to a case study. Additionally, method validation is an important part of ensuring the reliability of the research procedure. This Chapter presents the case study model as well as the validation methods.

4.1 Case study

A ship with a previously made in-house buckling analysis has been selected for the case study. The ship is over 100 meters long and has icebreaking capability with a material yield strength of 355 MPa. For the computational efficiency, a generic part of the model has been selected for the review. As shown in Figure 16, the part has a relatively simple structure, as it mainly contains planar plates. More complex regions, such as the aft and bow, have not been studied in the scope of the work.

Figure 16. Shell model of the case study part in which the hull is indicated in blue and the superstructure in red.

The case study part is located approximately between the midship section and a quarter of the ship length from the bow. Based on the previous buckling analysis of the ship, the region has detected to have multiple critical plate fields. Also, as stated in Chapter 2.4 and illustrated in Figure 7, according to the global load behaviours along the length, the highest bending moments and shear forces, can be expected to be subjected to the ends of the model. Additionally, the ice loads create compressive stresses on the plates.

Further, the case study model is mostly part of the superstructure, which is indicated in red in Figure 16. The structure in the superstructure is usually subjected to smaller loads than in the hull, meaning that requirements allow the plates to be thin and slender (DNV, 2024).

The structures as well as the stiffener and girder spacing of the ship are modelled according to general arrangement drawing. Decks, bulkheads, girders and brackets are modelled as shell elements. In turn, stiffeners and flanges of girders are modelled as beam elements.

Mesh has been defined to be relatively coarse with average size of elements 200x200 mm. The model mesh is shown in Figure 17. The boundary conditions and loads of the case study part are based on the global ship model. The boundary conditions include the displacements resulted from the global loads, and they are imported from the global model into the part. They are introduced to the model part via its edges as shown in Figure 18.

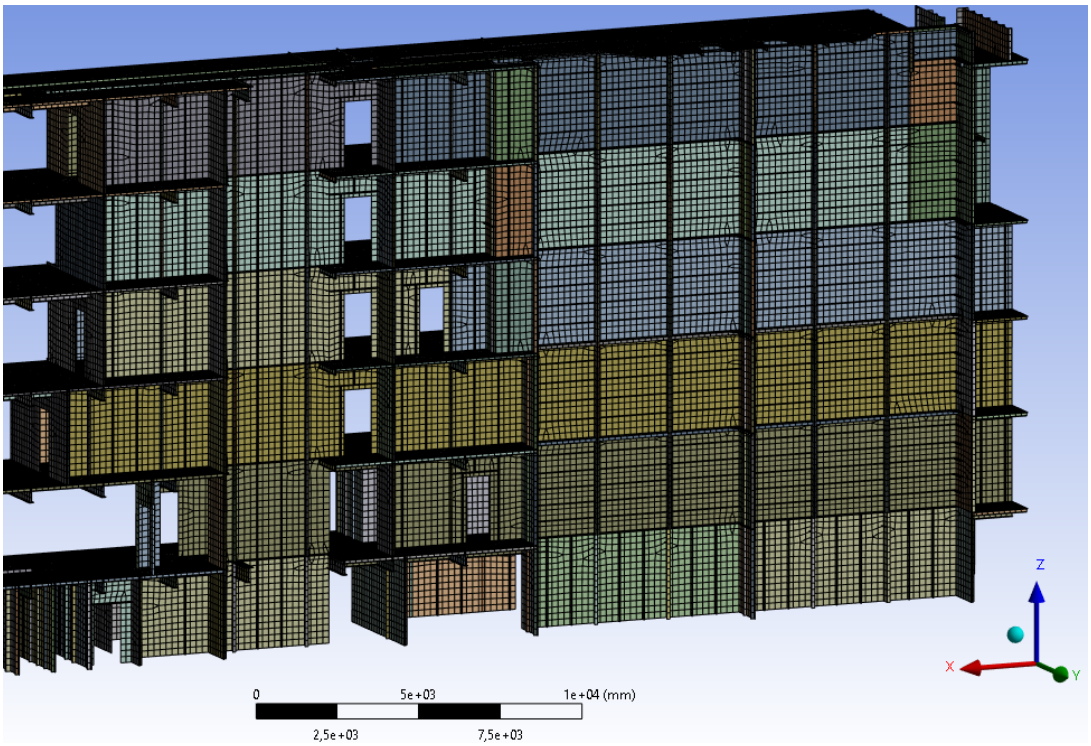

Figure 17. Mesh of the case study model.

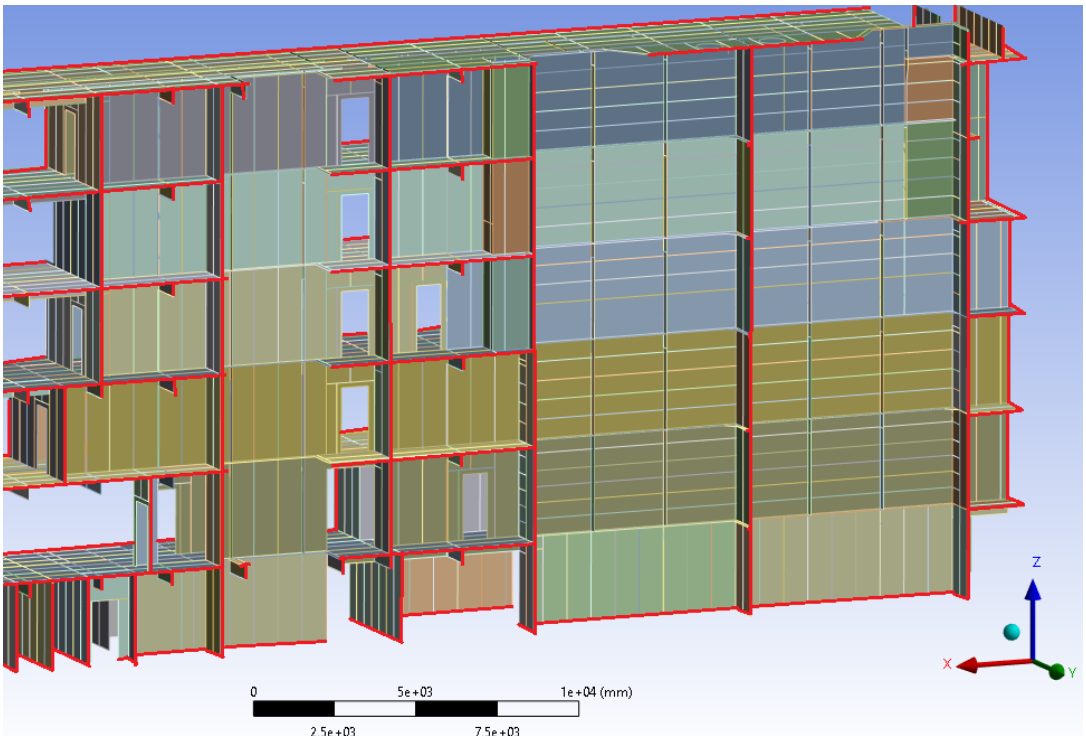

Figure 18. Boundary conditions of the case study model are indicated in red.

Displacements resulted from the global load conditions listed in Table 1 are imported to the model part. Load cases are created by combining them in the script. The aim is to find the worst-case scenarios to guarantee the structural integrity. However, the formed load combinations should be realistic, as extreme loading might result into increased weight without major impact on safety. According to the previous buckling analysis of the ship, the load cases presented in Table 2 are considered.

Table 2. Considered load cases in the study.

Load Case	Load Combination
1	Wave Bending Moment Maximum Hogging + Still Water Bending Moment Maximum Hogging
2	Wave Bending Moment Maximum Sagging + Still Water Bending Moment Minimum Hogging
3	Ice Bending Moment + Still Water Bending Moment Minimum Hogging
4	Ice Shear Force + Still Water Bending Moment Minimum Hogging

After calculating the plate field buckling and analysing the results, not accepted plate fields are reinforced. Since the case study model is a model part, modifications must be done to both the global model and the case study model. It ensures that the displacements caused by global loads and the obtained stresses are in line with the change.

4.2 Validation

In the study, validation is carried out using two different procedures: by comparing the results with a manually calculated buckling check and by performing a fine mesh analysis of the critical area to obtain accurate results. By using different validation procedures, the functionality of the research method can be comprehensively verified.

4.2.1 Manual Calculations

Manual calculation is a traditional procedure to perform the buckling check for the ship structures. The previous buckling analysis of the ship has been done by comparing the regulations criterion with the stress results obtained from FE analysis. The comparison can be done in many ways, but commonly spreadsheet program, such as Excel, is used.

Manual calculations compared to the case study are already performed earlier, and only the results obtained from it are used to validate the study method. The results only indicate which areas need to be strengthened according to the calculation. However, it is sufficient to prove the result accuracy of the study method.

The models used in the manual calculation and study method are similar, but they are different versions of the ship. Thus, some of the structures might differ between the models. In addition, the element size used in the methods are different resulting into different stress values.

The manual calculations are conducted according to LR regulations. They do not require calculation of biaxial loading or the combination of biaxial loading and shear force. (Lloyd's Register, 2021b) Thus, these are not analysed in the manual calculations, but it is done based on the comparison of critical and actual stresses. Validation proves that the buckling check carried out according to different guidelines obtain similar results.

The advantage of manual calculation is the allowance for the user to define the variables of each plate field according to the locations and other affecting factors which are simplified in the script. However, manual calculation is significantly slower method, so simplifying the analysis is also suggested with it. Thus, regulations applied in the manual calculation are simplified.

4.2.2 Local Model

A local model is needed when the user wants more accurate results of a certain area. With the local model, it is easier to create finer mesh without increasing the computational time excessively. In the work, the local model is created from a critical area detected during the process. The area has multiple plate fields that do not comply with the criteria.

Location and the mesh of the selected local model area are shown in Figure 19. Element mesh size of 100x100 mm was used, while in the case study mesh size of 200x200 mm was utilized. Boundary conditions and loads were defined with the same principle as in the case study model as indicated in Figure 20.

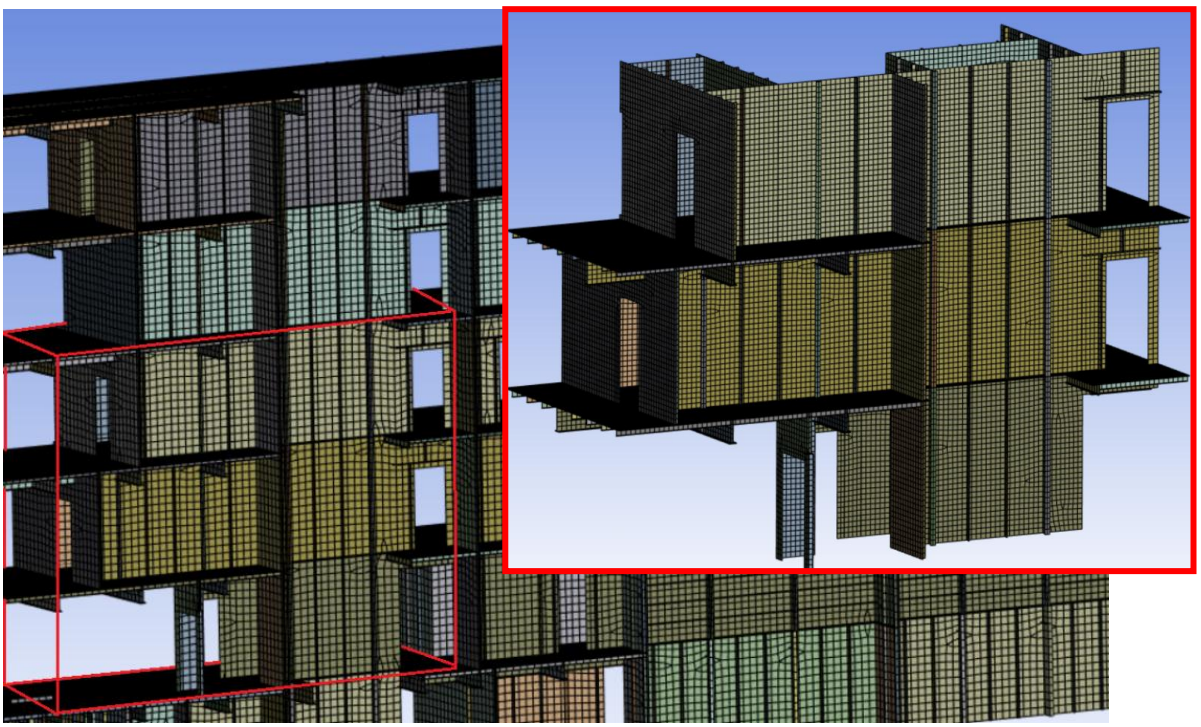

Figure 19. Location and mesh of the local model.

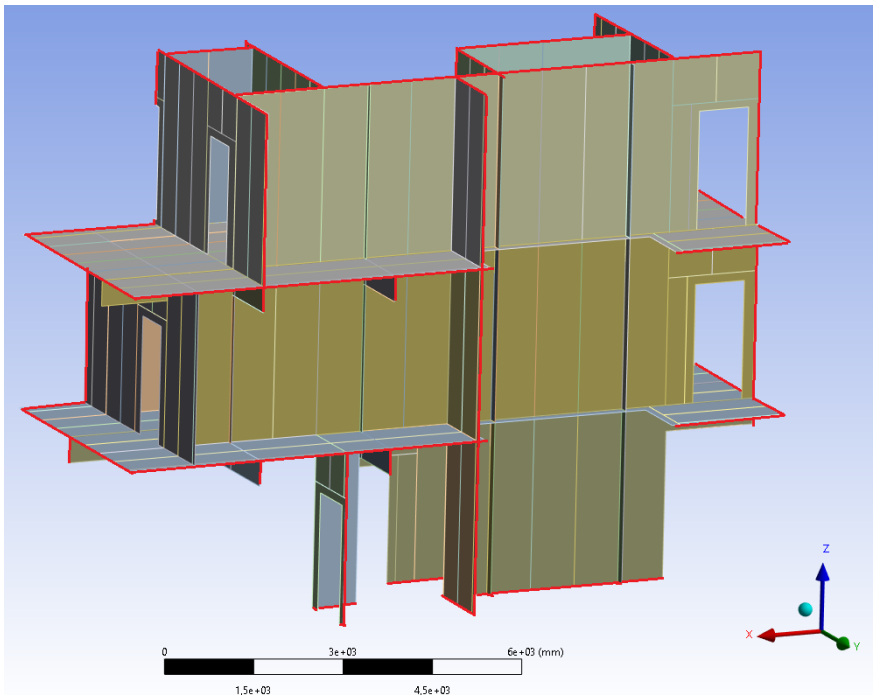

Figure 20. Boundary conditions of the local model are indicated in red.

The purpose of using the local model was to prove that sufficiently accurate results can be obtained even with a coarse mesh. It also indicates that the script can work with different models and mesh sizes. The local model contains the same simplifications and assumptions in the script as the case study model.

5 Results

This Chapter introduces the loading condition considered in the case study and presents the results of initial case study model part as well as strengthened model part. To fasten the process, the results of only one longitudinal section, xz oriented plane, is reviewed. It is selected based on the results from the previous buckling analysis of the ship. However, in reality, the analysis should be carried out for each plate field of the entire ship.

5.1 Loading Condition

When analysing the ship strength, buckling capacity must be calculated against every possible load case that the ship might encounter. For the computational efficiency, however, the buckling in the case study is checked only against the worst load case. Based on the FE analysis results, the most critical load combination is load case 4 according to Table 2.

The load case 4 being the worst load combination seems reasonable. As discussed in Chapter 4.1, the case study model is between the locations having the maximum bending moment and absolute maximum shear force magnitudes. Thus, the combination of bending moment and ice shear force will create high stresses in the case study model area. Further, still water bending moments are more realistic with the ice loads, as the ice breaks in waves, thus removing the ice load.

Moreover, due to the heavy propulsion and machinery located in the aft and bow, and due to the thick ice strengthening especially in the bow, the weight is mostly distributed in ends of the ship. This leads to the ship being always in hogging condition (Figure 8). However, when ice pressure occurs, the ice mitigates the condition, resisting the aft and bow from bending downwards.

5.2 Initial Model Part

The structure behaviour of the model part resulted from load case 4 obtained from Ansys is shown in Figure 21. As the plates are thin, the structures are unable to withstand the ice shear load bending the superstructure bulkheads slightly upwards, especially the structures close to the bow.

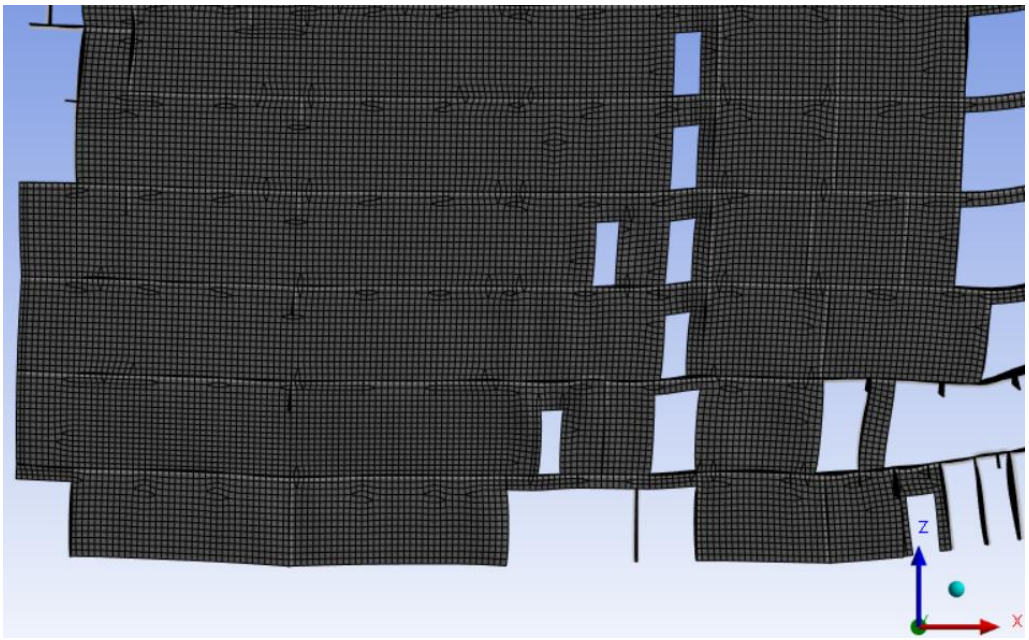

Figure 21. The structure behaviour of the case study model due to combination of ice shear force and still water bending moment in minimum hogging condition.

The model calculation is performed with the script, and the results are obtained according to Figure 22, in which the red plate fields indicate areas that exceed the allowed criteria. In turn, green and blue indicate that the plate field are well within the criteria. The model contains also grey areas. These are located around the openings, and it indicates that these plate fields are filtered out and not calculated in the in-processing phase as stated in Chapter 3.2.2. Greater result plot figure is attached in Appendix A.

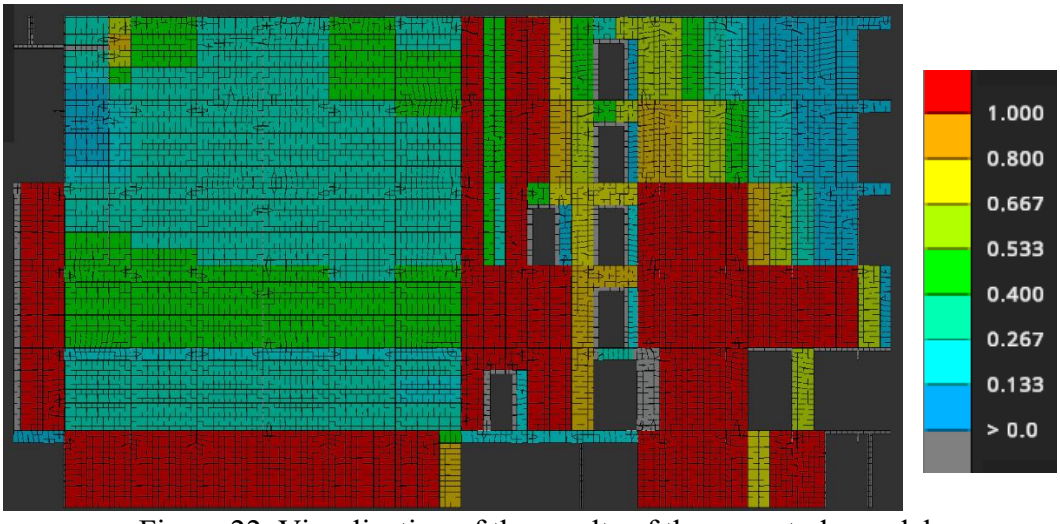

Figure 22. Visualization of the results of the case study model.

The comparison between Figure 21 and Figure 22 shows that the plate fields with the significant deformations also exceed the criteria. Further, all not accepted plate fields are transversally stiffened. Thus, they are more prone to buckling. This is due

to their free plate size, as they are larger compared to longitudinally stiffened plate fields. Moreover, the global loads act along the ship length meaning that longitudinal supporting increases the stiffness along its length.

However, it should be noted that also multiple transversally stiffened plate fields are within the criteria, and they are highlighted in Figure 23. Plate fields located inside the regions 1, 4, 5 and 7 in Figure 23 have additional strengthening compared to the plate fields close to them, whereas the plate fields in regions 3 and 6 in Figure 23 are only slightly below the criterion.

As the ship is under hogging condition, highest compression occurs in the bottom part and tension occurs in the upper structures. Also, as mentioned in Chapter 4.1, the superstructure encounters smaller loads. This explains why the plate fields in region 2 in Figure 23 are within the criterion.

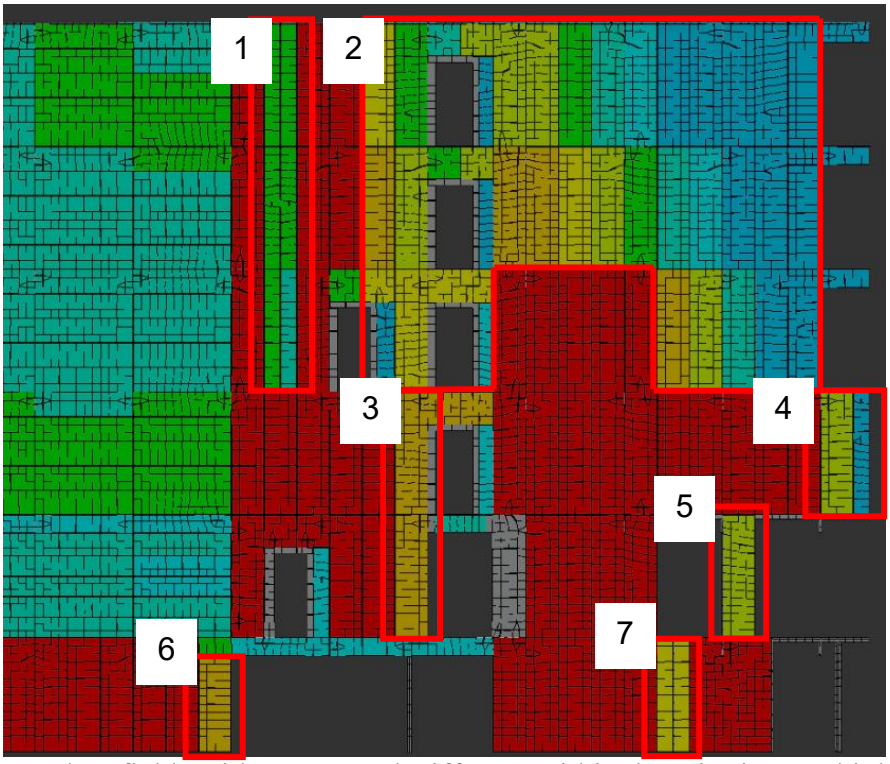

Figure 23. Plate fields with transversal stiffeners within the criterion are highlighted in red.

The plate fields with highest ratios are located in the hull, as it encounters the most significant loads. However, these plate fields are also close to the boundary conditions in the bottom edge as shown in Figure 18, meaning that the results might not be reliable.

When comparing study method results with the manual calculations, total of 10 differences in plate field results are found. This might result because the manual calculation does not consider biaxial or combined loading. Another reason could be that

some plate fields within the criteria are also strengthened, as the desire is to have large uniform panel sections to ensure structural integrity. The differences might be due to other reasons as well, such as the application of different classification society regulations or the use of different versions of the model. Overall, the results are similar, as shown in visual comparison in Appendix B.

Additionally, it is estimated that performing buckling check for all plate fields of the ship with manual calculation would take approximately two weeks of work. In turn, the use of study method would reduce the time to few days. The comparison shows that accurate results can be obtained with the study method efficiently.

Comparison between case study model and local model show that the buckling of exactly same plate fields is estimated to be above the criteria. However, some differences were found in the ratio values. The greatest difference between the ratios of not accepted plate fields is 4,2 %. This shows that results with sufficient accuracy can be obtained with a coarse mesh and hence efficient computation time especially when large models are analysed. Visual comparison can be found in Appendix B.

5.3 Strengthened Model Part

The case study model is strengthened according to the suggestions given based on the results of the previous buckling analysis of the ship. Increasing the buckling capacity can be executed in several ways, but to ensure efficient modification time, it is decided to accomplish by increasing the plate thickness. Increase of the thickness is generally considered also a fast and building-friendly approach for manufacturing of ship blocks instead of adding more stiffeners to reduce plate field sizes (Leal & Gordo, 2017). Strengthened plate panels are presented in Figure 24.

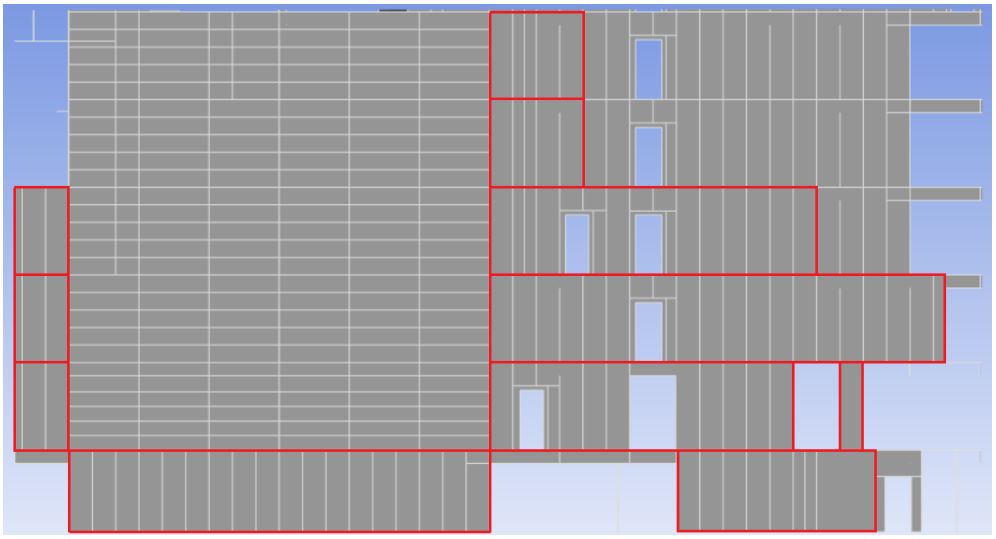

Figure 24. Strengthened plate panels of the model are indicated with red edges.

The structure behaviour of the strengthened model part resulted from load case 4 obtained from Ansys is shown in Figure 25. By comparing Figure 21 and Figure 25, it can be noted that with thicker plates, the deformation due to ice pressure is not as significant.

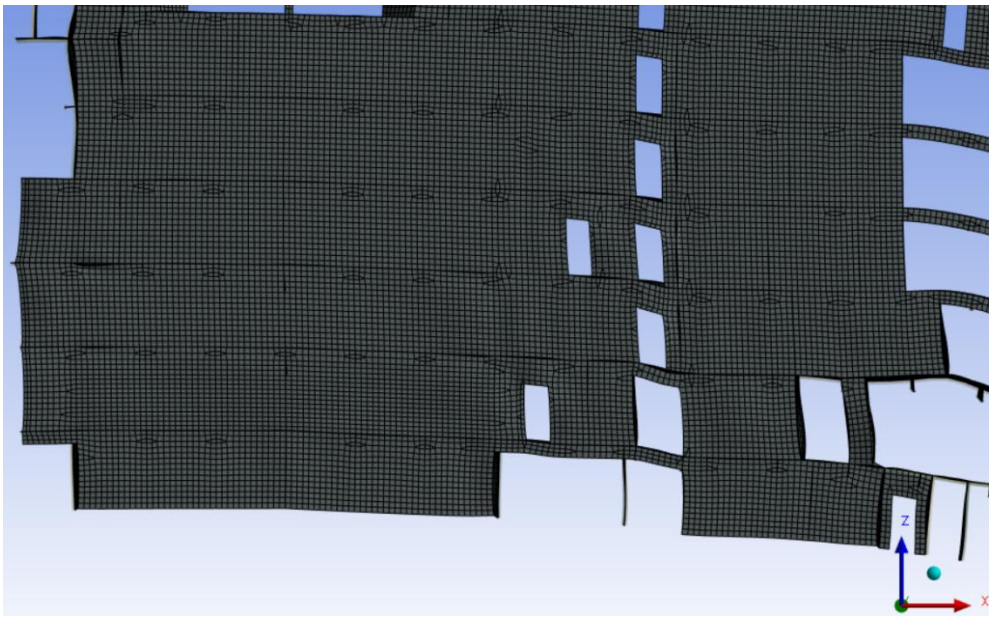

Figure 25. The structure behaviour of the strengthened model due to combination of ice shear force and still water bending moment in minimum hogging condition.

The model analysis is performed with the script, and the results are obtained according to Figure 26, in which it can be seen, that all the plate fields are within the limits. The highest ratios occur in the top plate fields instead of the hull, which are also located close to the boundary conditions. However, this might also be affected by the modifications, as the plate fields are not strengthened like the others creating higher stress distribution there. Greater result plot figure is attached in Appendix A.

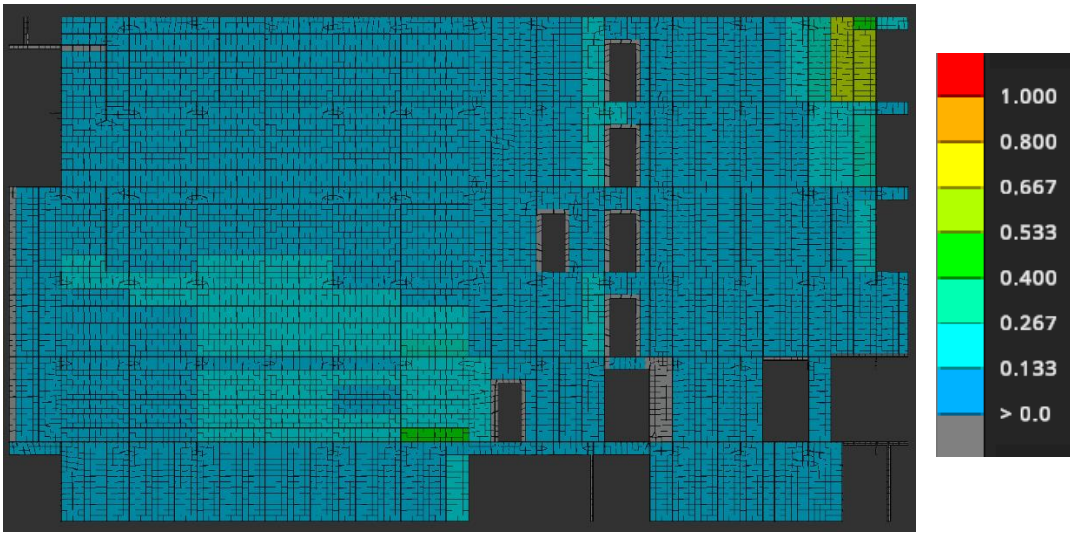

Figure 26. Visualization of the results of the strengthened model.

To achieve acceptable results, the thickness of the lower plates has been increased considerably. The change has been relatively small for the upper plates. Acceptable results have been achieved with the same modification also according to manual calculations, which further shows the similarity between the study method and manual calculations.

6 Discussion

The results obtained with the study method seem overall reasonable and the validation shows reliability for the method. However, comparing the results with other research on the topic is important, as the method contains some limitations and room for future development. These are discussed in this Chapter.

6.1 Result Reliability

The study method leads to equivalent results as in other publications on the topic. For example, Caldwell clarifies the steps of the research in his work, according to which buckling occurred in transversally stiffened plates before longitudinally stiffened plates (Caldwell, 1965). In turn, Zhang (2017) compares the use of longitudinal and transverse framing system and favours longitudinal framing system for long ships due to large global loads.

A study on the design of an ice-breaking supply vessel by Wang (2013) also reveals the problems related to the transversal structure. Further, the study discusses about the criticality of the superstructure in the global strength analysis of an ice-strengthened vessel. (Wang, 2013)

The hull plates of ice-strengthened ships are designed to withstand high loads, especially in the ice belt. Thus, they are relatively thick and not critical for buckling. The stress is distributed in the superstructure instead. Especially the inner plates in the superstructure are not expected to carry excessive external loads allowing them to be thin and making them prone to buckling.

Another consideration about the location of the critical area is its distance to the neutral axis. The neutral axis of the case study ship is located relatively low resulting into higher bending moments in the superstructure. The same has been observed in the study by Romanoff et.al. (2013) that examines the interaction between hull and superstructure of a passenger ship. As the neutral axis is located near the bottom, the superstructure was found to carry more bending moments than the hull. (Romanoff, et al., 2013)

In turn, as a combined load case of bending moment and shear force is considered in the case study, the effect of shear force would be emphasized closer to the neutral axis, as the bending moment is balanced at the neutral axis. The shear deformation is also greater around it. (Shama, 2013)

Thesis on buckling check of plate panels and column structures by Vuorela (2014) compares the buckling of plates at different thicknesses and sizes. It shows that plate size affects to the buckling capacity significantly. Further, according to her thesis, even a slight change in thickness can affect particularly the compressive stresses of the plate. (Vuorela, 2014) Özgüç also notes the same effect of these on the plate buckling (Özgüç, 2020).

Despite the complexity of FEM, many studies have shown its accuracy in buckling analysis as stated in Chapter 2.2.2. It makes it possible to examine the ship considering also, for example, structural discontinuities. Thus, to achieve accurate results, its use is suggested in the pre-processing phase.

6.2 Method Sensitivities

Even though similar results are obtained with the study method, validation methods and other research, certain simplifications are made in the script resulting into more inaccurate results. However, the results obtained are conservative, as the weakest of the simplified values, such as material strength and factors depending on supporting members, are used. Therefore, some plate fields contain safety margin.

Further, the script contains certain sensitivities. Firstly, the script does assumptions regarding on mesh size while saving the shell elements. There, the script assumes minimum dimensions for the shell element bodies, for example, flanges are thin but long. However, this might result into a case, in which elements are filtered out even though they should be considered in the analysis or elements that should be filtered out, are included in it.

Secondly, when node coordinate information is used to save shell elements or limiting boundaries, the coordinate values are rounded to two decimal places to eliminate inaccuracies in the FE model. However, if the modelling error is greater and, for example, the model bodies have not been connected to each other, the script may not detect all the desired ones. Additionally, even though the script considers elements of different shapes, the script contains assumptions about the elements having 4 nodes when forming the plates fields as explained in Chapter 3.2.2.

Even though the validation of the study method shows the result accuracy of the coarse mesh, it should not be made excessively coarse. Namely, Tõns analyses the buckling results using a mesh size being larger than the plate width, which resulted into peak stresses in the model (Tõns, 2009).

As stated in Chapter 3.2, the script uses PyAnsys libraries to process simulation data obtained from Ansys, the script cannot read files created by other FEM software. Thus, the pre-processing phase cannot be applied to other FEM software. This limits the use of the method, as it requires an Ansys license.

When considering the method efficiency, the study only takes a stand on the in-processing phase. It ignores, for example, the model creation and result analysing. Making possible modifications also takes time, which Blackwell has estimated in her thesis (Blackwell, 2022). In turn, the automation enables other work simultaneously during the analysis run. Therefore, full work capacity is only needed in the pre-processing and post-processing phases, as well as in modification making.

6.3 Future Work

Despite being already a functional procedure, the script is only applicable for buckling check of simple structural plates, and some limitations are related to the study. Although buckling analysis should be conducted for different structural elements, the study is limited to simple plates. Considering more complex plate fields will be done in future development. It is essential addition for the script, as it would make the procedure extensively functional. Additionally, the use of other methods, such as manual calculation, would not be needed anymore after making the additions. The calculation of other structural members will also be considered in future.

The approach of the study is based on DNV regulations. Although the procedure for buckling check is similar in different classification society guidelines, each ship should be designed based on the defined classification society. However, the use of the script could serve as a good indicative analysis in concept design, even if the ship was classified according to other society than DNV. Applying rules of other classification societies to the script is a further development for the project.

Although using a script instead of manual calculation is estimated to be more efficient, running a script is currently quite slow, especially for large models having a lot of elements and nodes. Thus, it is profitable to perform the calculation for local models. However, optimizing the script would be beneficial to make the running of global models well functional as well.

One of the development proposals would also be the possibility to examine only a limited area defined by the user of the entire ship model. In this case, despite the global model, the script would only consider the elements that are included in that area. This could also speed up the execution of the script even with a large model.

The reliability of the work could be increased by considering the types of support, meaning that the script would identify the factors limiting it. It would also be important to identify the location of the plate field in the ship, as this has also been considered in the calculations in the regulations. Considering these can save time from unnecessary changes and can have a positive effect on the weight of the vessel and the use of materials.

Further development for the visual representation could also be done. In addition to capacity, visualization would indicate how thick the plate fields should be to comply with the rules. This would make the modification phase more efficient, as multiple rerunning would not be needed. In turn, sometimes other modifications, such as modifying the structural arrangement, i.e. stiffeners, in a way that plate field could be optimized by size or thickness, are more profitable option, in which case the solution proposal would still be limited.

7 Conclusions

The purpose of the thesis was to utilize screening method to provide an efficient tool to evaluate buckling capacity against regulations. The aim was to find buckling critical locations and reduce the analysis time and human error of the buckling analysis. For this, a script was implemented.

The study focused on the buckling of the rectangular, planar and unstiffened plates without cutouts. The allowed buckling criteria were based on classification society DNV regulations, and they were used and applied in the script. Result visualization was done with an in-house 3D viewer.

Application of the method was tested with a case study of a generic global model part. The model creation was done using FEM software Ansys. A coarse mesh was defined, and global load combination was subjected to the model part. The combined longitudinal and transversal stress as well as shear stress were calculated, and the buckling response was evaluated through interaction function. The results were screened and plotted in 3D viewer.

Main observation of the initial case study analysis is the effect of the plate field size and the framing system, as transversally stiffened plate fields were shown to be more critical for buckling. In turn, the results of the strengthened model revealed that modifying part of the plate fields affect to the buckling capacity of the entire structures as the stress distribution changes when more stiffness is applied to the structures.

Validation of the method was done by using two different procedures. Manual calculations showed the study method accuracy and similarity between different classification society buckling regulations. In turn, the use of local model proved the study method functionality with different models as well as the result accuracy even with a coarse mesh.

Further, the comparison of the results to other research justified the method accuracy. It is also proven that the new method would reduce computational time significantly. However, the script contains still some sensitivities and assumptions, which may reduce the method accuracy. Thus, there is room for the script improvement and possible extension.

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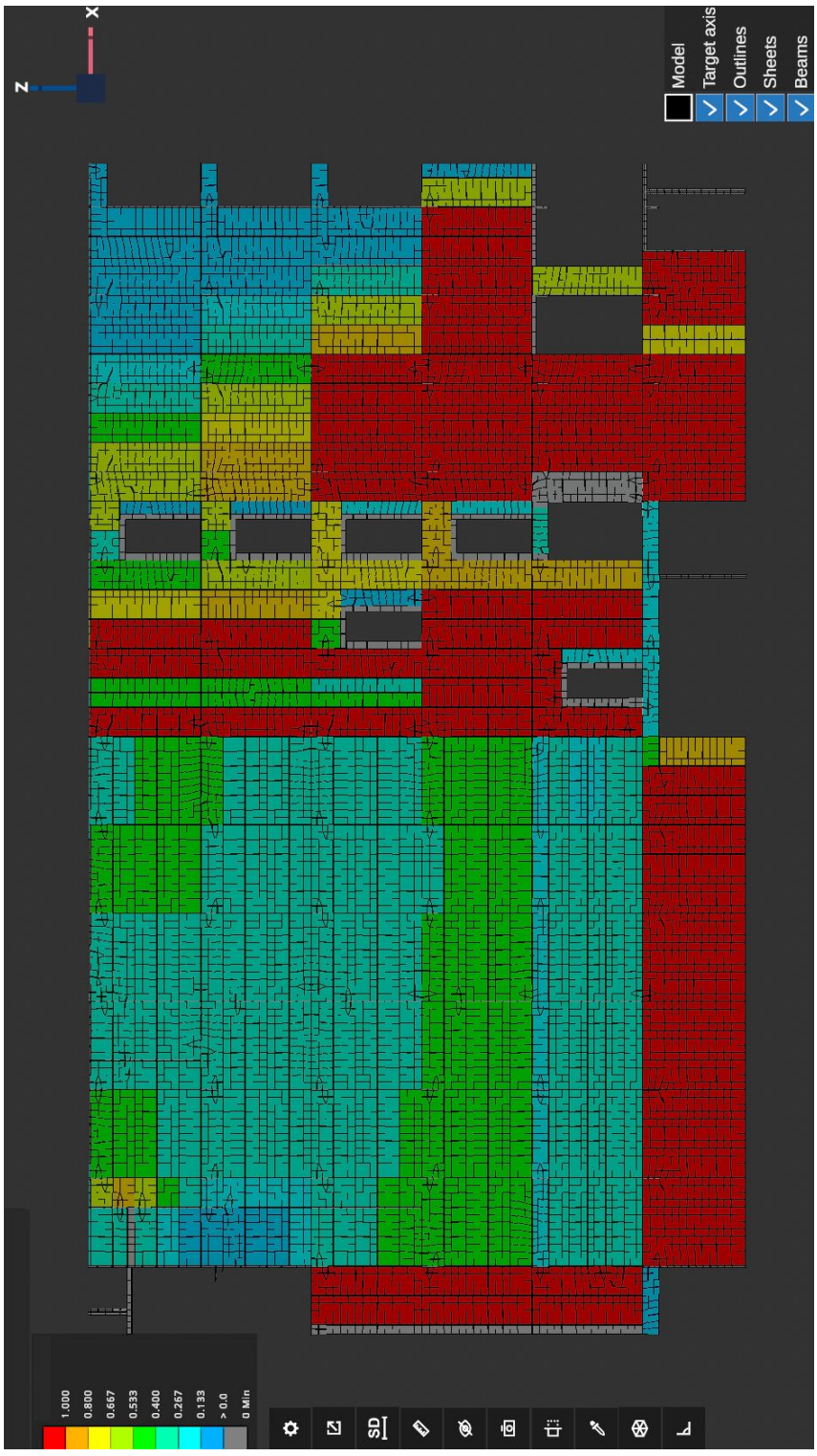
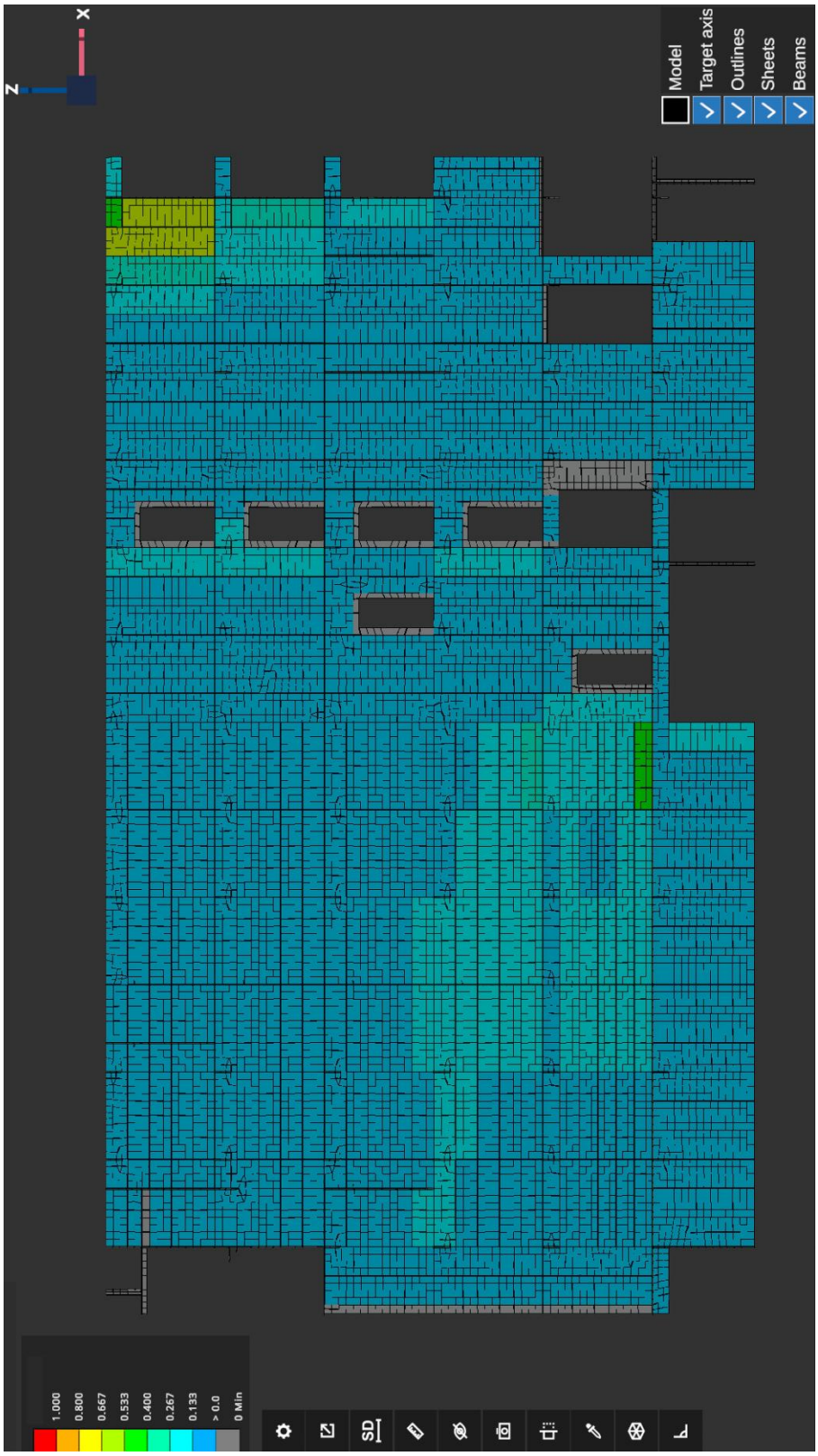
A. Result Plot

Initial Model Part



Initial state of the buckling screening of a case study model.

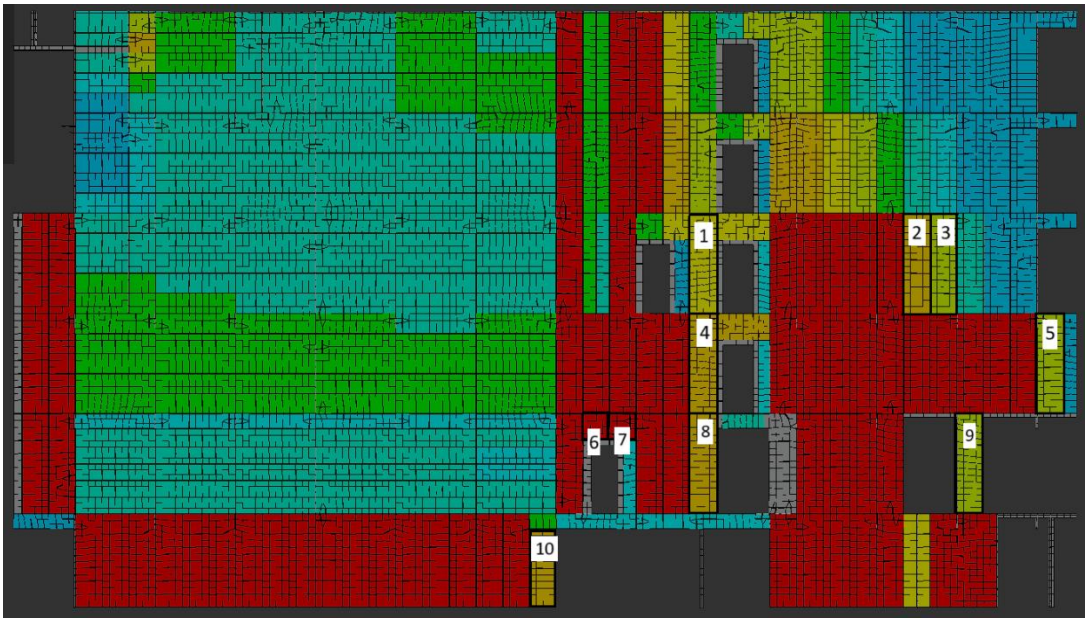
Strengthened Model Part



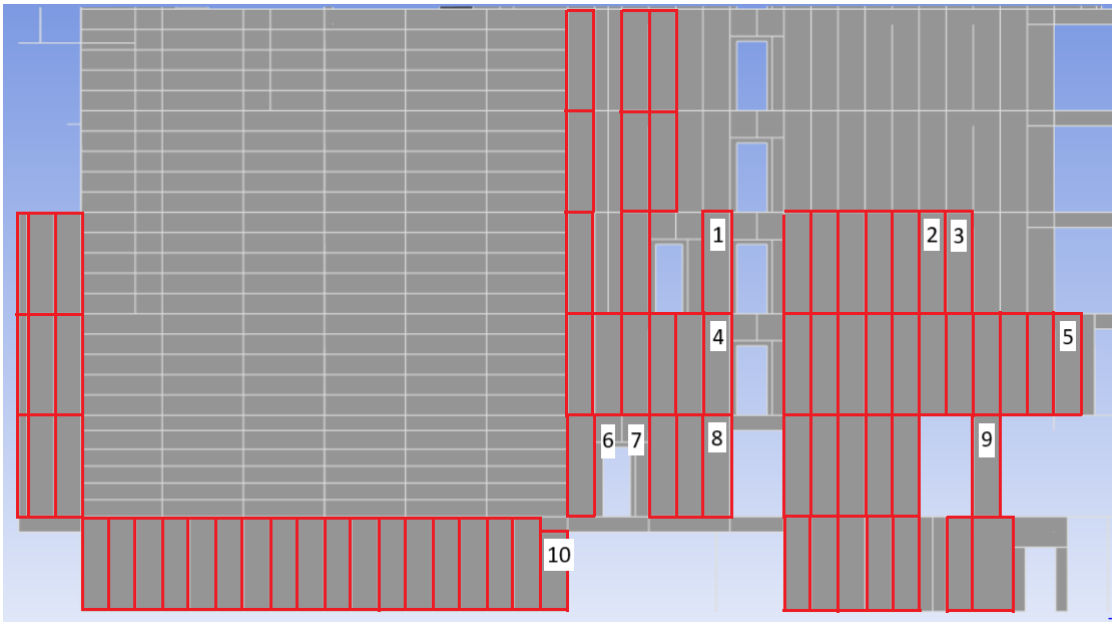
The buckling screening of a case study model with reinforced structures.

B. Result Comparison

Manual Calculation Comparison

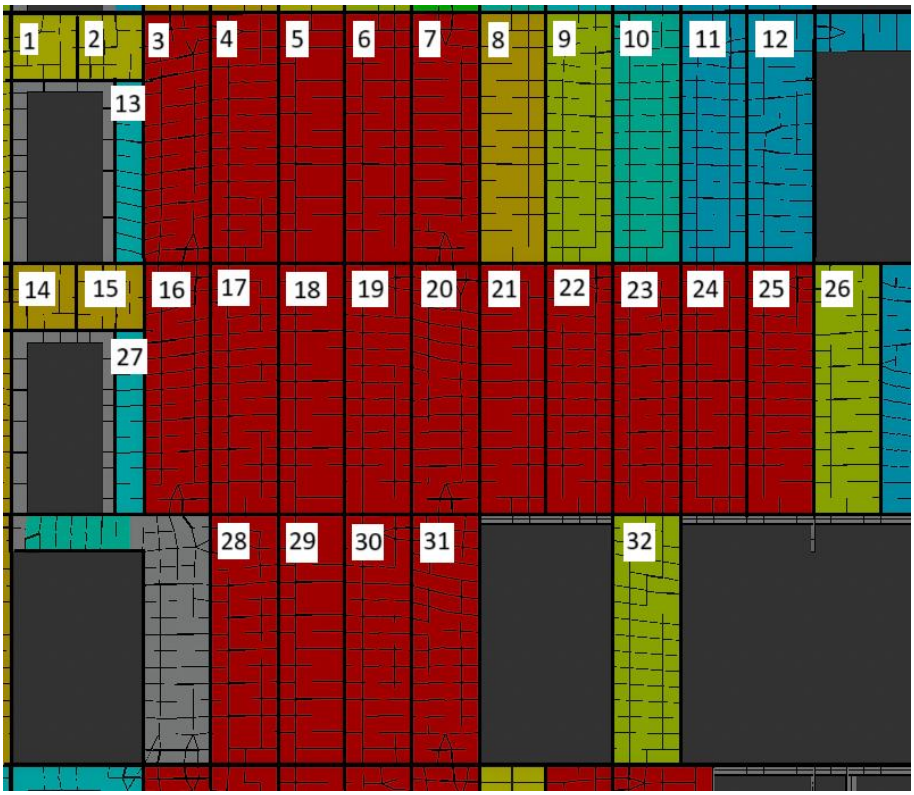


Result plot of the case study model.

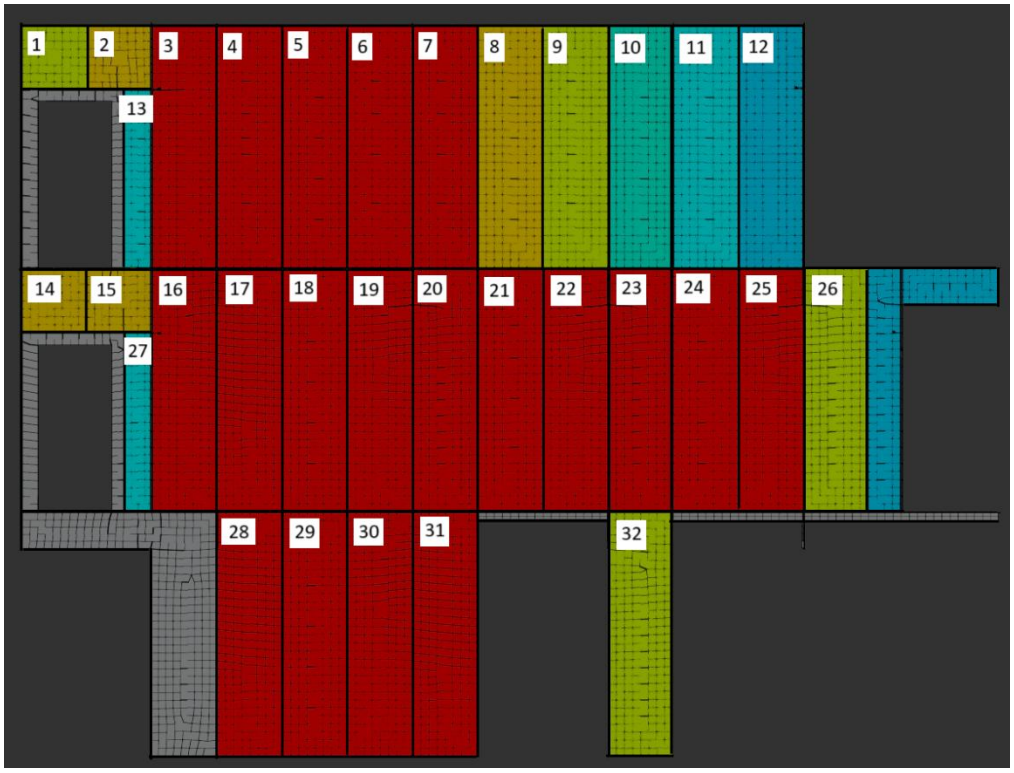


Reinforced plate fields according to manual calculations are indicated with the red edges.

Local Model Comparison



Result plot of the case study model.



Result plot of the local model.