PROJECT WORK FALL 2010
for
Stud. Techn. Nguyen Chi Thanh

Optimum layout of stiffened panels subjected to lateral pressure and inplane loads

Optimak utforming av avstivede paneler utsatt for lateraltrykk og trykkbelastninger i plateplanet

Stiffened panels constitute important structural elements in marine structures, ships and offshore platforms. An example is the pontoons of semi-submersibles. The panels will be subjected to simultaneous action of lateral pressure and in-plane, bi-axial compressive loads, which will govern the dimensions of the shell plate and stiffeners. In order to keep the weight and fabrication costs as low as possible it is essential that panels be designed with due consideration of the potential failure modes as well as fabrication costs, so as to obtain efficient “utilization” of the material.

The task is to determine optimum design with respect to weight and costs of stiffened panels in pontoons of floating platforms.

The work is proposed carried out in the following steps:

1) Brief description of the Aker H6 platform including structural lay-out and the scantlings of the pontoon panels. Review of typical load cases and characteristic action used in the design. Describe the fabrication process and the costs of fabrication, based on input from Aker Solutions.

2) Review of relevant characteristic resistance formulation given in DNV RPC202//Norsok N-004 for stiffened plates. The background for the various requirements shall be explained. The theory for PULS code shall be described briefly.

3) Through literature studies assess the costs of welding as a function of the thickness of the plating and the web for the girder for the relevant welding

4) On the basis of characteristic action effects supplied by Aker Solution, determine the dimensions of the stiffened panel according to DNV RPC202 and PULS. Perform parametric studies where e.g. the spacing of stiffeners and frames are varied. Determine the optimum dimensions of the panel taking into account fabrication costs and material consumption for the various alternatives.

5) Identify the governing failure criteria for the optimum panel, investigate the agreement between DNV RPC202 and PULS, and assess whether further improvement of the design through nonlinear finite element analysis may be achieved.

6) Perform parametric studies of the pontoon structure when also frame spacing is taken into account

7) Conclusions and recommendations for further work.

Literature studies of specific topics relevant to the thesis work may be included.

The work scope may prove to be larger than initially anticipated. Subject to approval from the supervisors, topics may be deleted from the list above or reduced in extent.

In the thesis the candidate shall present his personal contribution to the resolution of problems within the scope of the thesis work.

Theories and conclusions should be based on mathematical derivations and/or logic reasoning identifying the various steps in the deduction.

The candidate should utilise the existing possibilities for obtaining relevant literature.

Thesis format

The thesis should be organised in a rational manner to give a clear exposition of results, assessments, and conclusions. The text should be brief and to the point, with a clear language. Telegraphic language should be avoided.

The thesis shall contain the following elements: A text defining the scope, preface, list of contents, summary, main body of thesis, conclusions with recommendations for further work, list of symbols and acronyms, references and (optional) appendices. All figures, tables and equations shall be numerated.

The supervisors may require that the candidate, in an early stage of the work, presents a written plan for the completion of the work. The plan should include a budget for the use of computer and laboratory resources which will be charged to the department. Overruns shall be reported to the supervisors.

The original contribution of the candidate and material taken from other sources shall be clearly defined. Work from other sources shall be properly referenced using an acknowledged referencing system.

The report shall be submitted in two copies:

- Signed by the candidate
- The text defining the scope included
- In bound volume(s)
- Drawings and/or computer prints which cannot be bound should be organised in a separate folder.

Thesis supervisor

Prof. Jørgen Amdahl
Contact person at Aker Solutions: Marthe Almeland

Deadline: June 14, 2011

Trondheim, January 18, 2011

Jørgen Amdahl

Summary

This thesis has been to develop from the result of project thesis. The main task is now focused on the optimum layout for stiffened panel and girder.

Stiffened panels constitute important structural elements in marine structures, ships and offshore platforms. An example is the pontoons of semi-submersibles. This project analyzes the stiffened plate of the pontoon bottom for an offshore platform (Gjøa platform).

The aim of this thesis is to determine optimal design with respect to weight and costs of stiffened panels for the above platform. A briefly description of the Gjøa platform has been investigated. An introduction of typical loads and characteristic actions used in the design is also discussed. Besides, a review of relevant characteristic resistance formulation given in NORSOK N-004 (DNV-RPC201) for stiffened plates is also performed. Particularly, the theory of PULS code is also described briefly.

The stiffened plate and girder have been analyzed by means of PULS program and DNV-RPC201 spreadsheet. With these two programs, geometric parameters which characterizes the stiffened plate are investigated, i.e. stiffener spacings, plate thickness and the stiffener profile. In the present stage of this report, only three different stiffener spaces are considered for comparison of the two programs.

The optimal stiffened panel must be satisfied three parameters of optimum design function, that are maximum usage factor is limited with η=0.9, the weight and the fabrication cost must be always considered during design process.

The optimal design procedure will be divided into two parts with four different stiffener spaces. The weight and the fabrication cost are assessed as function of the plating thickness and stiffener dimension.

The first part will be performed with optimum layout of stiffener and panel dimension; the stiffened panel will be investigated by varying parameters such as plating thickness, stiffener dimension as well as stiffener spacing. In the second part, the girder optimum design shall be performed bases on new optimal stiffened panels have been previously performed.

Buckling assessment of the optimal stiffened panel will be also investigated and the corresponding optimal capacity curves will be investigated in DNV RP-C201 and PULS.

For the DNV RP-C201 the buckling assessment for stiffened plate as well as for the girder is performed by interaction equations. The maximum capacity will be found when the largest utilization ratio found for the four equations is at its minimum.

The current PULS apply six limit state functions for identifying critical conditions in different locations in the panel. A function corresponds to applied loads less than the critical condition in the corresponding point. The ultimate strength is found from the minimum of all defined limit states.

Finally, a new stiffened plate is found by trial and error analysis. The optimal girder and stiffener dimension, stiffener spacing and a new plating thickness are also determined. The objective variables of this optimal design are weight and fabrication cost of the stiffened panel.

With the designed result the conclusions with recommendations for further work are also done at the end of this report. The agreement between DNV RPC202 spreadsheet and PULS is studied. Moreover, a short comparison and discussion about the differences between DNV RP-C201 spreadsheet and program from Aker Solutions Company will be also investigated.

Preface

This report is the result of the Master Thesis for stud. techn. Nguyen Chi Thanh at The Norwegian University of Technology and Science (NTNU), Spring 2011.

The work herein is a continuation of a Project Thesis; this is convenient for me to do the further work in my Thesis. However, this also has some changes due to the result from project thesis. Besides, in agreement with supervisor the further improvement of the design through nonlinear finite element analysis will not perform in this thesis.

The process of performing this thesis by trial and error is somewhat laborious and annoyed. This is due to the closed form solutions implemented into the programs that the users can not either access the formulae or perform “optimal design” by iterations. As required, the objective variables the optimal design are weight and fabrication cost for the stiffened panel.

Performance of this thesis, besides essential knowledge about buckling of marine structures, I have chance to work with practical thesis that is provided from Aker Solutions Company. This helps me to get some practical knowledge during this thesis.

Besides, by doing with DNV RP-C201 spreadsheet and PULS I have opportunity to work with practical offshore standards, especially ‘‘Recommended Practice Det Norske Veritas (DNV), DNV-RP-C201’’ and ‘‘DNV-OS-C101 Design of Offshore Steel Structures’’. However, this also took me much time in order to understand as well as applying for optimal design in this thesis.

After finishing the project work and beginning with the thesis work I had some knowledge of using DNV RP-C201 spreadsheet as well as PULS. However, during the thesis work when perform buckling check for plate and stiffeners, this help me to understand deeply design procedure and the buckling assessment procedure in two programs.

Moreover, by investigating the agreement between DNV RP-C201 spreadsheet and PULS, and comparison between DNV RP-C201 and Aker Solutions’s program, I got a lot understanding of offshore standard DNV RP-C201, especially the torsional buckling strength assessment for different stiffener profile.

During the thesis work, problems were frequently discussed with various persons in Marine Technology Department. In particular would like to express a deep sense of gratitude and thanks profusely to Master Thesis supervisor Prof. Jørgen Amdahl (NTNU), who help me not only knowledge in this thesis, but also gave me method in order to solve a problem in research as well as in real life.

I specially thank Marthe Almeland at Aker Solutions, who is co-supervisor. She has given me many good practical advices and suggestions in this thesis.

Finally, I also would like to thank Eivind Steen at DNV for discussion on PULS program, Anders Rading at Aker Solutions for discussion on Nauticus spreadsheet for RPC201 and STIPLA program.

Nguyen Chi Thanh

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June 6, 2011

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Nomenclature

Abbreviations	Description
BS	Buckling Strength
DNV	Det Norske Veritas
FE	Finite Element
GEB	Global Eigenvalue
LE	Local Eigenvalue
PULS	Panel Ultimate Limit State
UC	Ultimate Capacity
UF	Usage Factor
NC	Norm Curve

Notation	Description	Unit
A	Cross-sectional area of stiffener	m^2
A_G	Cross section area of girder	m^2
A_w	Cross sectional area of web	m^2
A_e	Effective area	m^2
b	Width of flange	m
b_e	Effective width	m
C_{ij}	Membrane stiffness coefficients	
C_{xG} , $C_{\tau G}$, C_{yG}	Factors	
C_{xs}	Reduction factor due to stress in longitudinal direction	
C_{ys}	Reduction factor due to stresses in transverse direction	
D	Plate stiffness	N/mm
D_{ij}	Bending stiffness coefficients	
$\bar{D}_{ij}$	Neutral bending stiffness coefficients	
Δ	The rate of change	
∇^4 (...)	Laplace operator or bi-harmonic operator	
E	Young's modulus	N/mm^2
e	Flange eccentricity	mm
I	Moment of inertia	mm^4
i_e	Effective radius of gyration	
K_1	Curvature in plate middle-plan in x_1-direction, $K_1 = -W_{,11}$	
K_2	Curvature in plate middle-plan in x_1-direction, $K_2 = -W_{,22}$	
K_3	Twisting curvature in plate middle-plan in x_1-x_2 plane, $K_3 = -W_{,12}$	
Λ	Load proportionality factor	

Λ_{GE}	Load prop. Factor at ideal elastic buckling in global mode	
Λ_{LE}	Load prop. Factor at ideal elastic buckling in local mode	
L_0	Load effect (= S_d)	
L_u	Characteristic resistance (= r_k)	
L_1	Plate length in x_1 direction, i.e. Distance between transverse frames	m
L_2	Plate length in x_2 direction, $L_2 = (Ns + 1).s$	m
l	Length, element length	m
l_e	Effective length	m
δ	Variational operator	
δ_e	Load-deflection	
δo	Initial deflection	
δ_p	Plastic deflection	
k_{sp}	Factor	
M	Bending moment	N.mm
M_1, M_2	Line moment about x_2, x_1-axis, ref. Plate middle-plane	
$M_{P,Rd}$	Design bending moment resistance on plate side	N
M_{Sd}	Design bending moment	N
$M_{s,Rd}$	Design bending moment resistance on stiffener side	N
N_1, N_2	Line load in x_1, x_2 -direction	N/mm
N_3	In-plane shear load (x_1-x_2 plane)	N/mm
N_E	Euler buckling load	
$N_{kp,Rd}$	Design plate induced axial buckling resistance	
$N_{ks,Rd}$	Induced axial buckling resistance	
$N_{kp,Rd}$	Design plate induced axial buckling resistance	
N_{Rd}	Design load resistance	
N_{Sd}	Equivalent axial force	
N_x, N_y, N_z	Force in x, y, and z_dierection	
P_{Sd}	Design lateral pressure	
P_0	Equivalent lateral pressure	
Q_{ij}	Coupling bending-membrane stiffness coefficient	
s	Stiffener spacing	m
S_e	Effective width of stiffened plate	m
t, t_w	Plate thickness, stiffener web thickness	mm
U	Elastic strain energy	
u	Shear factor	

Z_p, Z_t, Z^*	Distance	
W_s	Weight of stiffened panel	
γ_m	Material factor	
η	Usage factor	
ε_1 , ε_2	Normal strain in plate middle-plan in x_1, x_2 - direction	
ε_3	Engineering shear strain in plate middle-plan in x_1-x_2 plane	
ε_{12}	Shear strain tensor in plate middle-plan in x_1-x_2 plane	
$\bar{\lambda}$	Reduced slenderness	
$\bar{\lambda}_T$	Reduced torsional slenderness	
μ	Parameter	
$\sigma_{x,Sd}$, $\sigma_{y,Sd}$	Design stress in longitudinal, transverse direction	N/mm^2
σ_1, σ_2	Nominal uniform stress in x_1, x_2 – direction	N/mm^2
$\sigma_{y,Rd}$	Resistance design stress	N/mm^2
σ_E	Euler stress	N/mm^2
$\sigma_{j,Sd}$	Design von Mises' equivalent stress	N/mm^2
σ_r	Characteristic buckling strength	N/mm^2
σ_y	Yield stress	N/mm^2
τ_{tf}	Tension field action	
τ_{Sd}	Design shear stress	
ψ_x and ψ_y	Factors	

Subscripts	**Description**
α,β	Placement of the stiffness coefficient of matrix

Superscripts	**Description**
L	Linear properties
N	Non-linear properties
T	Matrix transpose operator

1 INTRODUCTION TO THE GJØA PLATFORM

1.1 Brief description of the Gjøa platform

1.1.1 General

Gjøa is a semi-submersible production platform operated by Statoil. This platform requires a maximum of 40 megawatts of electricity from land supplied with a 100 kilometer-long, 90,000-volt alternating current cable. With the dedication of more than 4000 engineers and experts, more than 5000 workers and this platform came on the sea in 2010, finally.

Many modern technologies were used for Gjøa platform, for instance manufacturing techniques and reduction of the environment impact during operation. Moreover, together with the success of this platform, Statoil has replaced the new way in using powering platform, i.e. electricity generators, in stead of the traditional method such as gas turbines. This can reduce a large CO_2 amount that emissions per year. The more interesting information about this platform can be seen in the Table 1.1.

Table 1. 1: Field development of Gjøa (Ref. [1])

Description	Value
Production start-up	3Q 2010
Oil production capacity	13 800 Sm3/d
Gas production capacity	17 Mill Sm3/d
Semi displacement	59 000 tons
Topside dry weight	22 900 tons
Hull dry weight	13 900 tons
Subsea, Gjøa	5 templates / 13 wells
Subsea, Vega	3 templates / 6 wells

A general layout of Gjøa platform is shown in Figure 1.1

Figure 1. 1: General arrangement of Gjøa platform

1.1.2 The layout of structures of Gjøa semi hull

Gjøa was one of the largest field development projects in the North Sea that Aker Solutions designed, engineered and assembled the platform, which connected to the five sub-sea templates. With a topside weight of 22.000 tones and hull dry weight of 15.000 tones, see Table 1.2

Table 1. 2: The main dimension of the Gjøa platform (from [1])

N^0	Structure	Dimension	Unit
1	Topside dry weight	22900	ton
2	Topside size	110x85	m
3	Hull dry weight	13900	ton
4	Hull column spacing	67.5	m
5	Column width	17.8	m
6	Displacement	59000	ton
7	LQ capacity	100	Cabins
8	Oil export capacity	13.8	kSm^3/d
9	Gas export capacity	17	$MSm^{3/d}$

1.2 Sizing and dimensions of a stiffened panel on one pontoon

1.2.1 General introduction about pontoon

This section discusses more details in structural arrangement of the Gjøa platform. Unfortunately, there are many structural members need to be considered/ explained. However, only arrangement of structures at columns and pontoons are considered in this section according to the tasks of thesis. A 3D model of columns and pontoons is shown in Figure 1.2 in which the following structural members are included:

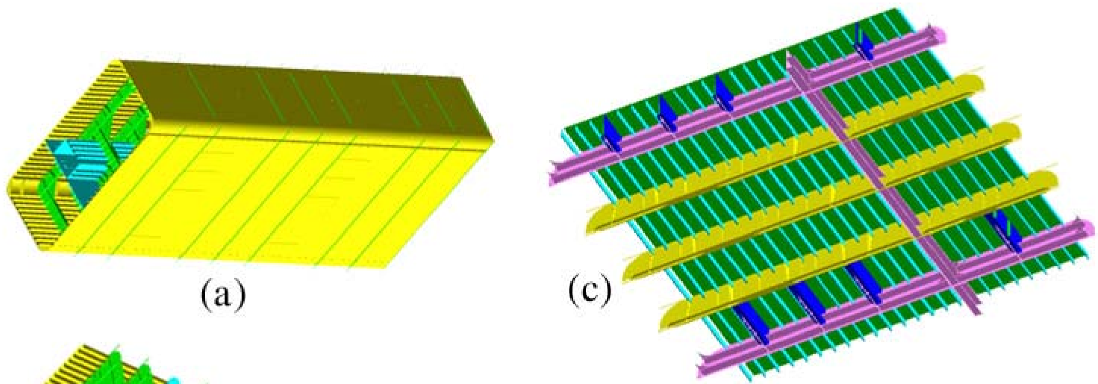
- Ring pontoon and four square columns with bilge radii.
- One pump room is located in each corner.
- Pontoon sides are in line with column sides.
- A central longitudinal bulkhead is located in each pontoon continuous into each column to achieve good structural continuity.
- Access tunnel is around the ring pontoon.
- Access shafts in all columns contain stairs, piping and cable racks.

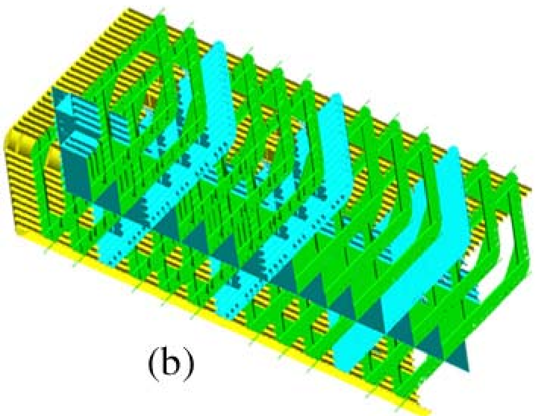
(a) (b)

a. General structural of columns and pontoon of Gjøa
b. Deck plate with stiffeners and girder of top plate.

Figure 1. 2: Layout of the hull structures (Ref. [1])

The most important part in this thesis is the pontoon top which will be shown with more details in the following text. Particularly, the dimension of pontoon as well as the inside structures (stiffeners, girders, transverse frames and the top plate) are illustrated in Figure 1.3.





a. Pontoon with the hull plate
b. Pontoon without bottom plate
c. Top plate of pontoon seen from bellow with yellow: girders; pink: water tight bulkheads; cyan: stiffeners; green: plate

Figure 1. 3: Detail structures of the pontoon (Ref. [1])

Obviously, the pontoon structure is indeed complex (Figure 1.3). It is assembled by a set of structural members such as stiffeners, bulkheads, girders and so on. The stiffeners are run continuously through the transverse frames (girders) and have equally spacing. The dimensions of the transverse frames are much larger than those of the stiffeners. Hence, the transverse frames could be assumed continuous. This means that the input of the transverse frames and the stiffeners are continuous in PULS and RP-C201 programs.

1.2.2 The size and dimension of stiffened panel on pontoon

From Figure 1.3 it can be seen that stiffeners and transverse frames are run continuously in the top of pontoon. However, there are interruptions in geometries between transverse frames and longitudinal bulkhead. However, in this thesis the girder will be assumed continuous during calculation procedure for stiffened plate as well as for girder check.

Table 1.3 shows the dimension of the stiffeners, stiffener spacing and plate thickness of the pontoon top (these dimensions are given by Aker Solutions).

Table 1. 3: Stiffener dimensions, spacing, span and plate thicknesses for Pontoon shell

Location	Stiffener [mm]	Plate thickness [mm]	Stiffener spacing [mm]	Stiffener span [mm]
Bottom	HP 340x12	20	625	3125
Deck	HP 320x12	16	625	3125
Side, lower	HP 340x12	20/25	625	3125
Side, upper	HP 320x12	20/25	625	3125

The size of the plate in the pontoon top is illustrated in Figure 1.4. The length of the pate is 43050mm the width is 17800mm. More detail of the top plate can be found in the Figure B3 in Appendix B.

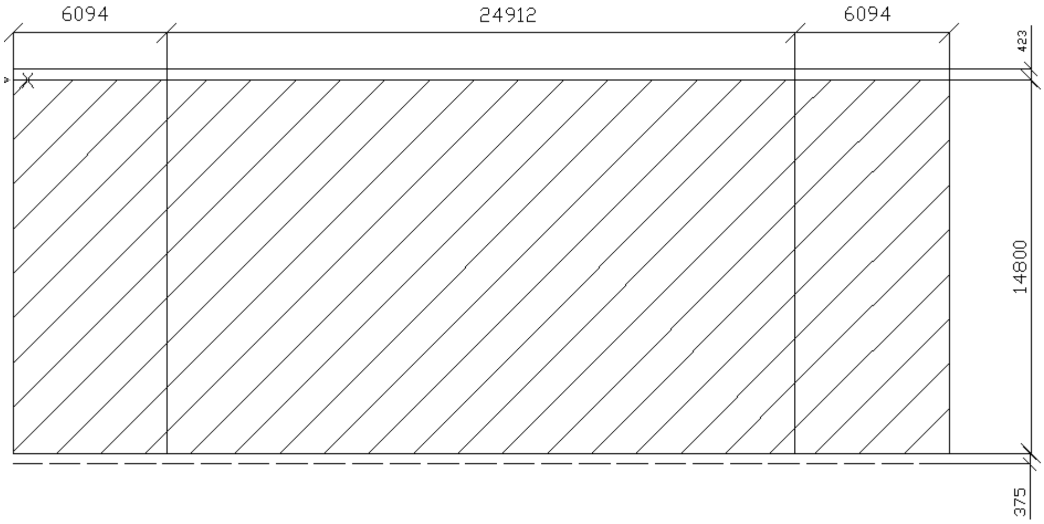


Figure 1. 4: The dimension of the deck plate of pontoon

Figure 1.5 illustrates of the scantlings of the stiffeners and the girders on the top plate of the pontoon (see Figure B3 and Figure B4 in the Appendix B for more details).

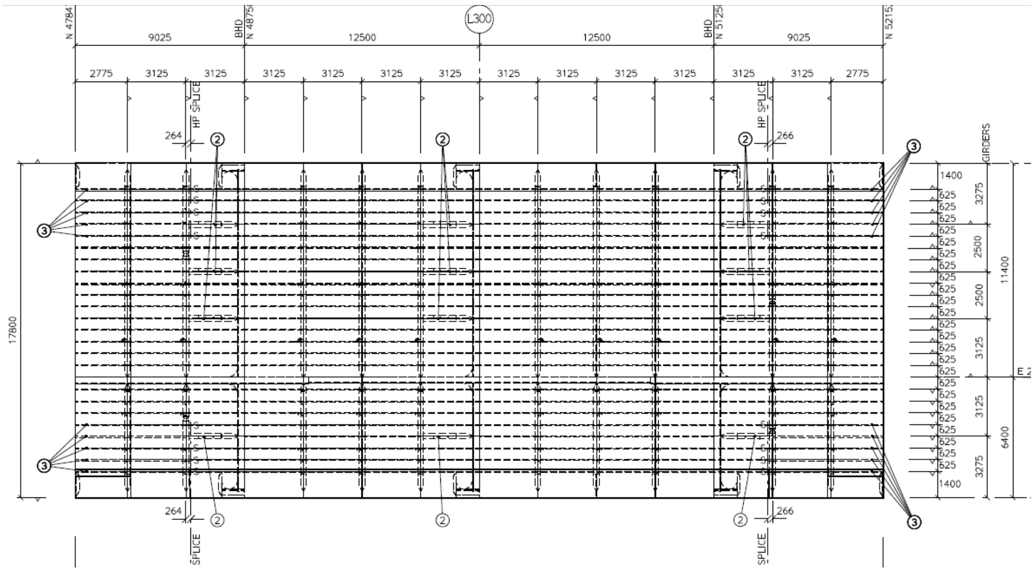


Figure 1. 5: Dimension of stiffened plate of the pontoon top

1.3 Global and local stress results from an operating condition

As provided by Aker Solutions, the design maximum compressive stresses appearing in the pontoon top are given in Table 1.4 below.

Table 1. 4: Maximum occurring stresses used for calculation

Maximum stresses [MPa]		
σ_x	σ_y	τ
-120	-77	80

During its operation, the top of pontoon is opposed to the lateral pressure from the sea. The lateral pressure is calculated as:

$$P_{ds} = 0{,}346 \text{ MPa}$$

Moreover, in the current stage of this thesis, the resulting usage factor (η) of 0.90 is used.

2 GENERAL THEORY FOR STIFFENED PLATES BUCKLING

2.1 Introduction

Stiffened plate is one of the common structural components in the marine structures. Typical examples are hull girder and superstructure of a ship, the pontoons of a semi-submersible and the deck or top of an offshore platform. In general, the top plate is subjected to a combined load such as hydrostatic pressure, shear force, and the biaxial in-plane loads which caused by the longitudinal bending of the hull girder and the hydrostatic pressure. An example of the stiffened plate under combined loads is shown in the Figure 2.1.

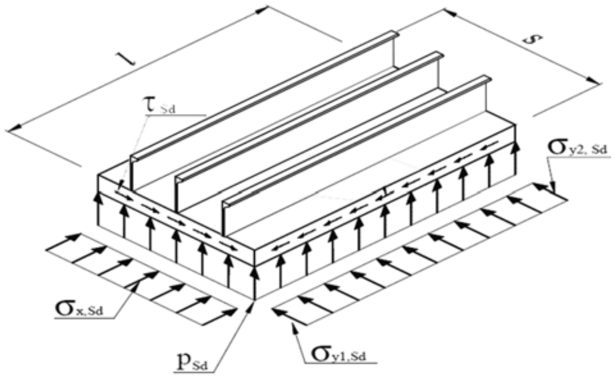


Figure 2. 1: Stiffened plate under combined loads (Ref. [3])

Figure 2.1 shows a stiffened plate under combined loads. $\sigma_{x,sd}$ is the axial load (considered as the uniformly distributed load); $\sigma_{y1,sd}$ and $\sigma_{y2,sd}$ are the transverse loads (maybe uniformly or linearly distributed loads); τ_{sd} is the shear stress and P_{sd} is the lateral pressure (this term is constant in PULS and RP-C201).

Nowadays, there are many available rules, codes and guidelines for buckling design of stiffened panels in the ship structures as well as for the offshore structures for example DNV (Standard N-003, Standard N-004, RP-C201, etc), ABS (ABS MODU Rules, ABS-126, ABS 127, ABS 130, etc). These rules are especially useful in quick design or quick calculation.

However, the simple design rules presently recommended by classification societies are not possible to handle the optimum design of stiffened panels, at least to my knowledge; particularly, if the designed load is the combinations of the compression in both longitudinal and transverse directions and lateral pressure. In this respect, this study proposes a simplified procedure in order to optimize the stiffened plate under these designed loads. The results of this procedure are then calibrated against numerical analysis which will be carried out in this report. The ultimate goal of this thesis is to develop a robust tool that can give the optimum design of the stiffened plate under this kind of designed load.

The formulation and theories discussed in this chapter is based mainly on [3], [4], chapter 3 of [5] and some parts from [6].

The stiffened plates under loading have been studied for decades and many methods are available in literature. In this section, only some of the well-known methods are mentioned.

2.2 DNV RP-C201 - Buckling strength of plated structures

2.2.1 General

This is a conventional buckling code for stiffened and unstiffened panels of steel. It is an update and development of the stiffened flat plate part of previous DNV Classification Note No. 30.1 “Buckling Strength Analysis”. Recommendations are given for plates, stiffeners and girders.

The structural stability shall be checked for the structure as a whole and for each structural member. Buckling strength analyses shall be based on the characteristic buckling strength for the most unfavorable buckling mode [3].

It is also noted that the DNV RP-C201 is also discussed in the NORSOK Standard N-004 although DNV RP- C201 is the update of the previous DNV Classification Note No. 30.1 “Buckling Strength Analysis” for stiffened flat plates. Therefore, these both standards shall be discussed together in this report.

Moreover, the characteristic resistance formulation given in this Standard will be discussed more detail in subsections of this chapter. Therefore, here is just general introduction of RP-C201.

2.2.2. Safety format and validity

This Recommended Practice is best suited to rectangular plates and stiffened panels with stiffener length being larger than the stiffener spacing (l >s). It may also be used for girders being orthogonal to the stiffeners and with the girder having significant larger cross-sectional dimensions than the stiffeners and Figure B1 in Appendix B is a reference for buckling check of plate.

The design check of the plated structures are generally performed with linear elastic finite element analyses for deformation of load effects. Linear finite element analyses will generally be adequate as long as the resistance is checked for the resultants from the integrated stresses in the analyses.

The RP-C201 document gives design recommendations to flat steel plate structures intended for marine structures. From Figure 2.2 the notation of plate panel elements are shown. The plate panel may be the web or the flange of a beam, or a part of box girders, bulkheads, pontoons, hull or integrated plated decks.

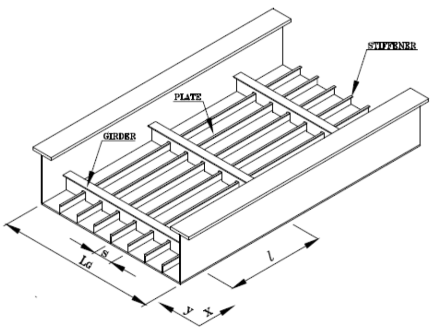


Figure 2. 2: Stiffened plate panel (Ref [3])

The methodology given in this section is only valid for webs and flanges that satisfy the requirements to cross section type III defined in Appendix A of [7].

This Recommended Practice is written in the load and resistance factor design format (LRFD format) to suit the DNV Offshore Standard DNV-OS-C101. This standard makes use of material (resistance) and load factors as safety factors. For the formulas used in this standard use a material factor, γ_m = 1.15. This is also different feature of this Standard as compare to PULS that will not give information about material factor.

2.3 Buckling of stiffened plates

2.3.1 Failure modes

According to [5] the possible failure modes of a stiffened panel under longitudinal compression may be classified as shown in the Figure 2.3.

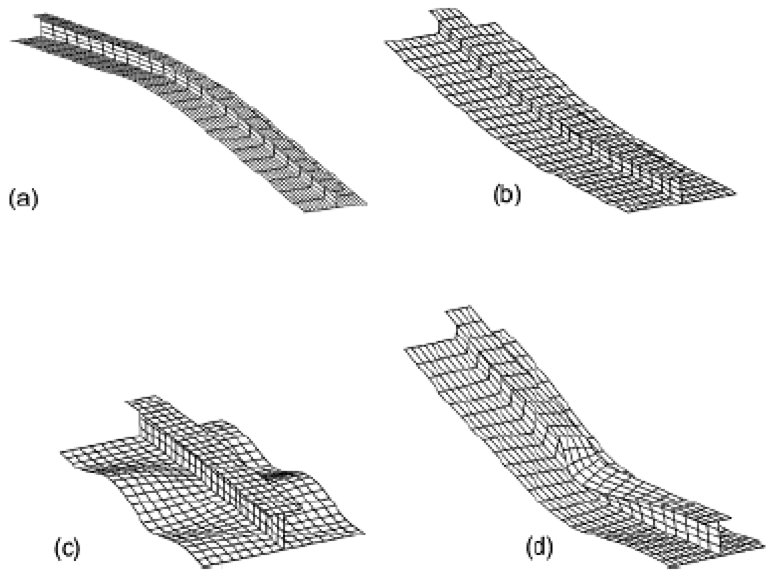


Figure 2. 3: The failure modes for stiffened panel under loading (Ref [5])

Plate buckling and ultimate collapse which means that the maximum plate load is exceeded and is followed by unloading of the plate. This leads to collapse of the stiffened panel before significant yield occurs in the stiffeners.

Interframe flexural buckling of the longitudinal stiffeners with associated plating. This type of failure involves yielding of the stiffeners, which is accelerated by loss of stiffness due to buckling or yielding of the plate.

Restrained torsional buckling of stiffeners, which is due to elastic or elasto-plastic loss of stiffness depending on the slenderness of the stiffeners, the rotational restraint provided by the plating and the initial out-of-shape.

Overall grillage buckling which involves bending of transverse girders as well as longitudinal stiffeners.

Most structures are designed to prevent overall grillage buckling. Therefore, this failure mode is unlikely except for lightly stiffened panels found in superstructure decks.

Besides, according to [8] the primary modes of overall failure for a stiffened panel subject to predominantly compressive loads may be categorized into the following six modes as shown in Figure 2.4.

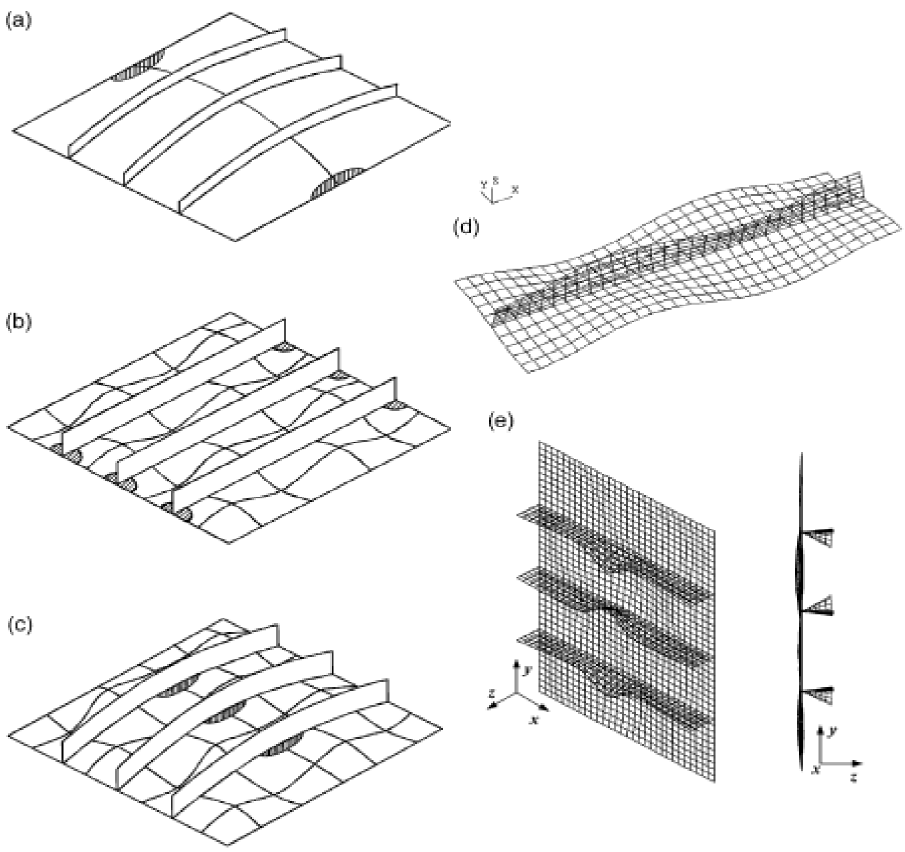


Figure 2. 4: Failure modes of stiffened plate subjected to loading [Ref 8]

From the Figure 2.4 (a). Mode I: Overall collapse after overall buckling of the plating and stiffeners as a unit. (b). Mode II: Plate-induced failure by yielding at the corners of plating between stiffeners. (c). Mode III: Plate-induced failure by yielding of plate–stiffener combination at mid-span. (d). Mode IV: Stiffener induced failure by local buckling of the stiffener web. (e). Mode V: Stiffener-induced failure by lateral–torsional buckling of stiffener. The characteristic of each mode has been described detail in [8].

2.3.2 Ideal Elastic-Plastic Strut Analysis

An approximate solution for the collapse load is given by intersection point of the load deflection curves calculated for an ideal elastic column and a perfectly plastic column. The elastic load-deflection curve for a pinned beam-column with a sinusoidal initial deflection of amplitude δ_o is given by:

$$\delta_e = \delta_0 \left(1 - \frac{N}{N_E}\right)^{-1} \tag{2.1}$$

Where N_E is the Euler buckling load.

This solution along with the plastic solution for bending towards the plate that is expressed as

$$\delta_p = \frac{M}{N} \tag{2.2}$$

Where the bending moment, *M*, and the axial force, *N*, must satisfy the plastic interaction curve of the cross-section. This depends on the direction of bending [5].

These Equations are plotted in Figure 2.5 and the collapse load is interpreted as the intersection between the two curves, are shown to agree well with results from finite element analysis.

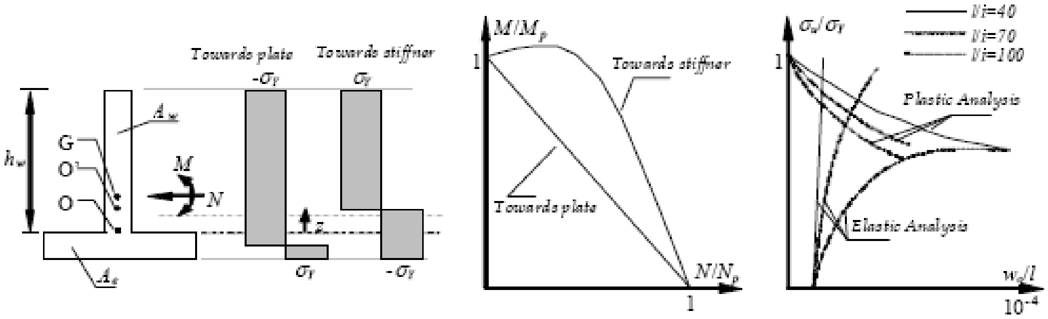


Figure 2. 5: Elastic-Plastic Strut Analysis of Plate-Stiffener (Ref [5])

2.3.3 Effective Width Method

This method is proposed by Faulkner that is based on the elastic critical load for a strut with pinned ends.

$$\sigma_E = \frac{\pi^2 E I_e}{l^2 (A_w + A_e)} \tag{2.3}$$

Modified for plasticity according to the Johnson-Ostenfield formulation

$$\frac{\sigma_E}{\sigma y} = 1 - \frac{\bar{\lambda}^2}{4} \qquad with\ \bar{\lambda}^2 \leq 2 \quad (2.4)$$

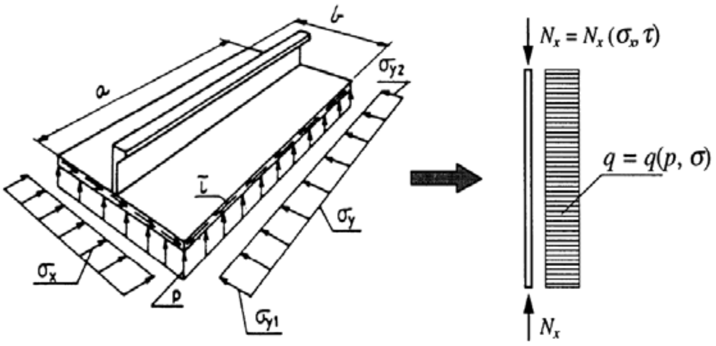
The effective moment of inertia of the stiffener is calculated for a tangent (reduced) effective width of the plate given by

$$\frac{b_e}{b} = \frac{1}{b}\sqrt{\frac{\sigma_y}{\sigma_e}} \tag{2.5}$$

Where σ_e is the edge stress. More detail about this method was described in chapter 3 of [5].

2.4 Buckling of Stiffeners according to DNV RP-C201

According to [3] the plate stiffener is modeled as a beam-column subjected to equivalent axial force and a lateral line load as shown in Figure 2.6.



(a) *Stiffened plate* (b) *Beam-column*

Figure 2. 6: A beam-column of the stiffened plate (Ref [5])

2.4.1 Equivalent load effects

Stiffened plates subjected to combined forces (see Figure 2.6) should be designed to resist an equivalent axial force that is given as:

$$N_{sd} = \sigma_{x,Sd}(\mathrm{A} + \mathrm{st}) + \tau_{tf}\, st \tag{2.6}$$

Where A : is cross-sectional area of stiffener

s : distance between stiffeners

t : plate thickness

$\sigma_{x,Sd}$: axial stress in plate and stiffener (compressive stresses as positive). This is also the requirement to input the value of stresses in RP-C201 and PULS program.

τ_{tf} : is the tension field action that is found from Eq. (7.2) of [3] for $\tau_{Sd} > \frac{\tau_{crl}}{\gamma_m}$

And $\tau_{tf} = 0$ for other cases, this is also the case that is used in calculation for RP-C201 and PULS in this thesis, i.e. the stiffened plate under combine load with compression in plane, shear force and lateral pressure without the tensile field will be analyzed.

And resist an equivalent lateral load that is determined from

$$q_{Sd} = (P_{Sd} + P_0).s \tag{2.7}$$

Where P_{Sd}: lateral design load

s: stiffener spacing

P_0: is determined from Eq. (7.9) and (7.10) of [3]

For situations where P_{Sd} is less than P_0, the stiffener need to be checked for P_0 applied in both directions

2.4.2 Effective plate width

The effective plate width for a continuous stiffener subjected to longitudinal and transverse stress and shear is calculated as:

$$\frac{s_e}{s} = C_{xs} C_{ys} \tag{2.8}$$

Where C_{xs}: reduction factor due to stress in longitudinal that is determined by Eq. (7.14) of [3]

C_{ys}: reduction factor due to stresses in transverse direction that is determined from (7.16) of [3] for compression and Eq. (7.17) for tension.

2.4.3 Lateral loaded plates and resistant of plate between stiffeners

From [5], there are two methods are mainly used for the buckling assessment of the plate: differential equilibrium equation and applying energy methods.

The equilibrium equation is given by Eq. (2.9).

$$\nabla^4 w = \frac{1}{D}\left(q + N_x \frac{\partial^2 w}{\partial x^2} + 2N_{xy} \frac{\partial^2 w}{\partial x \partial y} + N_y \frac{\partial^2 w}{\partial y^2} \right) \tag{2.9}$$

Where D is the plate stiffness, $N_x=\sigma_x t$, $N_y=\sigma_y t$, $N_z=\sigma_z t$ are the membrane stresses.

The Equation (Eq.) (2.9) is described more detail in chapter 3 of [5].

Alternatively, the energy methods can also be used to predict the critical load. This method depends on the selected displacement functions so that at least the principal boundary conditions should be satisfied. The total potential energy has the form as shown in Eq. (2.10)

$$\Pi = U + H \tag{2.10}$$

Where U is the elastic strain energy caused by bending deformation of the plate at critical load, H is the external compression load. More details of U and H can be found in Eq. (3.8) and Eq. (3.10) in chapter 3 of [5].

According to [3] for the plates subjected to the lateral pressure, either alone or in combination with in-plane stresses, design lateral pressure is given in Eq. (2.11).

$$P_{Sd} \le 4.0 \frac{\sigma_y}{\gamma_M} (\frac{t}{s}) \left[\psi_y + \left(\frac{s}{l} \right)^2 . \psi_x \right] \quad (2.11)$$

Where - P_{Sd} : design lateral pressure

- ψ_x and ψ_y : the factors that are calculated by Eq. (5.2) Eq. (5.3) of [3].

The stresses may be checked by the following formula

$$\sigma_{j,Sd} = \sqrt{\sigma_{x,Sd}^2 + \sigma_{y,Sd}^2 - \sigma_{x,Sd}.\sigma_{y,Sd} + 3\tau_{Sd}^2} \quad (2.12)$$

The Eq. (2.12) is for the design of a plate subjected to lateral pressure is based on yield-line theory, and accounts for the reduction of the moment resistance along the yield-line due to applied in-plane stresses. The reduced resistance is calculated based on von Mises' equivalent stress.

Due to the formula does not take account of second-order effects, plates subjected to compressive stresses shall also fulfill the requirements of buckling check for unstiffened plates as well as for stiffened plates.

Besides, the plate between stiffeners will normally be checked implicitly by the stiffener check since plate buckling is accounted for by the effective width method. However, in cases where $\sigma_{y,Sd}$ stress is the dominant stress it is necessary to check the plate resistance according to Eq. (2.13).

$$\sigma_{y,Sd} \le k_{sp}.\sigma_{y,Rd} \quad (2.13)$$

Where factor k_{sp} that is determined by Eq. (7.20) and $\sigma_{y,Rd}$ is found from Eq. (6.5) of [3]

2.4.4 Characteristic buckling strength of stiffeners

The characteristic buckling strength (σ_k) for stiffeners is determined

$$\frac{\sigma_k}{\sigma_r} = \frac{1+\mu+\bar{\lambda}^2 - \sqrt{\left(1+\mu+\bar{\lambda}^2\right)^2 - 4\bar{\lambda}^2}}{2\bar{\lambda}^2} \qquad \text{When } \bar{\lambda} > 0.2 \qquad (2.14)$$

$$\frac{\sigma_k}{\sigma_r} = 1 \qquad \text{When } \bar{\lambda} \le 0.2 \qquad (2.15)$$

The reduced slenderness is given as:

$$\bar{\lambda} = \sqrt{\frac{\sigma_r}{\sigma_E}} \qquad \text{with} \qquad \sigma_E = \pi^2 E \left(\frac{i_e}{l_e}\right)^2 \qquad (2.16)$$

For check at plate side σ_r is taken as σ_y.

For check at stiffener side if $\bar{\lambda}_T \le 0.6$, σ_r is taken as σ_y. Inverse case, if $\bar{\lambda}_T > 0.6$, σ_r is taken as σ_T; where σ_T is torsional buckling strength of stiffeners.

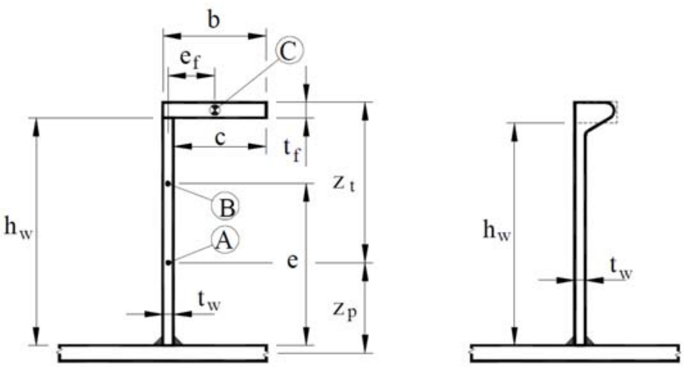
For check at plate side a parameter μ is defined

$$\mu = \left(0.34 + 0.08\frac{Z_p}{i_e}\right)\left(\bar{\lambda} - 0.2\right) \qquad (2.17)$$

For check at stiffener side this parameter is:

$$\mu = \left(0.34 + 0.08\frac{Z_t}{i_e}\right)\left(\bar{\lambda} - 0.2\right) \qquad (2.18)$$

Where Z_p and Z_t are defined as in the Figure 2.7



A = centroid of stiffener with effective plate flange.
B = centroid of stiffener exclusive of any plate flange.
C = centroid of flange.

Figure 2. 7: Cross section parameter for stiffeners and girders (Ref [3])

According [5] the effective radius of gyration is defined by

$$i_e = \sqrt{\frac{I_e}{A + b_e.t}} \quad (2.19)$$

The effective moment of inertia can be written as

$$I_e = I + e^2.A\left(1 + \frac{A}{b_e t}\right)^{-1} \quad (2.20)$$

Where *e* is the eccentricity of the stiffener (without plate flange) to the plate flange, (refer Figure 2.7), I is the moment of inertia of the stiffener without plate flange, b_e is the effective width the plating calculated as described in Section 2.3.3, and t is the plate thickness.

Besides, following [5] for plate induced failure there is a shift of the neutral axis due to loss of effective width. This causes an extra eccentricity for the plate/stiffener which has to be taken into account. This is illustrated in Figure 2.8.

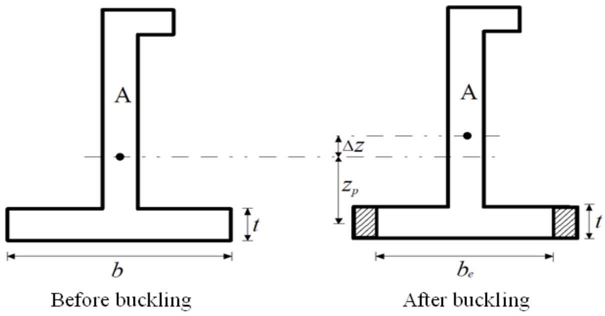


Figure 2. 8: Shift of effective neutral axis after plate buckling (Ref [5])

This shift of neutral axis is calculated as:

$$\Delta z = z_p \frac{(b - b_e)t}{A + bt} = z_p\left(1 - \frac{A + b_e t}{A + bt}\right) \quad (2.21)$$

The effective buckling length depends on the lateral pressure. When buckling without lateral pressure occurs, the effective length is assumed equal to frame spacing. If the lateral pressure appears, there are two failure modes need to be taken into account, namely asymmetric buckling and symmetric buckling with respect to the frame (see Figure 2.9).

Generally, the over-pressure may be on either the plate side or the stiffener side. This yields four potential buckling modes as shown in Figure 2.9.

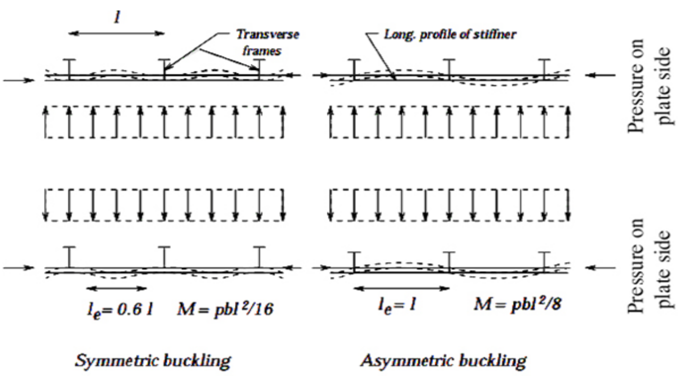


Figure 2. 9: The failure modes of plate according to later pressure (Ref [5])

2.4.5 Interaction equations for combined axial compression and lateral pressure

When stiffeners are under combined axial compression and bending forces, two failure modes that need to be estimated are:

i) Combined axial compression and bending on the compression side.

ii) Combined axial compression and bending on the tension side.

If the lateral pressure is acting on the plate side (Figure 2.10), the failure mode (i) is checked at points 1 and 4 while the failure mode (ii) is checked at points 2 and 3.

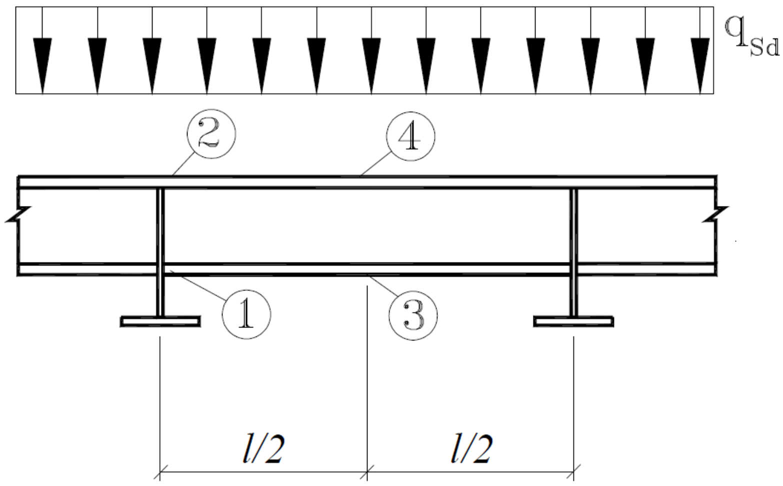


Figure 2. 10: Check- Points for interaction equations (Ref [3])

Corresponding to the cases which lateral pressure acting on the plate side, the following equations need to be fulfilled according to four checked points.

For checking at points 1 and 2, i.e. at support the interaction formulas are given by

On stiffener side
$$\frac{N_{Sd}}{N_{Ks,Rd}} + \frac{M_{1,Sd} - N_{Sd}.z^*}{M_{S1,Rd}(1 - \frac{N_{Sd}}{N_E})} + u \le 1 \quad (2.22)$$

On plate side
$$\frac{N_{Sd}}{N_{kp,Rd}} - 2.\frac{N_{Sd}}{N_{Rd}} + \frac{M_{1,Sd} - N_{Sd}.z^*}{M_{p,Rd}\left(1 - \frac{N_{Sd}}{N_E}\right)} + u \le 1 \quad (2.23)$$

For checking points 3 and 4, i.e. at mid-span of stiffener, the interaction formulas are given

On the plate side
$$\frac{N_{Sd}}{N_{ks,Rd}} - 2.\frac{N_{Sd}}{N_{Rd}} + \frac{M_{2,Sd} + N_{Sd}.z^*}{M_{st,Rd}\left(1 - \frac{N_{Sd}}{N_E}\right)} + u \le 1 \quad (2.24)$$

On stiffener side
$$\frac{N_{Sd}}{N_{Kp,Rd}} + \frac{M_{2,Sd} + N_{Sd}.z^*}{M_{p,Rd}(1 - \frac{N_{Sd}}{N_E})} + u \le 1 \quad (2.25)$$

For checking at point 1, i.e. at the support on stiffener side the value of N.z* is negative and positive sign for N.z* as check for the point 4, i.e. at the middle of stiffener on plate side.

Where N_{cr} is critical axial force ($N_{cr}=\sigma_{cr}.A$)

M is the moment ($M = \frac{1}{12}ql^2$ at stiffener supports and $M = \frac{1}{24}ql^2$)

M_{cr} is assumed equal to the first yield moment of the plate flange.

With negative value of N.z* is used as check for point 2, i.e. at the support on the plate side and positive value of N.z* is used as check for point 3, i.e. at the middle of stiffener on stiffener side.

Where $N_Y = \sigma_Y A_e$ is the yield force of the effective cross-section

$Ncr = \sigma crAe$ is the critical stress for pure axial compression

A_e is the effective area of stiffener and plate

For the case lateral pressure acting on stiffener side, the stresses change sign and the Equations (7.54) to (7.57) of [3] shall be used. However, this is not the case in this report, thus it will not mention here.

Optimized z*: As seen in Equations (2.22) to (2.25), z* is denoted as a working point, this means that distance from the applied force to the neutral axis. Together with this distance, a moment induced by the axial force will resist with that of later pressure. Moreover, the maximum resistance of the stiffened panel can also be found from the eccentricity z* (see Figure 2.11).

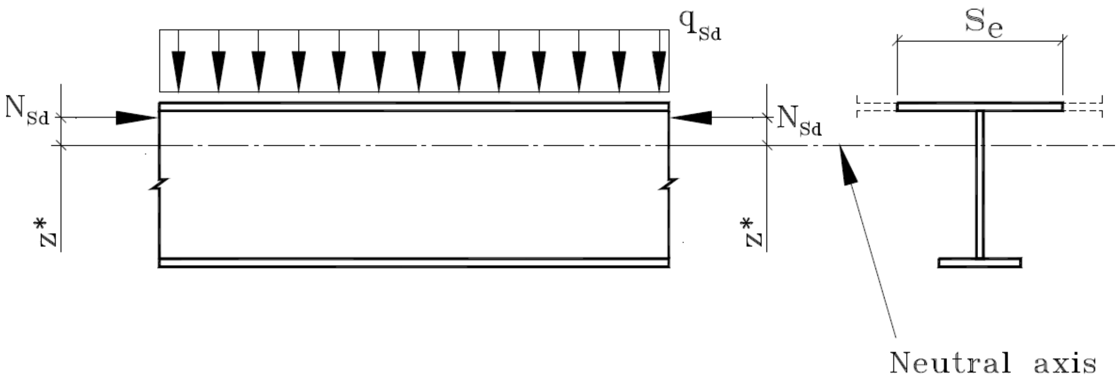


Figure 2. 11: Definition of z*- positive value is shown (Ref [3])

The maximum capacity can be found with respect to z* when the largest utilization ratio found for the four equations is at its minimum. This means that the minimum utilization will be obtained where the curves for utilization at mid span and support intersects. Besides, according to [5] if the eccentricity is neglected (z* = 0), one of the utilizations will be larger. Hence, it is always conservative to neglect the eccentricity.

Figure 2.12 shows that the largest value of utilization ratio is obtained at the intersection of check point 1 and check point 4.

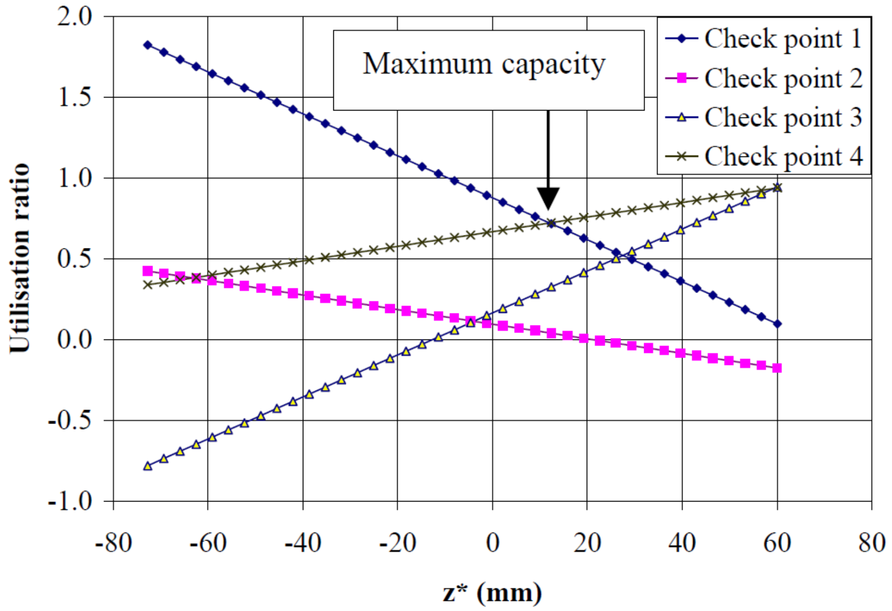


Figure 2. 12: Utilization ratios for the four interactions (Ref [3])

The second check is performed on the tension side of the stiffener in bending. Failure is based on linear interaction between utilization with respect to buckling and yielding, respectively.

If the stiffener is stocky, with a critical stress in the range of the yield stress, the first term is zero or negligible. Hence, pure tensile yielding is governing. For slender stiffeners, the first term becomes significant and reduces the allowable utilization in bending. The second term represents the utilization with respect to tensile yielding, and the compressive stress from the axial force must be subtracted.

2.5 Buckling of girder

2.5.1 General

The resistance of girders is in NORSOK N-004/DnV RPC201 calculated in the same manner as stiffeners. The effective flange of the girder l_e, needs to be estimated; see Figure 2.13.

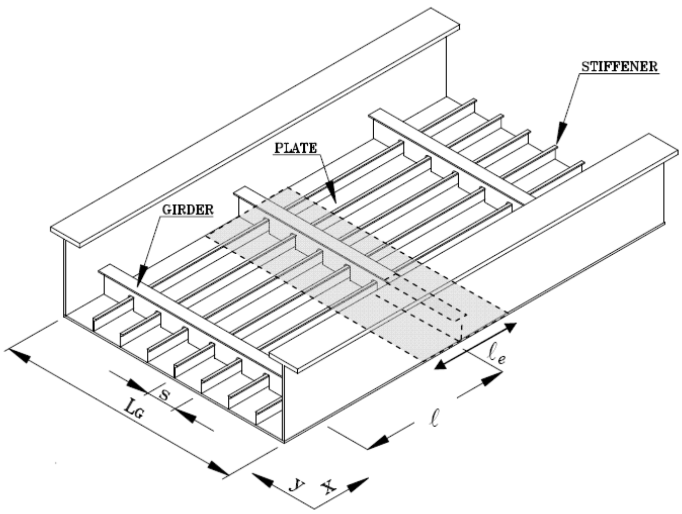


Figure 2. 13: Effective plate flange for girder

This means that the check for girders is similar to the check for stiffeners of stiffened plates in Equations (7.50) to (7.57) or (7.59) to (7.64) of [3] for continuous or sniped girders, respectively.

2.5.2 Girder forces

Forces shall be calculated according to Section 8.2 of [3], the axial force should be taken as Eq. (2.26).

$$N_{y,Sd} = \sigma_{y,Sd}\left(l.t + A_G\right) \quad (2.26)$$

Where l : girder spacing

A_G : cross section area of girder

t : thickness

The lateral line load should be determined in Eq. (2.27)

$$q_{Sd} = (p_{Sd} + p_0).l \quad (2.27)$$

Where P_{Sd}: design lateral pressure

P_0: equivalent lateral pressure

2.5.3 Effective widths of the girders

The effective width for the plate of the girder is taken as Eq. (2.28).

$$\frac{l_e}{l} = C_{xG}.C_{yG}.C_{\tau G} \tag{2.28}$$

For the determination of the effective width, there are two options denoted method 1 and method 2. These methods are described as bellow:

a) Method 1

Calculation of the girder by assuming that the stiffened plate is effective against transverse compression (σ_y) stresses. This means that the stiffener and plate should be checked for the σ_y stresses imposed by the bending of the girder.

In this method the effective width factors C_{xG} and $C_{\tau G}$ are determined follow Eq. (8.19) and Eq. (8.22) of [3], while factor $C_{yG} = 1$.

b) Method 2

Calculation of the girder by assuming that the stiffened plate is not effective against transverse compression stresses (σ_y). In this case the plate and stiffener can be checked with σ_y stresses equal to zero.

In this method the effective width for the girder should be calculated as if the stiffener was removed. This means that the σ_y stresses imposed by the bending of the girder can be neglected when checking plate and stiffener.

2.6 Buckling Strength of the Plated Structure – PULS Buckling Code

2.6.1 General

Buckling of thin-walled stiffened plates is a non-linear phenomenon. However, from a global hull strength perspective, practical design procedures have to be based on linear elastic structural stress analyses with separate buckling checks of local elements. Such linearized design procedures are well established today [9].

In order to provide such a design procedure it is essential that the buckling model describe as closely as possible the real non-linear structural behavior. To accomplish such a task, a new computerized buckling procedure called Panel Ultimate Limit State (PULS) is proposed.

The model is based on an orthotropic version of Marguerre's non-linear plate theory. By using non-linear plate theory, the strength model is more theoretically consistent than existing code formulations, which are mainly based on empirical curve fitting to a limited number of numerical and experimental results [10]. Complicated items such as biaxial loading combined with in-plane shear loads and nonlinear mode interaction problems are dealt with in a sound physical framework, and empirical approximations are reduced to a minimum.

Computerized buckling codes like present PULS model has obvious benefit of predicting more closely real non-linear structural behavior than existing rules and guidelines. This gives an improved basis for weight optimizations, together with a more consistent control of safety margin against failure [9]. It also provides additional valuable information, i.e. typically buckling mode shapes, elastic buckling and failure boundaries in load space, stress distributions and stiffness properties.

The program's procedure is a simplified non-linear buckling model for assessing strength of integrated hull elements [4].

Nowadays, it is developed for integrated stiffened flat panels as typically found in ship hulls between frames and girders. It gives strength information at two levels:

i. Elastic buckling and design ultimate capacity of stiffened panels.

ii. Reduced stiffness properties of compressed and buckled panels.

PULS program including three elements, namely unstiffened plate element (U3), stiffened panel element (S3), stiffened plate element (T1). However, due to the task of thesis will be worked with the module (S3), the stiffened plate element (S3) in PULS is mainly focused to introduce in this report.

2.6.2 Theoretical background

The buckling mode in PULS program is based on the orthotropic version of Von Karman and Marguerre's geometric nonlinear plate theories. The Eq. (2.29) shows the relationship between membrane strain and displacement [11].

$$
\begin{aligned}
\varepsilon_{11} &= u_{1,1} + \tfrac{1}{2}W_{,1}^{2} + W_{,1}W_{0,1} \\
\varepsilon_{22} &= u_{2,2} + \tfrac{1}{2}W_{,2}^{2} + W_{,2}W_{0,2} \\
\varepsilon_{12} &= \tfrac{1}{2}(u_{1,2} + u_{2,1}) + \tfrac{1}{2}(W_{,1}W_{,2}) + \tfrac{1}{2}(W_{,1}W_{0,2} + W_{,2}W_{0,1})
\end{aligned}
\qquad (2.29)
$$

i ii

Here, the term (i) represents Von Karman theory for perfect plate while term (ii) shows Margurre theory for the imperfect plate. Besides, the PULS procedure is based on six-dimensional orthotropic macro material law as shown in Figure 2.14.

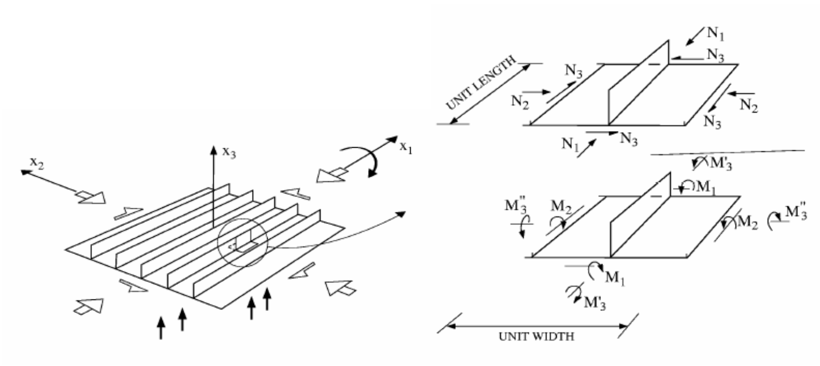


Figure 2. 14: Six-dimensional macro model for stiffened panel (Ref [4])

According to the non-linear plate theory, this macro material law takes the form of an incremental relation between the in-plane loads (N_1 ,N_2 ,N_3) and moments (M_1 ,M_2 ,M_3), and the corresponding strains (ε_1,ε_2,ε_3) and curvatures (k_1,k_2,k_3) of the continuous plating. In mathematical terms the orthotropic macro material law takes the following form as bellow:

$$
\begin{bmatrix} \Delta N1 \\ \Delta N2 \\ \Delta N3 \\ \Delta M1 \\ \Delta M2 \\ \Delta M3 \end{bmatrix}
=
\begin{bmatrix}
C_{11} & C_{12} & C_{13} & Q_{11} & Q_{12} & Q_{13} \\
C_{21} & C_{22} & C_{23} & Q_{21} & Q_{22} & Q_{23} \\
C_{31} & C_{32} & C_{33} & Q_{31} & Q_{32} & Q_{33} \\
Q_{11} & Q_{21} & Q_{31} & D_{11} & D_{12} & D_{13} \\
Q_{12} & Q_{22} & Q_{32} & D_{21} & D_{22} & D_{231} \\
Q_{13} & Q_{23} & Q_{33} & D_{31} & D_{32} & D_{33}
\end{bmatrix}
\begin{bmatrix} \Delta\varepsilon_{1} \\ \Delta\varepsilon_{2} \\ \Delta\varepsilon_{3} \\ \Delta K_{1} \\ \Delta K_{2} \\ \Delta K_{3} \end{bmatrix}
\qquad (2.30)
$$

Where symbol Δ denotes incremental quantities. Each of the coefficients in the stiffness matrix has two contributions, i.e. linear part and nonlinear part. In the PULS code it is defined as a set of reduced orthotropic macro stiffness coefficients:

$$\begin{aligned} C_{\alpha\beta} &\equiv C^L_{\alpha\beta} + C^N_{\alpha\beta} \\ D_{\alpha\beta} &\equiv D^L_{\alpha\beta} + D^N_{\alpha\beta} \\ Q_{\alpha\beta} &\equiv Q^L_{\alpha\beta} + Q^N_{\alpha\beta} \end{aligned} \tag{2.31}$$

Where α and β are coefficients that ranging in [1÷3]. The linear part is denoted by the superscript L while the superscript N indicates the non-linear part. Besides, the non-linear corrections, $C^N_{\alpha\beta}, D^N_{\alpha\beta}, Q^N_{\alpha\beta}$ are assessed by using a numerical procedure.

The macro model stiffness relation is written on sub-matrix notation as:

$$\begin{bmatrix} N \\ M \end{bmatrix} = \begin{bmatrix} C & Q \\ Q^T & D \end{bmatrix} \begin{bmatrix} \varepsilon \\ k \end{bmatrix} \quad \Leftrightarrow \quad \begin{bmatrix} \varepsilon \\ k \end{bmatrix} = \begin{bmatrix} M & S \\ S^T & F \end{bmatrix} \begin{bmatrix} N \\ M \end{bmatrix} \tag{2.32}$$

The resulting uncoupled moment-curvature relation is defined as:

$$M = \widetilde{D}k \tag{2.33}$$

Where $\widetilde{D}$ is the neutral orthotropic bending stiffness matrix and defined as:

$$\widetilde{D} = D - \left[(Q)^T (C)^{-1} Q \right] \tag{2.34}$$

2.6.3 Design principles

The design principle should be found from some basic designed document and for the PULS's design application is based on the three main principles [4].

i. Elastic local buckling of any of the component plates in a panel section is accepted, i.e. accept the elastic buckling deflections.

ii. Permanent buckles are not accepted, i.e. do not accept permanent buckles in plate.

iii. Global (overall) buckling of the panel is not accepted, i.e. to ensure strong stiffeners.

2.6.4 Local Eigenvalue (LE)

For the stiffened panel there are three typical local buckling modes are plate buckling, torsional stiffener buckling, stiffener web plate buckling interaction with plate buckling.

The values for in-plane stresses at instant where local elastic buckling starts are indicated as

$$\begin{aligned} \sigma_{1LE} &= \Lambda_{LE}\sigma_{10} \\ \sigma_{2,1LE} &= \Lambda_{LE}\sigma_{20,1} \\ \sigma_{2,2LE} &= \Lambda_{LE}\sigma_{20,2} \\ \sigma_{3LE} &= \Lambda_{LE}\sigma_{30} \end{aligned} \qquad (2.35)$$

Where Λ_{LE} is the eigenvalue of the load proportionality parameter L calculated by the program. The values of σ_{1LE}, $\sigma_{2,1LE}$, $\sigma_{2,2LE}$, σ_{3LE} are called the local elastic buckling stresses under a combined load situation.

The local plate/stiffener deflection is indicated by the Eq. (2.36).

$$w_l(x,y) = \sum_{m=1}^{Ms}\sum_{n=1}^{Ns} A^s_{mn} \sin\left(\frac{m\pi x}{a}\right)\sin\left(\frac{n\pi y}{b}\right) \qquad (2.36)$$

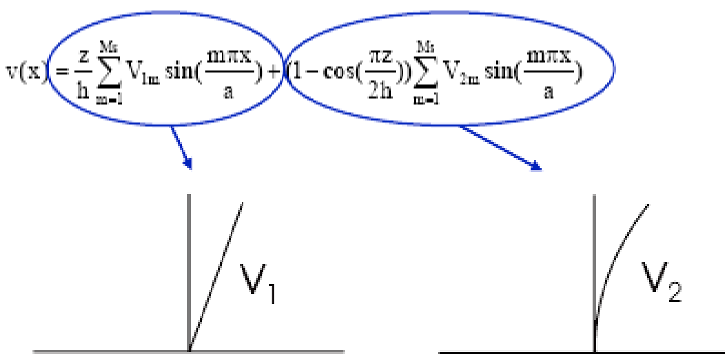


Figure 2. 15: Deflection of the stiffener (Ref [11])

2.6.5 Global level

Global buckling is associated with an overall mode lifting the stiffeners out-of-plane together with the continuous plating assuming lateral support along all four outer edges.

The global eigenvalues are found by scaling the simultaneously combined loads σ_{10}, $\sigma_{20,1}$, $\sigma_{20,2}$, σ_{30} in proportion until global buckling takes place. The global buckling loads are accordingly

$$\begin{aligned}\sigma_{1GE} &= \Lambda_{GE}\sigma_{10}\\ \sigma_{2,1GE} &= \Lambda_{GE}\sigma_{20,1}\\ \sigma_{2,2GE} &= \Lambda_{GE}\sigma_{20,2}\\ \sigma_{3GE} &= \Lambda_{GE}\sigma_{30}\end{aligned} \tag{2.37}$$

Where Λ_{GE} is the global eigenvalue (GE) of the load, parameter Λ is found by the program. The nominal stresses σ_{1GE}, $\sigma_{2,1GE}$, $\sigma_{2,2GE}$, σ_{3GE} are called the global elastic buckling stresses under a combined load situation.

The eigenvalue problem is formulated as

$$(\mathrm{K} - \Lambda \mathrm{K}_g)\mathrm{q} = 0 \tag{2.38}$$

The global/lateral deflection of the panel is illustrated by Eq. (2.39).

$$w_g(x,y) = \sum_{m-1}^{M_S}\sum_{n-1}^{N_S} A_{mn}^S \sin\left(\frac{m\pi x}{a}\right)\sin\left(\frac{n\pi y}{b}\right) + \sum_{m-1}^{M_C}\sum_{n-1}^{N_C} \frac{A_{mn}^C}{2}\left(1-\cos\left(\frac{2m\pi x}{a}\right)\right)\sin\left(\frac{n\pi y}{b}\right) \tag{2.39}$$

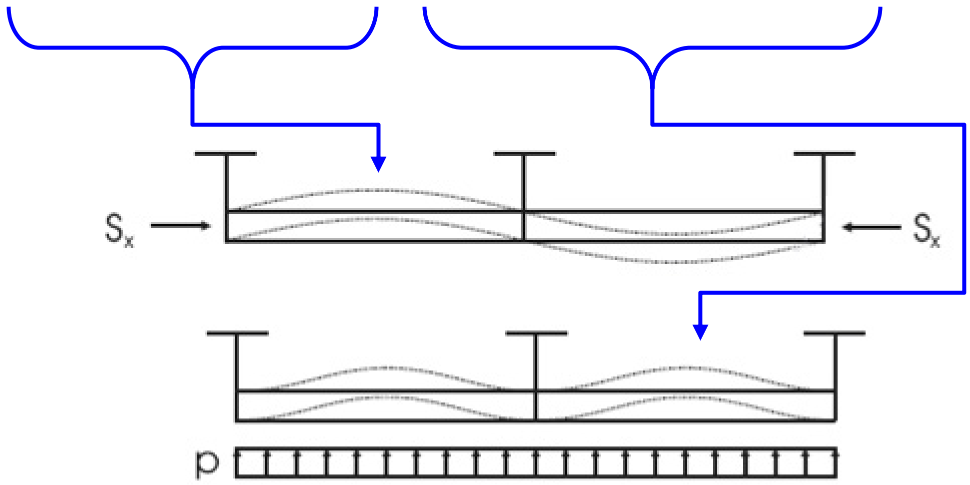


Figure 2. 16: Lateral deflection of the panel (Ref [11])

2.6.6 Stress limit states

According to the DNV user manual PULS, the limit state evaluations are based on the redistributed membrane stress distributions within the stiffened panel. Membrane stresses in this context means stresses in the middle-plane of the thin-walled component plates (plating, stiffener web, stiffener flange) upon which the stiffened panel is built.

The current PULS version apply six limit state functions f_i's (i = 1÷6) for identifying critical conditions in different locations in the panel. The six limit states are formulated for capturing critical stress conditions in selected critical positions:

$$f^{(i)}(N_1, N_2, N_3) > 0 \quad \Rightarrow \text{acceptable} \qquad (2.40)$$

If $f^{(i)}(N_1, N_2, N_3) > 0$, i.e. at the limit state, each of limit state functions describe a surface in load space (N_1, N_2, N_3). And we can see more detail in the Figure 2.17.

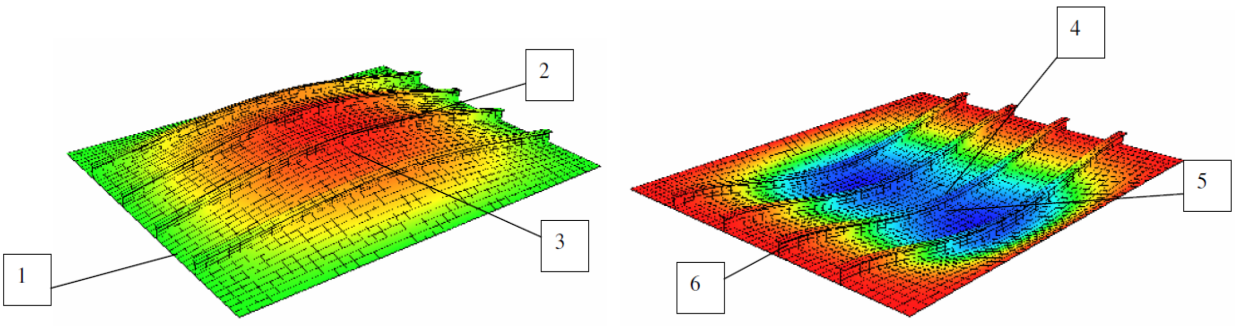


Figure 2. 17: Stress control point in critical positions (Ref [4])

Figure 2.17 indicates six limit states which each value of i indicates one case of loading as follows:

i = 1; **Plate criterion**: Stress control along plate edges – based on max edge stresses along supported edges.

i = 2; **Stiffener tension criterion**: Stress control in stiffener; at mid span $x_1 = L_1/2$; in stiffener flange for global panel deflecting towards stiffener flange, tension criterion - rare for compressive loads, but kicks in for tension loads.

i = 3; **Plate compression criterion**: Stress control in plate; at mid span $x_1 = L_1/2$; in plating for global panel deflecting towards stiffener flange, compression criterion.

i = 3; **Stiffener compression criterion**: Stiffener criterion Stress control in stiffener; at mid span $x_1 = -L_1/2$: in stiffener flange for global panel deflecting towards plating, compression criterion.

i = 5; **Plate tension criterion**: Stress control in plate; at mid span $x_1 = -L_1/2$; in plating for global panel deflecting towards plating, tension criterion.

i = 6; **Stiffener bending stress criterion at support**: Stress and capacity control at support $x_1=0$; compressive or tension criterion, kicks in for cases with lateral pressure. This limit state is used to control the bending and shear capacity of the stiffeners under the influence of combined lateral load and in-plane loads.

2.6.7 Safety margin

The usage factor η calculated in PULS represents the ratio between the applied -loads and the corresponding ultimate strength (see Eq. (2.41)). The acceptable criterion is $\eta \le \eta_{allow}$, where η_{allow} (also $\eta_{\max}$) is determine from the rule.

$$\eta = \frac{L_0}{L_u} \tag{2.41}$$

Where L_0 and L_u are radius vectors in the load space and defined as (see Figures 2.18)

$$L_u = \sqrt{\left(\sigma_{1u}^2 + \sigma_{2u}^2 + \sigma_{3u}^2\right)} \tag{2.42}$$

And L0 is determined by Eq. (2.43).

$$L_0 = \sqrt{\left(\sigma_{10}^2 + \sigma_{20}^2 + \sigma_{30}^2\right)} \tag{2.43}$$

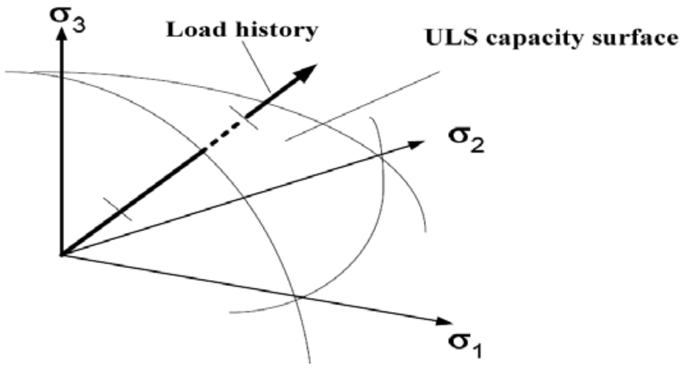


Figure 2. 18: Definition of safety margin/usage factor in 3D –view (Ref [4])

The PULS program also provides capacity curves under combined loads. The capacity curves are illustrated in two-dimensional load-spaces (Figure 2.19). They are to be understood as limit boundaries covering the load-space selected by the user. They inform about the strength of the plates in the different load directions and under any load combination.

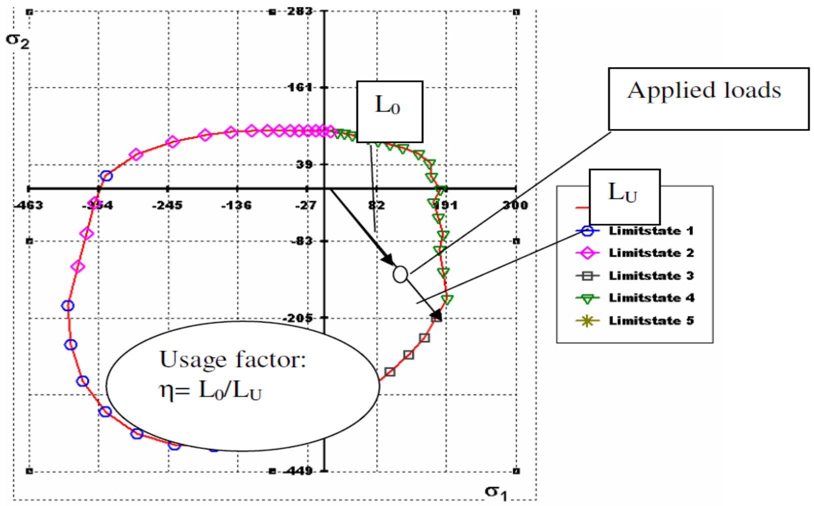


Figure 2. 19: Definition of safety margin/usage factor in 2D-view (Ref [4])

2.6.8 Lateral pressure

In PULS program the lateral pressure can be defined as uniformly distributed across the panel. In the Ultimate Capacity analysis this lateral pressure is fixed while the in-plane load is increased until the subsequent collapse is reached.

The bending stiffness pressure limit P_{Fs} is:

$$P_{Fs} = 12\sigma_F \frac{W_{\min}}{sL_1^2} \tag{2.42}$$

Where W_{min} is the minimum section modulus of stiffener/plate unit and defined as:

$$W_{\min} = \frac{I}{h_w + 0.5t_f + 0.5t_p - z_g} \tag{2.43}$$

The moment of inertia (I) of stiffener/plate unit is calculated by Eq. (2.44).

$$I = \frac{1}{12}b_f t_f^3 + b_f t_f (h_w + 0.5t_f + 0.5t_p - z_g)^2 + \frac{1}{12}t_w h_w^3 + h_w t_w (0.5h_w + 0.5t_p - z_g)^2 + \frac{1}{12}St_p^3 + St_p z_g^2 \tag{2.44}$$

Where z_g is the neutral axis measured from the plate middle-plane.

2.6.9 PULS EXCEL Spreadsheet

The PULS Excel spreadsheet and the PULS advance (AV) use the same computational routines. The spreadsheet offers easy input of a large number of panels, and therefore makes parameter studies easy to perform. The spreadsheet is organized in input sheets and output sheets for the S3 and U3 elements. The PULS spreadsheet is able to read and write pbp-files which are compatible with the PULS AV.

Calculate all panels in the input file and writes all input and output into the output sheet. If an error occurs during the computation, an error message is written in the output sheet. This will be indicated in chapter 3 when redesign for stiffened panel.

There are two groups of option buttons in the input sheet:

1) **Row by row/ combinations of input**: These options let the user choose how the panels are generated from the input sheet.
2) **Delete/save old results**: Delete or save the results already written to the output sheet.

All parameters regarding each panel are written to the output sheet. A Set extent button is made so that the user easily can hide and show the desired columns. An alternative to this button is to manually hide or unhide the columns.

Due to the task of the thesis, the parameters of stiffened panel will be varied such as stiffener dimension, plate thickness, stiffener spacing, etc. Therefore, Excel spreadsheet is a useful tool to perform this. However, it is still not really convenient for user during design process, this will be discussed more detail later in the conclusion and further work parts.

3 OPTIMIZING LAYOUT FOR STIFFENED PANEL

3.1 Introduction

Plate girders and recently shear walls are being widely used by structural engineers, as well as ship and aircraft designers. The role of stiffeners is proved to be vital in design of such structures to minimize their weight and cost [18]. Besides, plate thickness and stiffener spacing also play an important part with respective to the weight and fabrication cost for stiffened plate.

In this chapter these above parameters will be varied according to DNV RP-C201 spreadsheet and PULS program. Parametric studies shall be performed where e.g. the spacing of stiffeners and frames are varied. The optimum dimensions of the panel will be determined in order to satisfy the fabrication costs and weight function for the various alternatives.

3.2 Analysis given information for redesign procedure of the panel

According to the given information that provided by Aker Solutions, the input data for the basic case is illustrated in the Table 3.1.

Due to the distance of stiffener on the plate of the pontoon top (see Figures 1.3 and 1.5) provides equally distributed, so in order to redesign for stiffened panel a specific dimension of the pontoon top should be chosen. Here the dimension of the panel will be chosen according to number of stiffener and frame spacing or girder spacing.

The dimension of the panel, L_1, i.e. panel length in x_1 direction or distance between transverse frames is chosen equal to the girder spacing. Dimension L_2, i.e. panel length in x_2 direction, the length of L_2 is given as $L_2 = (N_s + 1).s$. Where N_s is the number of stiffeners that is set to be nine stiffeners in this report and s is the stiffener spacing. The length of the girder is chosen as the same manner with stiffener and panel dimension.

Other parameters are given from Aker Solutions Company. The information of stiffened panel used for redesign is now shown in Table 3.1.

Table 3. 1: Input data for design procedure

Symbol		Value	Unit	Note
Stiffened panel				Top
Stiffener length_L_1		3125	[mm]	
Panel length_L_2		6250	[mm]	
Plate thickness_ t_p		16	[mm]	
Stiffener				
Number of Stiffeners		9		
Stiffener spacing_ s		625	[mm]	
Stiffener profile		HP Bulb		ColvilleBulb
Stiffener height_h		320	[mm]	
Web thickness _t_w		12	[mm]	
Girder				
Girder length_L_G		6250	[mm]	
Material factor_γ		1.15		
Girder profile		T		
Total height_h_{tot}		1250	[mm]	
Web thickness_t_w		15	[mm]	
Flange width_b		300	[mm]	
Flange thickness_t_f		20	[mm]	
Material				
Material classification		Steel		
Modulus of Elasticity_ E		210000	[MPa]	
Poisson ratio_ν		0.3		
Shear modulus_ G		80769	[MPa]	
Yield stress for plate_σ_{Fp}		420	[MPa]	
Yield stress for stiffener_σ_{Fs}		420	[MPa]	
Applied Load				
Axial stress_σ_1		-120	[MPa]	
Transverse stress	σ_{21}	-77	[MPa]	
	σ_{22}	-77	[MPa]	
Shear stress_τ_{12}		80	[MPa]	
Lateral pressure_P on plate side		0,346	[MPa]	

3.3 Applied loads analysis for panel in basic case

As provided by Aker Solutions, the initial configuration of the panel which satisfied the applied loads is known. These applied loads (axial force, transverse force and shear force) are kept constant through the present analysis.

In this respect, the present report proposes some new configurations which also fulfill the requirements of usage factor of 0.9. This is done by varying the new configurations, i.e. variation of the three parameters, namely plate thickness, stiffener spacing and stiffener dimension by means of PULS and RP-C201. It is noted that stresses will also be changed for each new configuration and also the corresponding capacity curve. The task of the present report is to iterate these three parameters until the usage factor of 0.9 is achieved.

It is realized that this trial and error process is time-consuming and somewhat laborious. This is due to the fact that the PULS and RP-C201 programs are not explicitly functioned in order to automatically calculate the input stresses for each new configuration.

Therefore, it is necessary to built up a small spreadsheet in Excel so that the new stresses corresponding to new configuration are calculated. These stresses are then inputted into PULS and RP-C201 programs for computing of usage factor (η). This is performed as follow.

The axial force formula is defined as:

$$N_x = \sigma_1 . A_{tot} \tag{3.1}$$

Where σ_1 is the axial stress

A_{tot} is the area of the panel. In this case $A_{tot} = [A_{plate} + A_{stiff}] = [A_p.(n+1) + A_s.n]$

n : is the number of stiffeners

A_p : is the area of plate with respect to per stiffener $A_p = t \times s$

s : is the stiffener spacing

t is the plate thickness

A_s is the area of each stiffener

$$\sigma_1 = \frac{N_x}{A_{tot}} \tag{3.2}$$

Where n: number of stiffener spacing.

Similarly, the transverse force can be found by equation (3.3). Here, it is noted that stiffeners have no effect on the transverse strength and shear strength of the panel.

$$N_y = \sigma_2 . A \tag{3.3}$$

Where σ_2 is transverse stress

$A = L_1.t_p$: is plate area

From Eq. (3.3) the transverse tress is determined as:

$$\sigma_2 = \frac{N_y}{A} \tag{3.4}$$

The shear force is given by Eq. (3.5).

$$Q = \tau_{12}.L_1.t_p \quad (3.5)$$

Where τ_{12} : is the shear stress calculated in Eq. (3.6),

t_p : is the plate thickness.

$$\tau_{12} = \frac{Q}{L_1.t_p} \quad (3.6)$$

The weight of stiffened panel is determined with following procedure:

- For the stiffeners: $W_s = m_1.L_1$

Where m_1 : is the mass per length of stiffener

L_1 : is the length of stiffener

- For the plate panel: $Wp = L_1.L_2.t.\rho = V_p.\rho$

Where L_2 : is the length of panel (in this case L_2 equal to the girder length.

T : is plate thickness

$\rho = 7850$ kg/m^3 : is the density of steel

The results of applied loads for the initial configuration (provided by Aker Solutions) of stiffened panel are shown in Table 3.2.

Table 3. 2: Applied loads acting on the panel

Axial force – N_x

σ_1 [N/mm^2]	t_p [mm]	s [mm]	h_s x t_w [mm]	A_s [mm^2]	A_p [mm^2]	n	W_s [kg]	N_x [KN]
-120	16	625	320x12	5147	10000	9	3581	-17559

Transverse force –N_y

σ_2 [N/mm^2]	t_p [mm]	s [mm]	h_s x t_w [mm]	A_p [mm^2]	L_1 [mm]	n	W_s [kg]	N_y [KN]
-77	16	625	320x12	50000	3125	9	3581	-3850

Shear force – Q

τ_{12} [N/mm^2]	t_p [mm]	s [mm]	h_s x t_w [mm]	A_p [mm^2]	L_1 [mm]	n	W_s [kg]	Q [KN]
80	16	625	320x12	50000	3125	9	3581	4000

σ_1: axial stress; σ_2: transverse stress; τ_{12}: shear stress; t_p: plate thickness; s: stiffener spacing; A_p: plate area; L_1: length in x_1,i.e. stiffener direction; L_2: length of plate in x_2, i.e. transverse direction; h_s: stiffener height; t_w: stiffener thickness; n: stiffener number; W_s: stiffened panel's weight; As: stiffener cross sectional area.

From the result in Table 3.2, the forces acting on the panel in basic case are listed more clearly in Table 3.3 as follow

Table 3. 3: The acting loads for basic case

σ_1 [Mpa]	σ_2 [Mpa]	τ_{12} [Mpa]	h_s x t_w [mm]	t_p [mm]	n	s [mm]	W_s [kg]	N_x [KN]	N_y [KN]	Q [KN]	UF
-120	-77	80	320x12	16	9	625	3581	-17559	-3850	4000	0.9

σ_1: axial stress; σ_2: transverse stress; τ_{12}: shear stress; t_p: plate thickness; s: stiffener spacing; h_s: stiffener height; t_w: stiffener thickness; n: stiffener number; W_s: stiffened panel's weight. N_x, N_y, Q: axial load, transverse load, shear load

From the Table 3.3 it is seen that, with the given stresses the acting forces is calculated correspondingly. And these forces will be used to calculate the acting stresses on the panel as varying its parameters, e.g. stiffener spacing, plate thickness and stiffener dimension.

3.4 Calculation of fabrication cost for the panel

3.4.1 General

Estimate the cost of the welding can be a difficult task because of many variables involved. The cost of the welding, like the cost of any industrial process, includes the cost of labor, material and overhead. Welding cost are used to make the cost estimates for bidding on welding work, for setting rates for incentive programs, and for comparing welded construction and competing processes.

The cost of the weldment is of major importance. This includes the cost of the weld, the cost of the material required, the reparation of the parts, and the postweld treatment required [15].

Material cost: the cost of new stock required to produce the weldment is fixed by the supplier. It is often possible to help control these costs by getting bids from several suppliers and combining as many jobs as possible in order to get any discount for bulk purchases.

Labor costs: total labor cost includes wages and benefits. Insurance, sick leave, vacation, social security, retirement, and other benefits can range from 25% to 75% of the total labor cost. Because the labor costs are figured on an hourly basis, they can be controlled only by increasing productivity.

Filler metal: The cost of filler metal per pound is only a small part of its actual cost. The major welding processes (SMAW, GMAW, and FCAW) have widely varying deposition and efficiency rates.

Overhead costs: Overhead costs are often intangible costs related to doing business. These costs include building rent or mortgage, advertising, insurance, utilities, taxes, licenses, governmental fees, accounting, loan payments and property upkeep.

However, in order to perform these analyses as well as calculations it must be known a lot of information such as welding, electrode, welding type, welding price, welding position and so on. With a given simple factor table, these above costs could not be calculated in detail and we have to make some assumptions to simplify calculation of fabrication cost.

3.4.2 The simplified assumption for calculation

Because the input information for the cost of fabrication with no welding procedure, welding type, and electrode cost, welding price and other missed parameters, the calculation for the welding cost must be assumed that:

+ The panel is welded with single pass and no root opening.

+ The legs' length of weld is equal each other, i.e. the fillet weld is isosceles triangle or leg height equal to leg width.

+ The price corresponding to 3mm throat thickness is 50 kroner per meter.

See the Figure 3.1 for more illustration.

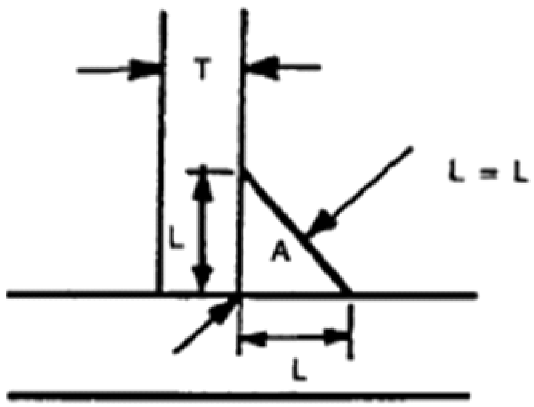


Figure 3. 1: The fillet weld shape (Ref [14])

Table 3. 4: Symbol explanation

T: thickness of the stiffener/girder.
L: the height of welding leg.
A: throat thickness

3.4.3 The fabrication cost formulation of stiffened panel and girder

According to [14] and [16] the cross sectional area of a fillet weld is equal to 1/2 of the weld leg height times the weld leg width, this is determined in Eq. (3.7).

$$\text{Leg length} = \frac{\text{Throat thickness}}{\text{Cos}45^0} = \frac{A}{0.7} \qquad (3.7)$$

From Figure 3.1 it can be seen that the throat thickness, A is the height of isosceles right triangle. Besides, according to [13] the throat thickness is calculated by Eq. (3.8).

$$A = 0.5 \times T \qquad (3.8)$$

Where T is the material thickness and according to the definition of T in [13] for fillet welds the base metal thickness which for welds between dissimilar thicknesses is that of the thicker material. Hence in the case thicknesses of panel and stiffener are different, T will be chosen for the thicker material.

And according to given throat thickness and Norm Curve (NC) in Table 3.5 the fabrication cost is determined by Eq. (3.9).

$$F_c = N_c \text{ x } P_b \tag{3.9}$$

Where N_c: is the Norm Curve corresponding to A

P_b: is the basic price of steel

Because of without any information from the company, the basic price must be assumed for the basic case. After reference from experts and consultants from marine and welding industry, the basic price of 3mm throat thickness per meter is assumed to be 50Kr (Norway Kroner). This price is also got agreement of Marthe Almeland at Aker Solution, who is co-supervisor in this thesis.

The Equation (3.9) is used for calculation for the fabrication cost per stiffener per meter, in order to calculate the total fabrication cost for stiffened panel this value should be multiplied with the stiffener as well as the number of stiffeners on the panel.

Table 3. 5: The relation between Throat Thickness and Norm Curve of fillet weld

A [mm]	NC	A [mm]	NC	A [mm]	NC	A [mm]	NC	A [mm]	NC
3.0	1.00	7.0	4.05	11.0	9.15	15.0	16.30	19.0	25.45
3.5	1.30	7.5	4.60	11.5	9.95	15.5	17.35	19.5	26.75
4.0	1.60	8.0	5.15	12.0	10.75	16.0	18.40	20.0	28.05
4.5	1.95	8.5	5.75	12.5	11.60	16.5	19.50	20.5	29.15
5.0	2.30	9.0	6.35	13.0	12.45	17.0	20.60	25.0	43.00
5.5	2.70	9.5	7.05	13.5	13.40	17.5	21.80	30.0	61.10
6.0	3.10	10.0	7.70	14.0	14.30	18.0	22.95	35.0	83.10
6.5	3.60	10.5	8.45	14.5	15.30	18.5	24.20	40.0	108.8

A: throat thickness of fillet weldment; NC: Norm Curve value given from Aker Solutions Company

From the given information from Aker Solutions Company that shown in Table 3.5 and using the formula as shown in Eq. (3.9), the fabrication cost for the stiffened plate as well as the welding cost for the girder should be chosen base on the basic price curve in Figure 3.2.

By using this curve the welding cost will be easily and quickly chosen as the thickness of the plate and stiffener or girder is known. From this curve the basic price according to throat thickness will be chosen, then the fabrication cost per stiffener or girder will be found by multiply the value found from this graph by the length of the stiffener or girder.

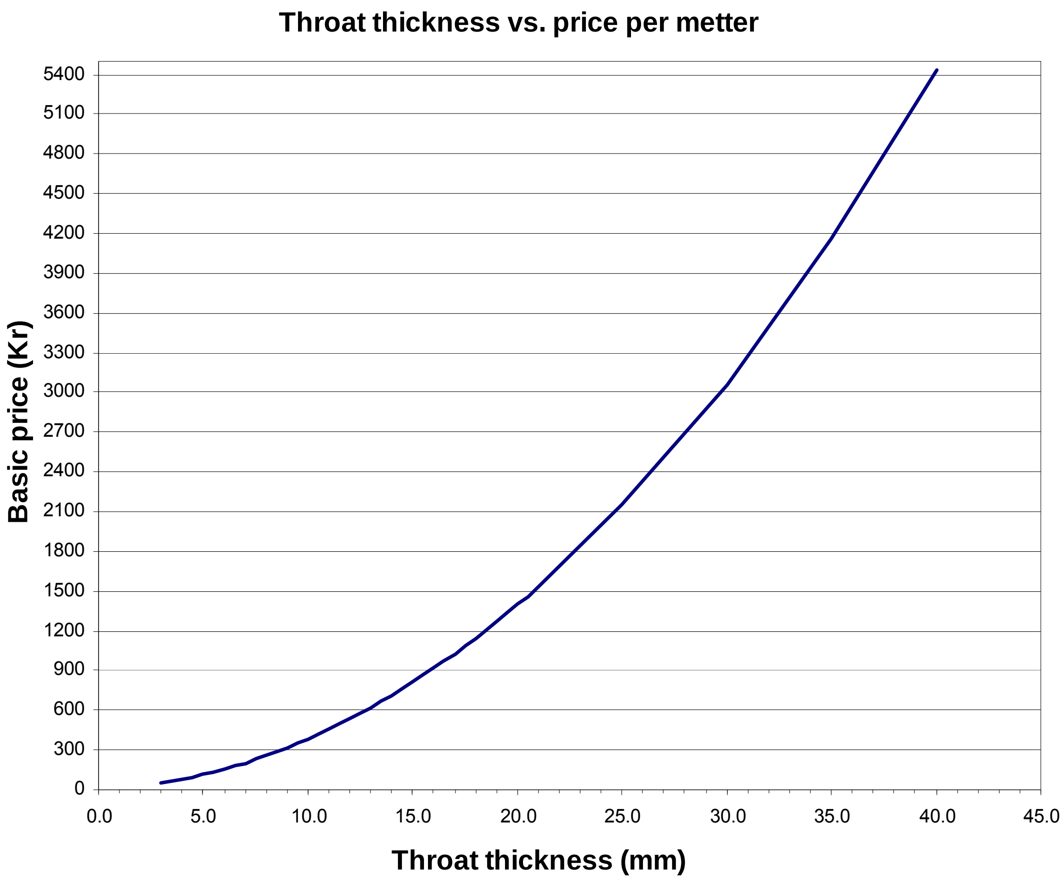


Figure 3. 2: The fabrication cost is plotted as a function of throat thickness

Basing on the above theories, assumptions and formulas, the fabrication cost of the basic case is calculated. And from the Table 3.6 indicates that the total fabrication cost for the basic case with nine stiffeners in this situation is 7242.3Kr.

Table 3. 6: The fabrication cost for the basic case without any varying

$t_p\_s\_h_sxt_w$ [mm]	t_p [mm]	t_w [mm]	A [mm]	NC	n	L_s [mm]	P_b [Kr/m]	P_s [Kr]	P_t [Kr]
16_625_320x12	16	12	8	5.15	9	3125	50	804.7	7242.3

t_p: plate thickness; s: stiffener spacing; hs: stiffener height; t_w: stiffener thickness; n: stiffener number; A: throat thickness; NC: Norm curve value; Ls: stiffener length; P_b: basic price per meter; Ps: cost per stiffener; P_t: total cost.

From now, the value in Table 3.5 and Table 3.6 is considered as value of basic case. The subsequent optimal design for stiffened panel should be based on these values.

3.5 Analysis with the RP-C201 spreadsheet

3.5.1 Analysis for basic case

As mentioned in Section 3.2 the RP-C201 is now used in order to analysis for the basic stiffened panel. The usage factor (UF) must be equal to 0.9 that is thought as a target value.

When this value ($\eta = 0.9$) is achieved, the configuration is therefore selected. At this stage, the buckling capacity curve can be built upon as the following steps:

Table 3. 7: Buckling capacity curve design procedure

Step	Description
1	Initialize σ_1 to zero and try different values of σ_2 until $\eta = 0.9$ (approximately). Mark this first point as ($\sigma_1 = 0$, σ_2) in the interaction diagram.
2	Repeat step 1st with σ_1 = -50MPa, -100MPa, -150MPa and -180MP, etc so as to get more four points of (σ_1, σ_2).
3	The last point is performed inversely by setting σ_2 to zero and try different values of σ_1 until $\eta = 0.9$ (approximately).
4	Finally, the interaction curve is built by connecting the points (σ_1, σ_2) found above.

The values of these points are calculated according to above steps will be shown in Table 3.8 bellow.

Table 3. 8: Buckling capacity check for the given panel

No	Stress_σ_1 [N/mm^2]	Stress_σ_2 [N/mm^2]	Usage Factor (η)
1	-0	-69	0.90
2	-50	-80	0.90
3	-100	-91	0.90
4	-130	-67	0.90
5	-150	-40	0.90
6	-169	0	0.90

With the value in the Table 3.8, the corresponding interaction curve for the basic case will be plotted in Figure 3.3.

With this interaction curve it is easily interpolated that the plate field is free of buckling as long as the (σ_1, σ_2) staying under the interaction curve. This is an easy and fast way to check the analysis results.

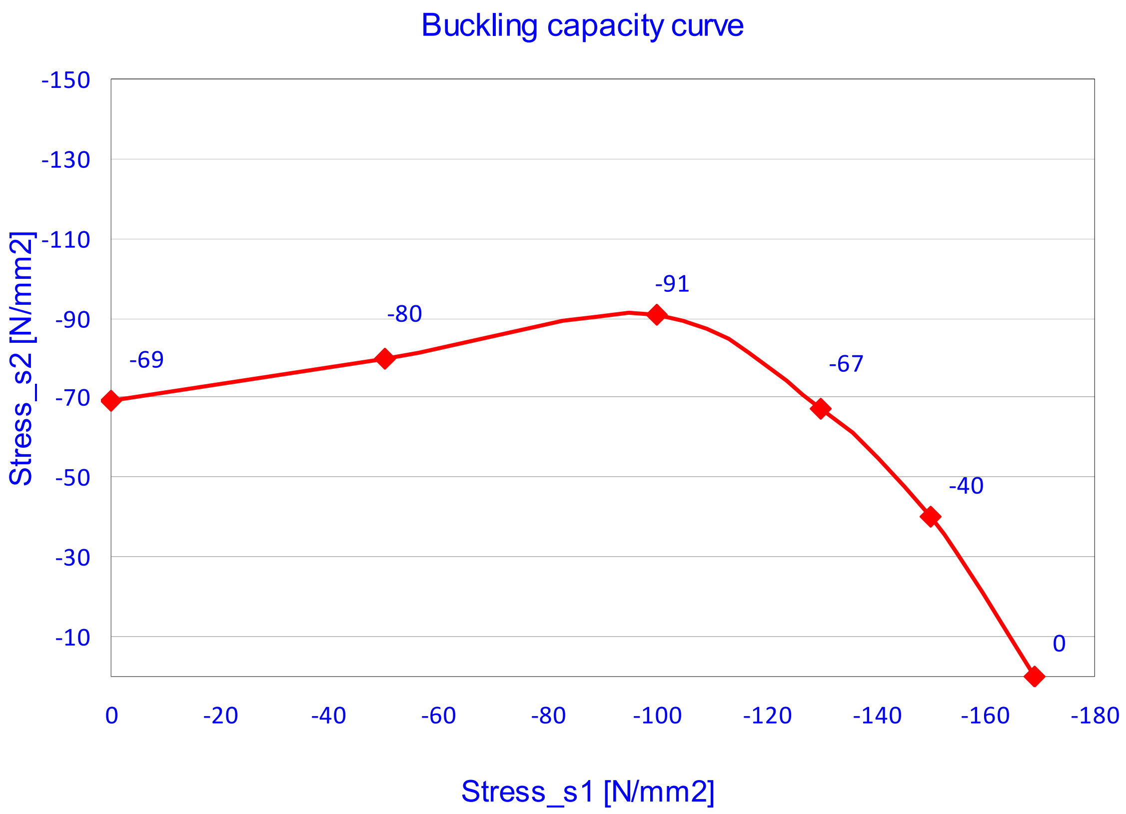


Figure 3. 3: Buckling capacity check for stiffened plate with basic case

Here, it should be remarked that the curve shown in this Figure is for the initial configuration; on the other hand this is the interaction curve of the stiffened panel for the basic case for design.

The new configurations will be discussed in the next section. Moreover, this graph is also considered as a basic case for panel when its parameters are varied to get optimal panel.

3.5.2 Redesigning for stiffened plate

In this section, the procedure presented in section 3.2.1 is applied. The aim is to optimize the stiffened panel with the objective functions of fabrication cost and weight. The details of this procedure are illustrated in the following text.

Before starting to redesign for stiffened panel, it is noted that the values of stresses, i.e. σ_1, $\sigma_{2,1}$, $\sigma_{2,2}$ in Tables below are positive for compression stress. The shear stresses and lateral pressure are always positive in RP-C201 spreadsheet.

With the information of stiffened panel in basic case that is given in Table 3.5 and Table 3.6, the optimal design procedure will be performed with four circumstances.

Firstly, the stiffened panel in basic case will be redesign to find if there is an optimal stiffened panel. In this case the stiffener spacing is still fixed with s=625mm, number of stiffeners, n=9. The panel's parameters such as stiffener dimension, plating thickness should be varied in order to get an optimal panel that can be satisfied usage factor less than or equal to 0.9, lower value of weight and fabrication cost than basic case.

Secondly, the optimal design procedure will be performed with reducing stiffener spacing, s=568mm. This means that the number of stiffeners is now increased with n=10.

Then, reducing number of stiffeners with n=8 now, this means that the spacing of stiffeners is now with s=694mm. Perform varying plating thickness and stiffener dimension in order to get an optimal configuration that can be satisfied requirements quoted above.

Finally, goes further with increasing stiffener spacing with s=780mm and number of stiffeners, n=7. Then perform with the same manner so that the optimal panel can be figure out.

3.5.2.1 Optimal design for panel with stiffener spacing s=625mm, stiffener number n=9

Firstly, the basic case shall be considered for redesign, this means that the stiffened panel with stiffener spacing s=625mm, the number of stiffeners n=9 will be considered to optimize (see Table 3.6)

The purpose is that the stiffener spacing is kept, then the stiffener dimension and the plate thickness will be varied to get a smaller weight as well as a lower fabrication cost for the panel.

Table 3. 9: Varying stiffener dimension and plate thickness with s = 625mm, n=9

N^0	t_p_s_h_s x t_w mm	σ_1 N/mm^2	$\sigma_{2,1}$ N/mm^2	$\sigma_{2,2}$ N/mm^2	τ_{12} N/mm^2	η	Buckling check	W_s [kg]
1	16_625_320x12	120	77	77	80	0.9	point 1	3581
2	15_625_370x14	113.1	82.1	82.1	85.3	0.9	Point 1	3799
3	14_625_400x16	107.3	88	88	91.4	0.95	Point 1	4000
4	14_625_430x17	102.2	88	88	91.4	0.9	Point 4	4200
5	17_625_280x12	120	72.5	72.5	75.3	1.03	Point 1	3585
6	17_625_300x12	118.2	72.5	72.5	75.3	0.92	Point 1	3636
7	17_625_300x13	116.1	72.5	72.5	75.3	0.9	Point 1	3703
8	18_625_280x13	113.2	68.4	68.4	71.1	0.94	Point 1	3800
9	18_625_300x11	115.5	68.4	68.4	71.1	0.91	Point 1	3724
10	18_625_300x12	113.4	68.4	68.4	71.1	0.88	Point 1	3789

σ_1: axial stress; σ_{21}, σ_{22}: transverse stress; τ_{12}: shear stress; t_p: plate thickness; s: stiffener spacing; h_s: stiffener height; t_w: stiffener thickness; η: usage factor; W_s: stiffened panel's weight.

From the Table 3.9 it can be seen that there is no panel can be better than the basic case because when the plate thickness or stiffener scantling is changed, the usage factor will be larger than 0.9, i.e. this is out of the validity range of requirement of usage factor.

There are also 2nd, 4th and 7th panels are satisfied for usage factor η=0.9, but these ones have higher weight as compare to the basic case, i.e. this is not satisfied for requirement of reducing weight and fabrication cost for the optimal panel.

In addition, when reducing plate thickness and increasing stiffener dimension, this can reach η=0.9, but it is not reasonable because the weight will be larger respectively, e.g. 14mm and 15mm for plate thickness in this Table, whereas increasing plate thickness and reducing small stiffener dimension is more reasonable because the weight of panel can be reduced or slightly changed.

Besides, most of panels in this situation will be subjected the maximum load at Point 1, i.e. the maximum load at the support on stiffener side or in other words the beam – column failure will occur in this situation, for more information about this see Figure 2.12.

From Table 3.10 it can be seen that, the 2nd panel provides a smallest fabrication cost due to reducing of plate thickness. However, as considering for weight requirement, this one can not be satisfied. Therefore, in this situation the 1st panel (basic one) should be still considered as an optimal panel.

Besides, it is impossible to satisfy three requirements in the same time for an optimal panel that are limited usage factor with η= 0.9, lower weight and fabrication cost. In order to simplify for design procedure, in this thesis the fabrication cost will be mainly focused as the weight requirement for optimal stiffened panel can not be satisfied. For this reason the 2nd panel will be chosen as an optimal panel for the basic case.

And in the subsequent summarized Table for optimal panels will be discussed both situations, i.e. optimal panel will be selected based on weight requirement or fabrication cost.

Table 3. 10: The fabrication cost for the basic case as varying thickness and stiffener dimension

N^0	t_p_s_h_s x t_w [mm]	A [mm]	NC	n	Ls [m]	P_b [Kr/m]	Ps [Kr]	P_t [Kr]
1	16_625_320x12	8	5.15	9	3.125	50	804.7	7242.3
2	15_625_370x14	7.5	4.6	9	3.125	50	718.8	6469.2
3	14_625_400x16	8	5.15	9	3.125	50	804.7	7242.3
4	14_625_430x17	8.5	5.75	9	3.125	50	898.4	8085.6
5	17_625_280x12	8.5	5.75	9	3.125	50	898.4	8085.6
6	17_625_300x12	8.5	5.75	9	3.125	50	898.4	8085.6
7	17_625_300x13	8.5	5.75	9	3.125	50	898.4	8085.6
8	18_625_280x13	9	6.35	9	3.125	50	992.2	8929.8
9	18_625_300x11	9	6.35	9	3.125	50	992.2	8929.8
10	18_625_300x12	9	6.35	9	3.125	50	992.2	8929.8

t_p: plate thickness; s: stiffener spacing; hs: stiffener height; t_w: stiffener thickness; n: stiffener number; A: throat thickness; NC: Norm curve value; Ls: stiffener length; P_b: basic price per meter; Ps: cost per stiffener; P_t: total cost.

With results from Table 3.9 and Table 3.10 the usage factor is now plotted versus with the weight and fabrication cost as shown in Figure 3.4. It can be seen clearly that there is no stiffened panel can be satisfied the weight requirement; hence the 1st should be still the optimal one. However, if it is focused on fabrication cost, the 2nd panel provides a considerable lower value than basic case. This can be seen more clearly in Figure 3.4.

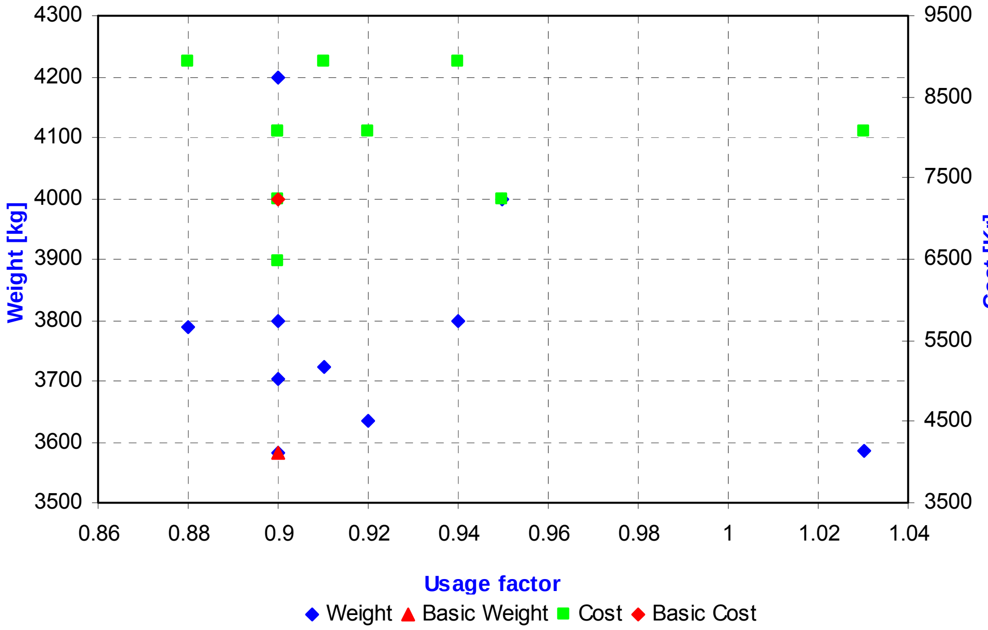


Figure 3. 4: Select optimal stiffened panel with s=625mm and n=9

3.5.2.2 Optimal design for panel with stiffener spacing; s=568mm, stiffener number; n=10

One stiffener is now added on stiffened panel while the dimension of panel is unchanged. The objective is for increasing the strength of the panel then the plate thickness will be reduced as well as the stiffener dimension will be changed until an optimal result is achieved for the panel.

Now, the usage factor of panel is reduced to η=0.84 this means that when reducing the stiffener spacing as well as increasing the stiffener numbers, the panel will be stronger and the plate thickness as well as stiffener dimension could be reduced.

Table 3. 11: Varying the stiffener dimension and plate thickness with s = 568mm, n=10

N^0	t_p_s_h_s x t_w mm	σ_1 N/mm^2	$\sigma_{2,1}$ N/mm^2	$\sigma_{2,2}$ N/mm^2	τ_{12} N/mm^2	η	Buckling check	W_s [kg]
1	16_568_320x12	115.9	77	77	80	0.84	Point 4	3706
2	16_568_300x12	119.5	77	77	80	0.91	Point 1	3597
3	16_568_300x13	117.1	77	77	80	0.89	Point 1	3672
4	15_568_340x12	119	82.1	82.1	85.3	0.91	Point 4	3612
5	15_568_340x13	116.3	82.1	82.1	85.3	0.9	Point 1	3697
6	14_568_370x15	110.1	88	88	91.4	0.92	Point 1	3903
7	14_568_400x14	107.1	88	88	91.4	0.87	Point 1	4012
8	17_568_280x12	116.4	72.5	72.5	75.3	0.94	Point 1	3694
9	17_568_300x11	116.9	72.5	72.5	75.3	0.89	Point 1	3678
10	18_568_280x12	111.8	68.4	68.4	71.1	0.9	Point 1	3847

σ_1: axial stress; σ_{21}, σ_{22}: transverse stress; τ_{12}: shear stress; t_p: plate thickness; s: stiffener spacing; h_s: stiffener height; t_w: stiffener thickness; η: usage factor; W_s: stiffened panel's weight.

After varying for parameters, there are four panels should be considered that are 3rd, 5th, 9th, and 10th panels (see Table 3.11). However, in general view all of them have higher weight than the weight of panel in basic case. This means that these panels can not be satisfied the weight requirement.

For the buckling check, it can be seen that most of panels in this situation should be check at point 1 that is corresponding to Eq. (2.22), the beam – column failure will occur in the panel in this situation. This means that the plate will be failed in bending mode at the support on stiffener side.

Next step, these above panels will be optimized with respective to fabrication cost. The parameters of these panels will be unchanged, i.e. keep the same manner with optimal design for weight function. The performance of optimal fabrication cost is shown in the Table 3.12.

Table 3. 12: The fabrication cost for the case s=568mm, n=10

N^0	$t_p\_s\_h_s \times t_w$ [mm]	A [mm]	NC	n	Ls [m]	P_b [Kr/m]	Ps [Kr]	P_t [Kr]
1	16_568_320x12	8	5.15	10	3.125	50	804.7	8047
2	16_568_300x12	8	5.15	10	3.125	50	804.7	8047
3	16_568_300x13	8	5.15	10	3.125	50	804.7	8047
4	15_568_340x12	7.5	4.6	10	3.125	50	718.8	7188
5	15_568_340x13	7.5	4.6	10	3.125	50	718.8	7188
6	14_568_370x15	7.5	4.6	10	3.125	50	718.8	7188
7	14_568_400x14	7	4.05	10	3.125	50	632.8	6328
8	17_568_280x12	8.5	5.75	10	3.125	50	898.4	8984
9	17_568_300x11	8.5	5.75	10	3.125	50	898.4	8984
10	18_568_280x12	9	6.35	10	3.125	50	992.2	9922

t_p: plate thickness; s: stiffener spacing; hs: stiffener height; t_w: stiffener thickness; n: stiffener number; A: throat thickness; NC: Norm curve value; Ls: stiffener length; P_b: basic price per meter; Ps: cost per stiffener; P_t: total cost.

With result of optimal design in fabrication cost that is shown in Table 3.12, it is seen that the 7th panel gives smallest fabrication cost due to reduced 2mm plate thickness, but this one gives a far lower of usage factor than basic case, i.e. the usage factor is far lower than 0.9, hence this panel should not be chosen.

Besides, it clearly sees that panels 4th, 5th, and 6th provide a lower value of fabrication cost than basic case. However, considering again in Table 3.11 shows that panels 4th and 6th can not be satisfied the usage factor requirement of 0.9.

Therefore, in this in this situation the 5th panel shall be considered as optimal panel for fabrication cost.

For more illustration of the optimal panel compares to the basic stiffened panel, a graph shows the relation between usage factor versus with panel's weight as well as its fabrication cost will be plotted in Figure 3.5.

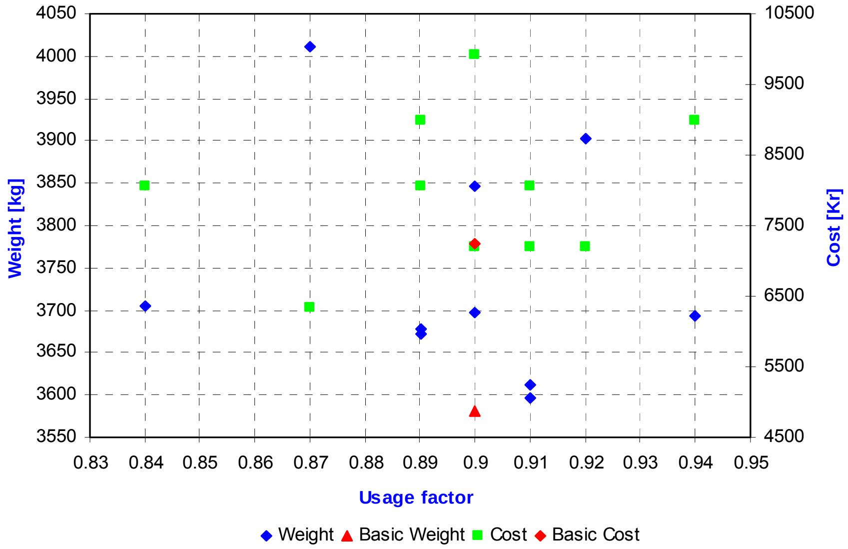


Figure 3. 5: Select optimal stiffened panel with s=568mm and n=10

3.5.2.3 Optimal design for panel with stiffener spacing; s=694mm, stiffener number; n=8

As can be seen that when increasing stiffener spacing as well as reducing the number of stiffeners, the strength in panel will be significantly decreased. From the Table 3.13 it is clear to see that the value of usage factor is now rapidly increased and reaches to η=0.98. Hence, in this situation the panel should be varied plate thickness or stiffener dimension in order to increase the strength for stiffened panel first, i.e. the usage factor must be reduced to the value of η=0.9.

Now the redesign procedure is divided into three ways, first the panel thickness is fixed and stiffener dimension is varied, i.e. increase dimension. By doing this the weight of panel rapidly increases and 3^{rd} panel gives a reasonable value for usage factor.

Then the panel thickness is reduced and in the same time stiffener dimension will be increased, i.e. couple varying for panel thickness and stiffener dimension. With the same situation the weight of panel is also rapidly increased and usage factor η=0.9 for panel 5^{th}.

Finally, the panel thickness is increased and stiffener dimension is reduced correspondingly. This way shows that the weight gives a slightly increase when increasing panel thickness and in this way the 6^{th} panel is suitable for usage factor requirement. The optimal design procedure is shown in Table 3.13 below.

Table 3. 13: Varying the stiffener profile and plate thickness with s = 694mm, n=8

N^0	t_p_s_h_s x t_w mm	σ_1 N/mm^2	$\sigma_{2,1}$ N/mm^2	$\sigma_{2,2}$ N/mm^2	τ_{12} N/mm^2	η	Buckling check	W_s [kg]
1	16_694_320x12	124.4	77	77	80	0.98	Point 4	3456
2	16_694_340x14	118.3	77	77	80	0.93	Point 4	3636
3	16_694_370x13	115.8	77	77	80	0.88	Point 4	3713
4	15_694_430x20	98.1	82.1	82.1	85.3	0.83	Point 4	4377
5	15_694_430x15	108.6	82.1	82.1	85.3	0.9	Point 4	3957
6	17_694_320x12	119.2	72.5	72.5	75.3	0.89	Point 4	3609
7	17_694_300x13	120.1	72.5	72.5	75.3	0.97	Point 1	3581
8	18_694_300x13	115.2	68.4	68.4	71.1	0.93	Point 1	3735
9	18_694_320x12	114.3	68.4	68.4	71.1	0.81	Point 1	3762
10	19_694_300x13	110.7	64.8	64.8	67.4	0.89	Point 1	3888

σ_1: axial stress; σ_{21}, σ_{22}: transverse stress; τ_{12}: shear stress; t_p: plate thickness; s: stiffener spacing; h_s: stiffener height; t_w: stiffener thickness; η: usage factor; W_s: stiffened panel's weight.

There are three panels have usage factors close to 0.9 that are 5^{th}, 6^{th}, and 10^{th} panels, but all of them are higher than basic case as considering for the weight requirement. There is only the 6^{th} panel has the smallest weight (3609kg) that is close to the weight in the basic case, should be accepted for the weight requirement.

The buckling check for all stiffened panels in Table 3.13 shows that the panel will be subjected compression-bending failure on compression side. This means that when fixing or reducing plate thickness and increasing stiffener dimension, the midspan failure will occur in panel. Inversely, when plate thickness is increased and stiffener dimension is reduced, the failure will occur at the support on stiffener side.

Now, these panels will be checked for the satisfactory of the welding cost. This procedure is shown in Table 3.14.

Table 3. 14: The fabrication cost for the case s=694mm, n=8

N^0	t_p_s_h_s x t_w [mm]	A [mm]	NC	n	Ls [m]	P_b [Kr/m]	Ps [Kr]	P_t [Kr]
1	16_694_320x12	8	5.15	8	3.125	50	804.7	6437.6
2	16_694_340x14	8	5.15	8	3.125	50	804.7	6437.6
3	16_694_370x13	8	5.15	8	3.125	50	804.7	6437.6
4	15_694_430x20	10	7.7	8	3.125	50	1203.1	9624.8
5	15_694_430x15	7.5	4.6	8	3.125	50	718.8	5750.4
6	17_694_320x12	8.5	5.75	8	3.125	50	898.4	7187.2
7	17_694_300x13	8.5	5.75	8	3.125	50	898.4	7187.2
8	18_694_300x13	9	6.35	8	3.125	50	992.2	7937.6
9	18_694_320x12	9	6.35	8	3.125	50	992.2	7937.6
10	19_694_300x13	9.5	7.05	8	3.125	50	1101.6	8812.8

t_p: plate thickness; s: stiffener spacing; hs: stiffener height; t_w: stiffener thickness; n: stiffener number; A: throat thickness; NC: Norm curve value; Ls: stiffener length; P_b: basic price per meter; Ps: cost per stiffener; P_t: total cost.

The optimal design for the panel with respective to fabrication cost is now shown in Table 3.14. Correspondence with the result from Table 3.13 above, there are three panels shall be checked the welding cost with the basic case that are 5th, 6th, and 10th panels.

It can be seen that the 10th panel has a significantly higher in fabrication cost as compare this one to the basic case. Now, the 6th panel suggests a slightly lower value of welding cost than basic case, whereas the 5th panel indicates a considerable lower fabrication cost than the 6th as well as the basic case.

As previously mentioned in this thesis the fabrication cost will be mainly focused as compare to the panel weight. For this reason, the 5th panel should be chosen as an optimal stiffened panel in this situation.

Similar to previous situations, the optimal value in Table 3.13 and Table 3.14 is now indicated as a graph with the usage factor is plotted versus with the weight of the stiffened panel as well as with fabrication or welding cost of the panel (see Figure 3.6)

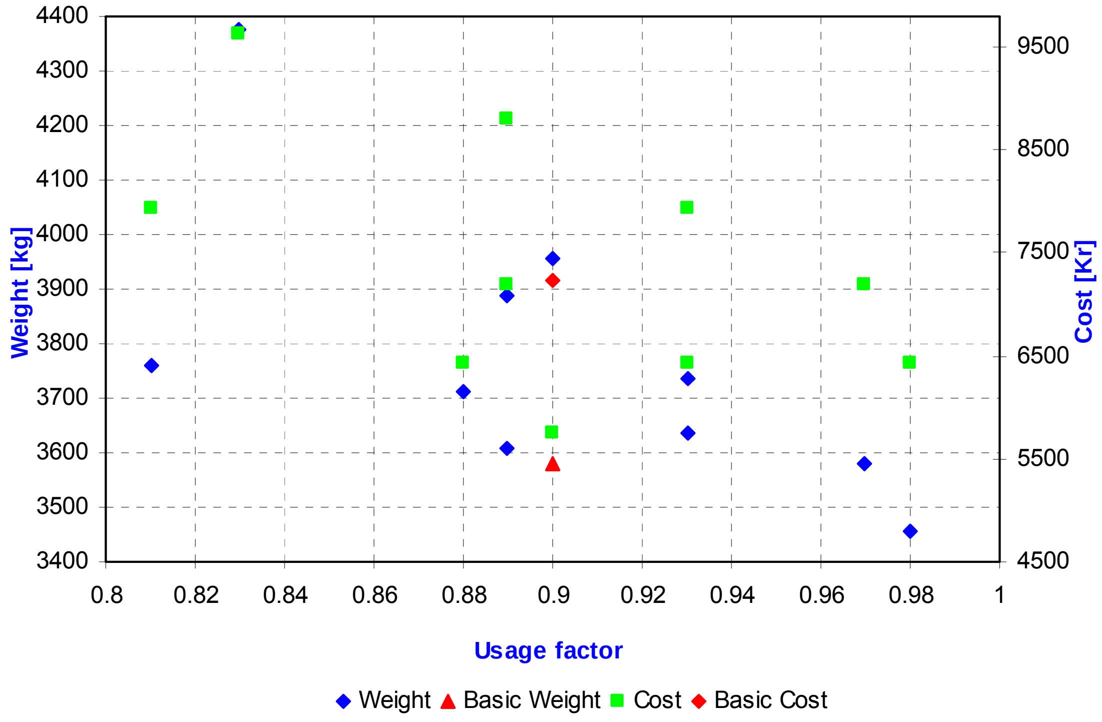


Figure 3. 6: Select optimal stiffened panel with s=694mm and n=8

From Figure 3.6, the weight and fabrication cost is indicated as triangular and tetragon in red color. The weight of panel correspondent to each dimension is indicated as blue tetragons, whereas the welding cost is illustrated with green squares.

On the line correspondent to the usage factor η=0.9, there is no panel gives lower weight than basic case. However, for the welding cost there is a panel gives remarkable lower than basic case. That is the 5th panel that has been chosen before.

3.5.2.4 Optimal design for panel with stiffener spacing; s=780mm, stiffener number; n=7

Performing similarly with previous situations, now the spacing between stiffeners is increased with s=780mm and the number of stiffeners will be reduced with n=7.

When the stiffener spacing is increased, the strength of stiffened panel is now significantly reduced. This is indicated by the value of usage factor is far 0.9 and reaches to η=1.29 as shown in the Table 3.15.

Table 3. 15: Varying the stiffener dimension and plate thickness with s = 780 mm, n=7

N^0	$t_p\_s\_h_s \times t_w$ [mm]	σ_1 N/mm^2	$\sigma_{2,1}$ N/mm^2	$\sigma_{2,2}$ N/mm^2	τ_{12} N/mm^2	η	Buckling check	W_s [kg]
1	16_780_320x12	129.2	77	77	80	1.29	Point 1	3330
2	16_780_400x15	112.4	77	77	80	0.9	Point 4	3827
3	15_780_430x15	114.7	82.1	82.1	85.3	0.98	Point 1	3750
4	15_780_430x20	104.4	82.1	82.1	85.3	0.9	Point 1	4118
5	17_780_370x13	116	72.5	72.5	75.3	0.88	Point 4	3709
6	17_780_340x14	118.2	72.5	72.5	75.3	0.96	Point 1	3641
7	18_780_320x13	116.6	68.4	68.4	71.1	0.86	Point 1	3692
8	18_780_320x12	118.4	68.4	68.4	71.1	1.01	Point 1	3637
9	19_780_320x12	113.6	64.8	64.8	67.4	0.97	Point 1	3790
10	19_780_320x13	112	64.8	64.8	67.4	0.83	Point 1	3845

σ_1: axial stress; σ_{21}, σ_{22}: transverse stress; τ_{12}: shear stress; t_p: plate thickness; s: stiffener spacing; h_s: stiffener height; t_w: stiffener thickness; η: usage factor; W_s: stiffened panel's weight.

With the usage factor is now η= 1.29, it is necessary to increase the strength of the panel first, i.e. reduced usage factor of panel to be equal to 0.9 or close to this value. Hence, in this situation the panel must be increased for the plating thickness or stiffener dimension, so that increasing its strength.

As the same with other situations, all optimal panels give higher weight than basic case. However, according to usage factor requirement there are three panels shall be considered for continuing to check with the fabrication cost requirement.

From the Table 3.15, it is seen that the 2^{nd}, 4^{th}, and 5^{th} panels are now satisfied the requirement of strength. The redesign for these panels in order to satisfy the fabrication cost requirement will be performed in Table 3.16.

For buckling check, as can be seen the panels in this situation are the same failure mode with the previous situation that is the compression-bending failure on compression side. This means that the failure will occur at the points 1 and point for of stiffened panel in this situation. For more illustration see again the Figure 2.10, Section 2.4.5.

Table 3. 16: The fabrication cost for the case s=780mm, n=7

N^0	$t_p\_s\_h_s \times t_w$ [mm]	A [mm]	NC	n	Ls [m]	P_b [Kr/m]	Ps [Kr]	P_t [Kr]
1	16_780_320x12	8	5.15	7	3.125	50	804.7	5632.9
2	16_780_400x15	8	5.15	7	3.125	50	804.7	5632.9
3	15_780_430x15	7.5	4.6	7	3.125	50	718.8	5031.6
4	15_780_430x20	10	7.7	7	3.125	50	1203.1	8421.7
5	17_780_370x13	8.5	5.75	7	3.125	50	898.4	6288.8
6	17_780_340x14	8.5	5.75	7	3.125	50	898.4	6288.8
7	18_780_320x13	9	6.35	7	3.125	50	992.2	6945.4
8	18_780_320x12	9	6.35	7	3.125	50	992.2	6945.4
9	19_780_320x12	9.5	7.05	7	3.125	50	1101.6	7711.2
10	19_780_320x13	9.5	7.05	7	3.125	50	1101.6	7711.2
11	18_780_400x16	9	6.35	7	3.125	50	992.2	6945.4

t_p: plate thickness; s: stiffener spacing; hs: stiffener height; t_w: stiffener thickness; n: stiffener number; A: throat thickness; NC: Norm curve value; Ls: stiffener length; P_b: basic price per meter; Ps: cost per stiffener; P_t: total cost.

According to result from Table 3.15, the Table 3.16 should be checked for three panels that are 2nd, 4th, and 5th panels. It is seen that the requirement of reducing fabrication cost is significantly satisfied because the amount of stiffener is now reduced from 9 to 7.

In addition, the Table 3.16 shows that the 4th panel gives higher value of welding cost than basic case, the 5th panel suggests a slightly lower cost than basic case, whereas the 2nd panel provides a considerable lower value of fabrication cost than the basic case.

Therefore, the optimal panel is chosen for this situation is the 2th panel as the fabrication cost is considered in this case. The optimal design procedure is now plotted in Figure 3.7.

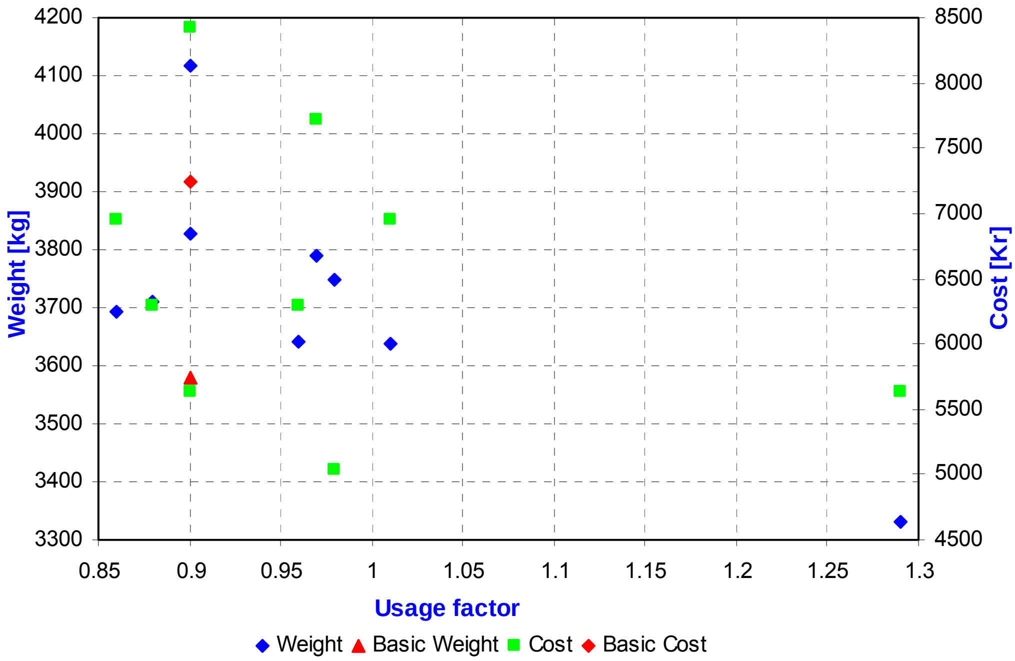


Figure 3. 7: Select optimal stiffened panel with s=780mm and n=7

Now, with the summarized Table below (Table 3.17) these optimal panel will be shown according to reducing weight, lower fabrication cost while they are still satisfied the usage factor η=0.9 or near to this value.

Table 3. 17: Summarized Table for optimal panels

N^0	t_p_s_h_s x t_w [mm]	σ_1 N/mm^2	σ_2 N/mm^2	τ_{12} N/mm^2	η	Buckling check	W_s [kg]	P_t [Kr]
Stiffener Spacing; s = 568mm and numbers of stiffeners; n = 10								
1	15_568_340x13	116.3	82.1	85.3	0.9	Point 1	3697	7188
Stiffener Spacing; s = 625 and number of stiffeners; n = 9								
2	15_625_370x14	113.1	82.1	85.3	0.9	Point 1	3799	6469.2
Stiffener Spacing; s= 694mm and number of stiffeners; n = 8								
3	15_694_430x15	108.6	82.1	85.3	0.9	Point 4	3957	5750.4
Stiffener Spacing; s = 780mm and number of stiffeners; n = 7								
4	16_780_400x15	112.4	77	80	0.9	Point 4	3827	5632.9

σ_1: axial stress; σ_2: transverse stress; τ_{12}: shear stress; t_p: plate thickness; s: stiffener spacing; h_s: stiffener height; t_w: stiffener thickness; η: usage factor; W_s: stiffened panel's weight; Pt: total cost

From the Table 3.17 there are four panels are considered, the 2nd panel is the basic case and other panels will be selected based on this panel.

In general view, it is clearly seen that all of panels has a higher weight than the basic case, except for 1st panel, but this panel gives high fabrication cost. Thus this panel should not be chosen as an optimal panel.

The increasing of weight means that during design process when varying the plate thickness or changing stiffener dimension the weight function will increase because plate thickness or stiffener dimension of panels must be increased. In addition, from the Table 3.17 all of the stiffener dimensions are increased.

In particular view, it can be seen that the 3rd and 4th panels give higher weight than the weight of panel in basic case. However, the 4th panel can be accepted for optimal situation because this panel provides a lowest fabrication cost as compare to others in Table 3.17. This panel can satisfy reducing fabrication cost requirement, even if its weight is still slightly higher than the basic one.

Therefore, a new optimal panel has been now chosen according to the fabrication cost is mainly focused. This panel with new scantling for plating thickness, stiffener dimension and new applied loads are given in Table 3.18 bellow.

Table 3. 18: Optimal configuration of stiffened panel as fabrication cost is focused

N^0	$t_p\_s\_h_s$ x t_w [mm]	σ_1 N/mm^2	σ_2 N/mm^2	τ_{12} N/mm^2	η	Buckling check	W_s [kg]	P_t [Kr]
Stiffener Spacing; s = 625 and number of stiffeners; n = 9								
2	16_625_320x12	120	77	80	0.9	Point 1	3581	7242.3
Stiffener Spacing; s = 780mm and number of stiffeners; n = 7								
4	16_780_400x15	112.4	77	80	0.9	Point 4	3827	5632.9

σ_1: axial stress; σ_2: transverse stress; τ_{12}: shear stress; t_p: plate thickness; s: stiffener spacing; h_s: stiffener height; t_w: stiffener thickness; η: usage factor; W_s: stiffened panel's weight; Pt: total cost

However, if the weight requirement is considered as the fabrication cost, the optimal panel with new configuration is given in Table 3.19. Although the fabrication cost in this panel is not far lower than basic case, its weight is close to the weight of panel in basic case. Therefore, if it is balanced between weight and fabrication cost in optimal function, the panel in Table 3.19 bellow should be chosen as an optimal one.

Table 3. 19: Summarized Table for optimal panel as balance weight and cost requirements

N^0	$t_p\_s\_h_s$ x t_w [mm]	σ_1 N/mm^2	σ_2 N/mm^2	τ_{12} N/mm^2	η	Buckling check	W_s [kg]	P_t [Kr]
Stiffener Spacing; s = 625 and number of stiffeners; n = 9								
2	16_625_320x12	120	77	80	0.9	Point 1	3581	7242.3
Stiffener Spacing; s = 694mm and number of stiffeners; n = 8								
4	17_694_320x12	119.2	72.5	75.3	0.89	Point 4	3609	7182.2

σ_1: axial stress; σ_2: transverse stress; τ_{12}: shear stress; t_p: plate thickness; s: stiffener spacing; h_s: stiffener height; t_w: stiffener thickness; η: usage factor; W_s: stiffened panel's weight; Pt: total cost

From Table 3.18 and Table 3.19, two selected optimal panels will be plotted in Figure 3.8 bellow. From this Figure it can be seen that if the weight is focused the 1st panel (panel has value of weight 1 and cost 1) shall be chosen, whereas if fabrication cost is considered, the 2nd panel should be better, i.e. panel has weight 2 and cost 2 in Figure 3.8 will be the best one.

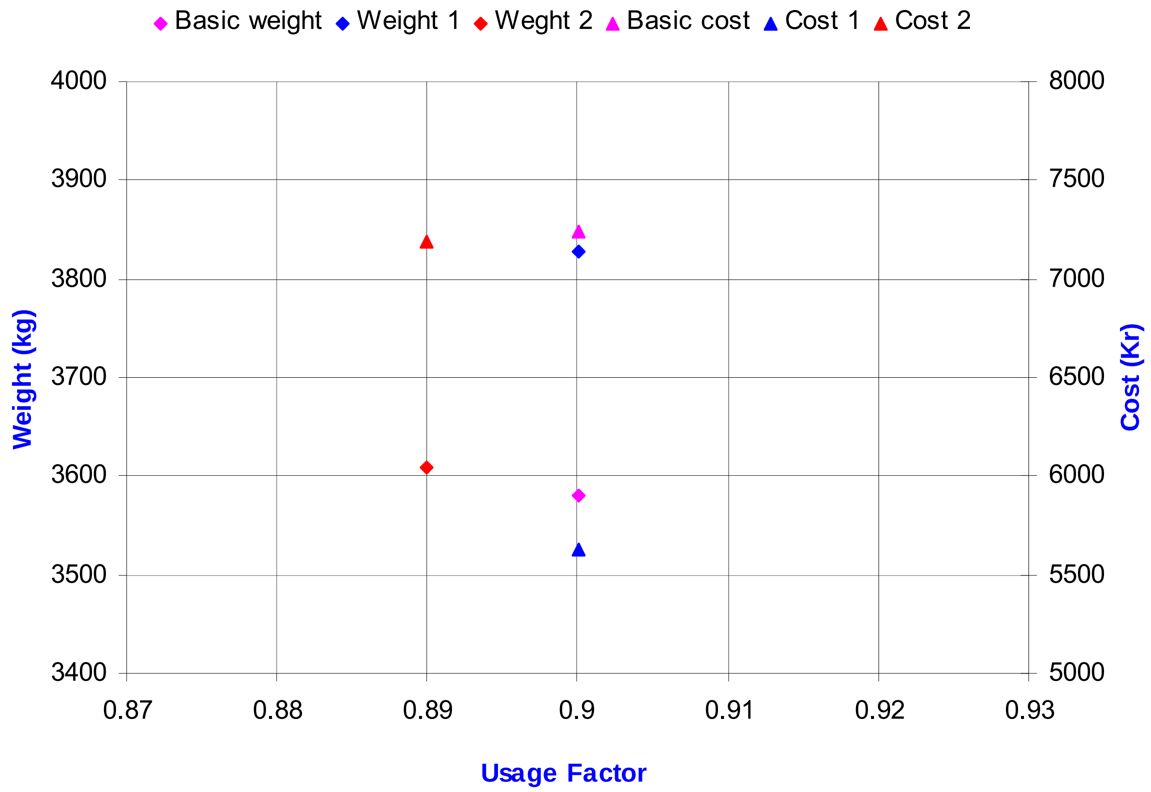


Figure 3. 8: Select optimal panel according to weight and fabrication cost

As mentioned above, it is impossible to be satisfied both of weight and fabrication cost of optimal design functions in the same time. And in this thesis the fabrication cost should be mainly focused as the weight function can not be satisfied.

Besides, because of the slight difference in the weight between panels, a new optimal panel should be selected based on the lowest fabrication cost and provided a slightly higher in weight should be accepted.

Finally, the optimal configuration of stiffened panel analyzed in RP-C201 which can be satisfied requirements of the usage η=0.9 and fabrication cost requirement is achieved. This optimal stiffened panel with new configuration is given in Table 3.20.

Table 3. 20: Optimal configuration for stiffened panel performed by RP-C201

N^0	$t_p\_s\_h_s \times t_w$ [mm]	σ_1 N/mm^2	σ_2 N/mm^2	τ_{12} N/mm^2	η	Buckling check	W_s [kg]	P_t [Kr]
Stiffener Spacing; s = 625 and number of stiffeners; n = 9 (basic case)								
2	16_625_320x12	120	77	80	0.9	Point 1	3581	7242.3
Stiffener Spacing; s = 780mm and number of stiffeners; n = 7								
4	16_780_400x15	112.4	77	80	0.9	Point 4	3827	5632.9

σ_1: axial stress; σ_2: transverse stress; τ_{12}: shear stress; t_p: plate thickness; s: stiffener spacing; h_s: stiffener height; t_w: stiffener thickness; η: usage factor; W_s: stiffened panel's weight; Pt: total cost

3.6 Optimum layout of the panel by PULS program

3.6.1 Given data and choosing of the input parameters

Now the optimal design is performed by PULS program, and the input data is shown in Table 3.21.

Table 3. 21: Input data of stiffened panel by using PULS

Geometry		Value	Unit	Note
Plate				Top
Panel width L1		3125	[mm]	
Panel length L2		6250	[mm]	
Plate thickness t_p		16	[mm]	
Stiffener				
Number of Stiffeners		9		
Stiffener spacing s		625	[mm]	
Stiffener type		ColvilleBulb		
Stiffener height h		320	[mm]	
Web thickness _t_w		12	[mm]	
Material				
Material classification		Steel		
Plate material		Steel NVNS		
Modulus of Elasticity E		210000	[N/mm^2]	
Poisson ratio ν		0.3		
Shear modulus G		80769	[N/mm^2]	
Yield strength for plate σ_{Fp}		420	[N/mm^2]	
Yield stress for stiffener σ_{Fs}		420	[N/mm^2]	
Load				
Axial stress σ_1		-120	[N/mm^2]	
Transverse stress	σ_{21}	-77	[N/mm^2]	
	σ_{22}	-77	[N/mm^2]	
Shear stress τ_{12}		80	[N/mm^2]	
Lateral pressure p		0.346	[N/mm^2]	
Boundary condition				
Location of panel		Integrated panel, continuous plating		

Similarly with the DNV RP-C201, before starting to redesign for stiffened panel by PULS it is noted that the compression stresses is used as positive value, the value of shear stress is always positive. The lateral pressure is assumed uniformly distributed on panel. The positive value is taken as lateral pressure acting on plate side and when the lateral pressure acting from stiffener side, the negative value should be used for input.

3.6.2 Redesign stiffened panel by PULS

Since the goal of this thesis is optimal structural system for plate and stiffeners to reduce fabrication costs and weight. Therefore, this section dedicates to find the optimal solution by varying stiffener spacing, stiffener dimension and plate thickness and maintain utilization of the plate field.

As stated above due to the aim of comparison of two programs, the stiffener spacing is used with the same values as calculated in RP-C201 (Table 3.22).

Table 3. 22: The analysis of the basic case by PULS

N^0	t_p_s_h_s x t_w [mm]	σ_1 N/mm^2	σ_2 N/mm^2	τ_{12} N/mm^2	UC	BS	W_s [kg]
1	16_625_320x12	120	77	80	0.56	0.59	3581

σ_1: axial stress; σ_2: transverse stress; τ_{12}: shear stress; t_p: plate thickness; s: stiffener spacing; h_s: stiffener height; t_w: stiffener thickness; η: usage factor; W_s: stiffened panel's weight; UC: Ultimate capacity; BS: Buckling strength

The failing stress control for the panel is limit state 3 (see Figure 2.17 for more illustration). The maximum sideways displacement in the top of stiffeners at ultimate capacity and maximum sideways displacement across stiffener web height (local mode).

Strengthening action for dominating deflection in this case: increase sideways stiffeners stiffness, increase stiffener flange width, reduce stiffener web height, reduce stiffener span.

And from the Table 3.23 the fabrication cost for this panel will be calculated

Table 3. 23: The fabrication cost for the basic case

N^0	t_p_s_h_s x t_w [mm]	A [mm]	NC	n	Ls [m]	P_b [Kr/m]	Ps [Kr]	P_t [Kr]
1	16_625_320x12	8	5.15	9	3.125	50	804.7	7242.3

t_p: plate thickness; s: stiffener spacing; hs: stiffener height; t_w: stiffener thickness; n: stiffener number; A: throat thickness; NC: Norm curve value; Ls: stiffener length; P_b: basic price per meter; Ps: cost per stiffener; P_t: total cost.

With the usage factor η=0.56 shows an unreasonable result when perform optimal design in PULS. This unconservative result will be discussed more detail in the section comparison of two programs later that.

However, it is also interesting to see that what is going on when PULS is used to design for stiffened panel for offshore structure.

Due to it is impossible to define an input for the material factor, γ_m in PULS program. Therefore the allowable usage factors that using for buckling and yield check will be chosen to be 0.78, i.e. $\eta_{max} = 0.78$. This means that material factor γ_m is set equal to 1.15 and the usage factor is determined by the ratio of $0.9/\gamma_m$.

The strength of stiffened panel for the basic case will be indicated as the ultimate capacity curve that is plotted in Figure 3.9 bellow.

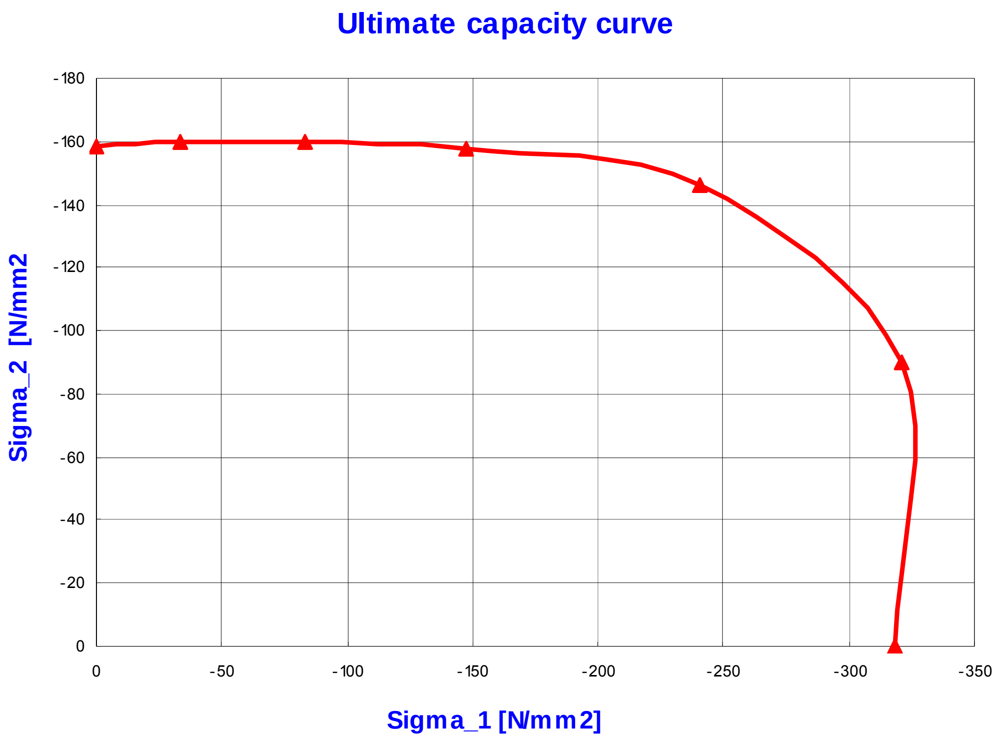


Figure 3. 9: The ultimate capacity curve of the panel in basic case

The basic case is now redesigned to find an optimal panel that gives a better result than basic one, this procedure is performed in the Table 3.22.

3.6.2.1 Optimal design for panel with stiffener spacing; s=625mm, stiffener number; n=9

This panel is kept the stiffener spacing and varied the panel thickness and stiffener dimension as given in Table 3.24.

Table 3. 24: Varying the stiffener dimension and plate thickness with s = 625 mm, n=9

N^0	$t_p\_s\_h_s \times t_w$ [mm]	σ_1 N/mm^2	σ_2 N/mm^2	τ_{12} N/mm^2	UC	BS	Buckling Check	W_s [kg]
1	16_625_320x12	120	77	80	0.56	0.59	State 3	3581
2	16_625_240x12	132.5	77	80	Limited	0	-	3246
3	16_625_260x10	133.4	77	80	0.59	0.61	State 3	3224
4	15_625_260x10	140.1	82.1	85.3	0.68	0.73	State 3	3070
5	14_625_260x11	144.6	88	91.4	0.78	0.89	State 1	2973
6	17_625_240x12	126.5	72.5	75.3	Limited	0	-	3400
7	17_625_260x10	127.4	72.5	75.3	0.52	0.52	State 3	3377
8	18_625_240x12	121.1	68.4	71.1	Limited	0	-	3553
9	18_625_260x10	121.9	68.4	71.1	0.47	0.47	State 3	3530
10	19_625_240x12	116.1	64.8	67.4	Limited	0	-	3706

σ_1: axial stress; σ_{21}, σ_{22}: transverse stress; τ_{12}: shear stress; t_p: plate thickness; s: stiffener spacing; h_s: stiffener height; t_w: stiffener thickness; W_s: stiffened panel's weight; UC: Ultimate capacity; BS: Buckling strength

From the result in Table 3.24, the values are explained as follow:

Cases 1, 3, 4, 7 and 9 show the failing stress control is limit state 3.

Case 5 shows the failing stress control limit state 1.

The maximum sideways displacement in the top of stiffener and displacement across stiffener web height (local mode)

Strengthen: Increase sideways stiffeners stiffness, increase stiffener flange width, reduce stiffener web height, reduce stiffener span

Cases 2, 6, 8 and 10 are limited, this means that according to PULS check the lateral pressure in these cases must be:

Case 2 the pressure must be below 0.339 MPa.

Case 6 the pressure must be below 0.341 MPa

Case 8 the pressure must be below 0.343 MPa.

Case 10 the pressure must be below 0.345 MPa.

In this case the stiffened panel in case 5 is considered as an optimal panel according to the reducing of panel's weight as well as satisfying the usage factor.

Now, these panels will be checked the satisfaction of the fabrication cost function. The design process is performed as shown in Table 3.25.

Table 3. 25: The fabrication cost for the case s=625mm; n=9

N^0	t_p_s_h_s x t_w [mm]	A [mm]	NC	n	Ls [m]	P_b [Kr/m]	Ps [Kr]	P_t [Kr]
1	16_625_320x12	8	5.15	9	3.125	50	804.7	7242.3
2	16_625_240x12	8	5.15	9	3.125	50	804.7	7242.3
3	16_625_260x10	8	5.15	9	3.125	50	804.7	7242.3
4	15_625_260x10	7.5	4.6	9	3.125	50	718.8	6469.2
5	14_625_260x11	7	4.05	9	3.125	50	632.8	5695.2
6	17_625_240x12	8.5	5.75	9	3.125	50	898.4	8085.6
7	17_625_260x10	8.5	5.75	9	3.125	50	898.4	8085.6
8	18_625_240x12	9	6.35	9	3.125	50	992.2	8929.8
9	18_625_260x10	9	6.35	9	3.125	50	992.2	8929.8
10	19_625_240x12	9.5	7.05	9	3.125	50	1101.6	9914.4

t_p: plate thickness; s: stiffener spacing; hs: stiffener height; t_w: stiffener thickness; n: stiffener number; A: throat thickness; NC: Norm curve value; Ls: stiffener length; P_b: basic price per meter; Ps: cost per stiffener; P_t: total cost.

From Table 3.25 if the fabrication cost is considered, the stiffened panel in case 5 also gives a lowest value of fabrication cost.

Therefore, in this situation the optimal panel should be the 5^{th} panel.

3.6.2.2 Optimal design for panel with stiffener spacing; s=568mm, stiffener number; n=10

The stiffened panel with stiffener spacing s=568mm, stiffener number n=10 is now redesign. This panel is kept the stiffener spacing and varied the panel thickness as well as stiffener dimension in order to get new optimal configuration (see Table 26)

Table 3. 26: Varying the stiffener dimension and plate thickness with s = 568 mm, n=10

N^0	$t_p\_s\_h_s$ x t_w [mm]	σ_1 N/mm^2	σ_2 N/mm^2	τ_{12} N/mm^2	UC	BS	Buckling Check	W_s [kg]
1	16_568_320x12	115.9	77	80	0.51	0.51	State 3	3706
2	16_568_240x10	133.7	77	80	Limited	0	-	3219
3	16_568_240x11	131.3	77	80	0.55	0.55	State 3	3275
4	13_568_280x12	139.6	94.8	98.5	0.78	0.88	State 3	3081
5	13_568_400x14	111.3	94.8	98.5	0.7	0.78	State 1	3859
6	17_568_240x10	127.6	72.5	75.3	Limited	0	-	3372
7	17_568_240x11	125.5	72.5	75.3	0.5	0.5	State 3	3428
8	18_568_240x10	122.1	68.4	71.1	Limited	0	-	3525
9	19_568_240x10	117	64.8	67.4	Limited	0	-	3679
10	20_568_240x10	112.3	61.6	64	Limited	0	-	3832

σ_1: axial stress; σ_2: transverse stress; τ_{12}: shear stress; t_p: plate thickness; s: stiffener spacing; h_s: stiffener height; t_w: stiffener thickness; W_s: stiffened panel's weight; UC: Ultimate capacity; BS: Buckling strength

From results in Table 3.26, they are now analyzed as follow:

Cases 1, 3 and 4 show the failing stress control limit state 3.

Case 5 shows the failing stress control limit state 1.

The maximum sideways displacement in the top of stiffener and displacement across stiffener web height (local mode).

Strengthen: increase sideways stiffener stiffness, increase stiffener flange width, reduce stiffener web height, reduce stiffener span

Case 7 shows the failing stress control limit state 3.

The maximum lateral stiffener displacement (global mode).

Strengthen: increase stiffener bending stiffness, increase web height, increase stiffener flange, reduce stiffener span.

Cases 2, 6, 8, 9 and 10 are limited, this means that according to PULS check the lateral pressure in these cases must be:

Case 2 the pressure must be below 0.337 MPa.

Case 6 the pressure must be below 0.339 MPa.

Case 8 the pressure must be below 0.341 MPa.

Case 9 the pressure must be below 0.343 MPa.

Case 10 the pressure must be below 0.345 MPa.

From the Table 3.26, it can be seen that the 4th panel can be satisfied the requirement of usage factor as well as the reducing of weight of panel. Hence this panel could be considered as an optimal panel according to the reduced weight requirement.

Then, the optimal design for fabrication cost will be performed in Table 3.27.

Table 3. 27: The fabrication cost for the case s=568mm, n=10

N^0	t_p_s_h_s x t_w [mm]	A [mm]	NC	n	Ls [m]	P_b [Kr/m]	Ps [Kr]	P_t [Kr]
1	16_568_320x12	8	5.15	10	3.125	50	804.7	8047
2	16_568_240x10	8	5.15	10	3.125	50	804.7	8047
3	16_568_240x11	8	5.15	10	3.125	50	804.7	8047
4	13_568_280x12	6.5	3.6	10	3.125	50	562.5	5625
5	13_568_400x14	7	4.05	10	3.125	50	632.8	6328
6	17_568_240x10	8.5	5.75	10	3.125	50	898.4	8984
7	17_568_240x11	8.5	5.75	10	3.125	50	898.4	8984
8	18_568_240x10	9	6.35	10	3.125	50	992.2	9922
9	19_568_240x10	9.5	7.05	10	3.125	50	1101.6	11016
10	20_568_240x10	10	7.7	10	3.125	50	1203.1	12031

t_p: plate thickness; s: stiffener spacing; hs: stiffener height; t_w: stiffener thickness; n: stiffener number; A: throat thickness; NC: Norm curve value; Ls: stiffener length; P_b: basic price per meter; Ps: cost per stiffener; P_t: total cost.

Now, from the Table 3.27 the 4th panel provides the lowest fabrication cost as compare to others, so it is considered as an optimal stiffened panel.

Therefore, combination of requirements between Table 3.26 and Table 3.27, the 4th panel should be chosen as an optimal panel in this situation.

3.6.2.3 Optimal design for panel with stiffener spacing; s=694mm, stiffener number; n=8

Perform similarly, now the stiffener number is reduced from 10 to 8 stiffeners, this means that the stiffener spacing is now increased with s=694mm. This spacing is fixed during this situation and the panel's parameters will be varied in order to get a new optimal scantling. The Table 3.28 shows the performance of optimum design for the panels.

Table 3. 28: Varying the stiffener dimension and plate thickness with s = 694 mm, n=8

N^0	$t_p\_s\_h_s \times t_w$ [mm]	σ_1 N/mm^2	σ_2 N/mm^2	τ_{12} N/mm^2	UC	BS	Buckling Check	W_s [kg]
1	16_694_320x12	124.4	77	80	0.64	0.72	State 3	3456
2	16_694_260x11	135	77	80	0.66	0.74	State 3	3188
3	16_694_260x10	137.2	77	80	Limited	0	-	3138
4	15_694_280x12	135.7	82.1	85.3	0.74	0.87	State 3	3170
5	15_694_260x11	141.8	82.1	85.3	0.76	0.89	State 3	3035
6	14_694_400x14	118.1	88	91.4	0.78	0.93	State 1	3639
7	13_694_430x20	105.5	94.8	98.5	0.82	0.94	State 1	4071
8	17_694_260x10	130.8	72.5	75.3	0.59	0.63	State 3	3291
9	17_694_240x12	130	72.5	75.3	Limited	0	-	3311
10	18_694_240x12	124.2	68.4	71.1	Limited	0	-	3465

σ_1: axial stress; σ_2: transverse stress; τ_{12}: shear stress; t_p: plate thickness; s: stiffener spacing; h_s: stiffener height; t_w: stiffener thickness; W_s: stiffened panel's weight; UC: Ultimate capacity; BS: Buckling strength

The result from Table 3.28 is indicated that:

Cases 1: failing stress control limit state 3. The maximum sideways displacement across stiffener web height and maximum sideway displacement in the top of stiffener (local mode).

Strengthen: increase sideways stiffeners stiffness, increase stiffener flange width, reduce stiffener web height, reduce stiffener span

Case 2: failing stress control limit state 3. Maximum plate displacement between stiffeners at ultimate capacity (local mode).

Strengthen: increase plate thickness, reduce stiffener spacing, increase web thickness.

Case 3: the pressure must be below 0.346 MPa.

Case 4: failing stress control limit state 3. Maximum plate displacement between stiffeners at ultimate capacity (local mode).

Strengthen: increase plate thickness, reduce stiffener spacing, increase web thickness.

Case 5: failing stress control limit state 3. Maximum plate displacement between stiffeners at ultimate capacity (local mode).

Strengthen: increase plate thickness, reduce stiffener spacing, increase web thickness.

Case 6: failing stress control limit state 1. The maximum sideways displacement across stiffener web height and maximum sideway displacement in the top of stiffener (local mode).

Strengthen: Increase sideways stiffener stiffness, increase stiffener flange width, reduce stiffener web height, reduce stiffener span.

Case 7: failing stress control limit state 1. The maximum sideways displacement across stiffener web height and maximum sideway displacement in the top of stiffener (local mode).

Strengthen: increase sideways stiffener stiffness, increase stiffener flange width, reduce stiffener web height, reduce stiffener span

Case 8: failing stress control limit state 3.Maximum plate displacement between stiffeners at ultimate capacity (local mode).

Strengthen: increase plate thickness, reduce stiffener spacing, increase web thickness.

Case 9: the pressure must be below 0.309 MPa.

Case 10: the pressure must be below 0.309 MPa.

As can be seen the results in Table 3.29, the optimal panel in this case is for the 5th panel which suggests the lowest weight as well as it can be satisfied with usage factor requirement.

Table 3. 29: The fabrication cost for the case s=694mm, n=8

N^0	t_p_s_h_s x t_w [mm]	A [mm]	NC	n	Ls [m]	P_b [Kr/m]	Ps [Kr]	P_t [Kr]
1	16_694_320x12	8	5.15	8	3.125	50	804.7	6437.6
2	16_694_260x11	8	5.15	8	3.125	50	804.7	6437.6
3	16_694_260x10	8	5.15	8	3.125	50	804.7	6437.6
4	15_694_280x12	7.5	4.6	8	3.125	50	718.8	5750.4
5	15_694_260x11	7.5	4.6	8	3.125	50	718.8	5750.4
6	14_694_400x14	7	4.05	8	3.125	50	632.8	5062.4
7	13_694_430x20	10	7.7	8	3.125	50	1203.1	9624.8
8	17_694_260x10	8.5	5.75	8	3.125	50	898.4	7187.2
9	17_694_240x12	8.5	5.75	8	3.125	50	898.4	7187.2
10	18_694_240x12	9	6.35	8	3.125	50	992.2	7937.6

t_p: plate thickness; s: stiffener spacing; hs: stiffener height; t_w: stiffener thickness; n: stiffener number; A: throat thickness; NC: Norm curve value; Ls: stiffener length; P_b: basic price per meter; Ps: cost per stiffener; P_t: total cost.

From the Table 3.29 when the fabrication cost is considered, the 5th panel provides a considerable value. The 6th panel also gives lowest value of fabrication cost, but as considering for requirement of weight and panel's strength this panel will not be chosen.

Combining of requirements in the Table 3.28 and Table 3.29 the optimal panel in this situation should be the 5th panel.

3.6.2.4 Optimal design for panel with stiffener spacing; s=780mm, stiffener number; n=7

As can be seen one stiffener is now reduced while the dimension of panel is unchanged. This mean that the stiffener spacing is increases further now and reaches to s=780mm. By varying the plate thickness and stiffener dimension correspondent with each other until an optimal result is achieved for the panel, during this process the spacing will be fixed.

The performance and result for new optimal panel is now shown in Table 3.30 bellow.

Table 3. 30: Varying the stiffener dimension and plate thickness with s = 780 mm, n=7

N^0	t_p_s_h_s x t_w [mm]	σ_1 N/mm^2	σ_2 N/mm^2	τ_{12} N/mm^2	UC	BS	Buckling Check	W_s [kg]
1	16_780_320x12	129.2	77	80	0.73	0.9	State 3	3330
2	16_780_280x11	136	77	80	0.75	0.92	State 3	3166
3	15_780_400x14	119.3	82.1	85.3	0.77	0.97	State 1	3606
4	15_780_260x12	144.2	82.1	85.3	Limited	0	-	2987
5	17_780_260x12	130.8	72.5	75.3	Limited	0	-	3293
6	17_780_280x11	129.8	72.5	75.3	0.66	0.78	State 3	3320
7	18_780_260x12	124.9	68.4	71.1	Limited	0	-	3447
8	19_780_260x12	119.6	64.8	67.4	Limited	0	-	3600
9	20_780_280x11	114	61.6	64	0.47	0.49	State 3	3780
10	20_780_260x12	114.8	61.6	64	Limited	0	-	3753

σ_1: axial stress; σ_2: transverse stress; τ_{12}: shear stress; t_p: plate thickness; s: stiffener spacing; h_s: stiffener height; t_w: stiffener thickness; W_s: stiffened panel's weight; UC: Ultimate capacity; BS: Buckling strength

From Table 3.30 the results will be analyzed as follow:

Cases 1: failing stress control limit state 3. The maximum plate displacement between stiffeners at ultimate capacity (local mode). Strengthen: increase plate thickness, reduce stiffener spacing, increase web thickness.

Case 2: failing stress control limit state 3. The maximum plate displacement between stiffeners at ultimate capacity (local mode). Strengthen: increase plate thickness, reduce stiffener spacing, increase web thickness.

Case 3: failing stress control limit state 1. The maximum plate displacement between stiffeners at ultimate capacity (local mode). Strengthen: increase plate thickness, reduce stiffener spacing, increase web thickness.

Case 4: the pressure must be below 0.336 MPa.

Case 5: the pressure must be below 0.340 MPa.

Case 6: failing stress control limit state 3. The maximum plate displacement between stiffeners at ultimate capacity (local mode). Strengthen: increase plate thickness, reduce stiffener spacing, increase web thickness.

Case 7: the pressure must be below 0.342 MPa.

Case 8: the pressure must be below 0.344 MPa.

Case 9: failing stress control limit state 3. The maximum plate displacement between stiffeners at ultimate capacity (local mode). Strengthen: increase plate thickness, reduce stiffener spacing, increase web thickness.

Case 10: the pressure must be below 0.346 MPa.

From the Table 3.30 the 1st panel could be satisfied the strength requirement, besides it also provides lower value of weight as compare to the basic case. Hence, this panel could be considered as an optimal panel according to the requirement of reducing of panel's weight.

Next, the optimal design for the fabrication cost will be performed. The Table 3.31 bellow will give an optimal panel which gives the lowest fabrication cost. o

Table 3. 31: The fabrication cost for the case s=780mm, n=7

N^0	t_p_s_h_s x t_w [mm]	A [mm]	NC	n	Ls [m]	P_b [Kr/m]	Ps [Kr]	P_t [Kr]
1	16_780_320x12	8	5.15	7	3.125	50	804.7	5632.9
2	16_780_280x11	8	5.15	7	3.125	50	804.7	5632.9
3	15_780_400x14	7.5	4.6	7	3.125	50	718.8	5031.6
4	15_780_260x12	7.5	4.6	7	3.125	50	718.8	5031.6
5	17_780_260x12	8.5	5.75	7	3.125	50	898.4	6288.8
6	17_780_280x11	8.5	5.75	7	3.125	50	898.4	6288.8
7	18_780_260x12	9	6.35	7	3.125	50	992.2	6945.4
8	19_780_260x12	9.5	7.05	7	3.125	50	1101.6	7711.2
9	20_780_280x11	10	7.7	7	3.125	50	1203.1	8421.7
10	20_780_260x12	10	7.7	7	3.125	50	1203.1	8421.7

t_p: plate thickness; s: stiffener spacing; hs: stiffener height; t_w: stiffener thickness; n: stiffener number; A: throat thickness; NC: Norm curve value; Ls: stiffener length; P_b: basic price per meter; Ps: cost per stiffener; P_t: total cost.

From the Table 3.31 when the fabrication cost is considered, there are two panel give the same value of fabrication cost because they have the same plate thickness, i.e. t_p=15mm.

However, when combining with requirement in Table 3.31 the panel in case 4th can not be satisfied, thus the panel in case 3 will be chosen as an optimal panel according fabrication cost in this situation.

Therefore, according to the satisfactoriness of the panel in Table 3.30 and Table 3.31 the panel in case 3rd is the best one after varying the panel thickness and stiffener dimension.

After comparing four situations of varying for stiffened panels above, now a summarized table will show the optimal panels of each situation as follow (see Table 3.32).

Table 3. 32: Optimal configuration of stiffened panel by PULS

N^0	t_p_s_h_s x t_w [mm]	σ_1 N/mm^2	σ_2 N/mm^2	τ_{12} N/mm^2	UC	BS	Buckling Check	W_s [kg]	P_t [Kr]
Stiffener Spacing; s = 625mm and number of stiffeners; n = 9									
1	14_625_260x11	144.6	88	91.4	0.78	0.89	State 1	2973	5695.2
Stiffener Spacing s = 568mm and number of stiffeners n = 10									
2	13_568_280x12	139.6	94.8	98.5	0.78	0.88	State 3	3081	5625
Stiffener Spacing; s = 694mm and number of stiffeners; n = 8									
3	15_694_260x11	141.8	82.1	85.3	0.76	0.89	State 3	3035	5750.4
Stiffener Spacing; s = 780mm and number of stiffeners; n = 7									
4	16_780_320x12	129.2	77	80	0.73	0.9	State 3	3330	5632.9

σ_1: axial stress; σ_2: transverse stress; τ_{12}: shear stress; t_p: plate thickness; s: stiffener spacing; h_s: stiffener height; t_w: stiffener thickness; W_s: stiffened panel's weight; UC: Ultimate capacity; BS: Buckling strength; Pt: total cost.

From the Table 3.32 it can be seen that all of panels have lower value of fabrication cost as well as the panel's weight as compare to the basic case.

Besides, it is also seen that the difference of fabrication cost between panels is small, so the optimal panel should be chosen for which panel provides a lowest value of weight. For this reason, from Table 3.32 the optimal panel is the 1st panel with new scantling that can be satisfied the strength requirement, lower weight as well as reduced fabrication cost function.

This means that by using PULS the optimal panel can be satisfied not only for the weight requirement, but also for the lower fabrication cost of the panel.

Finally, the optimal panel with new configuration that is redesign by PULs is now chosen. The information of this optimal panel is shown in Table 3.33 bellow.

Table 3. 33: Optimal panel when using PULS

N^0	$t_p\_s\_h_s \times t_w$ [mm]	σ_1 N/mm^2	σ_2 N/mm^2	τ_{12} N/mm^2	UC	BS	Buckling Check	W_s [kg]	P_t [Kr]
Stiffener Spacing; s = 625mm and number of stiffeners; n = 9									
1	16_625_320x12	120	77	80	0.56	0.59	State 3	3581	7242.3
Stiffener Spacing; s = 625mm and number of stiffeners; n = 9									
2	14_625_260x11	144.6	88	91.4	0.78	0.89	State 1	2973	5695.2

σ_1: axial stress; σ_{21}, σ_{22}: transverse stress; τ_{12}: shear stress; t_p: plate thickness; s: stiffener spacing; h_s: stiffener height; t_w: stiffener thickness; W_s: stiffened panel's weight; UC: Ultimate capacity; BS: Buckling strength; Pt: total cost.

From Table 3.33. it can be seen that if stiffened panel is redesigned by PULS, the optimal panel with new configuration can be satisfied both weight and fabrication cost requirements. The ultimate capacity of optimal panel is now compared with the panel in basic case by the curves as shown in Figure 3.10.

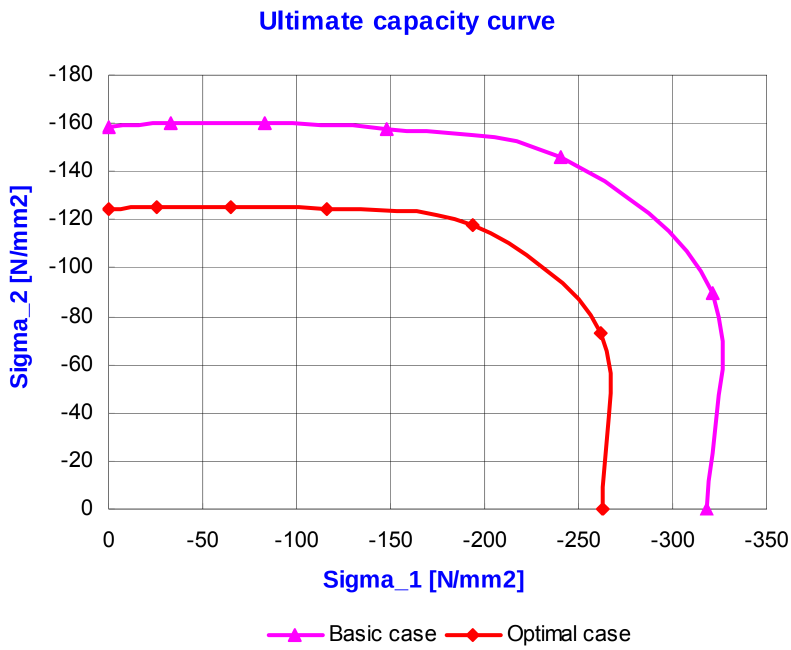


Figure 3. 10: Ultimate capacity between optimal panel and panel in basic case

As can be seen from Figure 3.10 the ultimate capacity of the new panel provides far distance in stresses as compare to the panel in basic case. By doing this, the weight and the fabrication cost function is now significantly reduced as shown in Table 3.33.

4 COMPARISON OF OPTIMAL DESIGN PROCEDURE

4.1 Comparison of the result provided by DNV RP-C201 spreadsheet and PULS

After calculation in PULS and RP-C201 for the stiffened panel, there are some conclusions for two program as follow:

With the DNV RP-C201 spreadsheet provided an optimal configuration for stiffened panel as shown in Table 4.1.

Table 4. 1: Optimal configuration for stiffened panel performed by RP-C201

N^0	t_p_s_h_s x t_w [mm]	σ_1 N/mm^2	σ_2 N/mm^2	τ_{12} N/mm^2	η	Buckling check	W_s [kg]	P_t [Kr]
Stiffener Spacing; s = 625 and number of stiffeners; n = 9 (basic case)								
2	16_625_320x12	120	77	80	0.9	Point 1	3581	7242.3
Stiffener Spacing; s = 780mm and number of stiffeners; n = 7								
4	16_780_400x15	112.4	77	80	0.9	Point 4	3827	5632.9

σ_1: axial stress; σ_2: transverse stress; τ_{12}: shear stress; t_p: plate thickness; s: stiffener spacing; h_s: stiffener height; t_w: stiffener thickness; η: usage factor; W_s: stiffened panel's weight; Pt: total cost

For optimal design procedure is performed by PULS provided a different new scantling for optimal panel as shown in Table 4.2.

Table 4. 2: Optimal configuration for stiffened panel performed by PULS

N^0	t_p_s_h_s x t_w [mm]	σ_1 N/mm^2	σ_2 N/mm^2	τ_{12} N/mm^2	UC	BS	Buckling Check	W_s [kg]	P_t [Kr]
Stiffener Spacing; s = 625mm and number of stiffeners; n = 9									
1	16_625_320x12	120	77	80	0.56	0.59	State 3	3581	7242.3
Stiffener Spacing; s = 625mm and number of stiffeners; n = 9									
2	14_625_260x11	144.6	88	91.4	0.78	0.89	State 1	2973	5695.2

σ_1: axial stress; σ_2: transverse stress; τ_{12}: shear stress; t_p: plate thickness; s: stiffener spacing; h_s: stiffener height; t_w: stiffener thickness; W_s: stiffened panel's weight; Pt: total cost; UC: Ultimate capacity; BS: Buckling strength

The result in Table 4.1 indicates that optimal panel can not be satisfied both the weight and fabrication cost requirement in the same time. The result shows in this Table provides a new configuration that can satisfy for fabrication cost even though the weight is higher than the weight of panel in basic case. This panel is also met the limited value of usage factor; η=0.9.

The result in Table 4.2 is to show that if the stiffened panel is analyzed by PULS, this will give an optimal panel that can be satisfied both weight as well as in fabrication cost requirements. However, this program is not conservative to use with offshore structure.

There is a big different between two programs. The RP-C201 is considered as a conventional buckling code for stiffened and unstiffened panels of steel. Inversely, the PULS is considered as a computerised semi-analytical model (for steel and aluminum) that is based on a non-linear plate theory. However, as apply for offshore structure the RP-C201 is more conservative than PULS, i.e. PULS is applied for ship structure only. See Table 4.4 for more illustration.

For the detail result about usage factor we can see that the spreadsheet RP-C201 shows a quickly change in the usage factor result when we change parameters of the stiffened panel, i.e. plate thickness, stiffener dimension. However, with PULS we can see that the value of the usage factor changed slightly when we change the same values in RP_C201. Personally, I see that the first reason comes from the analyzing procedure of two programs. It is clear that the RP_C201 is a recommended practice spreadsheet, i.e. it basics strongly on the formulae in NORSOK Standard – N004, so the calculating procedure is quite simple and fast.

On other hand, PULS is a complicated program, i.e. it based on a lot of formulae and codes which come from different methods (e.g. non-linear analysis, energy method, etc). Thus, the analyzing procedure is of course more complicated and not easy to understand thoroughly. There are also many factors, equations and formulae need to be analyzed in the same problem. The result is therefore affected by these variables in the PULS program.

The lateral pressure has slight effect to the usage factor in PULS whereas it has a strongly influence on result of ultimate capacity of panel when design procedure is performed by DNV RP-C201 spreadsheet, see Table 4.3 for more illustration

Table 4. 3: Comparison of usage factor with regard to lateral pressure

N^0	σ_1 N/mm^2	σ_2 N/mm^2	τ_{12} N/mm^2	P_{ds} N/mm^2	UC RP-C201	UC PULS
1	120	77	80	0.346	0,9	0.59
2	120	77	80	0	0,68	0,54

σ_1: axial stress; σ_2: transverse stress; τ_{12}: shear stress; Pds: lateral pressure; UC: Ultimate capacity;

In can be also see more detail in the Figure 4.1 bellow. The left Figure (PULS) shows a small gap as compare to this gap in the RP-C201.

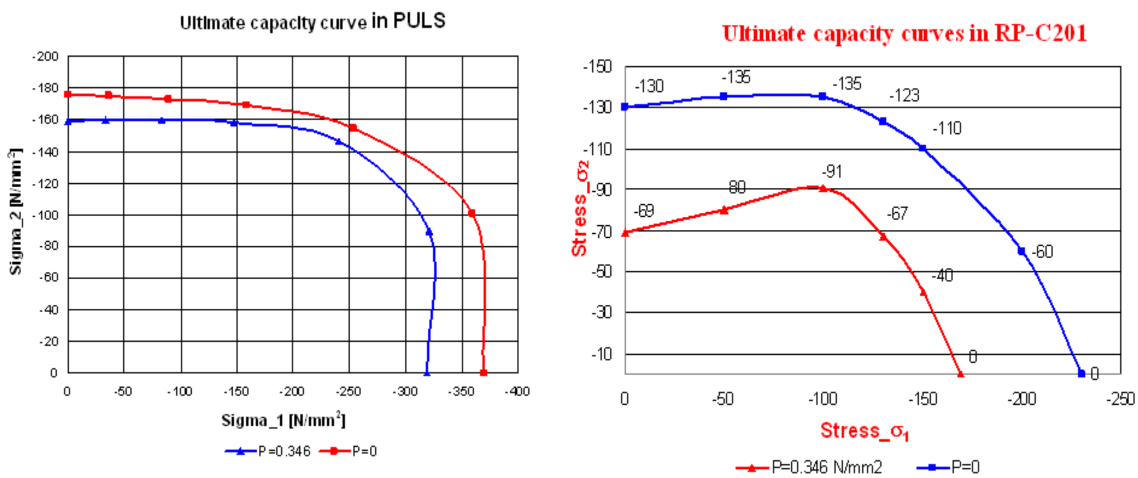


Figure 4. 1: Ultimate capacity curve in RP-C201 and PULS with different lateral load

Table 4. 4: Comparison of usage factor provided by different programs

N^0	t_p_s_h_s x t_w	σ_1	$\sigma_{2,1}$	$\sigma_{2,2}$	τ_{12}	P_{ds}	Usage Factor		
	[mm]	N/mm^2	N/mm^2	N/mm^2	N/mm^2	N/mm^2	Aker Solutions	RP-C201	PULS
1	16_625_320x12	120	77	77	80	0.346	0,9	0,9	0,56

σ_1: axial stress; σ_{21}, σ_{22}: transverse stress; τ_{12}: shear stress; t_p: plate thickness; s: stiffener spacing; h_s: stiffener height; t_w: stiffener thickness; Pds: lateral pressure.

From the Table 4.4 it can be seen a unreasonable result that is provided by PULS, this result seem to be not conservative. This mean that the PULS is not conservative when applying for stiffened panel in offshore structure. The reason to say that because some reasons as follow:

- According to [9] the design model for ultimate and buckling strength assessment of stiffened plates, PULS provides a set of reduced anisotropic/orthotropic macro material coefficients that can be used in refined linear global finite element (FE) analysis of ship hulls to reflect the increased membrane flexibility experienced by compressed stiffened panels.
- Besides, when found this result the author and supervisor have discussed with an expert at Det Norske Vertitas Software, Eivind Steen who has clear understanding of PULS program. He also confirmed that PULS is mainly used for ship structure.
- Moreover, the result of calculation in two programs was compared to the calculating result from Aker Solution and it was seen that the result in RP-C201 is close to the given value from Aker Solution, while PULS gives a big difference as compare to Aker Solution's result. The ultimate capacity curves for stiffened panel plot by these three programs are shown in Figures C1, C2, and C3 in Appendix C.

For the reasons as mentioned above, the design procedure for stiffened panel should be based on the DNV RP-C201 in this thesis.

The PULS has the range of validity for input and the program automatically checks the input data with critical range and suggests to user with a message, especially when an error occurs during design procedure, whereas the RP-C201 can not perform this. Therefore, the designer should be very careful during design process or on other word, the user must have good experience or good knowledge during design

Both of programs are still not convenient for the automatic calculation in design aspect. In addition, when performing of optimal design for stiffened panel by means of these two programs, it took a lot of time by trial and error analysis in order to get an optimal configuration for stiffened panel.

For this reason, new spreadsheets are built in PULS and RP-C201 with the purpose is to automatically update for stresses when the panel thickness, stiffener dimension, stiffener numbers are changed. Besides, the weight as well as fabrication cost will be also automatically calculated when any parameter of stiffened panel is varied. This can help the design procedure to be more convenient and faster. For more illustration of these spreadsheet refer to Figures A1, A2, A3 in Appendix A.

4.2 Small discussion of difference between Nauticus DNV RP-201 spreadsheet and STIPLA from Aker solution

The reason of this comparison since there is a small difference in analysis result of two programs. The author do not know this comparison is fully correct or not (because this comparison just based on one value given from Aker Solutions) , but it is really interesting for author to get more understand this standard (DNV RP-C201) when perform this comparison. Once again this is just to learn more knowledge in DNV offshore standard as well as the RP-C201 spreadsheet.

During the time working with DNV RP-C201 spreadsheet in Nauticus program I have also checked with the result given from Aker Solutions Company.

The author have found some difference in design procedure that is performed in DNV RP-C201 spreadsheet and STIPLA program from Aker Solutions.

The difference as well as some discussed will be performed as shown in follow Tables.

Table 4. 5: Calculate for UF_{1s} (Formula 7.50 of [3], i.e. checking for stiffener at support)

	RP-C201			Aker solution		
Description	Symbol	Value	Unit	Symbol	Value	Unit
Design axial load	N_{sd}	1 850.95	KN	N_{sd}	1850.4	KN
Design stiffener buckling resistance	$N_{ks1,Rd}$	3 129.77	KN	$N_{ks1,Rd}$	4547.3	KN
Design bending moment	$M_{1,sd}$	260.96	KN.m	M1,sd	260.7	KN.m
Distance	z	0.0868	m	z	0.086	m
Design moment resistance on stiffener side	$M_{s1,Rd}$	266.67	KN.m	Ms1,Rd	292.7	KN.m
Euler buckling strength	Ne	83 935	KN	Ne	83936.1	KN
Shear factor	u	0.144		u	0.144	
Result	UF_{1s}=	1.120		UF_{1s}=	0.906	
Difference					0.214	

From Table 4.5 it can see that there are two terms are different between RP-C201 spreadsheet and Aker Solutions's program .

Table 4. 6: Calculate for UF_{1p} (Formula 7.51 of [3], i.e. checking for plate at support)

	RP-C201			Aker solution		
Description	Symbol	Value	Unit	Symbol	Value	Unit
Design axial load	N_{sd}	1 850.95	KN	N_{sd}	1850.4	KN
Design plate ind. buckling resistance	$N_{kp1,Rd}$	4 663.36	KN	$N_{kp1,Rd}$	4661.8	KN
Resistance design load	N_{Rd}	4 773.59	KN	N_{1Rd}	4771.9	KN
Moment	$M_{1,sd}$	260.96	KN.m	$M_{1,sd}$	260.7	KN.m
Distance	z	0.0868	m	z	0.086	m
Design moment resistance -plate side	$M_{p1,Rd}$	817.65	KN.m	$M_{p1,Rd}$	815.5	KN.m
Euler buckling strength	Ne	83 935	KN	Ne	83936.1	KN
Shear factor	u	0.144		u	0.144	
Result	UF_{1P}=	-0.109		UF_{1P}=	-0.107	
Difference					0.00	

From Table 4.6 shows that the RP-C201 spreadsheet and Aker Solutions's program give the same results.

Table 4. 7: Calculate for UF_{2s} (Formula 7.52 of [3], i.e. checking for stiffener at middle)

	RP-C201			Aker solution		
Description	Symbol	Value	Unit	Symbol	Value	Unit
Design axial load	N_{sd}	1 850.95	KN	N_{sd}	1850.4	KN
Design stiffener ind. buckling resistance	$N_{ks2,Rd}$	3 129.77	KN	$N_{ks2,Rd}$	4547.3	KN
Resistance design load	N_{Rd}	4 773.59	KN	N_{Rd}	771.90	KN
Moment	$M_{2,sd}$	130.48	KN.m	$M_{2,sd}$	130.30	KN.m
Distance	z	0.0868	m	z	0.086	m
Design moment res.on stiff. side in tension	$M_{st2,Rd}$	294.43	KN.m	Mst2,Rd	292.7	KN.m
Euler buckling strength	Ne	83 935	KN	Ne	83936.1	KN
Shear factor	u	0.144		u	0.144	
Result	UF_{2S}=	0.971		UF_{2S}=	0.787	
Difference					0.185	

From Table 4.7 it can be seen that there are also two terms are different between RP-C201 spreadsheet and Aker Solutions's program.

Table 4. 8: Calculate for UF_{2p} (Formula 7.53 of [3], i.e. checking for plate at middle)

	RP-C201			Aker solution		
Description	Symbol	Value	Unit	Symbol	Value	Unit
Design axial load	N_{sd}	1 850.95	KN	N_{sd}	1850.4	KN
Design plate ind. buckling resistance	$N_{kp2,Rd}$	4 663.36	KN	$N_{kp2,Rd}$	4661.8	KN
Moment	$M_{2,sd}$	130.48	KN.m	$M_{2,sd}$	130.30	KN.m
Moment	$M_{1,sd}$	260.96	KN.m	M1,sd	260.7	KN.m
Distance	z	0.0868	m	z	0.086	m
Design moment resistance - plate side	$M_{p2,Rd}$	817.65	KN.m	Mp2,Rd	815.5	KN.m
Euler buckling strength	Ne	83 935	KN	Ne	83936.1	KN
Shear factor	u	0.144		u	0.144	
Result	UF_{2P}=	0.905		UF_{2P}=	0.904	
Difference					0.00	

From Table 4.8 it can be seen that both the RP-C201 spreadsheet and Aker Solutions's program provides the same result.

Table 4. 9: Shear checking Comparison

Description	Symbol	Aker solutions	RP-C201	Unit
Design shear force	V_{sd}	337.9	337.9	KN
Design shear resistance	V_{Rd}	709	809.7	KN
Rate	V_{sd}/V_{Rd}	0.48	0.42	
Difference		0.06		

From Table 4.9 we can see that RP-C201 and Aker Solutions give a slight difference in the result of shear checking.

Table 4. 10: Comparison of "Effective width of stiffened plate"

Description	Symbol	Aker Solutions	RP-C201	Unit
Effective width of stiffened plate	S_e	477.9	477.87	mm
Difference	0.03			

From Table 4.10 shows that RP-C201 and Aker Solutions suggests a very close to each other result of calculation for S_e.

Table 4. 11: Comparison of "equivalent lateral pressure"

Description	Symbol	Aker Solutions	RP-C201	Unit
Effective width of stiffened plate	P_0	0.166	0.167	MPa
Different	0.00			

From Table 4.11 it is clear to see that both the RP-C201 and Aker Solutions's program indicates the same value of equivalent lateral pressure; P_0.

Table 4. 12: Value checking for N_{ks},R_d and f_k

Description	Symbol		Formula	Original Result	Unit
Design stiffener induced axial buckling resistance	$N_{ks,Rd}$	=	$Ae*f_k/\gamma_m$ =	3129.7	KN
Where					
Effective area	A_e	=	$A_s+S_e*t_p$ =	13070.5	mm^2
Cross sectional area of stiffener	A_s	=	5424.588		mm^2
Effective width of stiffened plate	S_e	=	477.87		mm
Plate thickness	t_p	=	16		mm
Characteristic buckling strength	f_k	=	$(f_k/f_r)*f_r$ =	275.364	
Where f_k/f_r according to equation (7.22) in DNV RP-C201.					
Rate	f_k/f_r	=		0.996122	
Characteristic strength	f_r	=	f_T =	276.4358	
Characteristic torsional buckling strength	f_T	=		276.4359	

According to DNV RP-C201 if reduced torsional slenderness $\lambda_T > 0.6$, f_r is set equal to f_T. Here, RP-C201 spreadsheet gives result of f_T is 276.4359 (see Table 4.12)

This value is calculated by Eq. (7.28) in DNV RP-C201, with l_T=3125mm, f_{ET}=391.41326, l_T=1.03587, the ratio f_T/f_y = 0.65818.

However, if we now assume fr=fy=420MPa, we will have new value for f_k and $N_{ks,Rd}$ as follow:

Table 4. 13: Modified Case

Description	Symbol	Value	Unit
Rate	$f_k/f_r =$	0.996122	
Characteristic strength	$f_r = f_y =$	420	MPa
Characteristic buckling strength	$f_k =$	418.3714	
New value for $N_{ks,Rd}$			
Design stiffener induced axial buckling resistance	$N_{ks,Rd} =$	4755.067	KN
Similarly we can find new value for $M_{s1,Rd}$			
Section modulus at flange tip:	W_{es}	806175	mm^3
Yield stress	f_r	420	MPa
Material factor	γ	1.15	
Design bending moment resistance on stiffener side	$M_{s1,Rd}$	294.4291	KNm
$M_{s1,Rd} = W_{es}*f_r/\gamma_m$ Equation (7.68) in DNV RP-C201			

From Table 4.13 it can be seen that when f_r is assumed equal f_y, the f_k will give new value then $N_{ks,Rd}$ and $M_{s1,Rd}$ will also give new value. Finally, a new value for UF_{1s}, i.e. the formula (7.50) of [3] is calculated as shown in Table 4.14.

Table 4. 14: New calculation for UF_{1s} (Equation 7.50 of [3])

	RP-C201			Aker solution		
Description	Symbol	Value	Unit	Symbol	Value	Unit
Design axial load	N_{sd}	1 850.95	KN	N_{sd}	1850.4	KN
Design stiff. Ind. buckling resistance	$N_{ks1,Rd}$	4 755.07	KN	$N_{ks1,Rd}$	4547.3	KN
Design bending moment	$M_{1,sd}$	260.96	KN.m	M1,sd	260.7	KN.m
Distance	z	0.0868	m	z	0.086	m
Design moment resistance on stiffener side	$M_{s1,Rd}$	294.43	KN.m	Ms1,Rd	292.7	KN.m
Euler buckling strength	Ne	83 935	KN	Ne	83936.1	KN
Shear factor	u	0.144		u	0.144	
Result	$UF_{1s}=$	0.9		$UF_{1s}=$	0.906	
Difference		0.006				

From the new result in Table 4.14, it is clear to see that the result of UF_{1s} that is calculated by DNV RP-C201 spreadsheet and Aker Solutions's program is almost the same. This means that if design procedure is performed according to Tables above, two programs will provide the same result with each other.

Similarly new value for UF_{2s}, i.e. the equation (7.52) is given in the Table 4.15 bellow

Table 4. 15: New calculation for UF_{2s} (Equation 7.52 of [3])

	RP-C201			Aker solution		
Description	Symbol	Value	Unit	Symbol	Value	Unit
Design axial load	N_{sd}	1 850.95	KN	N_{sd}	1850.4	KN
Design stiffener ind. buckling resistance	$N_{ks2,Rd}$	4 755.07	KN	$N_{ks2,Rd}$	4547.3	KN
Resistance design load	N_{Rd}	4 773.59	KN	N_{Rd}	4 771.90	KN
Moment	$M_{2,sd}$	130.48	KN.m	$M_{2,sd}$	130.30	KN.m
Distance	z	0.0868	m	z	0.086	m
Design moment resistance on stiff. side -tension	$M_{st2,Rd}$	294.43	KN.m	$M_{st2,Rd}$	292.7	KN.m
Euler buckling strength	Ne	83 935	KN	Ne	83936.1	KN
Shear factor	u	0.144		u	0.144	
Result	UF_{2S}=	0.769		UF_{2S}=	0.787	
Difference		0.01				

From the new results in Tables 4.14 and 4.15 shows that both the RP-C201 spreadsheet and Aker Solution's software give almost the same results of UF_{1s} and UF_{2s}, i.e. the calculation of Equation (7.50) and Equation (7.51) give the same result.

Finally, after checking for two programs the author give some suggestions as follow:

- There could be a difference in calculation of reduced torsional slenderness (λ_T) between two programs. For the RP-C201 spreadsheet it is found that λ_T>0.6, whereas λ_T is calculated in software that used by Aker Solutions gives smaller value than 0.6, i.e. λ_T<0.6 (in this case according to DNV RP-C201, the f_r will be assumed equal f_y. For more information we can check for DNV-RP C201 in [3], the 4th row goes further down from Equation (7.26).

- The program from Aker Solutions uses another method to calculate for f_k as well as for $N_{ks1,Rd}$ and $M_{s1,Rd}$, this means that it could be f_r is assumed equal f_y or f_T is assumed equal f_y in this calculation.

- Besides, this comparison has been discussed by the author and supervisor with Anders Rading at Aker Solutions Company, who has developed the program namely ''STIPLA''. Finally, we can get in agreement with each other about the methods that are used in two program. This means that the difference comes from the calculation method for torsional buckling of stiffeners.

- ''There are two methods for calculating f_{et} in the Dnv rule, Eq. (7.31) or the simplified Eq. (7.32) of [3]. Aker program use Eq. (7.32)/(7.33), based on converting the bulb profile to a L-profile. This gives a higher f_{et} then if the Equation (7.31) is used based on It calculated taking into account the bulb shape'' from Anders Rading.

In order to explain more about this, it should be seen again Tables 4.12, 4.13, and 4.14. Besides, according to [3] there are three methods to calculate for torsional elastic buckling strength, f_{ET} .

Generally, f_{ET} may be determined by Eq. (7.31) of [3]; this is given in Eq. (4.1) bellow:

$$f_{ET} = \beta \frac{GI_t}{I_{po}} + \pi^2 \frac{Eh_s^2 I_z}{I_{po} l_T^2} \tag{4.1}$$

For L and T stiffener profile f_{ET} will be calculated by Eq. (7.32) in [3]; this formula is given by Eq. (4.2).

$$f_{ET} = \beta \frac{A_W + \left(\frac{t_f}{t_W}\right)^2 A_f}{A_W + 3A_f} G \left(\frac{t_W}{h_W}\right)^2 + \frac{\pi^2 EI_z}{\left(\frac{A_W}{3} + A_f\right) l_T^2} \tag{4.2}$$

And for the flatbar stiffener f_{ET} shall be found by Eq. (7.34) from [3].

In these equations there is one dominated parameter that is stiffener torsional moment of inertia (St. Venant torsion) which significantly influences on the torsional elastic buckling strength. Aker program has been using Eq. (4.2) for calculation, this leads to a difference in result with Nauticus RP-C201 spreadsheet.

According to [17] and [20] the torsional moment of inertia is determined by Eq. (4.3) .

$$I_t = k_2 . b . t^3 \tag{4.3}$$

Where b : is the length of the long side

t : is the length of the short side

k_2 : is found from the from Table 3.43 bellow

Table 3.43: Cross-sectional constants k_1 and k_2 of the St. Venant torsion of rectangular shape (Refer from [20])

b/t	∞	10	5	3	2,5	2,0	1,5	1,0
k_1	3,00	3,20	3,44	3,74	3,86	4,06	4,33	4,80
k_2	0,333	0,312	0,291	0,263	0,249	0,229	0,196	0,141

In the case the stiffener is Bulb profile the constant k_2 may be very small due to the ratio b/t is close to 1. Hence, if the constant k_2 is taken as 1/3 for Eq. (3.10), this will give a unreasonable result for Bulb cross-sectional shape. This means that the formula $I_t = \frac{1}{3} b.t^3$ is used for Bulb profile will be non-conservative. Figure (2.7) should be an example for the difference between L profile and Bulb profile of stiffener.

5 OPTIMUM LAYOUT FOR THE GIRDER

5.1 General

For optimal design as well as buckling check with the girder, this task is only could be perform by DNV RP-C201 spreadsheet. The PULS can be applied for stiffened panel only and for application in girder check this program can not work.

Basic theory as well as the formulas of calculation that are used in RP-C201 spreadsheet for girder check has been introduced in the previous Section (see Section 2.5). Therefore, in this chapter the theories for calculation should not be introduced again.

It can see that, in order to redesign for girder, two parameters can be varied that is girder spacing and girder length. However, if changing two these parameters in the same time many other parameters will change correspondingly and it will takes a lot of time to recalculate for these parameter. Besides, in order to do this a strong computer program as well as an enough strong CPU should be used. However, in this thesis the design procedure is performed by RP-C201 spreadsheet only with simple computer.

Besides, since this is an additional task when the aim of thesis was changed at the end, the time is also limited in order to perform perfectly this task.

For above reasons, in this thesis the girder will be varied the spacing first and try to see the trend of change of usage factor of girder on plate side as well as the utilization of stiffener and plate. Then these parameters such as girder spacing as well as its dimension, stiffener dimension, plate thickness, etc will be varied, so that to meet the requirement of usage factor and weight.

5.2 Varying girder spacing for basic case

As can be seen in the Figure B4 in Appendix B the girder spacing is equally distribution on plate of pontoon top. Besides, in order to simplify design procedure in this thesis the girder will be considered with dimension relating to the dimension of the stiffened panel has be analyzed in previous sections.

According to the information of stiffened panel given in Table 3.1, the dimension of girder will be selected base on the information of panel in this Table.

The more detail illustration of the girder as well as the basic information of tanks are shown in the Figure B4 in Appendix B. The Table 5.1 bellow provides main information of the girder that is used for redesign as well as perform buckling check for the girder.

Table 5. 1: Information of Girder that using for redesign

Symbol	Value	Unit	Note
Girder			
Girder length_L_G	6250	[mm]	
Material factor_γ	1.15		
Girder profile	T		Welded T_bar
Total height_h_{tot}	1290	[mm]	
Web thickness_t_w	25	[mm]	
Flange width_b	300	[mm]	
Flange thickness_t_f	24	[mm]	
Material			
Material classification	Steel		
Modulus of Elasticity_ E	210000	[N/mm^2]	
Poisson ratio_ν	0.3		
Shear modulus_ G	80769	[N/mm^2]	
Yield stress for plate_σ_{Fp}	420	[N/mm^2]	
Yield stress for stiffener_σ_{Fs}	420	[N/mm^2]	

The check for girders is similar to the check for stiffeners of stiffened plates, this means that the Equations (2.22) to (2.25) will be used for the case of continuous girders.

With given information given in Table 5.1 combines with the given dimension of girder from Aker Solutions, the buckling check for girder of the basic case is now given in Table 5.2.

Table 5. 2: Original input dimension of girder for the basic case

N^0	l [mm]	h_{tot} [mm]	t_w [mm]	b [mm]	t_f [mm]	L_G [mm]	η	Girder Check	W_G [kg]	W_{tot} [kg]
1	3125	1250	15	300	20	6250	1.41	Point 1	1214.30	4795.30

l: girder spacing; h_{tot}: total height of girder; t_w: web thickness; b: flange width; t_f: flange thickness; L_G: girder length; η: usage factor; W_G : weight per girder; W_{tot} : total weight.$W_{tot} = W_s + W_G$

From Table 5.2 it is seen that the value of usage factor for girder in basic case is larger than 0.9.

As mentioned above, because of the difference between RP-C201spreadsheet in Nauticus program and the program from Aker Solutions, the input values for the girder will be slightly changed in order to be satisfied the first requirement that is for usage factor equals 0.9.

After varying, new values for the girder as well as the utilization factor for the girder are given in Table 5.3.

Table 5. 3: Modifying the input dimension of girder for the basic case

N^0	l [mm]	h_{tot} [mm]	t_w [mm]	b [mm]	t_f [mm]	L_G [mm]	η_G	Girder Check	W_G [kg]	W_{tot} [kg]
1	3125	1290	25	300	24	6250	0.9	Point 1	1935.52	5516.52

l: girder spacing; h_{tot}: total height of girder; t_w: web thickness; b: flange width; t_f: flange thickness; L_G: girder length; η_G: usage factor; W_G : weight per girder; W_{tot} : total weight; $W_{tot} = W_s + W_G$

The values in Table 5.3 will be considered as a basic case for performing girder buckling check as well as for optimal design for girder.

With the girder spacing is 3125mm and total length of the pontoon top that including all girder is 37550mm. This means that the number of girders on pontoon plate is thirteen girders (see Figure B4 in Appendix B). Now the girder spacing will be varied by increasing number of girder on the pontoon plate, i.e. reducing spacing between girders.

In this case the stiffener length becomes to be shorter and acting stresses on stiffened plate and girder will be changed in the transverse direction, hence a new calculation for these parameters should be done as shown in Table 5.4.

Table 5. 4: Reducing girder spacing for stiffened plate

N^0	Panel dimension t_p_s_h_s x t_w [mm]	n	l [mm]	σ_1 N/mm²	σ_2 N/mm²	τ_{12} N/mm²	Usage factor η_s	Usage factor η_G	Girder Check	W_{tot} [kg]
1	16_625_320x12	13	3125	120	77	80	0.9	0.9	Point 1	25161.70
2	16_625_320x12	14	2885	120	83.4	86.7	0.88	0.91	Point 1	27097.22
3	16_625_320x12	15	2679	120	89.8	93.3	0.88	0.92	Point 1	29032.73
4	16_625_320x12	16	2500	120	96.3	100	0.889	0.94	Point 1	30968.25
5	16_625_320x12	17	2344	120	102.7	106.7	0.92	0.97	Point 1	32903.77

Panel dimension: tp: plate thickness; s: stiffener spacing; hs: stiffener web height; t_w: stiffener web thickness;
l: girder spacing; n: number of girders; σ_1: axial stress; σ_2: transverse stress; τ_{12}: shear stress;
η_s: usage factor of stiffened panel; η_G: usage factor of girder. W_{tot} : total weight.

The result shown in Table 5.4 is for the assumption that the stiffener and the panel dimension is varied with the girder spacing. From this Table it is seen that when the number of girders is increased, i.e. reducing the girder spacing, the usage factor of the girder increases steadily and the weight also gives a linearly increase correspondingly to the increasing of girder number. Inversely, the usage factor of stiffened plate (η_{st}) provides a slightly change (increase) when reducing the girder spacing, this is due to the transverse stresses increase correspondingly.

For more illustration about this, Figure 5.1 bellow shows an increasing tendency of the usage factor and weight of girders when their spacing is reduced, i.e. the girder number is increased.

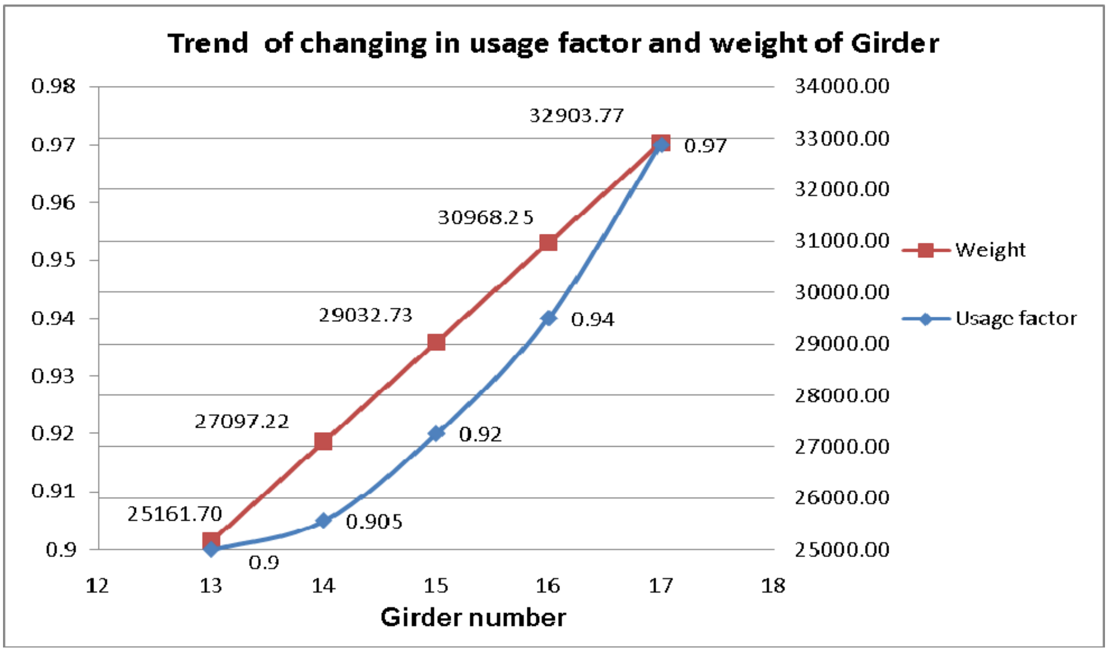


Figure 5. 1: Change tendency of usage factor and weight vs. reducing girder spacing

Besides, in the case if the panel and stiffener are assumed to be fixed and the girder spacing is reduced only, in this situation the values of usage factor for both the stiffened panel as well as for girder reduce steadily, as shown in Table 5.5.

Table 5. 5: Reducing girder spacing for stiffened plate

N^0	n	l [mm]	Usage factor η_s	η_G	Girder Check	W_{tot} [kg]
1	13	3125	0.9	0.9	Point 1	25161.70
2	14	2885	0.88	0.9	Point 1	27097.22
3	15	2679	0.88	0.92	Point 1	29032.73
4	16	2500	0.889	0.94	Point 1	30968.25
5	17	2344	0.92	0.97	Point 1	32903.77

l: girder spacing; n: number of girders; η_s: usage factor of stiffened panel;
η_G: usage factor of girder. W_{tot} : total weight.

Now, the girder spacing will be increased, i.e. the number of girders on pontoon panel will be reduced as shown in Table 5.6.

Table 5. 6: Increasing girder spacing for stiffened plate

N^0	Panel dimension $t_p\_s\_h_s \times t_w$ [mm]	n	l [mm]	σ_1 N/mm^2	σ_2 N/mm^2	τ_{12} N/mm^2	Usage factor η_s	η_G	Girder Check	W_{tot} [kg]
1	16_625_320x12	13	3125	120	77	80	0.9	0.9	Point 1	25161.70
2	16_625_320x12	12	3409	120	70.6	73.3	0.94	1.16	Point 1	23226.19
3	16_625_320x12	11	3750	120	64.2	66.7	1.25	1.23	Point 1	21290.67
4	16_625_320x12	10	4167	120	57.7	60	1.51	1.33	Point 1	19355.16
5	16_625_320x12	9	4688	120	51.3	53.3	1.89	1.5	Point 1	17419.64

Stiffened panel: tp: plate thickness; s: stiffener spacing; hs: stiffener web height; t_w: stiffener web thickness;
l: girder spacing; n: number of girders; σ_1: axial stress; σ_2: transverse stress; τ_{12}: shear stress;
η_s: usage factor of stiffened panel; η_G: usage factor of girder. W_{tot} : total weight.

From Table 5.6 shows that when the girder spacing is increased, the usage factor of girder dramatically increases. Correspondingly, the girder weight is linear changed when the numbers of girders are changed; see Figure 5.2 as follow for more illustration.

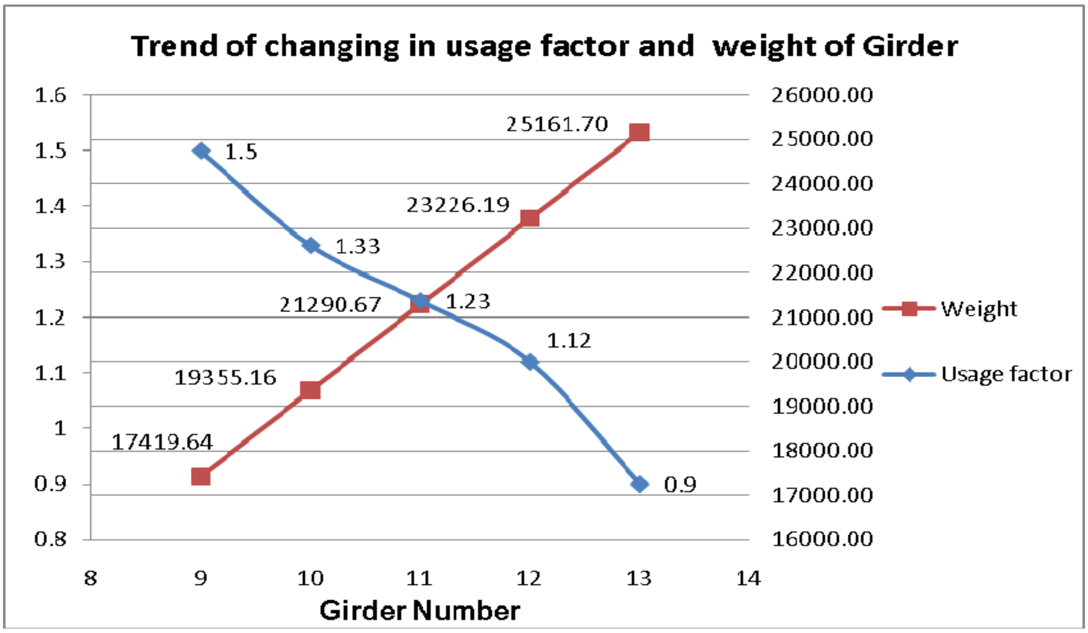


Figure 5. 2: Changing tendency of usage factor and weight vs. girder spacing increasing

The Figure 5.2 above shows that the number of girder is linearly relative to the weight, whereas the girder number is contrast with its strength.

5.3 Varying for the girder length

From the basic case for the girder dimension as be shown in Section 3.6.1, the girder length will be varied corresponding to four optimal cases of stiffened panel that has been done in section 3.3.2 and Table 3.17. However, in this Section there are just two cases will be varied for girder length. The first case is reducing of length of girder and another one with extension the girder length. This change is based on the length of the panels given in Table 3.17.

5.3.1 Redesign for girder and stiffened panel with stiffener spacing s=568mm

Firstly, the girder length is reduced correspondent to the stiffener spacing is 568mm, i.e. the girder length is changed from 6250mm to 5680mm with nine stiffeners on this stiffened plate. This is shown in Table 5.7.

Table 5. 7: Redesigning for the girder and stiffened plate with s=568mm

N^0	Panel dimension [mm]	Girder dimension [mm]					Usage factor		Girder Check	W_G	W_{tot}
	(t_p_s_h_s x t_s)	*l*	h_{tot}	t_w	b	t_f	η_s	η_G		[kg]	[kg]
1	15_568_340x13	3125	1290	25	300	24	0.925	0.738	Point 3	1759.0	6864.99
2	16_568_320x12	3125	1290	25	300	24	0.901	0.706	Point 1	1759.0	6874.99
3	16_568_320x12	3125	1230	23	300	24	0.901	0.902	Point 3	1582.4	6521.86

Stiffened panel: t_p: plate thickness; s: stiffener spacing; hs: stiffener web height; t_w: stiffener web thickness;
Girder: *l*: girder spacing; h_{tot}: total height of girder; t_w: web thickness; b: flange width; t_f: flange thickness; L_G: girder length;
η_s: usage factor of stiffened panel; η_G: usage factor of girder. W_G: gerder weight; W_{tot} : total weight.$W_{tot} = W_s+W_G$

From the Table 5.7 shows that when the girder length is reduced, its strength will be increased. As shown in Table 5.7 with the girder length is 5680mm, the usage factor reduces from 0.9 to about 0.7.

However, the strength of stiffened plate is reduced due to the stress acting on stiffened plate is now increased, thus it should be redesigned for stiffened panel in order to meet the requirement of usage factor with value 0.9. Because this stiffened panel was almost optimal previously (see Table 3.17), it is now easy to get new optimal dimension by slightly increasing panel thickness and in the same time the stiffener dimension is correspondingly reduced. Besides, it can be seen that during changing of stiffened plate in this case the strength of girder almost does not change or very slightly changes, this means that for short length the girder can gives a steady state in the strength.

When considering for the weight it can be seen that due to increase panel thickness, the weight of stiffened panel will be also increased. However, in this case the strength of girder is significantly increased, thus the girder dimension could be reduced to meet the requirement of weight function. From Table 5.7 shows a new dimension of girder with satisfaction of the requirement for reducing of weight of panel. In addition, from this Table new configuration of stiffened panel with two girders have a smaller value of weight as compare to original one.

In this case the girder check is performed according to Eq. (2.23), i.e. the girder will be beam-column failure at midspan; see Figure 2.10, Section 2.4.5 for more illustration.

The optimal fabrication cost of these girders are shown in Table 5.8 as follow.

Table 5. 8: The fabrication cost of the girders with length L_G= 5680mm

N^0	t_p_s_h_s x t_w [mm]	t_p (mm)	t_{GW} (mm)	A (mm)	NC	n	L_G (m)	P_b Kr/m	P_G Kr	P_t Kr
1	15_568_340x13	15	25	12.5	11.6	2	5.68	50	3294.4	6588.8
2	16_568_320x12	16	25	12.5	11.6	2	5.68	50	3294.4	6588.8
3	16_568_320x13	16	23	11.5	9.95	2	5.68	50	2825.8	5651.6

s: stiffener spacing; hs: stiffener height; t_w: stiffener thickness; A: throat thickness; NC: Norm curve value;
t_p: plate thickness; t_{GW}: girder web thickness; n: girder number; L_G: girder length; A: throat thickness;
P_b: basic price per meter; P_G: cost per gerder; P_t: total cost; NC: Norm curve value.

From the Table 5.8 shows that the optimal girder with new scantling is also can be satisfied for the reducing of fabrication cost.

Finally, from Tables 5.7 and 5.8 it is clear to see that the new girder satisfies not only the weight requirement, but also reducing fabrication cost function.

5.3.2 Redesign for girder and stiffened panel with stiffener spacing s=694mm

Secondly, the girder will be increased the length that is longer than the basic one, i.e. the girder length is now extended from 6250mm to 6940mm. The varying procedure is shown in Table 5.9 bellow.

Table 5. 9: Redesigning for the girder and stiffened plate with s=694mm

N^0	Panel dimension [mm] (t_p_s_h_s x t_s)	Girder dimension [mm]					Usage factor		Girder Check	W_G	W_{tot}
		l	h_w	t_w	b_f	t_f	η_{st}	η_G		[kg]	[kg]
1	17_694_320x12	3125	1290	25	300	24	0.86	1.49	Point 1	2149.20	8320.39
2	17_694_300x13	3125	1290	25	300	24	0.97	1.49	Point 1	2149.20	8289.39
3	16_694_340x13	3125	1290	25	300	24	0.9	1.56	Point 1	2149.20	8279.39
4	16_694_340x13	3125	1320	27	330	27	0.9	0.89	Point 1	2427.04	8835.08

Stiffened panel: t_p: plate thickness; s: stiffener spacing; hs: stiffener web height; t_w: stiffener web thickness;
Girder: *l*: girder spacing; h_{tot}: total height of girder; t_w: web thickness; b: flange width; t_f: flange thickness;
η_s: usage factor of stiffened panel; η_G: usage factor of girder; W_G: gerder weight; W_{tot} : total weight.$W_{tot} = W_s+W_G$

It can be seen that when extend the girder length, the strength of stiffened panel is increased. Thus in this case the stiffened panel can be slightly changed in order to reduce its weight, and in the Table the 2nd stiffened panel shows a lower weight than first one. However, when the girder length is extended, its strength will be significantly reduced and from Table 5.9 the usage factor of girder jumped from 0.9 to about 1.5. Therefore, the girder dimension is now redesigned to be satisfied the requirement of usage factor 0.9.

The first two stiffened panel in the Table shows that, the strength of girder is not really affected by changing the stiffener dimension. Conversely, it rather depends on panel thickness; the 3rd panel gives evidence about this. In the Table the usage factor of girder is increased as reducing panel thickness, even though the stiffener dimension increased.

The 4th stiffened panel is a new one with new girder dimension and panel thickness, however it can not give an optimal panel as considering for the weight requirement due to the girder dimension must be increased in this case to get usage factor is 0.9.

Besides, for this stiffened panel it can be seen that the girder will be failed at the support in beam-column failure mode.

The fabrication cost will be performed in order to determine the new welding cost corresponding to a new girder dimension. The result is shown in Table 5.10.

Table 5. 10: The fabrication cost of the girders with length LG= 6940mm

N^0	$t_p\_s\_h_s \times t_w$ [mm]	t_p (mm)	t_{GW} (mm)	A (mm)	NC	n	L_G (m)	P_b Kr/m	P_G Kr	P_t Kr
1	17_694_320x12	17	25	12.5	11.6	2	6.94	50	4025.2	8050.4
2	14_568_370x15	14	25	12.5	11.6	2	6.94	50	4025.2	8050.4
3	14_568_400x14	14	25	12.5	11.6	2	6.94	50	4025.2	8050.4
4	17_568_280x12	17	27	13.5	13.4	2	6.94	50	4649.8	9299.6

Stiffened panel: t_p: plate thickness; s: stiffener spacing; hs: stiffener web height; t_w: stiffener web thickness;
t_p: plate thickness; t_{GW}: girder web thickness; n: girder number; L_G: girder length; A: throat thickness;
P_b: basic price per meter; P_G: cost per gerder; P_t: total cost. NC: Norm curve value.

From Table 5.10 there is no stiffened panel as well as new girder dimension can provide a lower fabrication cost than basic case.

Combination both Tables 5.9 and 5.10 it is clear to see that for increase girder length the weight and fabrication cost of panel and girder will be increased. This situation could be redesign to get a new optimal dimension of girder by varying, e.g. reduce the web thickness of girder because this term could give a considerable influence on weight as well as the welding cost.

However, due to the limitation as mentioned above, this result is just to show and discuss for the change tendency of the usage factor and welding cost when varying the length and spacing of girder.

6 DISCUSSION - CONCLUSION - FUTURE WORK

6.1 Discussion - Conclusion

Firstly, the application of both the PULS and DNV RP-C201 is discussed.

Result of optimal panel shows a big difference between two programs. The DNV RP-C201 is considered as a conventional buckling code for stiffened and unstiffened panels, whereas PULS is considered as a computerized semi-analytical model that is based on non-linear plate theory.

The characteristic resistance formulation given DNV RP-C201 is strongly based on the formulae in NORSOK Standard – N004, so the calculating procedure is quite simple and fast. Conversely, PULS design model is based on complicated formulae as well as the rules and theories; hence the calculation procedure is also more complicated.

It is easier to check with the calculation procedure in DNV RP-C201 spreadsheet, whereas this is difficult to see this in PULS.

During design process PULS gives a range of validity, these validity limits are checked by the program. An error message is given when limits are exceeded. A summary is given on the status bar shown in the bottom of the PULS AV window [4]. Otherwise, the designer has to check the validity range by himself that also takes the time during the design process.

For agreement between two programs when applying for the offshore structure, the DNV RP-C201 is more conservative as compare to the application of PULS, i.e. PULS shall be more conservative as applied for stiffened panel for ship hull [9]. Therefore, the optimal result for stiffened panel and for the girder is mainly based on DNV RP-C201 spreadsheet.

Safety format is given in DNV RP-C201; the usage factor is taken as multiplication of material factor γ_m =1.15 and allowable usage factor according to working stress design standard UF. Otherwise, it is impossible to define material factor in PULS, thus the allowable usage factor is chosen by the ratio between the maximum safety margin (0.9 in this thesis) and material factor γ_m. This means that the allowable usage factor using for buckling and yield check should be 0.78. By doing this, the stiffened panel is strongly optimized with respective to the weight as well as fabrication cost function.

The assessment of ultimate and buckling strength for stiffened panel is favorably performed in PULS. However, it is impossible to do this for the girder in PULS, whereas in DNV RP-C201 these assessments shall be performed for both stiffened panel and girder in the same time.

Performance of parametric studies is performed faster and more favorable by PULS Excel spreadsheet. By using row by row/ combinations of input; these options let the user choose how the panels are generated from the input sheet [3]. This helps designer can vary many parameters of many stiffened panels in the same time, and each row indicates for each panel. While it takes so much time for designer in order to do this in DNV RP-C201 due to the inconvenience of spreadsheet.

Lateral pressure gives a significantly influence on usage factor as design procedure is performed by DNV RP-C201, while this shows a slight effect to the usage factor if design procedure is performed in PULS.

The results obtained in PULS show that the buckling strength of the stiffened panel is always lower than the ultimate capacity when stiffened panel is subjected to the combination loads.

Both these programs are mainly based on offshore standards, so the user has to have a good experience as well as essential knowledge with standards that these programs based on.

Secondly, the results of optimal design for stiffened panel and girder are discussed

The result of optimal stiffened panel shows that, it is impossible for an optimal stiffened panel to satisfy both variables of weight and fabrication cost in optimal design function. Therefore, during design process one of these variables must be chosen to focus. For this reason with the result of analyzing the fabrication cost is mainly focused in this thesis to find optimal panel.

Summarized Table of optimal stiffened panel (Table 3.17) shown that if the cost is focused only, optimal panel gives a significant higher than basic case. In the case if both requirements of the cost and the weight are balanced, another stiffened panel with slightly higher in weight and slightly lower in cost should be chosen. Therefore, the selection of optimal stiffened panel depends on design purpose, design situation and type of structures.
The comparison in Section 4.2 shows that in optimum design for stiffener, when the L and T profile is analyzed, the Equations (4.1) and (4.2) may be give the same result. However, if Bulb profile is considered, these Equations will provide two different results. And in this case the Eq. (4.1) is more conservative than Eq. (4.2) for Bulb profile.

For the girder assessment, due to limitation of the computer program facility as well as the limited time for investigation, the result in this report can not provide an optimal scantling for the girder corresponding to optimal stiffened panel. However, it provided a tendency of change in girder strength relating to the varying of its length as well as its spacing.

The strength of girder is strongly influenced by the plate thickness, whereas the stiffener spacing and its dimension give a slightly effect on girder strength.

Besides, the web thickness of girder also provides a significant effect on the strength of girder and it also considerably affects on the welding cost and weight of the girder.

6.2 Recommendation for future work

For the onshore structure or fixed offshore structure, e.g. jacket or jack up, the weight is not really influence on stability of structure. However, we also note that for onshore structure this will be not really problem, but with an offshore structure, e.g. pontoon of semi-submersible platform, the weight of structure is also very important because it may be influence on the buoyancy and stability capacity, the waterline of the platform, etc.

The girder assessment should be more investigated for further in design, since the girder check that was performed in this report based on some assumptions in order to simplify for design procedure. But in practical design these assumption does not really give a conservative result.

These two programs are still not convenient for design process because it really takes a lot of time to vary stiffened panel's parameters such as plate thickness, stiffeners dimension and stiffener as well as girder spacing during design process. Therefore, automatically update tool for stresses should be built in DNV RP-C201 spreadsheet and PULS in order to save for the design time.

The girder check module should be investigated in PULS advance as well as PULS Excel spreadsheet.

From the difference between DNV RP-C201 spreadsheet and Aker Solutions's program, this should be confirm which program gives more conservative in buckling check of stiffened panel. Therefore, Non-linear analysis program should be investigated for this difference between two programs. For instant Abaqus is a good program in order to perform this check.

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APPENDIX

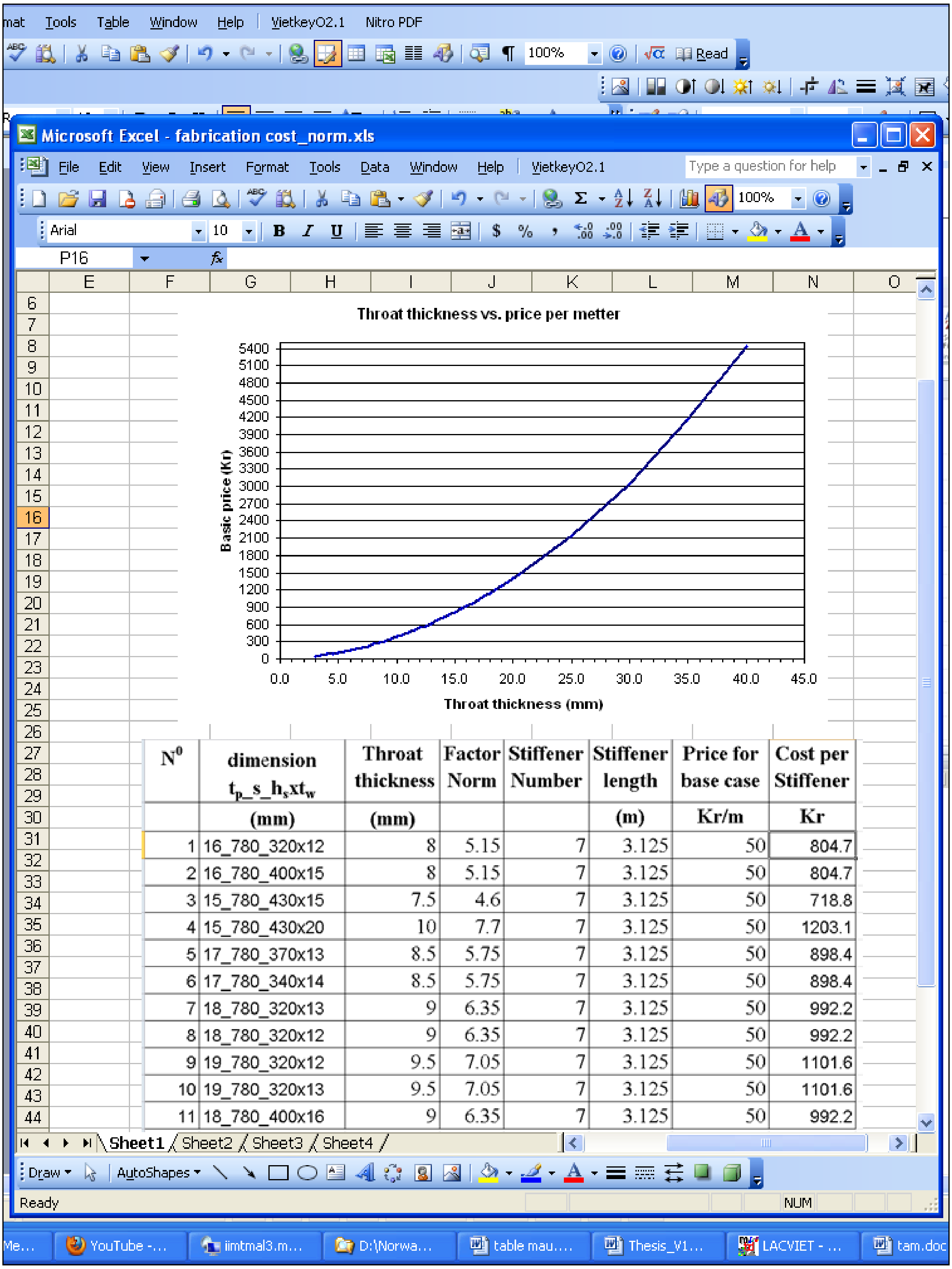
A- Calculating spreadsheets

	A	B	C	Q	R	S	T	U	V	W
1	sigma_1 [MPa]	sigma_2 [MPa]	Tau_12 [MPa]	Axial force [N]	Transverse force [N]	Shear force [N]	Usage factor_η	Weight [kg]	Flange width [mm]	Flange thickness [mm]
2	-120	-77	80	-17558760	-3850000	4000000	0.82	3581	53.6	31.4
29	Calculate in PULS									
30	-115.9	-77	80	-17558760	-3850000	4000000	0.8	3706	53.6	31.4
31	-119.5	-77	80	-17558760	-3850000	4000000	0.84	3597	50.1	28.8
32	-117.1	-77	80	-17558760	-3850000	4000000	0.89	3672	51.1	28.8
33	-119	-82.1	85.3	-17558760	-3850000	4000000	0.94	3612	53.6	31.4
34	-116.3	-82.1	85.3	-17558760	-3850000	4000000	0.94	3697	54.6	31.4
35	-110.1	-88	91.4	-17558760	-3850000	4000000	0.92	3903	61.6	35.5
36	-107.1	-88	91.4	-17558760	-3850000	4000000	0.92	4012	65.8	39.6
37	-116.4	-72.5	75.3	-17558760	-3850000	4000000	0.91	3694	50.1	28.8
38	-116.9	-72.5	75.3	-17558760	-3850000	4000000	0.9	3678	49.1	28.8
39	-111.8	-68.4	71.1	-17558760	-3850000	4000000	0.9	3847	50.1	28.8

Figure A 1: The spreadsheet for automatic calculate of loads and usage factor

No	Panel dimension (t_p_s_h_s x t_s)	r Number	σ_1 MPa	$\sigma_{2,1}$ MPa	$\sigma_{2,2}$ MPa	τ_{12} MPa	UF η	Buckling Check	Weight kg
1	16_568_320x12	10	115.9	77	77	80	0.84	Point 3	3706
2	16_568_300x12	10	119.5	77	77	80	0.91	Point 1	3597
3	16_568_300x13	10	117.1	77	77	80	0.89	Point 1	3672
4	15_568_340x12	10	119	82.1	82.1	85.3	0.91	Point 3	3612
5	15_568_340x13	10	116.3	82.1	82.1	85.3	0.9	Point 1	3697
6	14_568_370x15	10	110.1	88	88	91.4	0.92	Point 1	3903
7	14_568_400x14	10	107.1	88	88	91.4	0.87	Point 1	4012
8	17_568_280x12	10	116.4	72.5	72.5	75.3	0.94	Point 1	3694
9	17_568_300x11	10	116.9	72.5	72.5	75.3	0.89	Point 1	3678
10	18_568_280x12	10	111.8	68.4	68.4	71.1	0.9	Point 1	3847
2	16_568_300x12	10	119.5	77	77	80	0.91	Point 1	3597
3	16_568_300x13	10	117.1	77	77	80	0.89	Point 1	3672
4	15_568_340x12	10	119	82.1	82.1	85.3	0.91	Point 3	3612
5	15_568_340x13	10	116.3	82.1	82.1	85.3	0.9	Point 1	3697
6	14_568_370x15	10	110.1	88	88	91.4	0.92	Point 1	3903
7	14_568_400x14	10	107.1	88	88	91.4	0.87	Point 1	4012
8	17_568_280x12	10	116.4	72.5	72.5	75.3	0.94	Point 1	3694

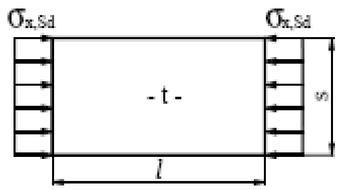
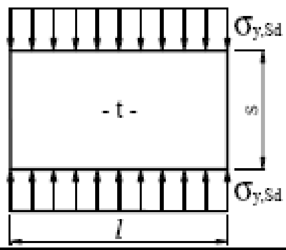
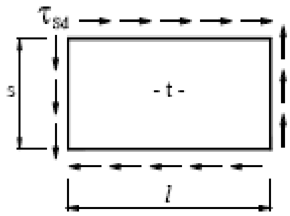
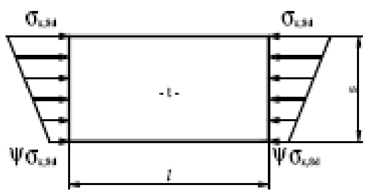
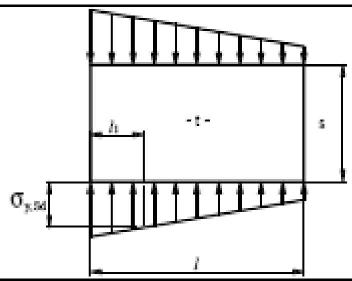
Figure A 2: The spreadsheet of calculating for panel weight



N⁰	dimension t_p_s_h_sxt_w	Throat thickness	Factor Norm	Stiffener Number	Stiffener length	Price for base case	Cost per Stiffener
	(mm)	(mm)			(m)	Kr/m	Kr
1	16_780_320x12	8	5.15	7	3.125	50	804.7
2	16_780_400x15	8	5.15	7	3.125	50	804.7
3	15_780_430x15	7.5	4.6	7	3.125	50	718.8
4	15_780_430x20	10	7.7	7	3.125	50	1203.1
5	17_780_370x13	8.5	5.75	7	3.125	50	898.4
6	17_780_340x14	8.5	5.75	7	3.125	50	898.4
7	18_780_320x13	9	6.35	7	3.125	50	992.2
8	18_780_320x12	9	6.35	7	3.125	50	992.2
9	19_780_320x12	9.5	7.05	7	3.125	50	1101.6
10	19_780_320x13	9.5	7.05	7	3.125	50	1101.6
11	18_780_400x16	9	6.35	7	3.125	50	992.2

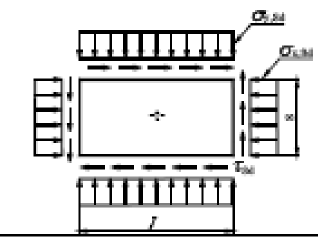
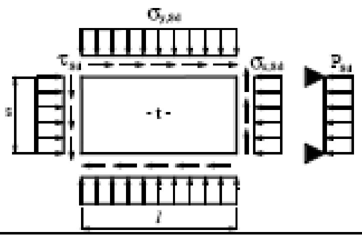
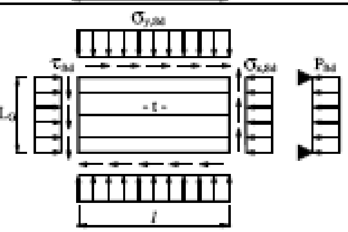
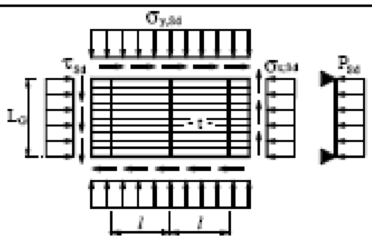
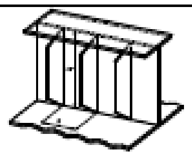
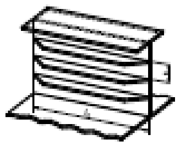
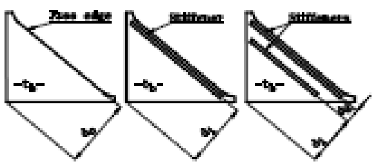
Figure A 3: The spreadsheet for automatic calculating of fabrication cost

B Information for stiffened plate and calculation factors

Description	Load	Sketch	Clause reference	Limiting value
Unstiffened plate	Longitudinal compression		6.2	$s < l$ Buckling check not necessary if $\frac{s}{t} \le 42\varepsilon$
Unstiffened plate	Transverse compression		6.3	$s < l$ Buckling check not necessary if $\frac{s}{t} \le 5.4\varepsilon$
Unstiffened plate	Shear stress		6.4	$s < l$ Buckling check not necessary if $\frac{s}{t} \le 70\,\varepsilon$
Unstiffened plate	Linear varying longitudinal compression		6.6	$s < l$ Buckling check not necessary if $\frac{s}{t} \le 42\,\varepsilon$
Unstiffened plate	Linear varying transverse compression		6.8	$s < l$ Buckling check not necessary if $\frac{s}{t} \le 5.4\varepsilon$

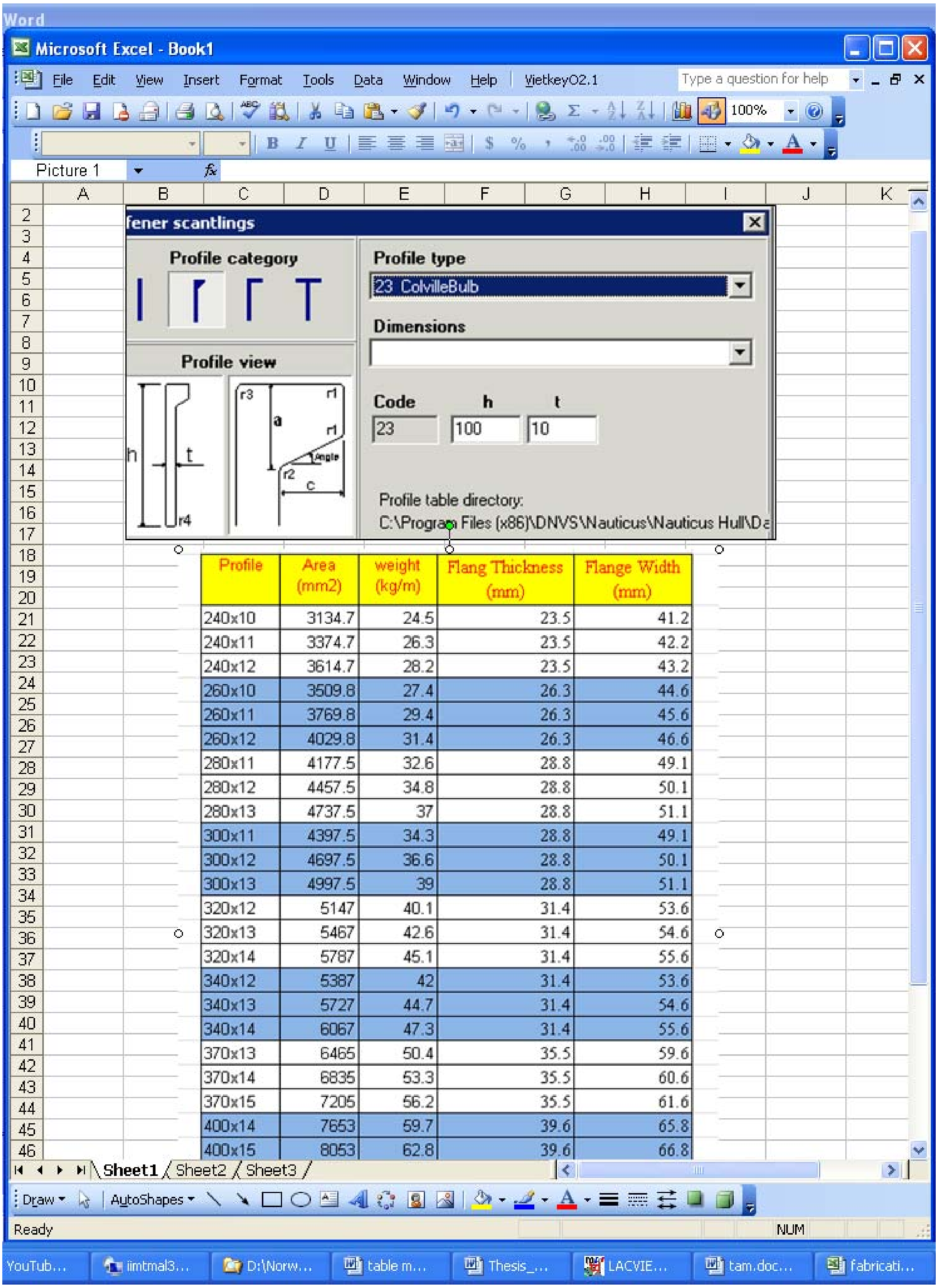
$\varepsilon = \sqrt{235/f_y}$ $\varepsilon = 1.0$ for $f_y = 235$ MPa $\varepsilon = 0.814$ for $f_y = 355$ MPa

Figure B 1: Reference Table for buckling check of plate

Description	Load	Sketch	Clause reference	Limiting value
Unstiffened plate	Combined longitudinal and transverse compression and shear		6.5	$s < l$ Buckling check not necessary if $\frac{s}{t} \leq 5.4\varepsilon$
Unstiffened plate	Uniform lateral load and in-plane normal and shear stresses		5 and 6.5	$s < l$ Buckling check not necessary if $\frac{s}{t} \leq 5.4\varepsilon$
Longitudinal stiffened plate panel	Longitudinal and transverse compression combined with shear and lateral load		5 and 7	
Girder supporting stiffened panel	Longitudinal and transverse compression combined with shear and lateral load		5 and 8	
Stiffeners to girder webs	Longitudinal and transverse compression combined with shear and lateral load	 	9.1	
Brackets			9.2	

$\varepsilon = \sqrt{235/f_y}$ $\varepsilon = 1.0$ for $f_y = 235$ MPa $\varepsilon = 0.814$ for $f_y = 355$ MPa

Figure B 2: Reference Table for buckling check of plate (cont)



Profile	Area (mm2)	weight (kg/m)	Flang Thickness (mm)	Flange Width (mm)
240x10	3134.7	24.5	23.5	41.2
240x11	3374.7	26.3	23.5	42.2
240x12	3614.7	28.2	23.5	43.2
260x10	3509.8	27.4	26.3	44.6
260x11	3769.8	29.4	26.3	45.6
260x12	4029.8	31.4	26.3	46.6
280x11	4177.5	32.6	28.8	49.1
280x12	4457.5	34.8	28.8	50.1
280x13	4737.5	37	28.8	51.1
300x11	4397.5	34.3	28.8	49.1
300x12	4697.5	36.6	28.8	50.1
300x13	4997.5	39	28.8	51.1
320x12	5147	40.1	31.4	53.6
320x13	5467	42.6	31.4	54.6
320x14	5787	45.1	31.4	55.6
340x12	5387	42	31.4	53.6
340x13	5727	44.7	31.4	54.6
340x14	6067	47.3	31.4	55.6
370x13	6465	50.4	35.5	59.6
370x14	6835	53.3	35.5	60.6
370x15	7205	56.2	35.5	61.6
400x14	7653	59.7	39.6	65.8
400x15	8053	62.8	39.6	66.8

Figure B 3: The information for stiffeners

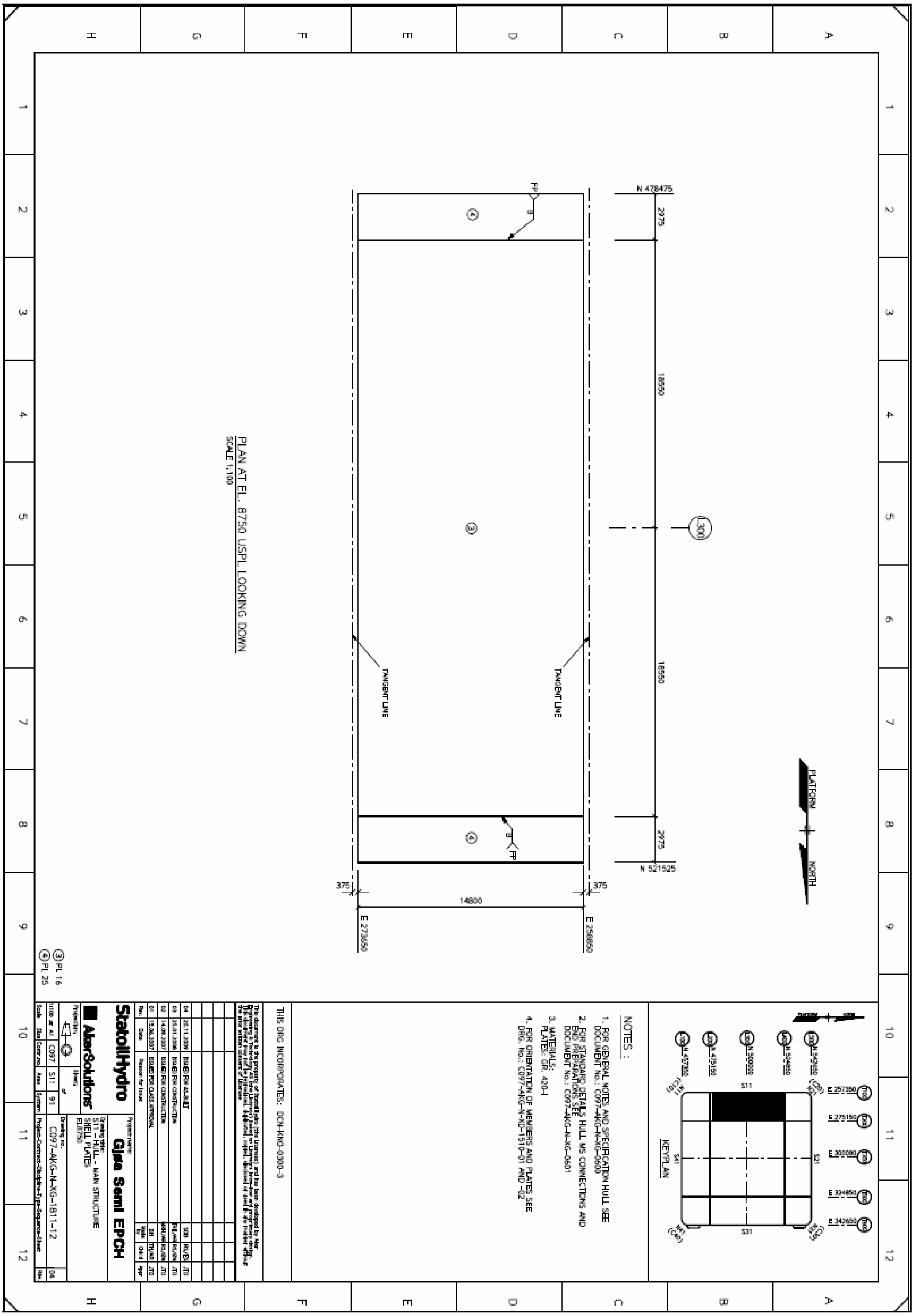


Figure B 4: The dimension of top plate

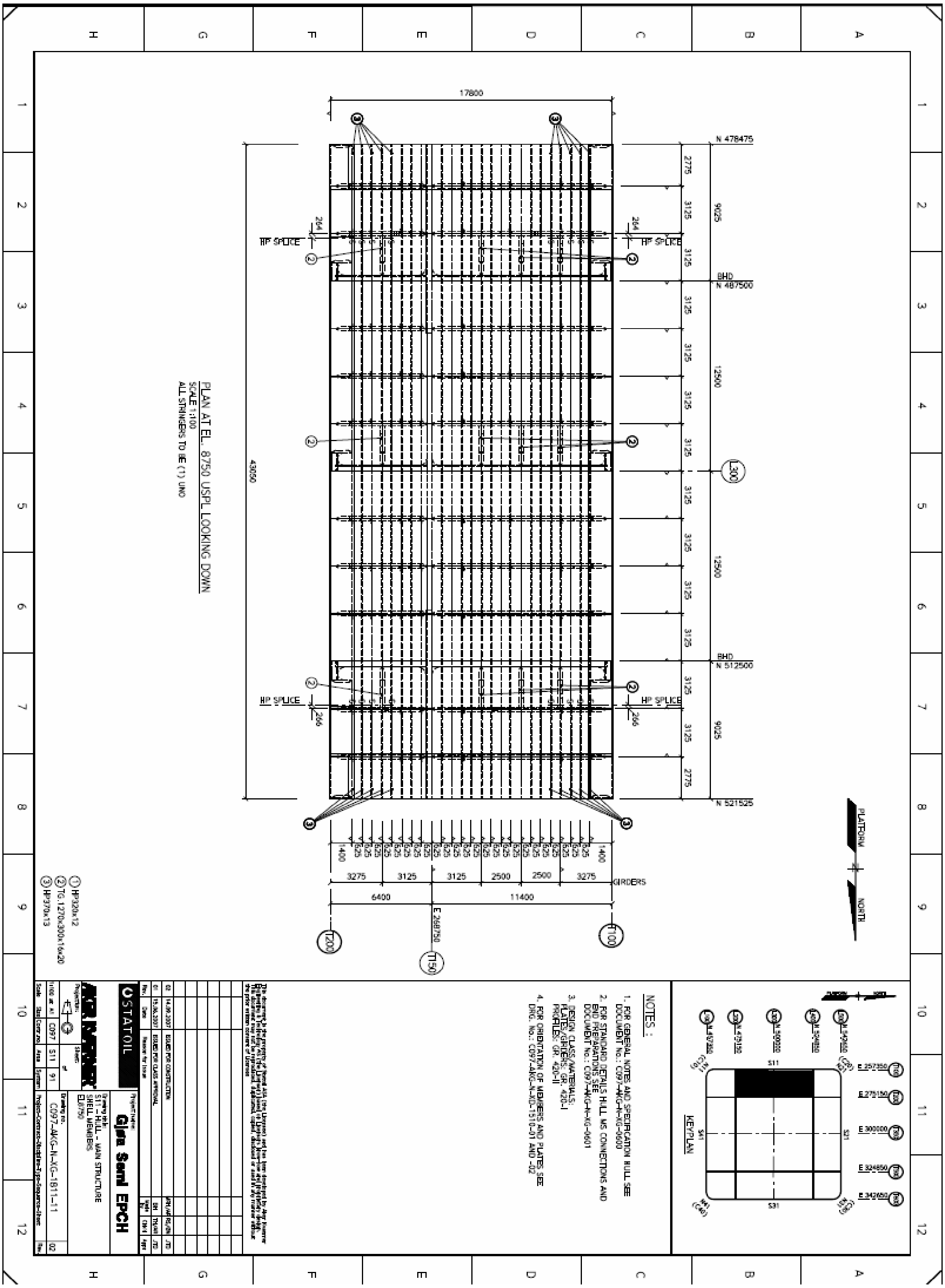


Figure B 5: Dimensions and arrangements of stiffeners on top plate

C Graphics of ultimate capacity and buckling check of stiffened plate

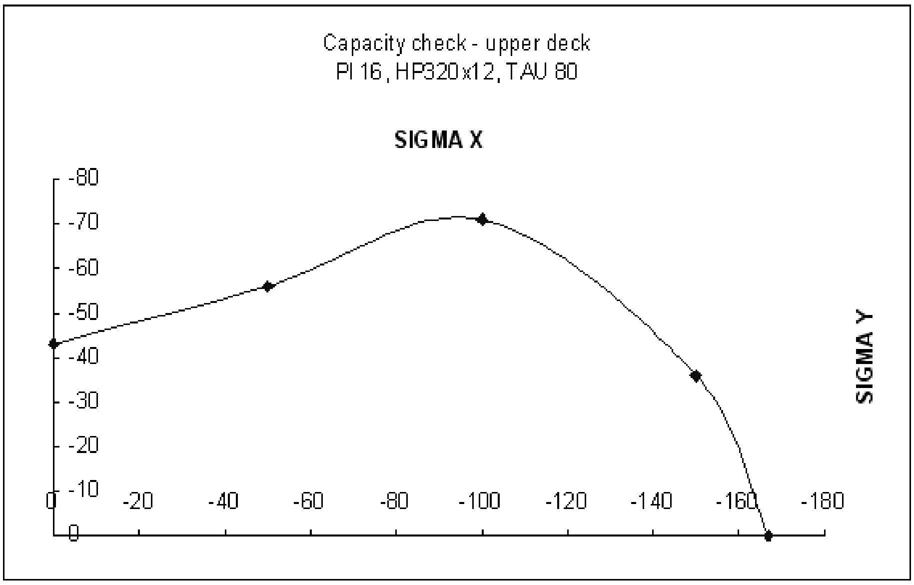


Figure C 1: Ultimate capacity curve performed by STIPLA program –Aker Solutions

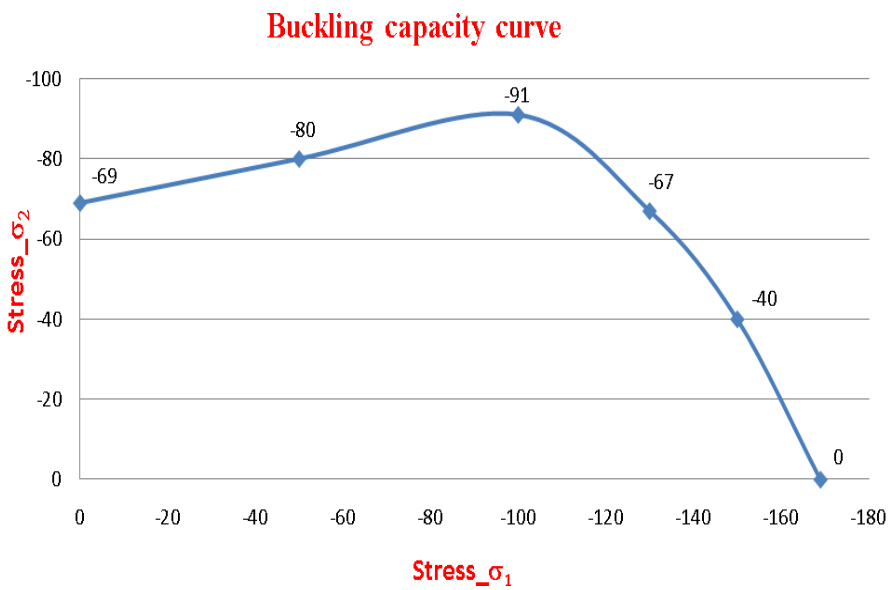


Figure C 2: Ultimate capacity curve performed by DNV RP-C201 spreadsheet

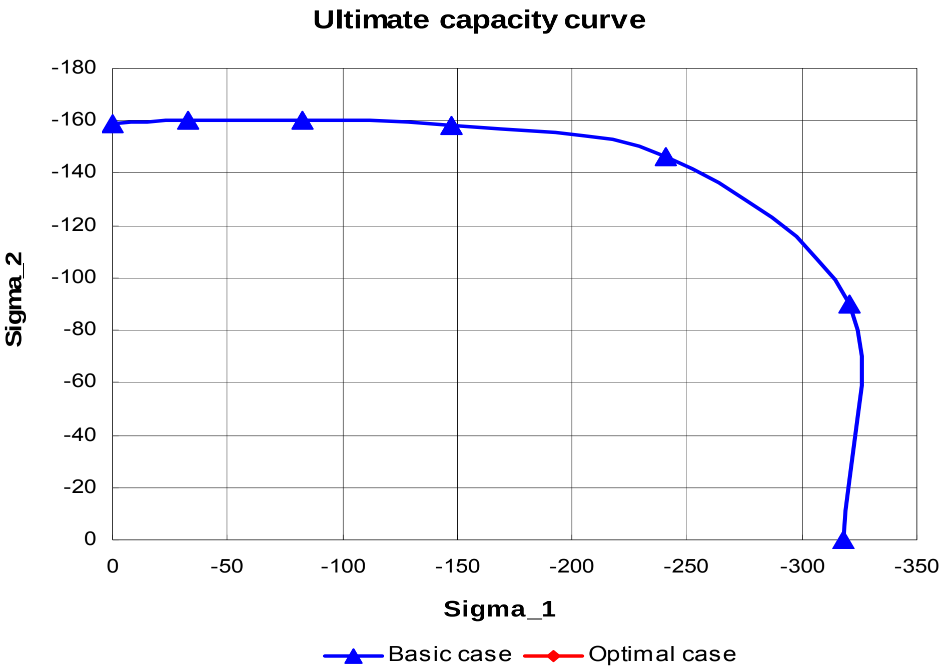


Figure C 3: Ultimate capacity curve performed by PULS

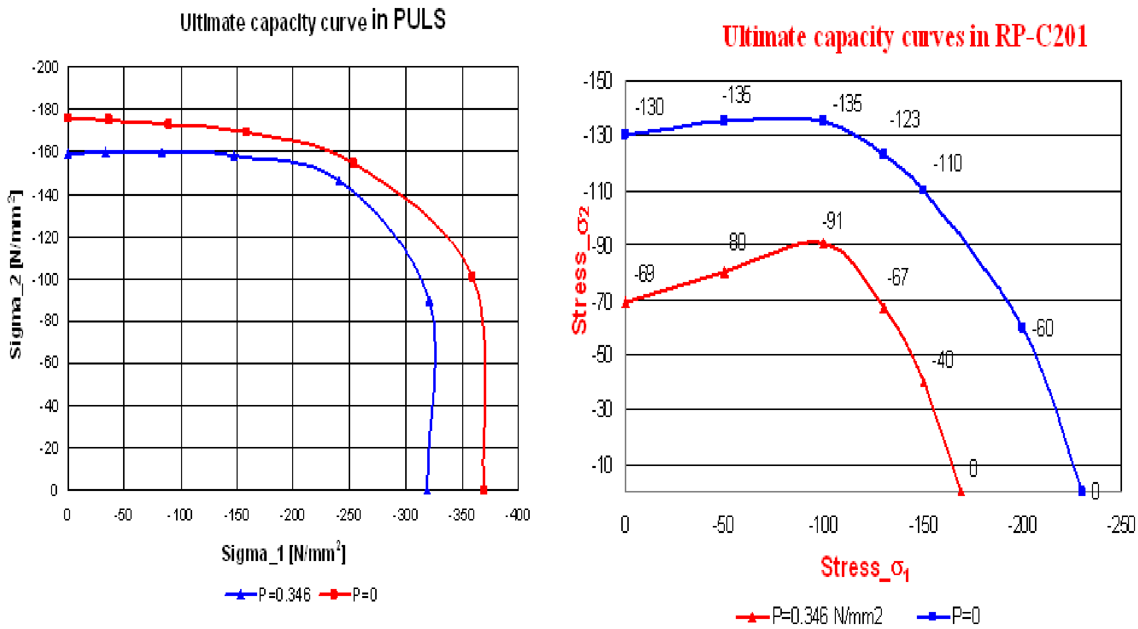
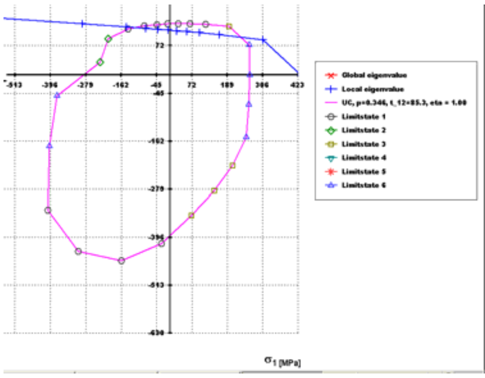
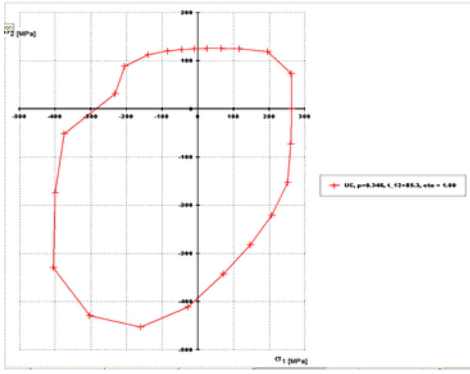


Figure C 4: Ultimate capacity curve in RP-C201 and PULS with different lateral load

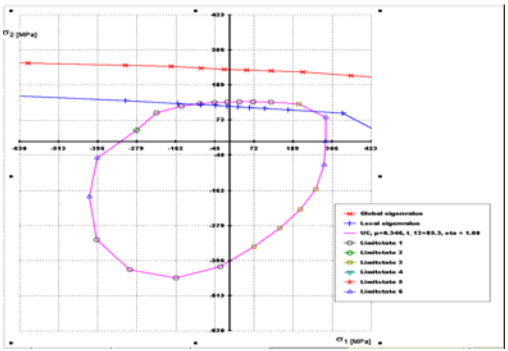
Egienvalue and ultimate capacity

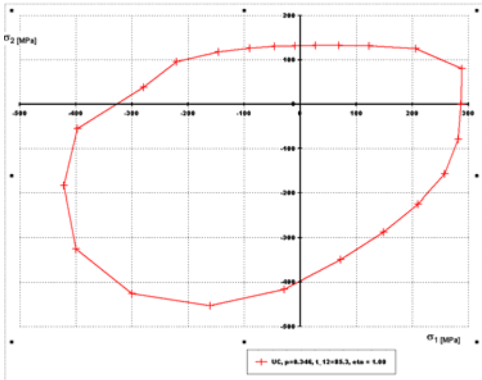
Ultimate capacity collection



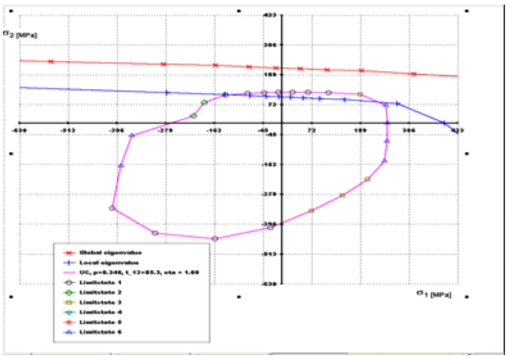


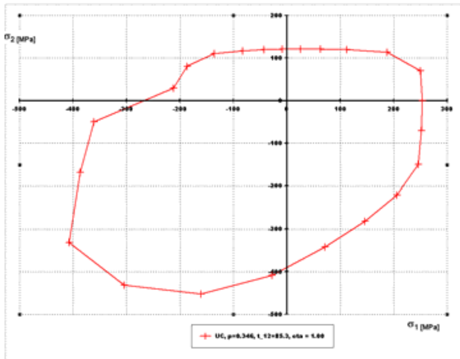
Stiffened panel with s=625mm, n=9



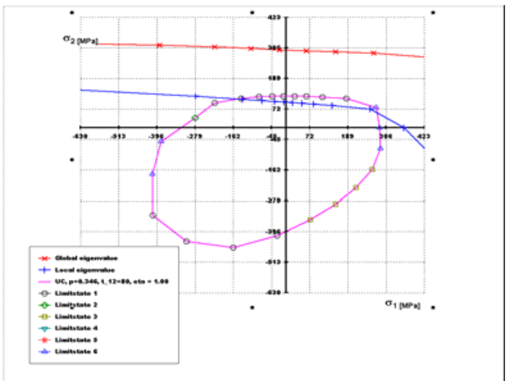


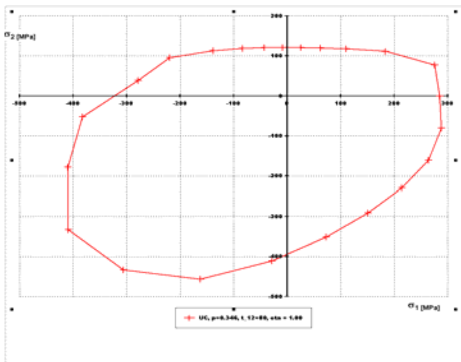
Stiffened panel with s=568mm, n=10





Stiffened panel with s=694mm, n=9





Stiffened panel with s=780mm, n=7

Figure C 5: Ultimate capacity curve and ultimate limit states of stiffened panel