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PETRI SATAMO
BEAM AND COLUMN SPLICE BOLT SHEAR FORCES WITH BIDIRECTIONAL BENDING

Master of Science Thesis

Examiner: Prof. Markku Heinisuo
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ABSTRACT

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In the literature, the designing of the rolled or welded, doubly symmetrical I- and H-profile bolted splice is usually presented with a load combination, which includes axial load, shear in one direction and bending in respect of strong axis. Because there often exists a load combination with biaxial bending simultaneously, the design method for calculating bolt shear forces in this situation is needed.

To design the joint reliable, the distribution of the forces in the joint must be known well. In the non-bearing type joint, the forces of the splice are usually supposed to be distributed in the ratio of the cross-section stiffnesses. With this method, generally acceptable results have been achieved for the joint member stresses. In the bearing type joint, the distribution of the forces for the bolts and splice plates is not as clear as with the non-bearing type splice. In this research, the stiffnesses of the splice members has been used for calculating stresses also in the bearing type splice.

This research belongs to the project developing biaxially loaded splice design program in Sweco Rakennetekniikka Oy. It consists of the theoretical calculation and the finite element analysis (FEA), where the calculation results are compared. With the FEA, the distribution of the stresses can be studied from the beginning of the stress test, with all load combinations.

The results of the research are mainly in-line with the FEA. A design program for calculating profile and splice plate stresses and bolt shear forces for biaxially loaded splice was mainly achieved, including both non-bearing and bearing type splice. For achieving an adequate reliability for the results of the calculation, and in some cases, more accurate results, additional research and tests with different types of the splices are needed.

TIIVISTELMÄ

PETRI SATAMO: Pilarin ja palkin jatkosliitoksen pulttien leikkausvoimien laskeminen kahteen suuntaan taivutetussa liitoksessa
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Avainsanat: jatkosliitos, pultattu jatkosliitos, universaaliliitos, palkin jatkosliitos, pilarin jatkosliitos, jatkosliitoksen suunnittelu, jatkosliitoksen mitoitus, jatkosliitoksen jännitykset, liitosvoimat, jatkosliitoksen voimat, jatkosliitoksen pulttien leikkausvoimat, kahteen suuntaan taivutettu liitos

Valssatun tai hitsatun, kaksoissymmetrisen I- tai H-profiilin pultatun jatkosliitoksen mitoitus esitetään kirjallisuudessa yleensä kuormitusyhdistelmällä, jossa on aksiaalinen voiman ja leikkausvoiman lisäksi taivutus vain vahvemman akselin suhteen. Koska liitoksessa voi olla taivutusta samanaikaisesti myös heikompaan suuntaan, tarvitaan monipuolisempi mitoitusmenetelmä liitoksen lujuuden laskemiseksi.

Jotta liitos pystytään mitoittamaan luotettavasti, täytyy voimien jakautuminen liitoksessa tuntea hyvin. Liitostyypissä, missä profiilien päät eivät kosketa toisiaan (non-bearing type), jatkosliitoksen voimien on yleensä oletettu jakautuvan liitososien poikkileikkausten jäykkyyksien suhteessa. Tällä menetelmällä liitoksen osien rasituksille on saatu jo aikaisemminkin yleisesti hyväksyttyjä tuloksia. Liitoksessa, jossa profiilien päät koskettavat toisiaan (bearing type), liitoksen voimien jakautuminen pulteille ja liitoslevyille ei ole yhtä selvää. Liitososien suhteellisten jäykkyyksien menetelmää on tässä tutkimuksessa käytetty myös jälkimmäisen liitostyypin voimien ja rasituksen laskemiseen.

Tutkimus on osa Sweco Rakennetekniikka Oy:ssä tehtävää projektia, jossa kehitetään yhtä aikaa kahteen suuntaan rasitetun jatkosliitoksen kestävyyden laskentaohjelmaa. Tutkimus koostuu teoreettisesta laskennasta sekä FE-analyysistä, johon laskennan tuloksia verrataan. FE-analyysin avulla jännitysten ja voimien jakautumista voidaan tutkia rasituksen alkuhetkestä asti kaikilla kuormitusyhdistelmillä.

Tutkimuksen tulokset ovat samansuuntaisia kuin FE-analyysissä. Työn tuloksena saatiin laskentaohjelma, jolla voi laskea kahdessa suunnassa yhtä aikaa rasitetun liitoksen osien jännitykset ja voimat sekä pulttien leikkausvoimat molemmilla liitostyypeillä. Laskentaohjelman tuloksien luotettavuuden varmistamiseksi sekä joissakin tapauksissa laskentatulosten tarkentamiseksi tarvitaan kuitenkin lisätutkimusta ja testejä erilaisilla liitoksilla.

PREFACE

This thesis was carried out between February 2016 and May 2017 in the Laboratory of Civil Engineering at Tampere University of Technology in collaboration with Sweco Rakennetekniikka Oy.

I would like to thank MSc. Juha Kukkonen in Sweco Rakennetekniikka Oy and professor Markku Heinisuo in Tampere University of Technology for their help and sharing their great knowledge of the subject. I would also like to thank my manager Tomi Eloranta for providing me a change to do this work and my colleagues for their support and advices.

Finally, I would say thanks for my parents for their support during the studies, and first, my wife for encouraging me to begin postgraduate studies in the university and giving her support through these years.

Tampere, November 16, 2017

Petri Satamo

TABLE OF CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

AISC	American Institute of Steel Construction
ANSI	American National Standard Institute
ASCE	American Society of Civil Engineers
BCSA	The British Constructional Steelwork Association Limited,
Eurocode	European standards
FCSA	Finnish Constructional Steelwork Association
FEA	Finite Element Analysis
SCI	The Steel Construction Institute

1. INTRODUCTION

1.1 Background

In the literature, the designing of the rolled or welded, doubly symmetrical I- and H-profile bolted splice is usually presented with a non-bearing type splice with a load combination, which includes axial load, shear in one direction and bending in respect of either strong or weak axis. There is a need for the calculation program, which includes both non-bearing and bearing type splice loaded with biaxial bending, together with conventional load cases and combinations.

Sweco Structures Ltd has a research project that aims to developing a calculation program for splice design. This thesis was also a part of this work as providing the method for calculating splice member forces needed in the joint design.

There have been previous projects, where the splice calculation has been developed. As a result of the *Joint Programme* the design program for splice was completed in 2003 by FCSA (Finnish Constructional Steelwork Association). The program included 4 different combinations of normal force, bending moment in 2 directions and shear force in 2 directions. Bending could combine in one direction at the same time, so there was not a load case for bidirectional bending.

The splice design program, *T11 Teräspilarin universaalijatkos*, was developed between 2008-2011 by The Finnish Association of Consulting Firms (Suunnittelu- ja konsulttitoimistojen liitto, SKOL) Eurocode calculation project. The program included the same load combinations as Joint.

Beam and column splices has been researched from the beginning of the 20th century. The earliest published investigation about bolted splice is from the year 1929 by Edwards, Whittemore and Stang, Transverse Tests of H-section Column Splices, 1929 [12]. The latest European, Eurocode-based instructions about bolted splice are presented in the publications P358 [5] and P398 [6] of The Steel Construction Institute (SCI). At least four experimental programs can be found in the literature: bolted splice test [12] mentioned above, non-bearing riveted web-flange splice tests with 4 specimens by Garrelts and Madsen in 1941 [11], non-bearing bolted web splice tests with 6 specimen by Kulak and Green in 1990 [7] and bolted, non-bearing splice tests with 32 specimen by Sheikh-Ibrahim, including both web and web-flange splices in 1995 [9].

1.2 Goal

The goal of this thesis was to find actual profile and splice plate stresses and bolt shear forces of the splice with FEA model and to study, how the corresponding results can be achieved with a theory, where stresses and bolt shear forces are calculated by the stiffnesses of the parts. The calculations were intended to form a basis for developing a splice design program for regular use by Sweco designers.

1.3 Purpose

The purpose of the thesis is to form a basis for the future development of the splice design program and to act as a support material for the doctoral dissertation of Juha Kukkonen, as he researches the designing of the splice with a component method.

1.4 Scope

An appropriate method for calculating joint member stresses with the given loads with elastic stress distribution was researched from the literature and applied in the theoretical calculations, taking into consideration the specifications of the Eurocodes. In addition to the conventional load cases, also biaxial bending and torsion about x-x axis were included.

FEA model of the corresponding splice was prepared and calculated with appropriate and load cases. The calculation results were compared to the results of the FEA and the differences of the results and the validity of the calculation theory is discussed.

The user interface of the calculation was intended to show the calculation process, not to be a real design application for daily use. However, the calculation process can be solved in making the design application in the future.

1.5 Research methods

Investigating the function and designing of the bolted, I- and H-profile web-flange splice from the literature formed an important part of the research. After the calculating theory was made clear, the Mathcad-based calculation program could be done. The advices from the mentors of this work were invaluable. In addition to the source material from TUT and Sweco, it was purchased from SCI. A great deal of the information was found also from the web.

The calculations were made with Mathcad Prime, version 3.1. The formulas were made according to Eurocodes SFS EN 1993-1-1, 1993-1-5 and 1993-1-8 and commonly known formulas of structural mechanics.

The FEA model was made with SpaceClaim, version R17.2 (2016.2). The FE analysis was made with Ansys Mechanical, version 17.2. The design results were compared to FE analysis results and other available researches and tests.

2. SPLICE

2.1 Typical splices

Moment resisting splices of the I- or H-sections are often made of longitudinal plates bolted to the flanges and the web. The splice plates can be located either to the other side of the flange, normally to the outer side, like in figure 2.1, or to both sides of the flange. In the web, double plates are most often used. When both the flanges and the web are spliced, the splice is called web-flange splice [9, p. 2].

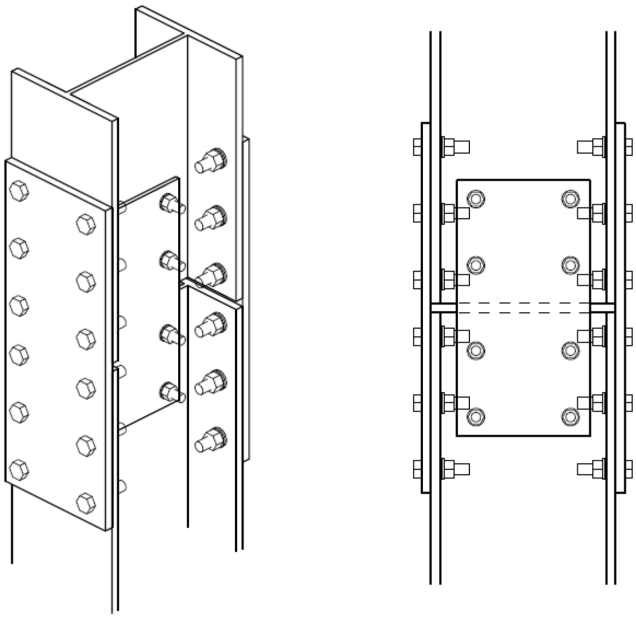
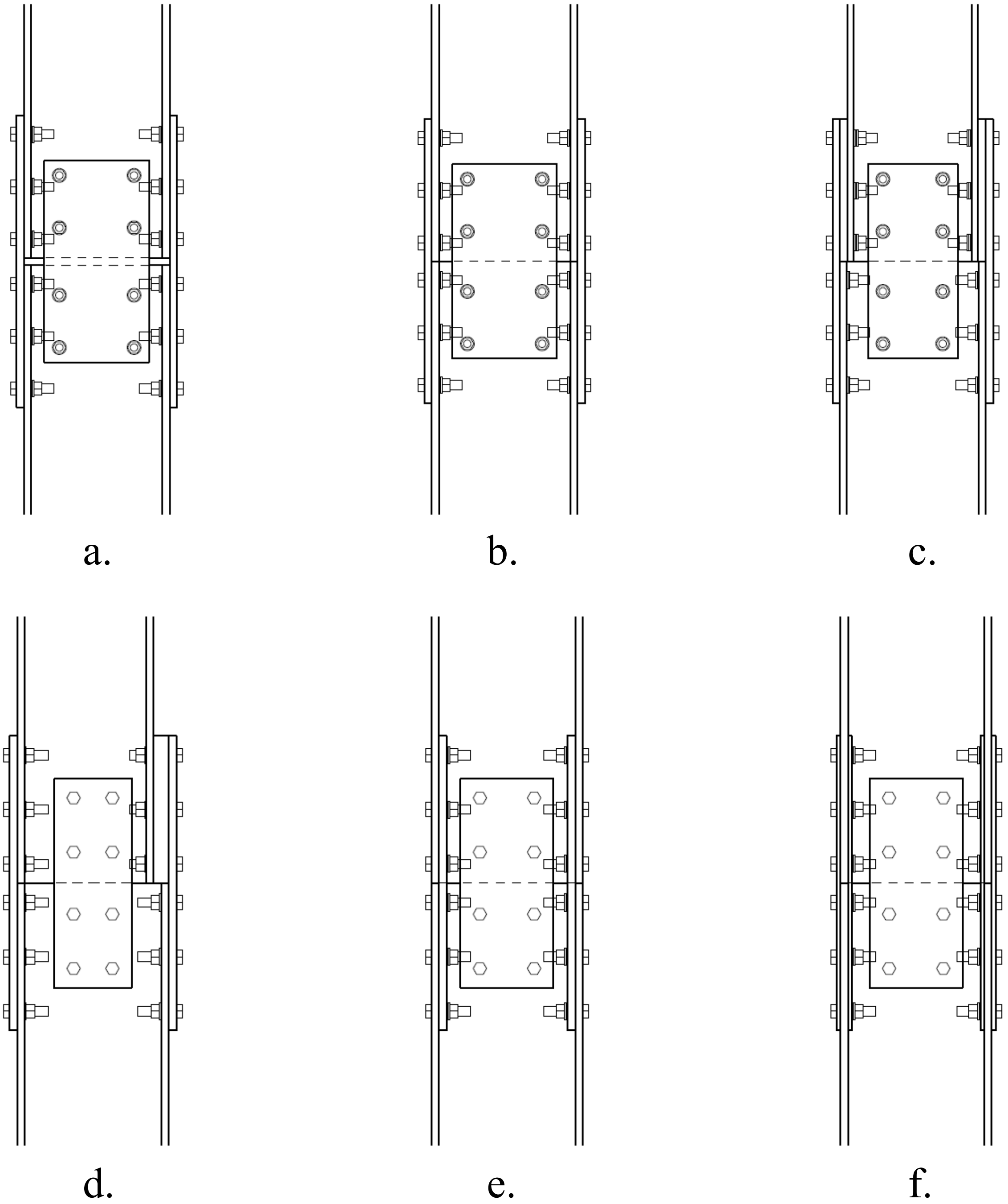


Figure 2.1. *Typical bolted web-flange splice*

There are many variations of the splices, depending on the requirements for the load distribution, demands for the evenness of the outer surface or appearance, for example. Common splice types are shown in figure 2.2:



a., b *Splice with and without gap*
c. *Symmetric splice with packing plates*
d. *Asymmetric splice with packing plate on the other side*
e. *Flange plates inside of the flanges*
f. *Flange plates on both sides of the flanges*

Figure 2.2. *Common variations of the bolted column and beam splices*

2.2 Function of the splice

Beam or column splice must transfer the axial load, shear force and moment of the beam at the location of the splice. Splices with longitudinal splice plates can be divided into two different types by their way to transform axial loads, splices with or without gap. In the first type, the axial loads are transferred wholly via splice plates and the bolts. In the latter type, the compressive forces can be partly transferred by the contact of the profile ends.

Usually, the joint is loaded mainly about the major axis, and the minor axis bending can be ignored. However, there is sometimes a situation where the minor axis bending must be considered together with the main axis bending. This is often a case with corner columns, columns with lateral bracing or columns with significant second order moments about minor axis.

In the non-bearing type joint, the forces of the splice are usually supposed to be distributed in the ratio of the cross-section areas (CSA) and stiffnesses. This means, that, for example, the normal force is distributed to the flanges and web by the ratio of their CSA in relation to the total CSA. In the bending about main axis, the bending moment for the web is calculated by the ratio of the second moment area (SMA) of the web in relation to the total SMA. After these calculations, the forces are distributed for the appropriate bolts. With this method, generally acceptable results have been achieved for the non-bearing splice bolt shear forces.

In the bearing type joint, the distribution of the forces between profiles, bolts and splice plates is not as clear as with the non-bearing type splice. According to Firas *et al.*, beam splice should not be thought of as a cross-section at one point, but rather as a mini-structure acting independently from the beam [10, p. 112]. In the same context, he continues, that "*treating the splice as a cross-section having a linear-elastic stress distribution does not necessarily represent the true distribution of stresses at ultimate load*." This research has been restricted to the elastic behavior of the splice, which is a common practice in designing. The bearing type splice is thought as a combination of cross-sections, where the forces are moved into from the profile to the plates via the bolts so, that there is no loss of force. This is explained more accurately in chapter 3.4.

The bending from the eccentricity of the shear force and its effect for the bolt shear forces has been discussed in many researches. As presented by Firas [9, p. 44], there are three approaches to the analysis of the eccentrically loaded bolts: elastic, plastic and nonlinear analysis. In the elastic analysis, the critical bolt lies the farthest from the rotation center of the bolt group. In the plastic analysis of the bolts, it is assumed that all the bolts reach their individual ultimate capacity at failure. In the non-linear analysis, the bolt shear forces are determined by instantaneous center of the rotation.

According to Firas, the plastic analysis does not represent the actual behavior of the eccentrically loaded bolted connections, where only critical bolt fails while the rest of the bolts are not fully loaded [9, p. 45]. In the non-linear analysis, the location of the instantaneous center is unknown and iterative method must be solved. As a conclusion of a test program of 6 bolted, non-bearing web splice by Kulak and Green, the assumption was made that the shear force acting at the centerline of the splice leads to good agreement between theory and experiment [7, p. 119]. Also, the test program of 15 bolted, non-bearing web-flange splices by Firas, came to the same conclusion [9, p. 191].

2.3 Properties and restrictions for the calculations

The properties and restrictions for the calculations are:

- Profile, splice plates and bolt groups behaves elastically.
- Whole cross-sections of the flanges, web and splice plates are effective in compression, providing that the profile has been chosen so that it is not exposed to local buckling. If not, the effective width of the cross sections must be used according to EN 1993-1-5 [2, chapter 4.4].
- One profile type can be used in the calculations. If the height and width of the profiles or flange and web thicknesses are different, the suitability of the calculation must be ensured. Also, if packing plates are used (see figure 2.3), the suitability of the calculation must be ensured. If the packing total thickness is greater than one-third of the bolt nominal diameter, it must be taken into consideration in bolt shear resistance [3, p. 25].

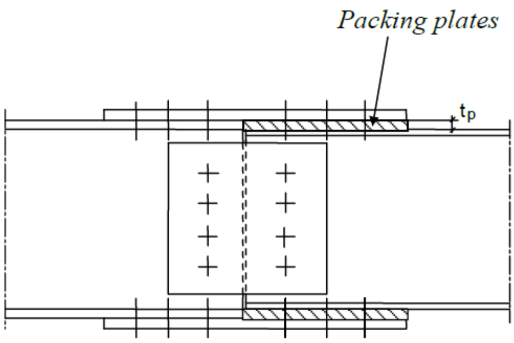


Figure 2.3. *Packing plates [2, figure 3.4]*

- Bolt groups should be symmetric about the centerline of the splice, see figure 2.4.
- Two longitudinal bolt rows are allowed both in the flange and the web per splice half. The number of the transverse bolt rows is basically not restricted (for example, in figure 2.4 flange plate is bolted with three transverse bolt rows per splice half).

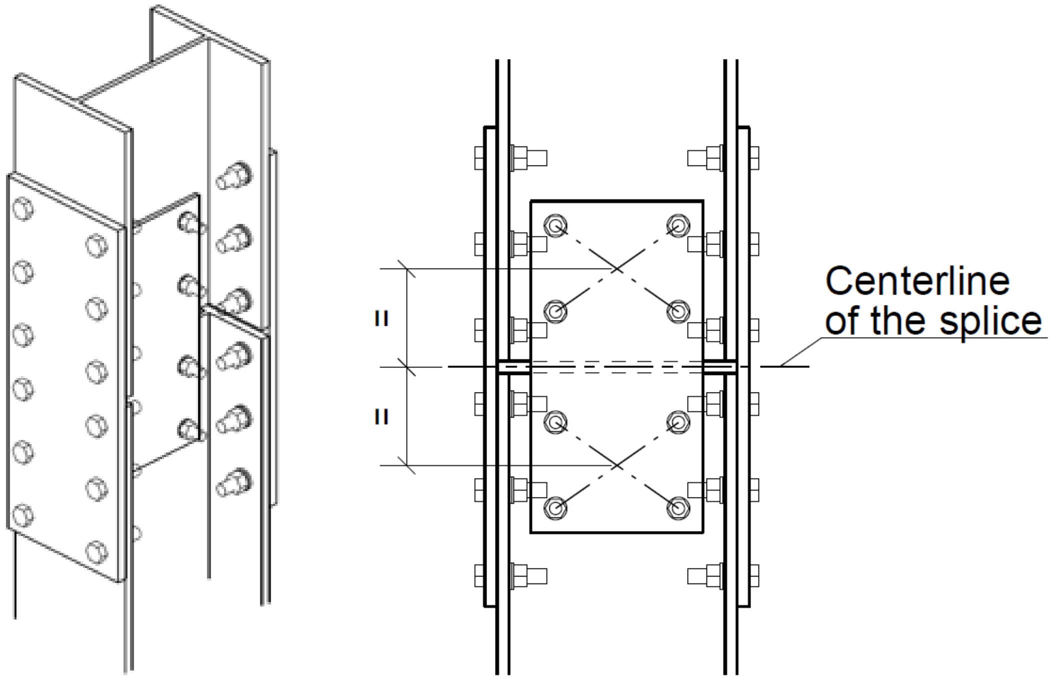


Figure 2.4. The centerline of the splice

- Primary loads are member axial force (compression or tension), bending about y-y and z-z axis, torsional moment about member longitudinal (x-x) axis and shear forces in the direction of the y-y and z-z axis. Six different load combinations can be calculated simultaneously.
- Available profiles: HEA100-1000, IPE80-600 and double symmetric welded profile. New profile types can easily be added with profile database, which is an Excel-table in certain form.

Following rules can be found for the eccentricity of the joining column and finish of the beam ends in the splice, see figure 2.6 and 2.7:

- The column splice must meet the requirements of the standard EN 1090-2 + A1 chapter D.2.9 (Functional manufacturing tolerances – Column splices and baseplates) [4] concerning non-intended eccentricity of the splice (figure 2.5):

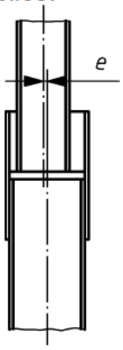
No	Criterion	Parameter	Permitted deviation Δ	
			Class 1	Class 2
1	Column splice: 	Non-intended eccentricity *e* (about either axis):	5 mm	3 mm

Figure 2.5. Non-intended eccentricity of the splice [4, chapter D.2.9]

- In the case of bearing type joint, the beam end cutting must meet the requirements of the standard EN 1090-2 + A1, chapter D.2.7 (Functional manufacturing tolerances – Components) [4] concerning surfaces finished for full contact bearing (figure 2.6).

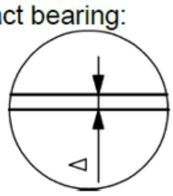
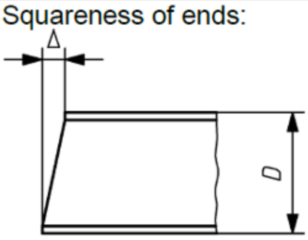
No	Criterion	Parameter	Permitted deviation Δ	
			Class 1	Class 2
5	Surfaces finished for full contact bearing: 	Gap Δ between straight edge and surface: NOTE No surface roughness criterion is specified.	Δ = 0,5 mm high spots not be proud by more than 0,5 mm.	Δ = 0,25 mm high spots not be proud by more than 0,25 mm.
6	Squareness of ends: 	Squareness to longitudinal axis: - ends intended for full contact bearing: - ends not intended for full contact bearing:	Δ = ± *D*/1 000 Δ = ± *D*/100	Δ = ± *D*/1 000 Δ = ± *D*/300 but |Δ| ≤ 10 mm

Figure 2.6. Surfaces finished for full contact bearing [4, chapter D.2.7]

As a comparison, in AISC specification [14, chapter M, p. 171] is said as follows:

"*Lack of contact bearing not exceeding a gap of 1/16 in. (2 mm), regardless of the type of splice used (partial-joint-penetration groove welded or bolted), is permitted. If the gap exceeds 1/16 in. (2 mm), but is equal to or less than 1/4 in. (6 mm), and if an engineering investigation shows that sufficient contact area does not exist, the gap shall be packed out with nontapered steel shims. Shims need not be other than mild steel, regardless of the grade of the main material.*"

The effect of the column end finish is researched in [13]. According to it, if a contact splice is placed inside the length of a column these initial additional imperfections will have an influence on the buckling behavior and thus the load carrying capacity of the column [13, p. 833]. Further, in the conclusions of the article is stated among other things, that

- quality of the sawing in the splice region of the ends of the column should be high, but no milling is necessary,
- different types of profiles (e.g., HEA with HEB) should be avoided and
- the flange cover plates should be connected at least with 4 bolts M24 grade 10.9 (100% prestressed) up to the depth of the section h = 500 mm, 4M27 grade 10.9 for greater profiles [13, p. 843].

In this research, the shape of the splice members is supposed to be ideal, so the effect of the imperfections is not considered.

3. CALCULATIONS

3.1 General

The calculations are based on the commonly known rules of the structural mechanics. There are also some points, where Eurocodes are applied. Those are for example the design resistances of the cross sections and some minimum loads.

The calculations include the distribution of the profile stresses, profile and plate forces and the most highly loaded bolt shear forces in the flanges and the web. Other calculations needed for completing the designing of the splice are not included in this research. Those are for example

- the cross-section class of the flange and splice plates in compression,
- the resistance of the flange and splice plates in axial force, bending and shear and their combinations,
- the local buckling resistance of the compressed plates,
- the effect of the fastener holes in the flange and splice plates under stress and
- the design of the bolt connections.

Rules for these calculations can be found in Eurocodes.

The basic procedure of the calculations is as follows:

- parameters of the profile, plates and bolt groups are given,
- specification of the loads and load combinations is made,
- after the given parameters and specifications, the profile and plate stresses, cross-section forces and bolt shear forces are calculated.

All calculations can be performed with 6 different load combinations simultaneously including normal force, bending about y-y and z-z axes, shear in y-y and z-z axes directions and torsional moment about beam x-x axis.

Coordinate system used in this research is analogical to EN 1993-1-1: 2005 conventions for member axes [1, p. 20] and is shown in figure 3.1.

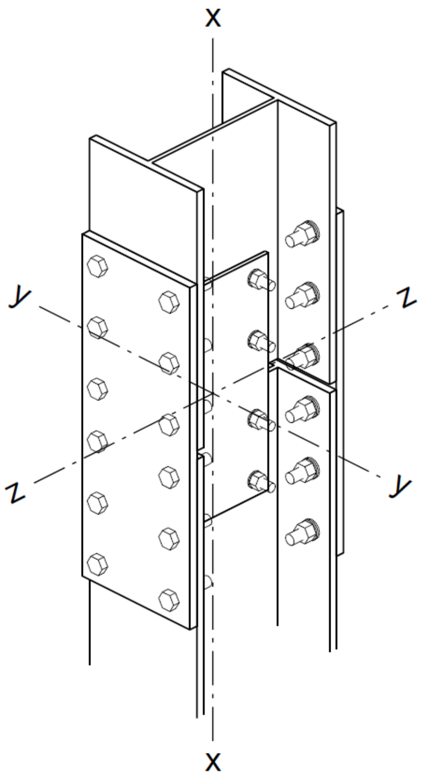


Figure 3.1. *Coordinate system*

3.2 Parameters

3.2.1 Profile

Profile type is given in the beginning of the calculations, see figure 3.2. Profile HEA and IPE cross-sectional specifications are saved in the database from where they are downloaded automatically. In the case of welded profile, program calculates them itself. For welded profile the size of welding can be given. Welding has an effect in some points of the calculations. The points are mentioned there separately.

$prof := \text{"HEA400"}$

- HEA, IPE or WI, for example "HEA400", "IPE400"
- Welded profile in the form WI400-10-15-300 ($h - t_w - t_f - b$)

$a_w := 5\ mm$ — Weld size if welded profile (does not effect to cross section properties unless WI-profile)

Figure 3.2. *Profile type.*

3.2.2 Bolts and plates

Information of the bolts and connection plates is given in the Excel sheet, from where they are read to the Mathcad. Distances between the bolt group center and joint middle point are calculated (see figure 3.3), as well as distance to the furthest bolt from bolt group center. Second moment of area of the bolt group in respect of the bolt group center is calculated (see figure 3.4).

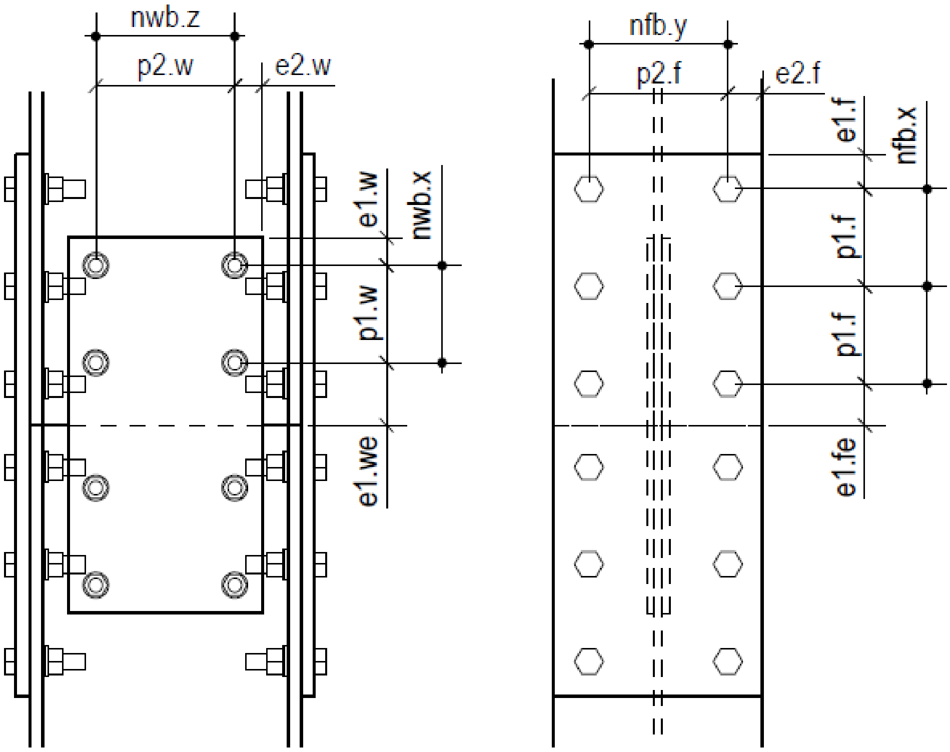


Figure 3.3. Web and flange bolt groups.

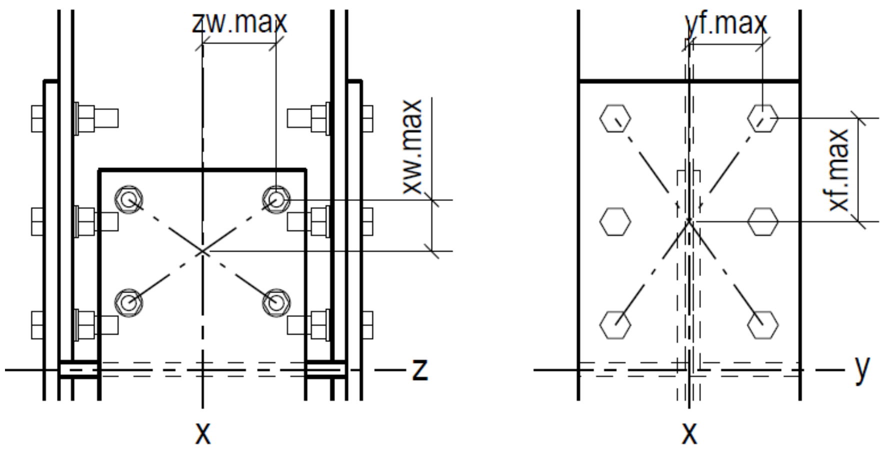


Figure 3.4. Distance between the bolt group center and furthest bolt in profile axes directions.

3.2.3 Loads

All loads are given in the Excel-sheet, which is read in Mathcad. The load cases are normal force, bending moment about y-y and z-z axis, torsional moment about x-x axis and shear force in y-y and z-z axis direction. Six load combinations can be used simultaneously in the calculations, but the amount of the combinations can be easily increased, if needed.

There are some rules about the minimum loads in Eurocodes:

- in the case of the bearing type splice, the splice plates should carry at least 25% of whole axial force [3, chapter 6.2.7.1(14)].
- if the members are not prepared for full contact in bearing, splice plates are used and the internal moments should be taken as not less than a moment equal to 25% of the cross-section plastic moment capacity about both axes [3, chapter 6.2.7.1(13)].
- if the members are not prepared for full contact in bearing, the internal shear force should be taken as not less than a shear force equal to 2.5% of the normal force capacity in the directions of both axes [3, chapter 6.2.7.1(13)]. Thus, in the case of gap between profiles, the minimum shear force $V_{z.Ed}$ and $V_{y.Ed}$ is not less than 2.5% of the design resistance $N_{c.Rd}$ of the cross-section for uniform compression.

As a comparison, in AISC specification is said for compression members with bearing joints [14, chapter J, p. 114], that splice plates should carry either an axial tensile force of 50% of the required compressive strength of the member or the moment and shear resulting from a transverse load equal to 2% of the required compressive strength of the member.

3.3 Profile stresses

3.3.1 Normal stress in the whole cross-section from axial force N

Normal stress is shown in figure 3.5. It is distributed to the whole cross-section of the profile, and it can be either compression (negative value) or tension (positive value).

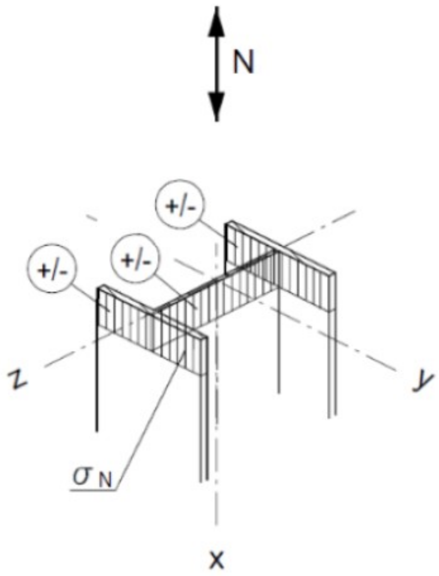


Figure 3.5. *Normal stress.*

3.3.2 Bending stress from the forces M_y and M_z

Bending M_y about the major axis causes evenly distributed stress to the flanges and triangular stress to the web, according to elastic stress distribution, see figure 3.6. Bending M_z about the minor axis causes triangular stress to the flanges. The deplanation of the cross-section due to torsional moment M_x is not considered in this work.

According to Firas *et al.* [9, p. 114], the web splice can be designed for the shear, moment due to the eccentricity of the shear and moment not resisted by the flanges. In this study the bending M_y is directed both to the flanges and the web. Bending from the eccentric shear force about y-y axis is directed only to the web and about z-z axis to the flanges. The load cases for the web and flange are:

Web: N + bending stress from M_y and $V_z \cdot e_{g.w}$ + shear from V_z
Flange: N + bending stress from M_y and M_z + shear from V_y and M_x.

The stress from the bending is calculated by the formula

$$\sigma = M\frac{y}{I}$$

where

σ = compression stress in the whole cross section

M = bending moment in respect of the profile main axis

y = distance between profile neutral axis and flange centerline

I = second moment of area of the profile in respect of the profile main axis.

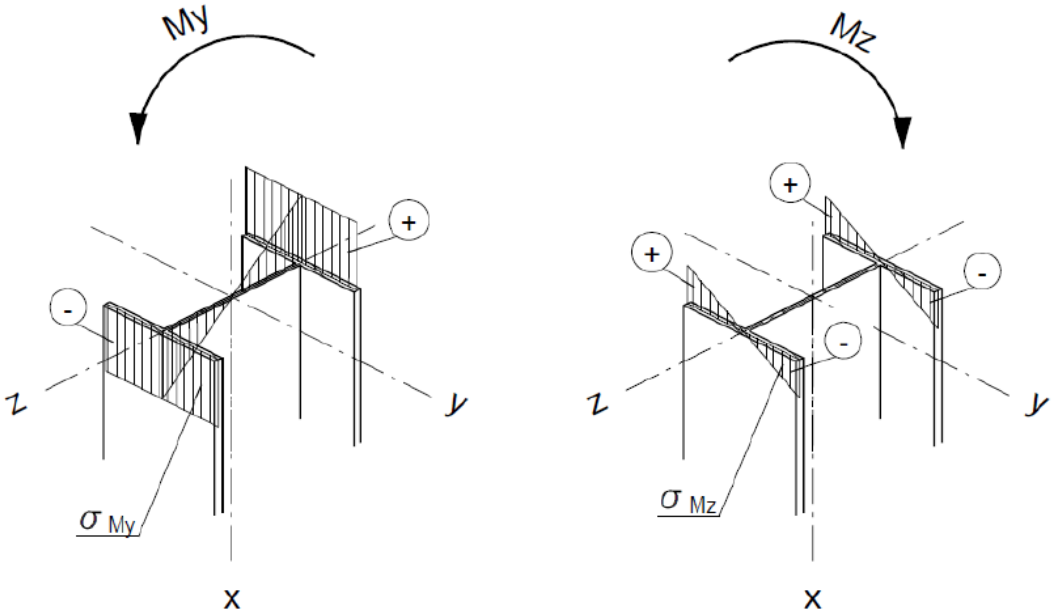


Figure 3.6. *Bending stresses.*

3.3.3 Bending stress from the eccentricity of the shear forces V_z and V_y

The eccentricity of the shear forces cause bending stress shown in figure 3.7. Using a symmetrical splice, each bolt group will carry one-half the eccentric moment. Therefore, the eccentricity of the shear force is the distance from the centerline of the splice to the centroid of the web bolts on one side of the splice [9, p. 114], thus here the dimensions $e_{g.f}$ for shear V_y and $e_{g.w}$ for shear V_z, see figure 3.8. Stress caused by V_z is directed wholly to the web and stress from V_y to the flanges.

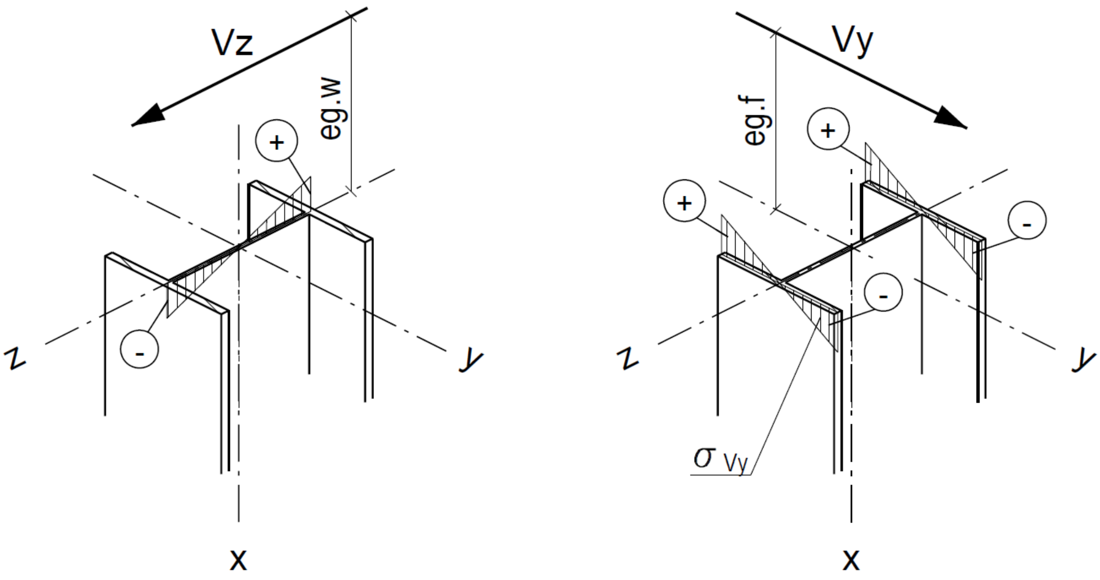


Figure 3.7. *Bending stresses from the eccentric shear forces.*

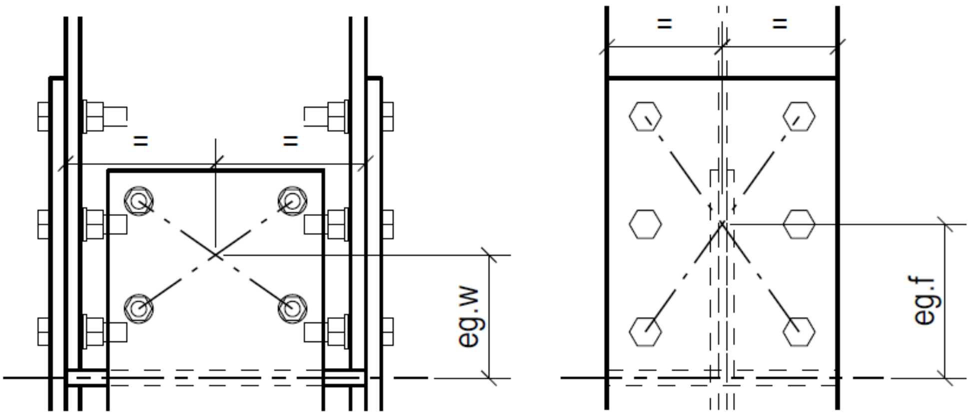


Figure 3.8. *Dimension $e_{g.w}$ and $e_{g.f}$.*

3.3.4 Shear stress from V_z, V_y and M_x

Shear stress comes from the shear forces along y- and z-axis direction and torsional moment about x-x axis. Shear stress V_z is distributed to the web, while shear stress V_y is directed wholly to the flanges as an evenly stress, as shown in figure 3.9. Torsional moment M_x causes shear stress for flanges.

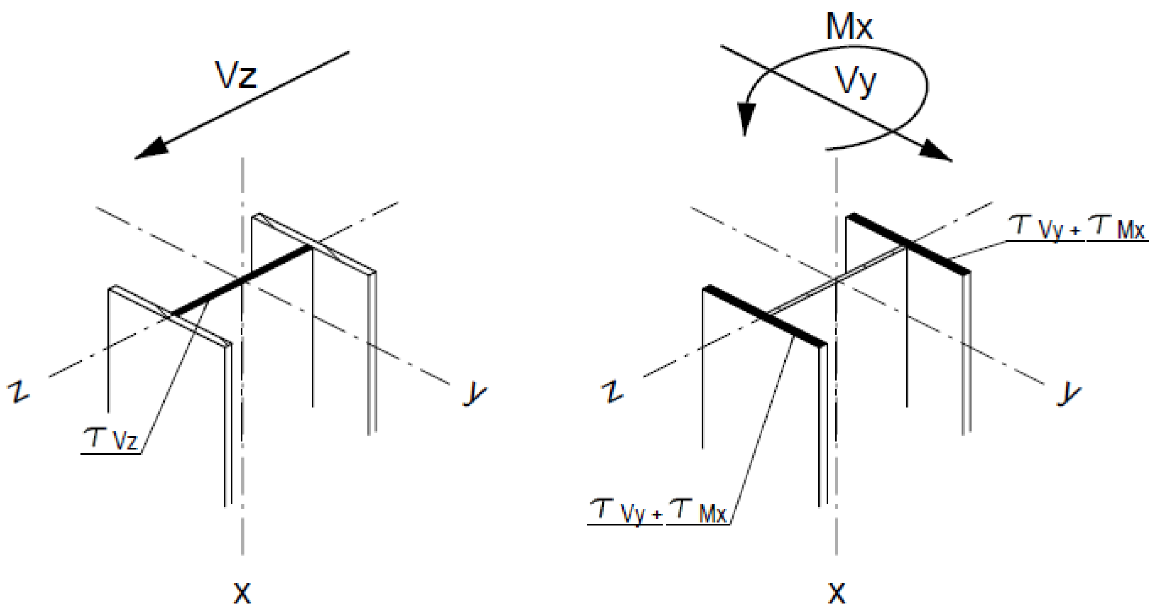
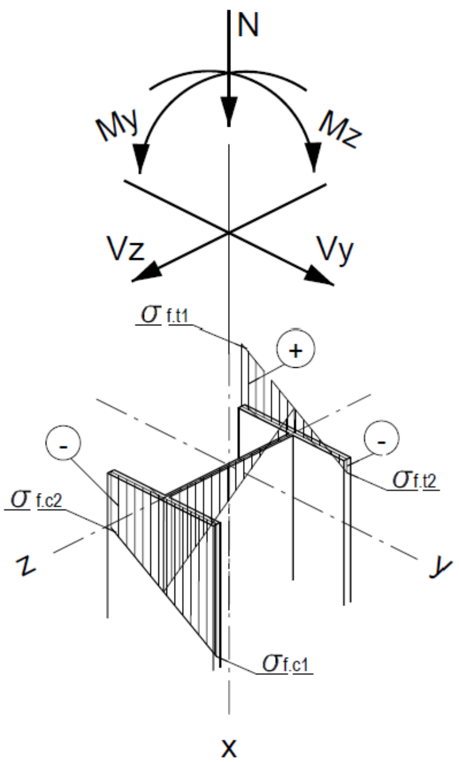


Figure 3.9. *Shear stresses from the shear forces.*

3.3.5 Combined stresses

Typical combined stress of the profile from the compressive normal force, biaxial bending and shear forces is shown in figure 3.10.



3.10. *Combined stress in the profile cross-section, [-] compression, [+] tension.*

3.4 Non-bearing type splice

Instructions for calculating a non-bearing type splice can be found in many sources. This calculation follows basically a method, which is shown in the P398 [6, p. 127-140].

3.4.1 Flange forces

Axial forces

The axial force of the compressed and tensioned flange (see figure 3.11) is a combination of the resultants of the stresses in the flange from the normal force N and bending M_y about major axis. Bending about the major axis from the eccentricity of the shear force V_z is directed wholly to the web and is thus not considered here.

$$F_f = F_{f.x.N} + F_{f.x.My}$$

where

F_f = flange axial force in compression or tension side

$F_{f.x.N}$ = flange axial force from the normal force N_{Ed}

$F_{f.x.My}$ = flange axial force from the bending M_y

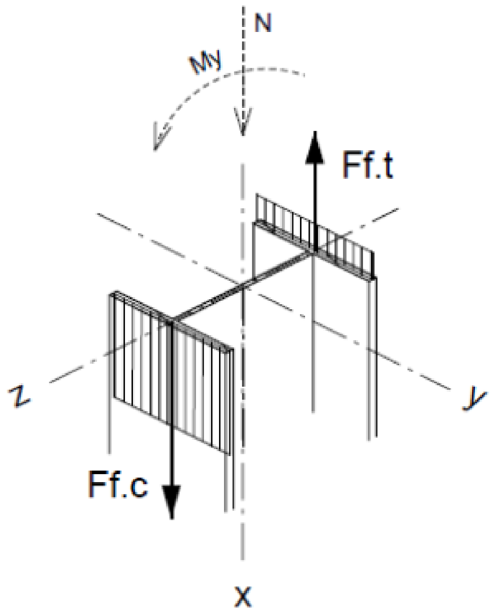


Figure 3.11. The resultants of the flange forces.

Bending

The bending moment of the flange about the minor axis (see figure 3.12) is calculated from the bending M_z and the eccentricity of the shear force V_y and torsion M_x. The formula is

$$M_{f.z} = M_{z.Ed} * \frac{I_{f.z}}{I_z} + \frac{V_{y.Ed}}{2} \cdot e_{g.f}$$

where

$M_{f.z}$	= bending moment of the flange about z-z axis
$M_{z.Ed}$	= design bending moment in respect of the profile main axis
$I_{f.z}$	= second moment of area of the cross-section (flange or web)
I_z	= second moment of area of the profile in respect of the profile main axis
$V_{y.Ed}$	= design shear force in the y-y axis direction
$e_{g.f}$	= eccentricity of the flange shear force

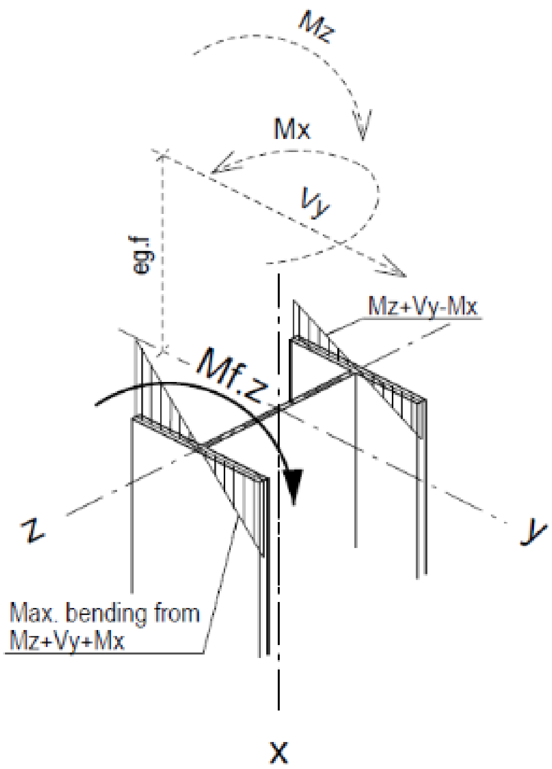


Figure 3.12. Flange bending about z-z axis.

Shear force

Shear force in the y-y axis direction is directed wholly to the flanges (see figure 3.13) and is calculated by the formula

$$V_f = \tau_f \cdot A_f$$

where

τ_f = shear stress of the flange

A_f = flange cross-section area

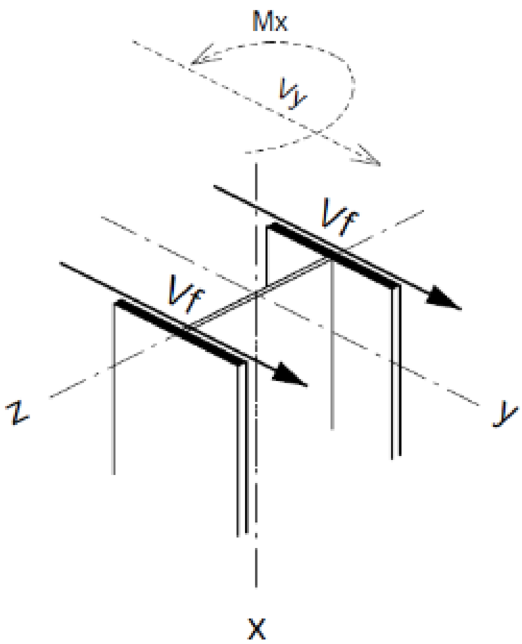


Figure 3.13. *Flange shear force along y-y axis.*

3.4.2 Shear forces of the flange bolts

Bolt shear force in the x-x axis direction

Critical bolt is the one which lies the furthest from the bolt group center. Shear force from the bending about z-z axis is calculated by the formula

$$\frac{F_{f.Ed}}{n_{fb}} + \frac{M_{f.z.Ed} \cdot y_{f.max}}{I_{p.fb}}$$

where

$F_{f.Ed}$ = force combination of the flange axial forces from N_{Ed} and $M_{y.Ed}$

n_{fb} = number of the flange bolts in the splice half

$M_{f.z.Ed}$ = combined bending of the flange due to $M_{z.Ed}$ and $V_{y.Ed}$

$y_{f.max}$ = the distance of the furthest bolt from the bolt group center in y-y axis direction

$I_{p.fb}$ = second moment of area of the bolt group in respect of the bolt group center.

Combined shear force is calculated by summarizing shear forces together, considering the direction of the forces. In the case of wholly tensioned section, the value of $V_{fb.x.t.Ed}$ gives bigger shear force than $V_{fb.x.c.Ed}$. The shear force of the bolts in the x-x axis direction is shown in figure 3.14.

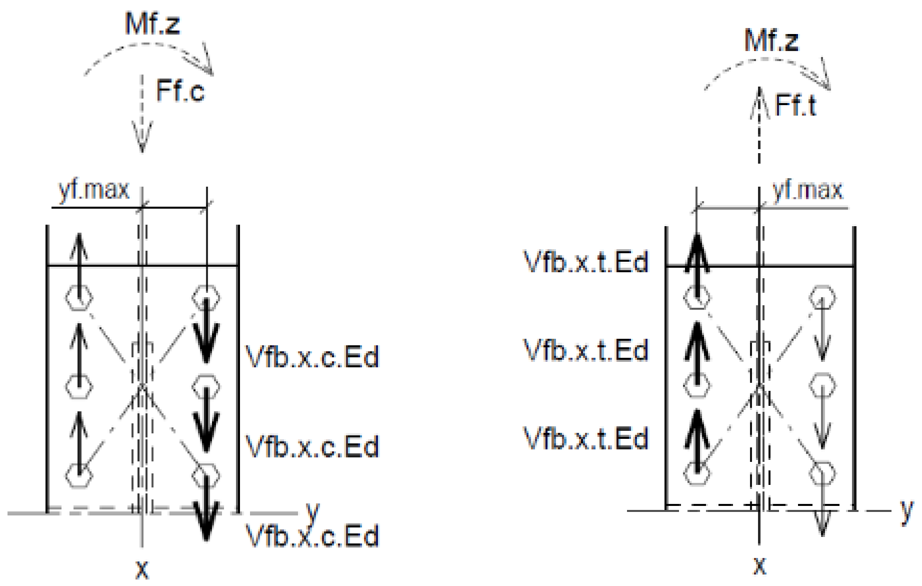


Figure 3.14. *Flange bolt shear forces in the compression and tension side in x-x axis direction.*

Bolt shear force in the y-y axis direction

Maximum shear force per flange bolt in the y-y axis direction is calculated by the formula

$$\frac{V_{f.Ed}}{n_{fb}} + \frac{M_{f.z.Ed} \cdot x_{f.max}}{I_{p.fb}}$$

where

$V_{f.Ed}$ = shear force of the flange due to $V_{y.Ed}$ and $M_{x.Ed}$

n_{fb} = number of the flange bolts in the splice half

$M_{f.z.Ed}$ = combined bending of the flange due to $M_{z.Ed}$ and the eccentricity of $V_{y.Ed}$

$x_{f.max}$ = the distance of the furthest bolt from the bolt group center in x-x axis direction

$I_{p.fb}$ = second moment of area of the bolt group in respect of the bolt group center.

The shear force of the bolts in the y-y axis direction is shown in figure 3.15.

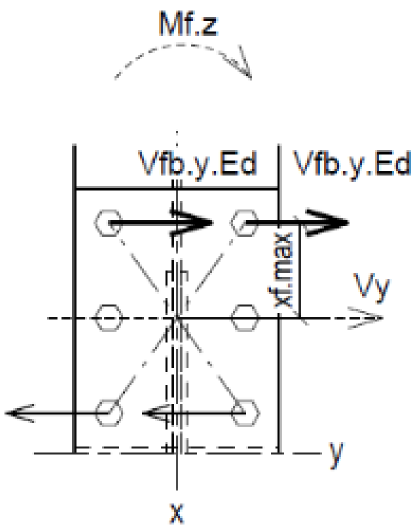


Figure 3.15. Flange bolt shear forces in the y-y axis direction.

Maximum shear force resultant of the flange bolt

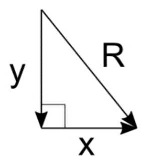
The forces are in the right angle in respect of each other, so the maximum force resultant of the flange bolt is calculated with Pythagoras theorem:

$$R = \sqrt{x^2 + y^2}$$

where

x = force component in x-x axis direction

y = force component in y-y axis direction



3.4.3 Web forces

Axial forces

Axial force from the normal force N_{Ed} (see figure 3.16) is distributed to the web in the ratio of the web area to the whole section area by the formula

$$F_w = N_{Ed}\frac{A_w}{A}$$

where

F_w = axial force of the web due to N_{Ed}

N_{Ed} = design value of the normal force

A_w = web cross-section area

A = total cross-section area of the profile

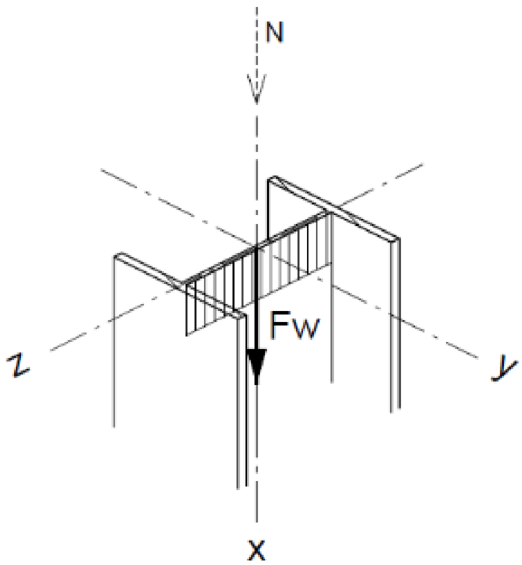


Figure 3.16. *Flange bolt shear forces in the y-y axis direction.*

Bending

Bending $M_{y.Ed}$ is directed partially to the web. Bending caused by the eccentricity of the shear force V_z is directed wholly to the web. The bending moment of the web (see figure 3.17) is calculated by the formula

$$M_{w.y} = M_{y.Ed}\frac{I_{w.y}}{I_y} + V_{z.Ed} \cdot e_{g.w}$$

where

$M_{w.y}$ = web bending about y-y axis

$M_{y.Ed}$ = the design force of the bending about y-y axis

$I_{w.y}$ = second moment area of the web

I_y = second moment area of the whole cross-section about y-y axis.

$V_{z.Ed}$ = the design force of the shear in z-axis direction

$e_{g.w}$ = the distance between the bolt group center and joint middle point.

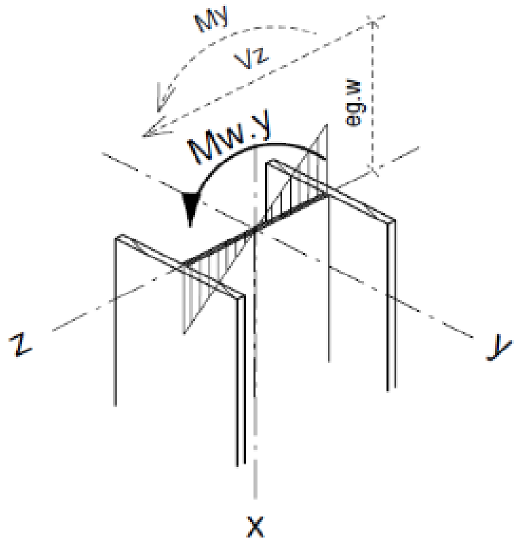


Figure 3.17. *Web bending about y-y axis.*

Shear force

The shear force in z-z axis direction (see figure 3.18) is directed wholly to the web, thus $V_{w.Ed} = V_{z.Ed}$.

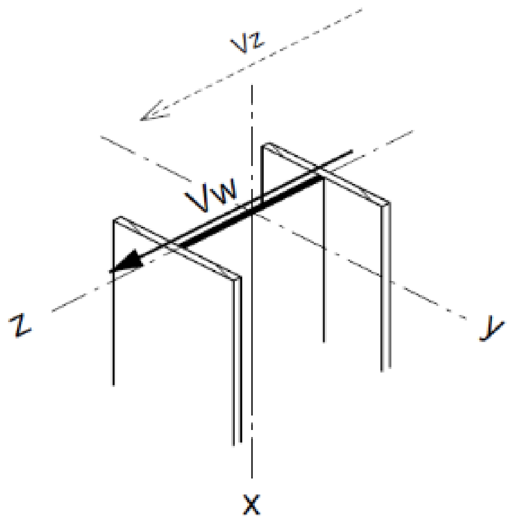


Figure 3.18. Web shear force along z-z axis.

3.4.4 Shear forces of the web bolts

Bolt shear force in the x-x axis direction

Web bolt shear force in the x-x axis direction comes from the axial force N_{Ed} and bending $M_{y.Ed}$. The bolt shear force is show in figure 3.19 and it is calculated by the formula

$$\frac{F_{w.x.Ed}}{n_{wb}} + \frac{M_{w.y.Ed} \cdot z_{w.max}}{I_{p.wb}}$$

where

$F_{w.x.Ed}$ = axial force of the web due to N_{Ed}

n_{wb} = number of the web bolts in the splice half

$M_{w.y.Ed}$ = combined bending of the web due to $M_{y.Ed}$ and the eccentricity of $V_{z.Ed}$

$z_{w.max}$ = the distance of the furthest bolt from the bolt group center in z-z axis direction

$I_{p.wb}$ = second moment of area of the bolt group in respect of the bolt group center.

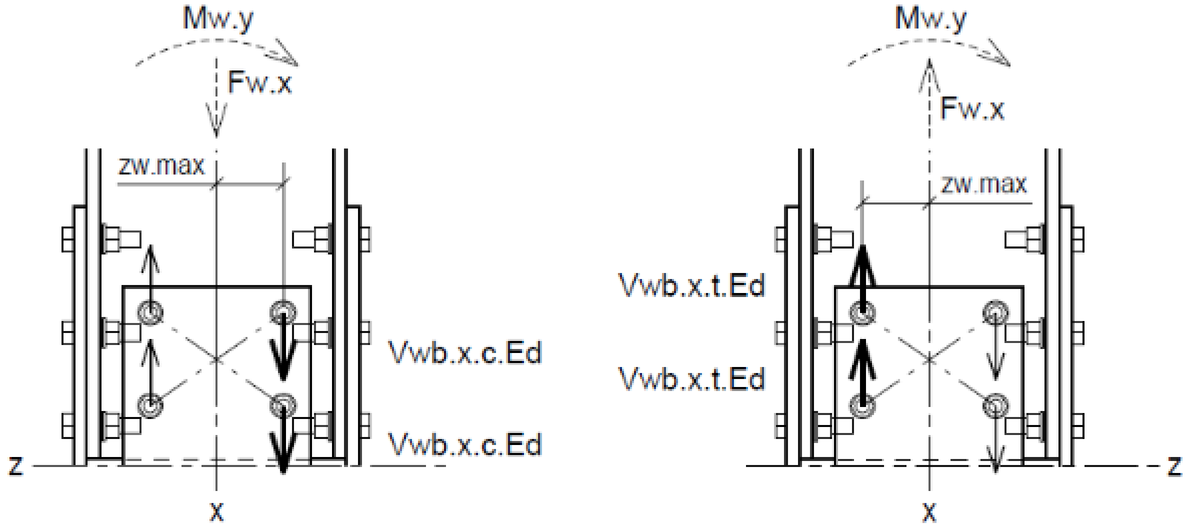


Figure 3.19. *Web bolt shear forces in the compression and tension side in x-x axis direction.*

Bolt shear force in the z-z axis direction

Web bolt shear force in the z-z axis direction comes from the web shear force, the bending about y-y axis and the eccentricity of the shear force in the z-z axis direction, see figure 3.20. The bolt shear force is calculated by the formula

$$\frac{V_{w.Ed}}{n_{wb}} + \frac{M_{w.y.Ed} \cdot x_{w.max}}{I_{p.wb}}$$

where

$V_{w.Ed}$ = shear force of the web due to $V_{z.Ed}$

n_{wb} = number of the web bolts in the splice half

$M_{w.y.Ed}$ = combined bending of the web due to $M_{y.Ed}$ and $V_{z.Ed}$

$x_{w.max}$ = the distance of the furthest bolt from the bolt group center in x-x axis direction

$I_{p.wb}$ = second moment of area of the bolt group in respect of the bolt group center.

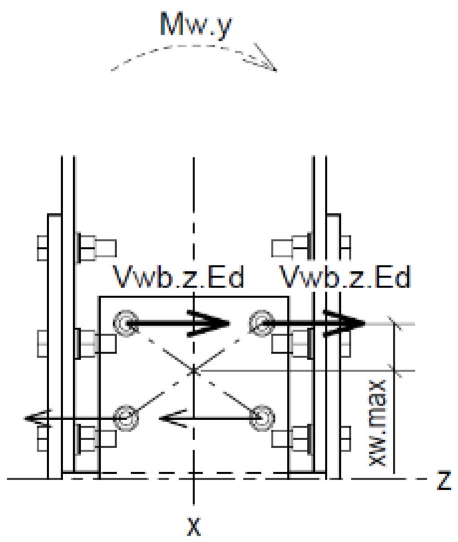


Figure 3.20. *Web bolt shear forces in the z-axis direction.*

Maximum shear force resultant of the web bolt

The maximum force resultant of the web bolt is calculated similarly as the flange bolt forces, thus $R = \sqrt{x^2 + y^2}$, where x and y are the force components in x- and z-axis direction.

3.5 Bearing type splice

3.5.1 Introduction

In the bearing type splice the force distribution in the joint differs from the non-bearing type splice, because part of the stress is transmitted through the profile ends. In the middle of the splice the bending stress from the moments M_y and M_z are supposed to be distributed according to the stiffnesses of the effective cross-sections. In the tension side, only the flange plate together with the web plates are supposed to be effective. In the compression side the flange, flange plate and part of the web are effective against bending together with the web plates. The stress distribution is shown in figures 3.21 and 3.22.

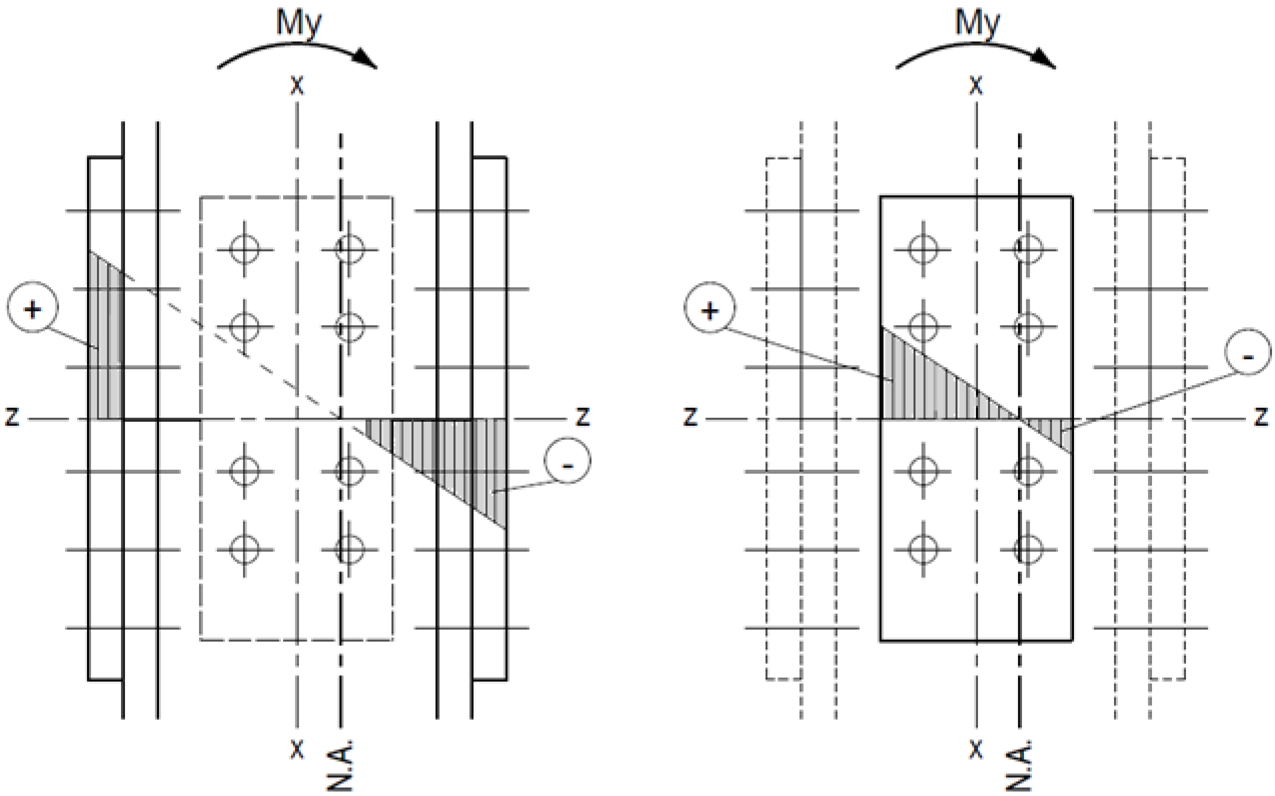


Figure 3.21. *The stress distribution of the profile and flange plates (left) and the web plate (right), bending M_y.*

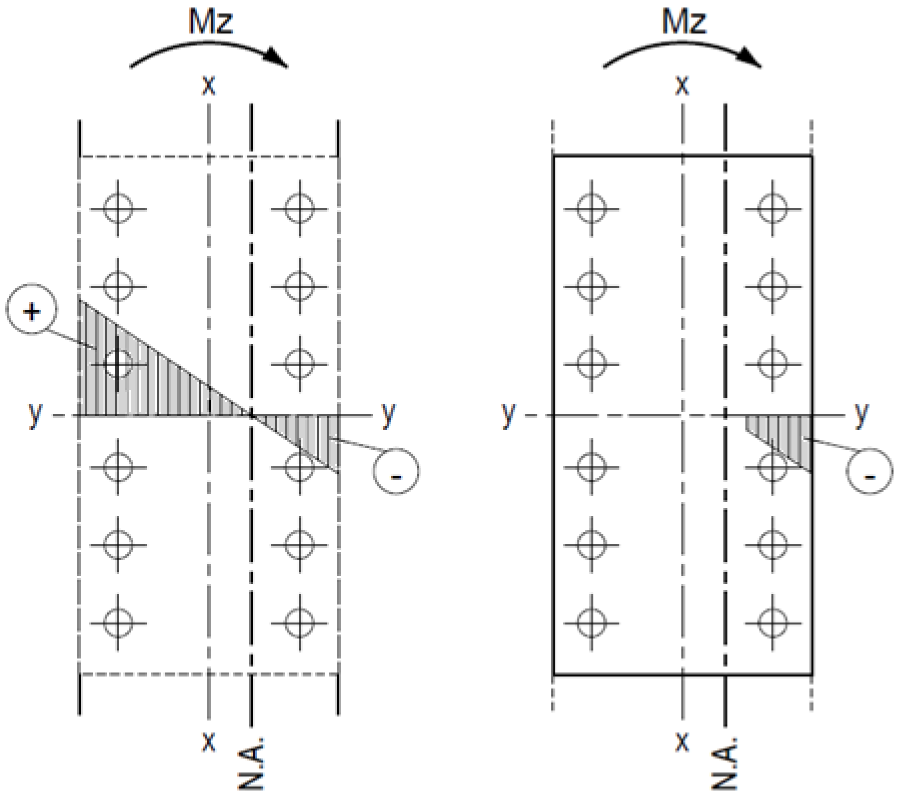


Figure 3.22. *The stress distribution of the flange (left) and the flange plate (right), bending M_z.*

3.5.2 Bending about the strong axis

The effective cross-sections

The effective cross-sections in the bending about strong axis (M_y) are shown as striped areas in figure 3.23.

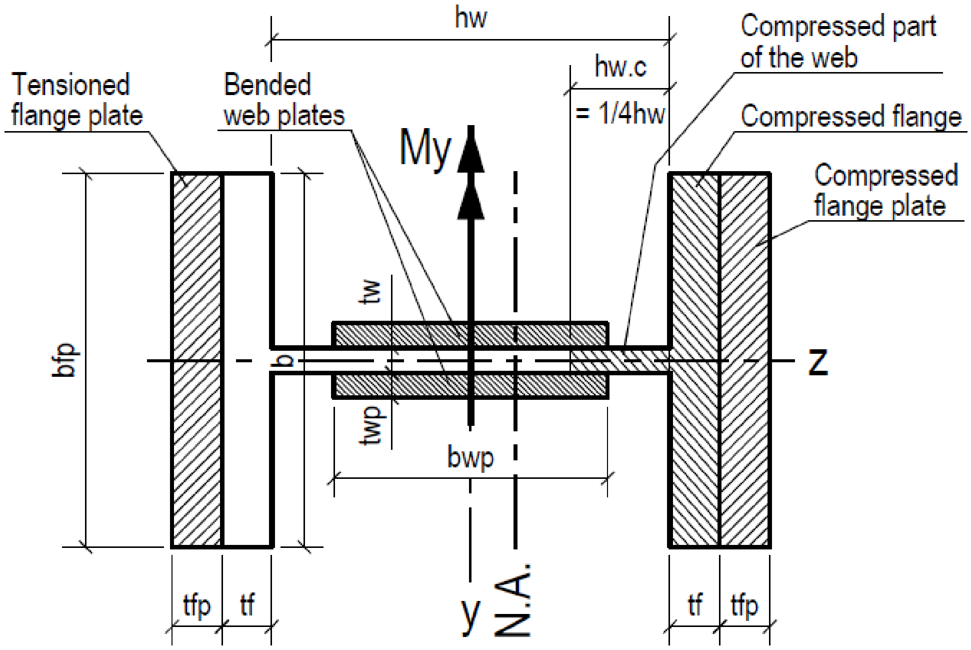


Figure 3.23. *The effective areas of the splice against bending $M_{y.Ed}$.*

Since in this study the profile and connecting plates has the same modulus of elasticity, the location of the bending neutral axis is equal to the centroid of the total effective area and can be calculated with the following formula:

$$z_0 = \frac{\sum_{i=1}^{n} A_i \cdot z_i}{A_{y.eff}}$$

where

z_0 = distance between y-y axis and the neutral axis (N.A.)

z_i = distance between y-y axis and centroid of ith cross-section

A_i = the area of the effective cross-section

$A_{y.eff}$ = total effective cross-section area

n = number of the cross-sections

The height of the compressed web $h_{w.c}$ is supposed to be $h_w/4$, which is approximately the same as the compressed web in FEA as shown in figure 3.24. The FEA is shown in chapters 4 and 5.

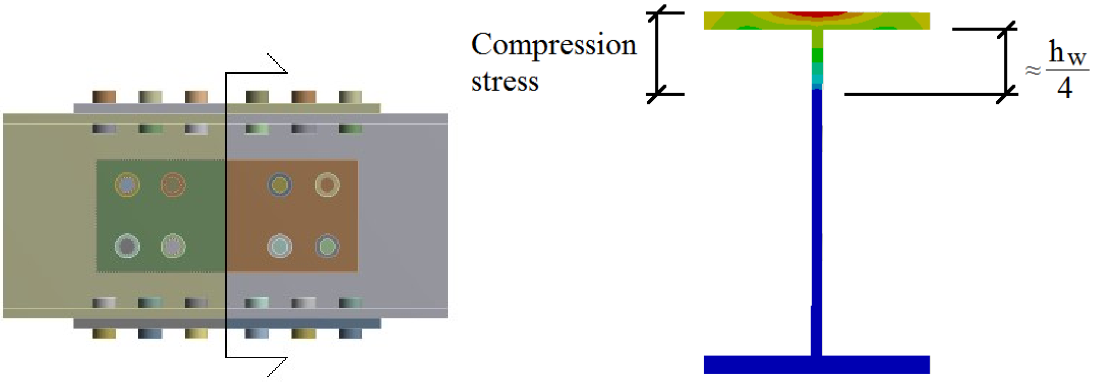


Figure 3.24. Compression stress in the contact face between the ends of the beams, bending M_y = 600 kNm.

Moment distribution of the effective cross-sections

Second moments of areas of the cross-sections are calculated with the formula

$$I_i + z^2 A_i$$

where

I_i = Second moment of the area of the cross-section

A_i = the area of the effective cross-section

z_i = distance between the centroid of the cross-section area and the neutral axis, see figure 3.25

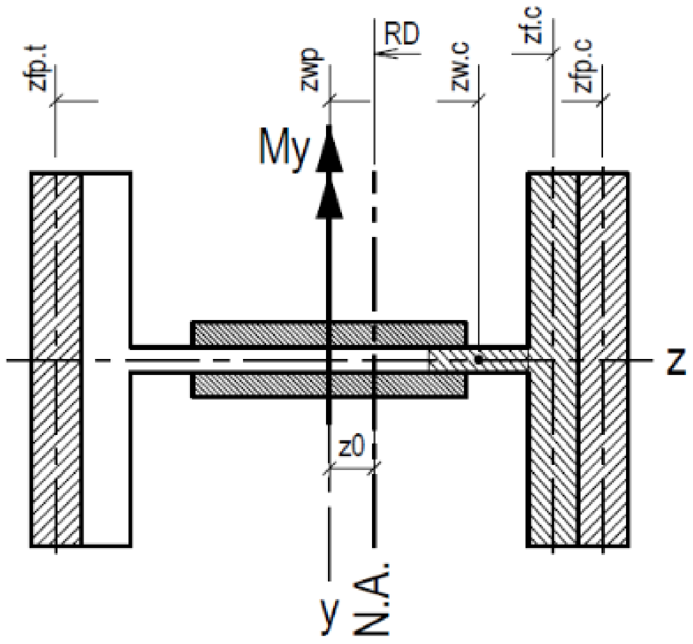


Figure 3.25. Distances between the cross-section areas and the neutral axis.

The total bending moment is distributed for each effective cross-section in respect of their stiffnesses with the following formula:

$$M_{y.i} = \frac{I_{y.i}}{I_{y.eff}} \cdot M_{y.Ed}$$

where

$M_{y.i}$ = the portion of the bending moment for the effective cross-section

$M_{y.Ed}$ = total design bending moment

$I_{y.i}$ = second moment of the area of the cross-section

$I_{y.eff}$ = second moment of the area of the entire effective cross-section

3.5.3 Bending about the weak axis

The effective cross-sections in the bending about weak axis (M_z) are shown as striped areas in figure 3.26.

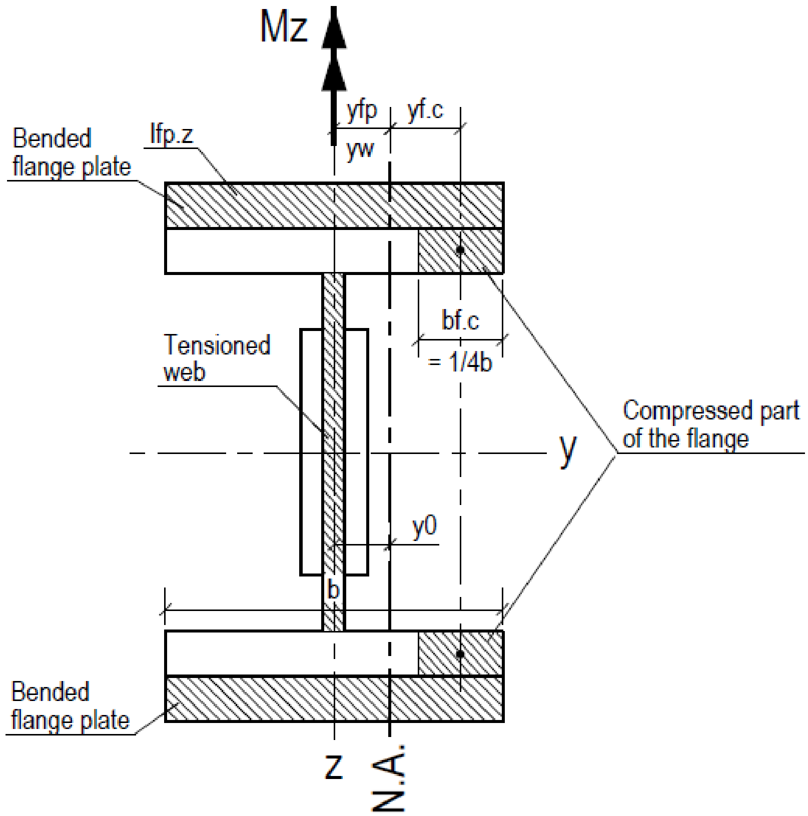


Figure 3.26. *The effective areas of the splice against bending $M_{z.Ed}$.*

The location of the bending neutral axis is calculated in the same way than in the bending about y-y axis. The height of the compressed part of the flange is supposed to be b/4. Web is supposed to be tensioned in the bending about z-z axis. The total bending moment is distributed for each effective cross-section in respect of their stiffnesses.

3.5.4 Splice member forces

The term "Splice member" indicates here to the flanges, flange plates, web and web plates. The distribution of the forces and bending moments is based on the theory, where flange and web forces are forwarded to the plates without loss.

Flange and flange plate forces

Axial force from the normal force N_{ed} is directed to the joint members by the ratio of the member cross-section area compared to the total area of the effective splice cross-section area. The formula is

$$F = \frac{A_i}{A_{splice}} N_{Ed}$$

where

N_{Ed}	= design normal load
A_i	= joint member cross-section area
A_{splice}	= total cross-section area of the splice including profile and splice plates.

Axial force of the joint member due to the bending M_y is calculated with formula

$$F = \frac{M_{i.My}}{z_i}$$

where

F	= axial force of the joint member
$M_{i.My}$	= the portion of the total bending moment M_y for the joint member
z_i	= bending lever arm from the neutral axis to the centroid of the cross-section area

Flange plate total bending about z-z axis comes from the bending M_z and the bending from the eccentricities of the shear force V_y and M_x. Flange plate shear force is calculated by multiplying the flange shear stress with flange cross-section area.

Web and web plate forces

Web axial force is calculated by the ratio of the cross-section areas of the web and the effective splice cross-section area, like in calculating the flange axial force. The tension from the bending M_z is added to the web axial force with formula

$$F = \frac{M_{w.Mz}}{y_w}$$

where

F	= tension of the web
$M_{w.Mz}$	= the portion of the total bending moment M_z for the web
y_w	= bending lever arm from the neutral axis to the centroid of the cross-section area.

Web bending about y-y axis is calculated as a combination of the bending M_y and the eccentricity of the shear force V_z. The shear force $V_{z.Ed}$ is directed wholly to the web and through it, to web plates.

3.5.5 Shear forces of the flange bolts

Bolt shear force in the x-x axis direction

Shear force per bolt from flange plate axial force caused by normal force N and bending M_y is calculated by dividing the flange axial force with the number of the flange bolts in the splice half. Bolt shear force from the flange plate bending about z-z axis is calculated by the formula

$$V_{fb} = \frac{M_{fp.z.Ed} \cdot y_{f.max}}{I_{p.fb}}$$

which basically the same as in the non-bearing case.

In calculating the shear force in tensioned side the leverage effect of the bending from the flange compressed part ($M_{f.Mz}$) is added to the shear force:

$$V_{fb} = \frac{M_{fp.z.Ed} \cdot y_{f.max}}{I_{p.fb}} + \frac{M_{f.Mz}}{y_{fb.t} \cdot n_{fb.x}}$$

where

$y_{fb.t}$	= the lever arm of the bolt calculated from the centroid of the flange compressed area, see figure 3.27.

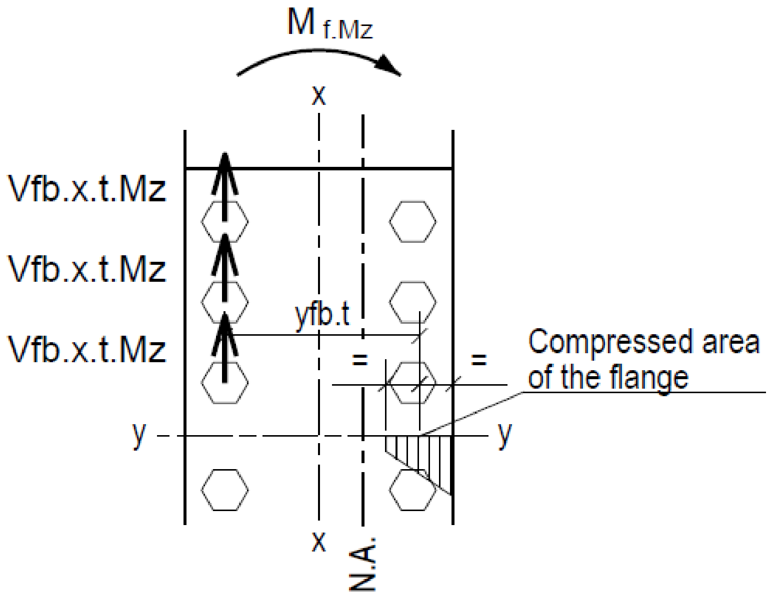


Figure 3.27. Bending moment of the flange compressed side.

Bolt shear force in the y-y axis direction

Shear forces in the y-y axis direction are calculated as in the non-bearing case.

3.5.6 Shear forces of the web bolts

Bolt shear force in the x-x axis direction

Shear force per bolt from the web normal force is calculated by dividing the web axial force with the number of the web bolts in the splice half. Total shear force per bolt in compression side of the web plates in bending about y-y axis is calculated with formula

$$V_{wbx.c.My} = \frac{M_{wp2.c.My}}{e_{wb.c} \cdot n_{wb.x}}$$

where

$M_{wp2.c.My}$ = the portion of the bending moment for the compressed part of the web plate

$e_{wb.c}$ = the lever arm of the web bolt in the compression side, see figure 3.28.

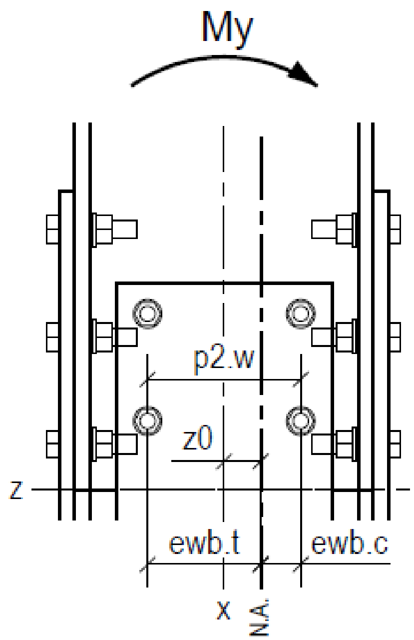


Figure 3.28. The lever arm $e_{wb.c}$ of the web bolt in the compression side.

The shear force in tension side is calculated in the same way. The location of the neutral axis is restricted so, that it should be between the bolts.

Bolt shear force in the z-z axis direction

Shear forces in the z-z axis direction are calculated as in the non-bearing case.

4. FINITE ELEMENT ANALYSIS

4.1 General

Finite element analysis (FEA) was performed by Ansys Structural Analysis for welded, wide-flange WI400-12-20-250 beam with bolted splice in the flange and the web. Two different structural cases were examined, bearing and non-bearing slice.

The structure was strained by five load cases and four load combinations under the structure elastic behavior. The behavior, stresses and forces of the beam and splice plates and the shear forces of the bolts were studied. At the end, the results of the FEA were compared to the Mathcad-calculations and the differences between results were examined.

4.2 Analysis set-up

4.2.1 Analysis settings

The analysis type was linear elastic. However, a relative high loading was used, which caused high utility ratio for the structure in some cases, and in the specimen 2, the loss of stability. Because the moderate displacements and possibly a local yielding were expected, large deflection -setting was set to on.

The increment of the load was divided into 3 or 6 parts by load steps and the results were picked every half second. The number of the load steps was 3 in all specimen, except the specimens no. 6 and 11, where the normal force was added during the load steps 1-3 and the rest of the loads during the load steps 4-6. Because of the possible nonlinearities in the system behavior, the maximum number of the substeps was adjusted to 1000 for to ensuring the sufficient slow raise of the loading.

Structure was loaded with a force applied to the solid face, which is a vector-based load. The load direction does not change as the structure rotates under load. This can have a little effect for the theoretical bending moments calculated for the structure. Therefore, the actual values of the moments in FE-model are used when calculating equivalent cases in Mathcad.

More about these setting can be read from the Ansys Help for example with the keywords “linear vs nonlinear analysis”, “conservative vs nonconservative behavior”, “substeps”, “load direction in a large-deflection analysis” and “load types”.

4.2.2 Materials

The bilinear material model was used, although the analysis was linear. A picture of what is appropriate load for the splice was achieved and could be used for estimating the validity of the analysis. The material model of the steel S355 is shown in figure 4.1. The slope of the first segment in the curve is equivalent to the Young's modulus of the material. The second segment is the tangent modulus, which is set to 1 MPa.

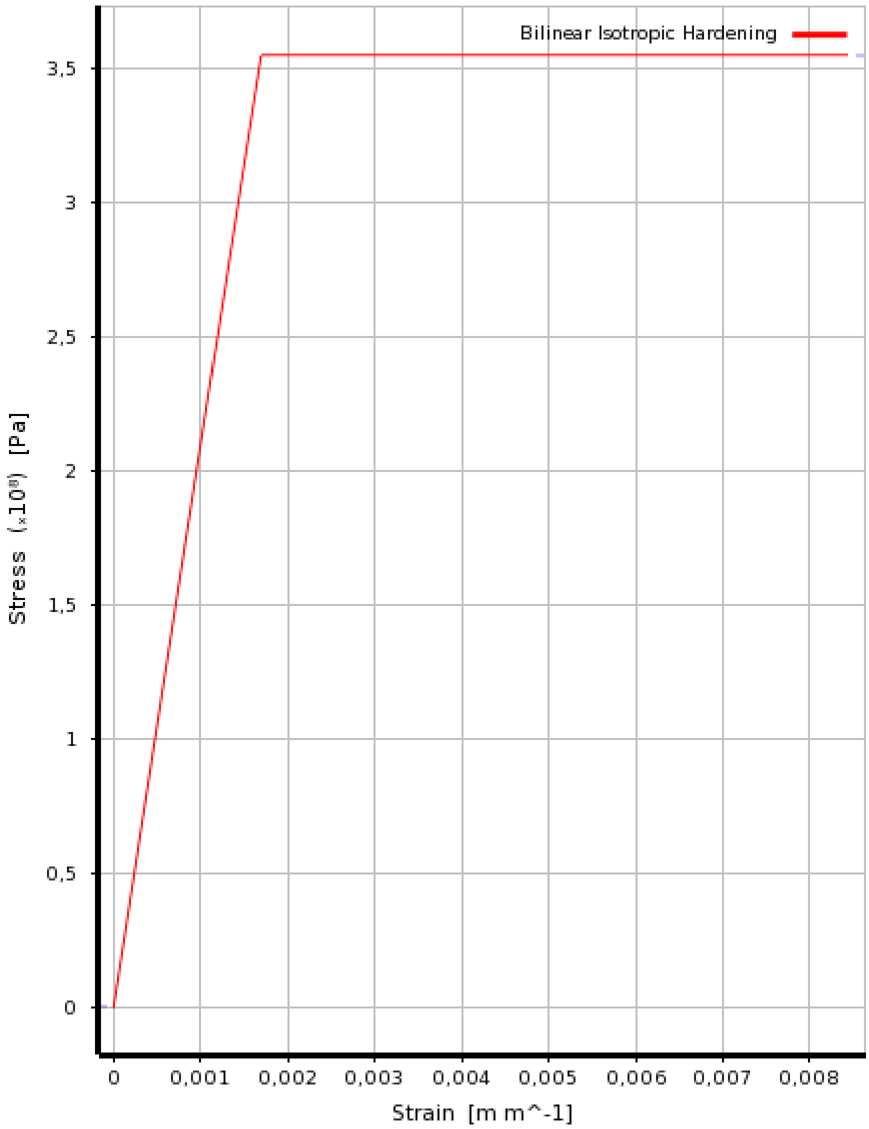


Figure 4.1. *Bilinear material model of S355 steel.*

Profiles and plates are isotropic S355 steel with following material properties:

Young’s modulus	2,1E+05	MPa
Poisson’s ratio	0,3	
Yield strength	355	MPa
Ultimate strength	510	MPa
Tangent modulus	1	MPa

Bolts are isotropic 8.8 grade steel with following material properties:

Young’s modulus	2,1E+05	MPa
Poisson’s ratio	0,3	
Yield strength	640	MPa
Ultimate strength	800	MPa
Tangent modulus	1	MPa

4.2.3 Structure

The analysis system consisted of 1-span welded wide-flange beam with a splice between the profiles. The profile type was welded I-profile, WI400-12-20-250 (h-t_w-t_f-b), see figure 4.2. Roundings or welds were not modelled. A non-bearing splice, where is a little gap between profiles, is shown in figure 4.3. To minimize the size of the FEA model, the profile began with beam elements at the supports and solids were in the middle of the beam. The mesh used in figure 4.3 is simplified than that used in the analysis for visual reasons.

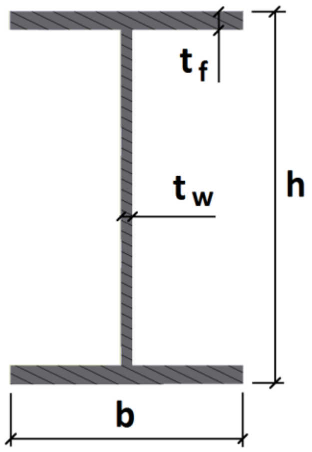


Figure 4.2. *Profile cross-section in FEA model.*

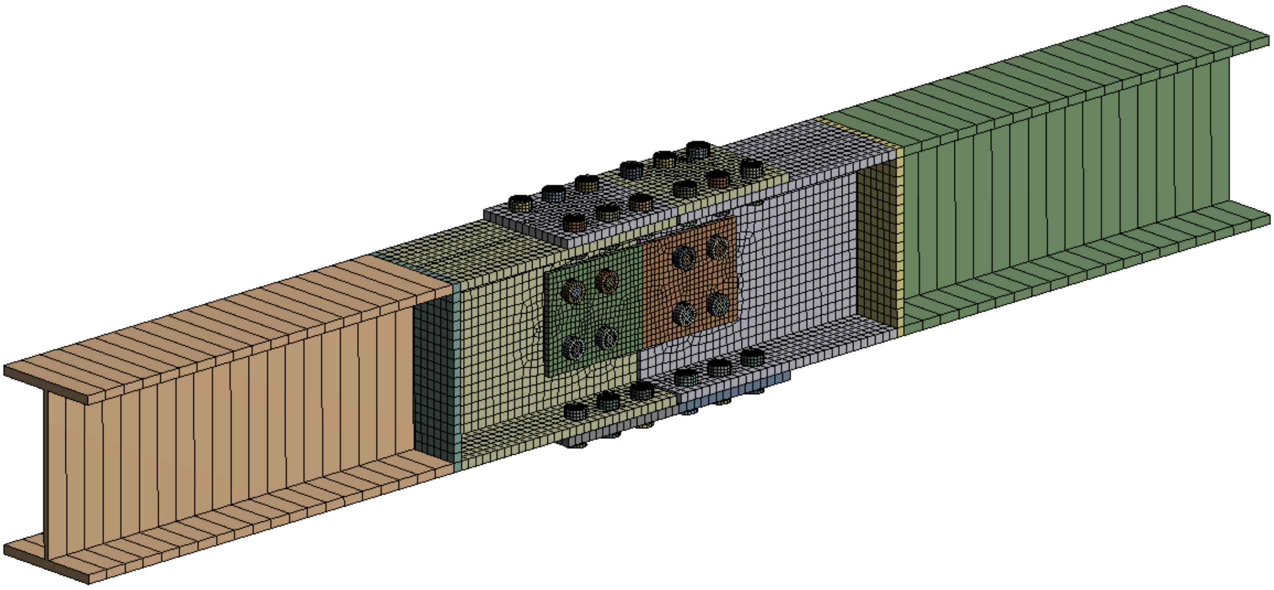


Figure 4.3. *FE-model of the structure.*

The structure layout of the non-bearing and bearing type splices was similar otherwise, but in the non-bearing case there was 10 mm gap between profiles, whereas in the bearing splice profile ends were together, see figure 4.4. The flange and web plates are continuous, although in figure (and in the FEA model) they consist of two solids.

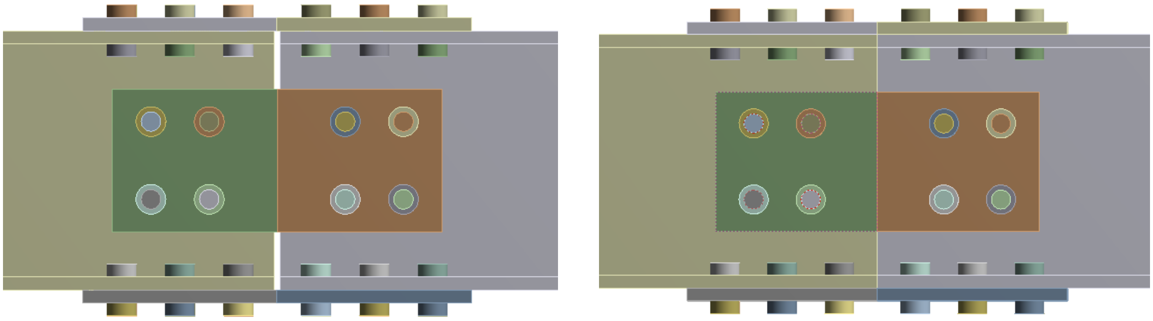


Figure 4.4. *Non-bearing (left) and bearing type splice.*

Solid parts are shown in figure 4.5 The flanges were bolted with 6+6 M30 grade 8.8 bolts and 20 mm plates outside the flanges. The web was bolted with 4+4 M30 grade 8.8 bolts and 12 mm plates both sides of the web. Plates, which are in the outer ends of the solid profiles, provide a place for lateral loads, because it's not accepted to set up multiple boundary conditions (in this case loads and joints) to the same point in Ansys.

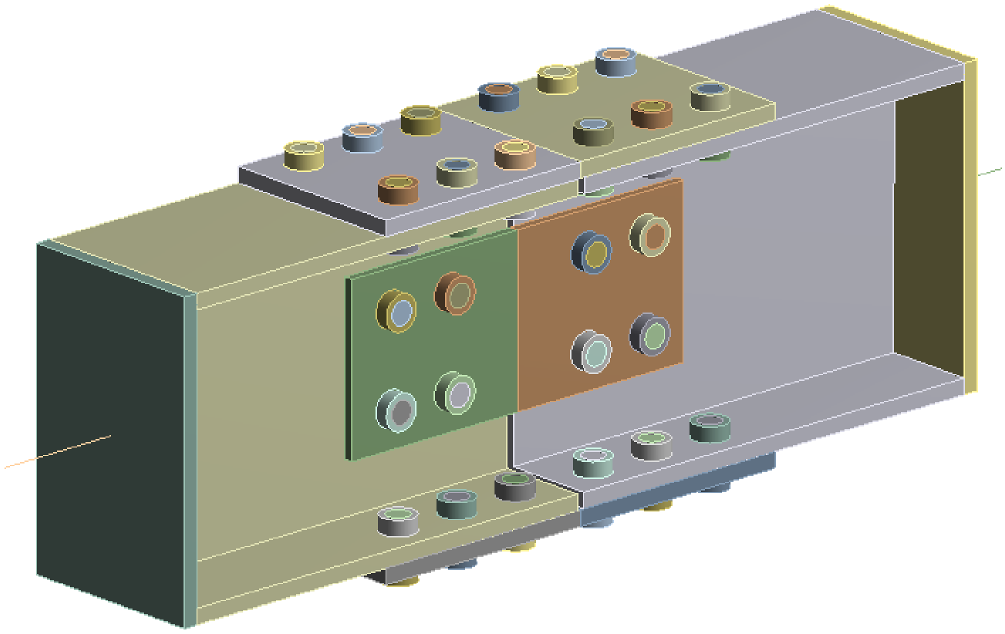


Figure 4.5. *Splice configuration.*

Bolt solids were divided into the shaft and the nut. The shaft was divided by the shear surfaces and bolt head inner surfaces so, that each part of the bolt shaft was equal to the thickness of the flange, web or plate, see figure 4.6. The shear force was then discovered from the contact surface of the bolt shaft slice.

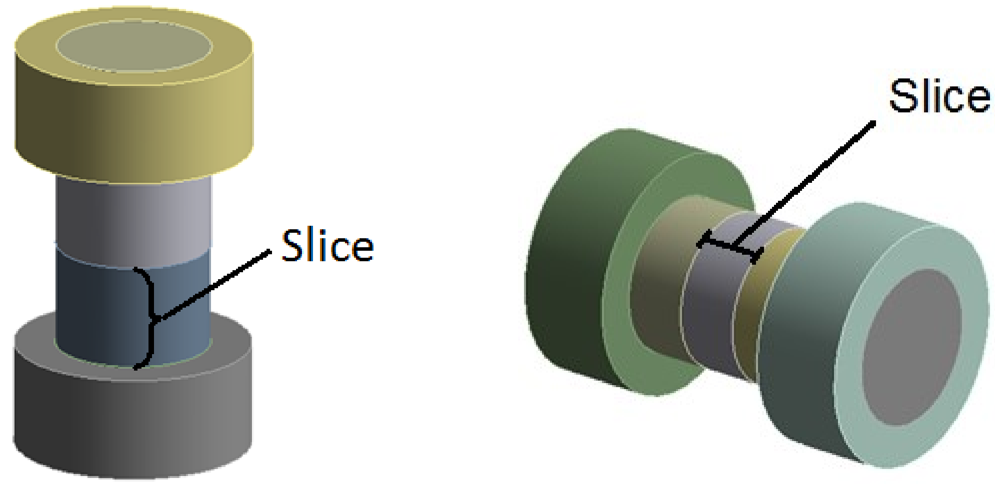


Figure 4.6. *Flange bolt (left) and web bolt.*

Main dimensions of the structure are shown in figure 4.7. The dimension point between the beam element (lined with vertical lines) and the solid is measured from the centerline of the solid end plate.

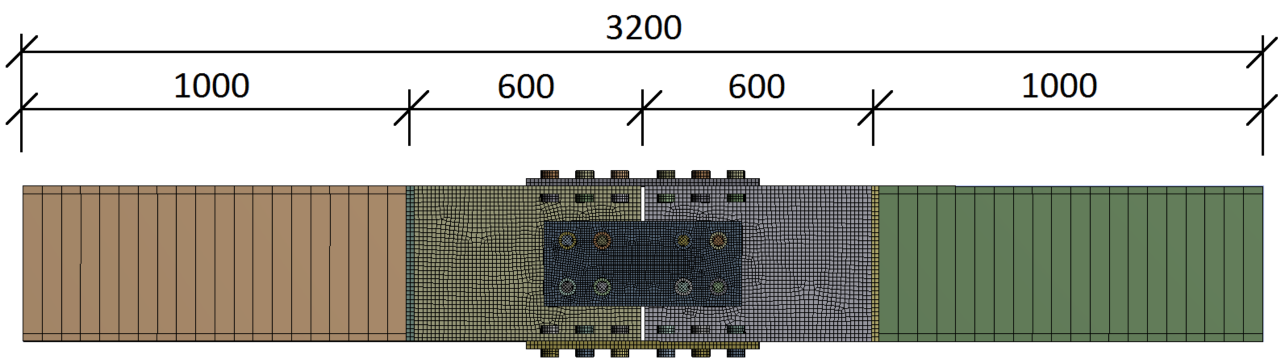


Figure 4.7. *Structure main dimensions.*

The dimensions of the non-bearing splice plates and bolt groups are shown in figure 4.8 and in tables 4.1 – 4.2. Bearing type splice has equal dimensions otherwise, but gap is 0 mm instead of 10 mm and bolt end distances to the profile end are 5 mm longer, thus $e_{1.we}$ is 105 mm and $e_{1.fe}$ is 60 mm in this example, therefore the distance between bolt groups remains equal.

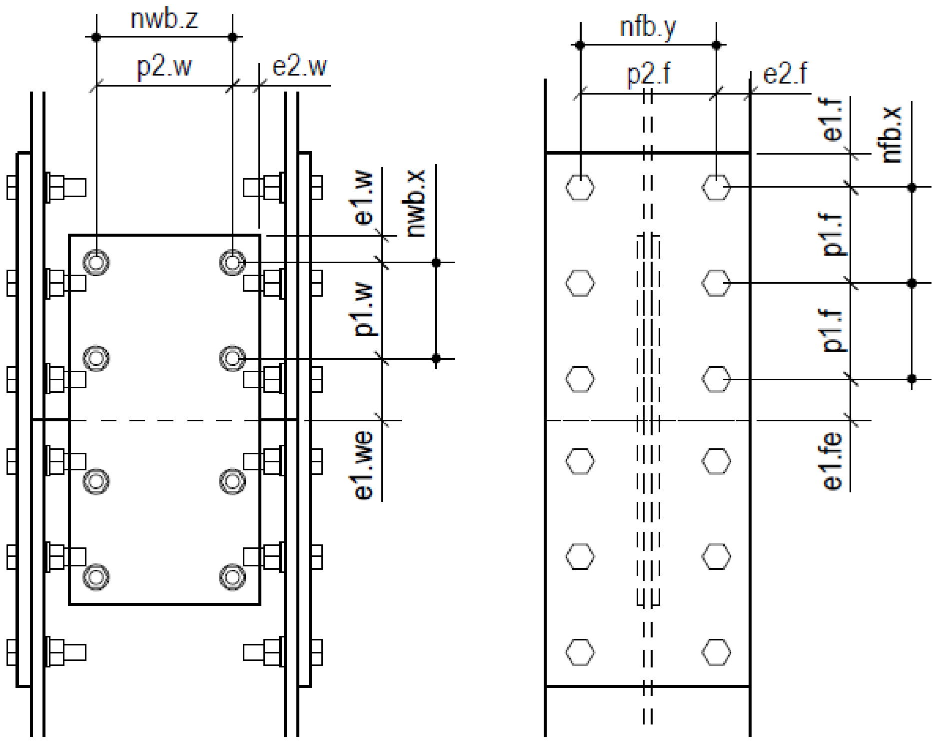


Figure 4.8. *Splice dimension symbols.*

Table 4.1. *Bolt group dimensions.*

Web bolts					Flange bolts				
d_{wb}	30	mm	Web bolt diameter		d_{fb}	30	mm	Flange bolt diameter	
$n_{wb.z}$	2	kpl			$n_{fb.y}$	2	kpl		
$n_{wb.x}$	2	kpl			$n_{fb.x}$	3	kpl		
$e_{1.w}$	60	mm			$e_{1.f}$	60	mm		
$e_{1.we}$	100	mm			$e_{1.fe}$	55	mm		
$e_{2.w}$	50	mm			$e_{2.f}$	45	mm		
$p_{1.w}$	90	mm			$p_{1.f}$	90	mm		
$p_{2.w}$	120	mm			$p_{2.f}$	160	mm		

Table 4.2. Gap, bolt hole and splice plate dimensions.

Gap	10	mm			
$d_{0.wb}$	33	mm	Web bolt hole diameter		
$d_{0.fb}$	33	mm	Flange bolt hole diameter		
Flange plate dimensions					
t_{fp}	20	mm			
b_{fp}	250	mm			
l_{fp}	600	mm			
Web plate dimensions					
t_{wp}	12	mm			
b_{wp}	220	mm			
l_{wp}	510	mm			

4.2.4 Supports

The beam elements were supported by body-ground -connections located in the vertices of the beam ends. The support reference coordinate systems are shown in figure 4.9.

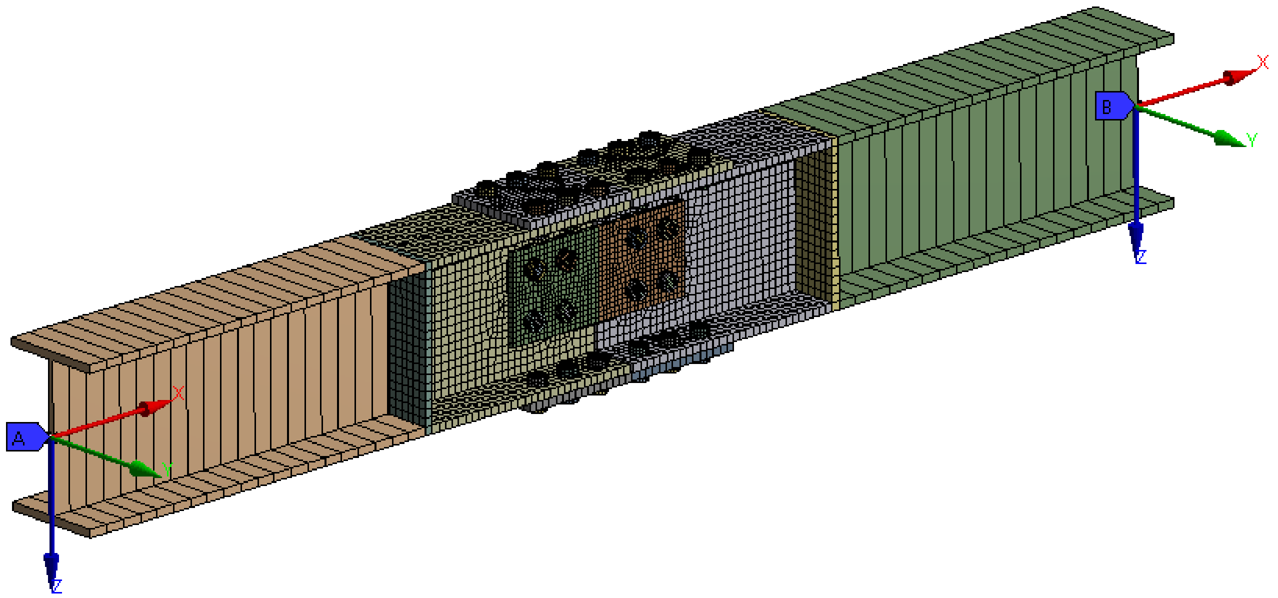


Figure 4.9. Support points (A and B).

The degrees of freedom (DOF) of the supports in the reference coordinate systems are shown in table 4.3:

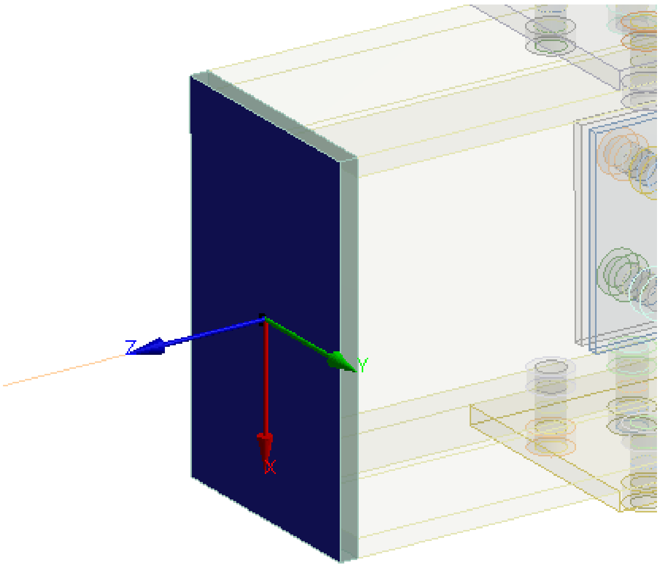
Table 4.3. *Degrees of freedom of the supports.*

Direction	**DOF, left support**	**DOF, right support**	**Description**
Ux	fixed	free	Translation about x-x axis (= beam axis)
Uy	fixed	fixed	Translation about y-y axis
Uz	fixed	fixed	Translation about z-z axis
Rx	fixed	fixed	Rotation about x-x axis
Ry	free	free	Rotation about y-y axis
Rz	free/fixed	free/fixed	Rotation about z-z axis

In bidirectional bending (My+Mz), the rotation about z-z axis is fixed because there can be only one rotation free at the same time in Ansys body-ground support.

4.2.5 Joints

The joint between the beam element and the solid end plate was made with fixed body-body - connection type, behavior was set to rigid. Details of the joint between the beam element and solid end plate is shown in figure 4.10.

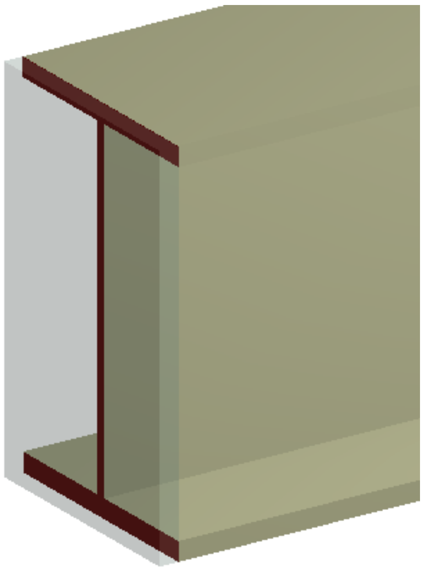


Details of "Fixed - Beam1 To PlateEnd1"	
Definition	
Connection Type	Body-Body
Type	Fixed
Solver Element Type	Program Controlled
Suppressed	No
Reference	
Scoping Method	Geometry Selection
Applied By	Remote Attachment
Scope	1 Vertex
Body	Beam1
Coordinate System	RCS1
Pinball Region	All
Mobile	
Scoping Method	Geometry Selection
Applied By	Remote Attachment
Scope	1 Face
Body	PlateEnd1
Initial Position	Unchanged
Behavior	Rigid
Pinball Region	All

Figure 4.10. *Joint between the beam element and solid end plate.*

4.2.6 Contacts

All profile-plate, profile-bolt head and plate-bolt head -contacts are frictionless to achieve as clean bolt shear force as possible. Contact between the bolt shaft and bolt hole is frictional, the friction coefficient is 0,2. There is no gap between bolt shaft and hole surface. Typical contacts for the profiles, end plates, splice plates and bolts are shown in figures 4.11-4.13.



Details of "Bonded - Prof1 To PlateEnd1"	
Scope	
Scoping Method	Geometry Selection
Contact	1 Face
Target	1 Face
Contact Bodies	Prof1
Target Bodies	PlateEnd1
Definition	
Type	Bonded
Scope Mode	Automatic
Behavior	Program Controlled
Trim Contact	Program Controlled
Trim Tolerance	8,1136 mm
Suppressed	No
Advanced	
Formulation	MPC
Detection Method	Program Controlled
Constraint Type	Program Controlled
Pinball Region	Program Controlled
Geometric Modification	
Contact Geometry Correction	None
Target Geometry Correction	None

Figure 4.11. *Contact between the solid end plate and the profile, contact details.*

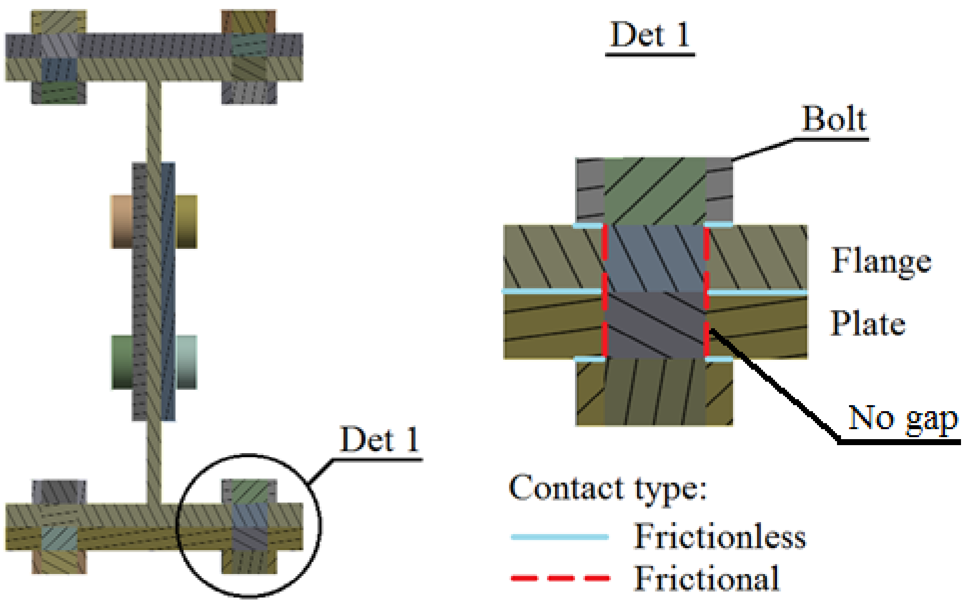


Figure 4.12. *Contacts of the bolt, profile and plate.*

Details of "Frictionless - PlateFlangeTop To Prof1"	
Scope	
Scoping Method	Geometry Selection
Contact	1 Face
Target	1 Face
Contact Bodies	PlateFlangeTop
Target Bodies	Prof1
Definition	
Type	Frictionless
Scope Mode	Automatic
Behavior	Asymmetric
Trim Contact	Program Controlled
Trim Tolerance	8,1136 mm
Suppressed	No
Advanced	
Formulation	Augmented Lagrange
Detection Method	Program Controlled
Penetration Tolerance	Program Controlled
Normal Stiffness	Program Controlled
Update Stiffness	Program Controlled
Stabilization Damping Factor	0,
Pinball Region	Program Controlled
Time Step Controls	None
Geometric Modification	
Interface Treatment	Adjust to Touch
Contact Geometry Correction	None
Target Geometry Correction	None

Details of "Frictional - BSFT 1 To Prof1"	
Scope	
Scoping Method	Geometry Selection
Contact	1 Face
Target	1 Face
Contact Bodies	BSFT 1
Target Bodies	Prof1
Definition	
Type	Frictional
Friction Coefficient	0,2
Scope Mode	Automatic
Behavior	Asymmetric
Trim Contact	Program Controlled
Trim Tolerance	8,1136 mm
Suppressed	No
Advanced	
Formulation	Augmented Lagrange
Detection Method	Program Controlled
Penetration Tolerance	Program Controlled
Elastic Slip Tolerance	Program Controlled
Normal Stiffness	Program Controlled
Update Stiffness	Program Controlled
Stabilization Damping Factor	0,
Pinball Region	Program Controlled
Time Step Controls	None
Geometric Modification	
Interface Treatment	Adjust to Touch
Contact Geometry Correction	None
Target Geometry Correction	None

Figure 4.13. *Details of the contacts between flange plate and profile (left) and between flange bolt and flange (right).*

Bolt shaft contact behavior is asymmetric and bolt shaft is set as a contact face, so the bolt shear force can be found from the contact side of the bolt shaft slice. Bolt shaft contact face is shown as a red area in figure 4.14.

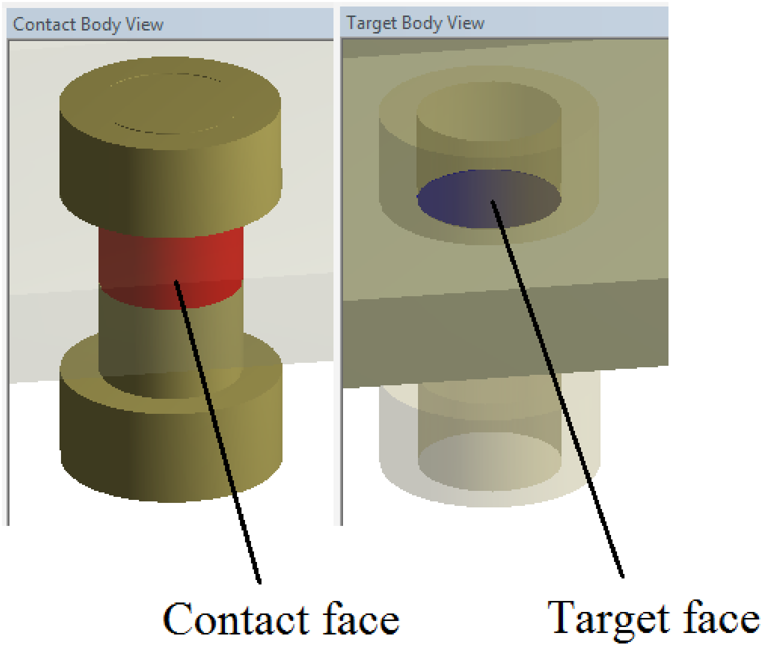


Figure 4.14. Contact and target face of the bolt.

4.2.7 Mesh

Splice members were meshed with hexahedral mesh with element mid-side nodes, which uses 20-node SOLID186 -element with middle nodes. Also, equivalent tetrahedral mesh with SOLID187 -element was used in the bolts. The element size was adjusted so, that there are three elements through the flange and plate and two elements through the web. Each bolt shaft slice has three elements through the thickness in the bolt axis direction. Bolt mesh is continuous although bolt consists of multiple slices. The mesh is shown in figures 4.15-4.17.

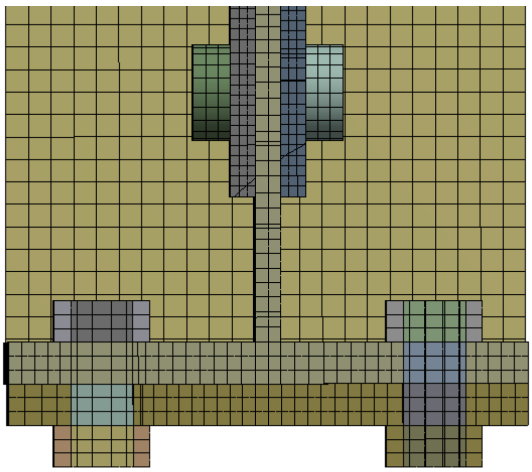


Figure 4.15. A detail from the cross-section showing mesh in the flange, web and bolt.

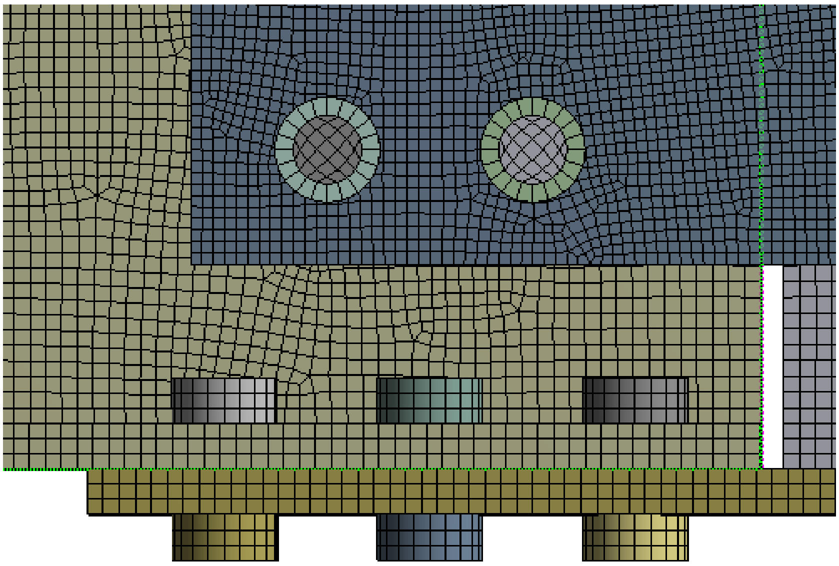


Figure 4.16. *A detail from the side of the splice showing mesh in the web, web plate and web bolt heads.*

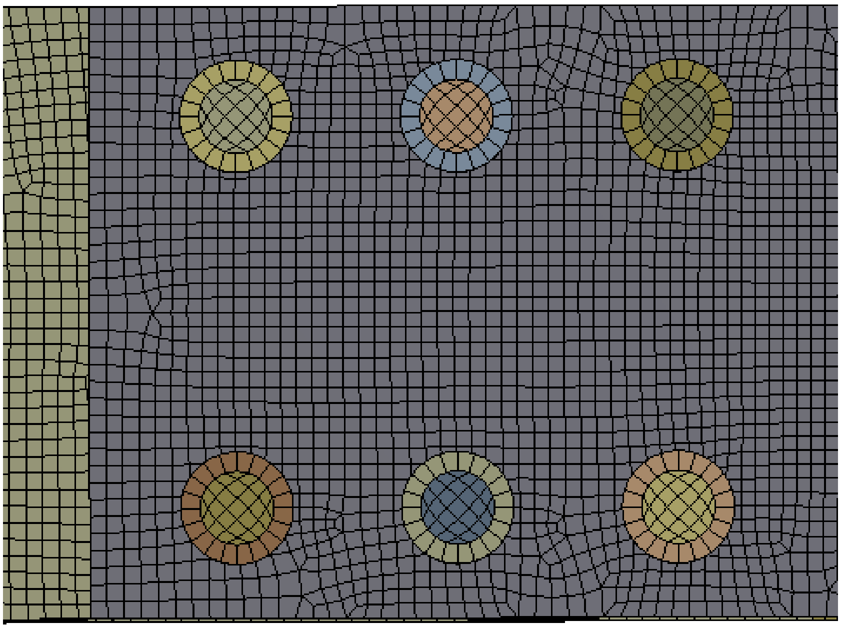


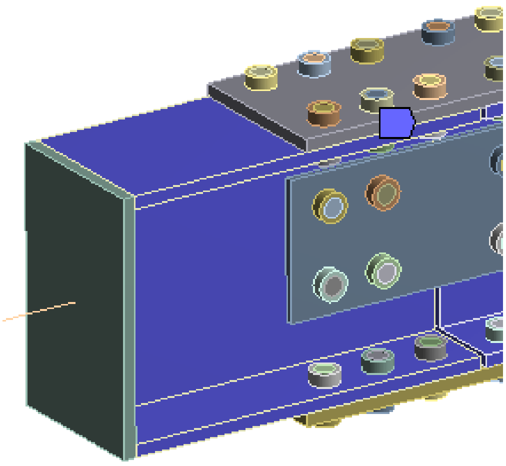
Figure 4.17. *A detail from the top of the splice showing mesh of the flange (olive green), flange plate and flange bolt heads.*

Details of the mesh general properties are shown in figure 4.18.

Details of "Mesh"	
Display	
Display Style	Body Color
Defaults	
Physics Preference	Mechanical
Relevance	0
Shape Checking	Standard Mechanical
Element Midside Nodes	Kept
Sizing	
Size Function	Uniform
Relevance Center	Coarse
Initial Size Seed	Active Assembly
Smoothing	Medium
Transition	Fast
Min Size	4,0 mm
Max Face Size	8,0 mm
Max Tet Size	Default (323,530 mm)
Growth Rate	Default (1,850)
Automatic Mesh Based Defeaturing	On
Defeature Size	1, mm
Minimum Edge Length	12,0 mm
Inflation	
Use Automatic Inflation	None
Inflation Option	Smooth Transition
Transition Ratio	0,272
Maximum Layers	5
Growth Rate	1,2
Inflation Algorithm	Pre
View Advanced Options	No
Advanced	
Number of CPUs for Parallel Part Meshing	Program Controlled
Straight Sided Elements	No
Number of Retries	0
Rigid Body Behavior	Dimensionally Reduced
Mesh Morphing	Disabled
Triangle Surface Mesher	Program Controlled
Topology Checking	No
Pinch Tolerance	Default (3,60 mm)
Generate Pinch on Refresh	No
Statistics	

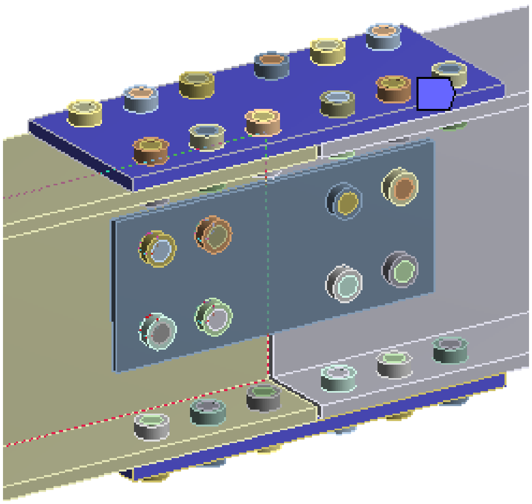
***Figure 4.18**. General mesh details*

Details of the mesh details for typical splice members are shown in figure 4.19-4.21.



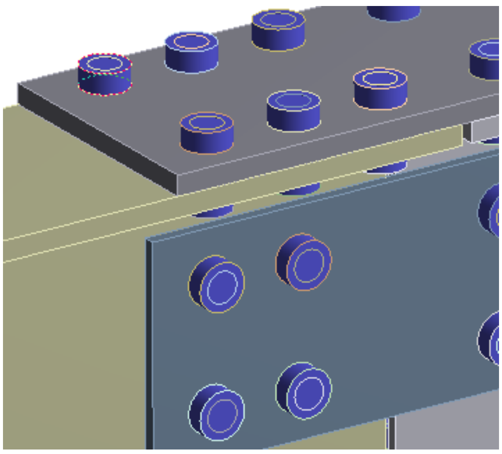
Details of "MultiZone Prof" - Method	
Scope	
Scoping Method	Named Selection
Named Selection	BodyProf
Definition	
Suppressed	No
Method	MultiZone
Mapped Mesh Type	Hexa
Surface Mesh Method	Uniform
Free Mesh Type	Not Allowed
Element Midside Nodes	Use Global Setting
Src/Trg Selection	Automatic
Source Scoping Method	Program Controlled
Source	Program Controlled
Sweep Size Behavior	Sweep Element Size
Sweep Element Size	Default
Advanced	
Preserve Boundaries	Protected
Mesh Based Defeaturing	On
Defeature Size	Default(1, mm)
Minimum Edge Length	20, mm
Write ICEM CFD Files	No

Figure 4.19. Details of the profile mesh



Details of "MultiZone PlateFlange" - Method	
Scope	
Scoping Method	Named Selection
Named Selection	BodyPlateFlange
Definition	
Suppressed	No
Method	MultiZone
Mapped Mesh Type	Hexa
Surface Mesh Method	Uniform
Free Mesh Type	Not Allowed
Element Midside Nodes	Use Global Setting
Src/Trg Selection	Automatic
Source Scoping Method	Program Controlled
Source	Program Controlled
Sweep Size Behavior	Sweep Element Size
Sweep Element Size	Default
Advanced	
Preserve Boundaries	Protected
Mesh Based Defeaturing	On
Defeature Size	Default(1, mm)
Minimum Edge Length	20, mm
Write ICEM CFD Files	No

***Figure 4.20**. Details of the flange plate mesh*



Details of "MultiZone Bolt" - Method	
Scope	
Scoping Method	Named Selection
Named Selection	BodyBolt
Definition	
Suppressed	No
Method	MultiZone
Mapped Mesh Type	Hexa/Prism
Surface Mesh Method	Program Controlled
Free Mesh Type	Not Allowed
Element Midside Nodes	Use Global Setting
Src/Trg Selection	Automatic
Source Scoping Method	Program Controlled
Source	Program Controlled
Sweep Size Behavior	Sweep Element Size
Sweep Element Size	Default
Advanced	
Preserve Boundaries	Protected
Mesh Based Defeaturing	On
Defeature Size	Default(1, mm)
Minimum Edge Length	47,124 mm
Write ICEM CFD Files	No

***Figure 4.21**. Details of the bolt mesh*

4.2.8 Loading

System was loaded by two equal lateral forces assigned to the end plates in the strong axis (y-y) and/or the weak axis (z-z) direction and with an axial force as shown in figure 4.22.

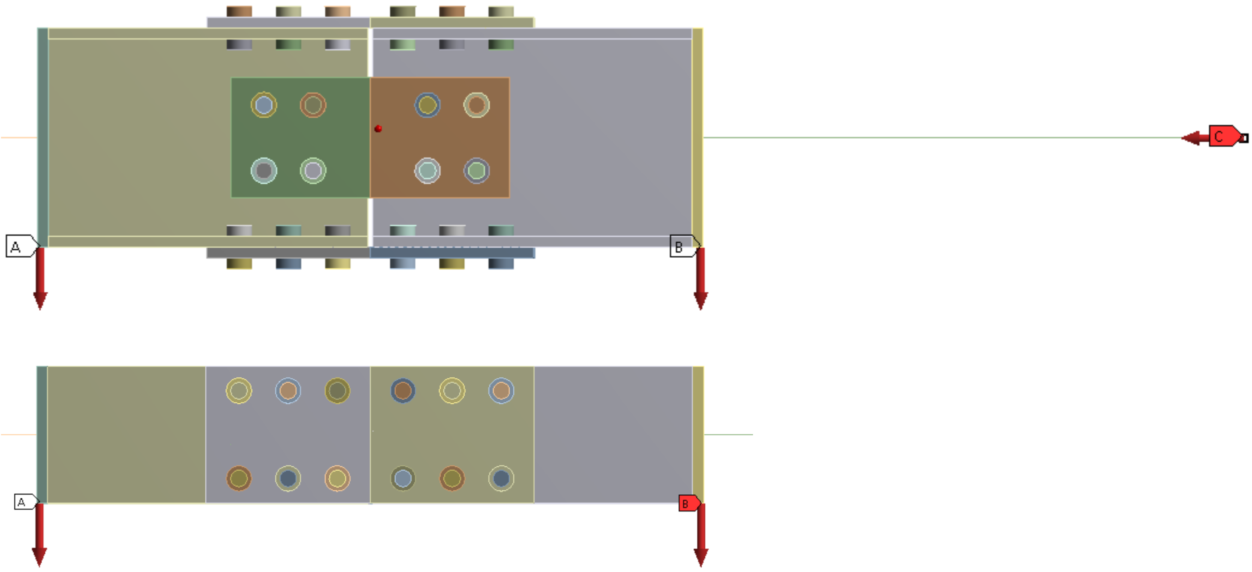


Figure 4.22. *Axial and lateral forces.*

Load acts in the bottom and side face (colored in red) of the solid end plate, see figure 4.23. The load is concentrated, although it appears to be eccentric in figure.

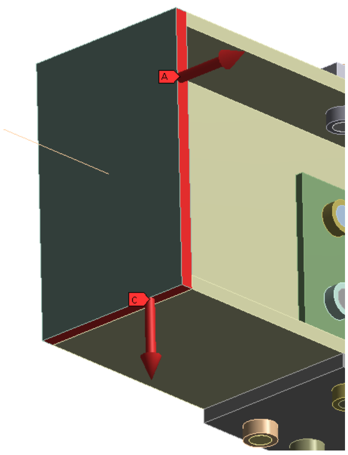


Figure 4.23. *Effecting areas of the loads in the solid end plate.*

4.3 Validation of the FE-analysis

Typical FEA model consists of structure (solids, beam elements etc.) and its boundary conditions (loads and supports). To achieve the correct results, it is essential to ensure that these components are defined correctly.

4.3.1 Mesh density

The effect of the mesh density was tested with two FEA model. The first model consisted of 2 elements and the second 3 elements through the profile flange and plate thickness. In the figure 2.24 is shown 3 elements through the flange thickness.

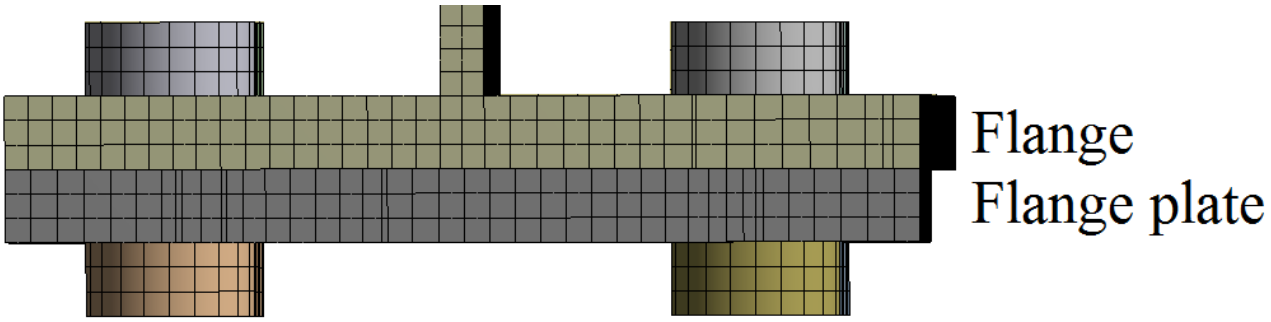
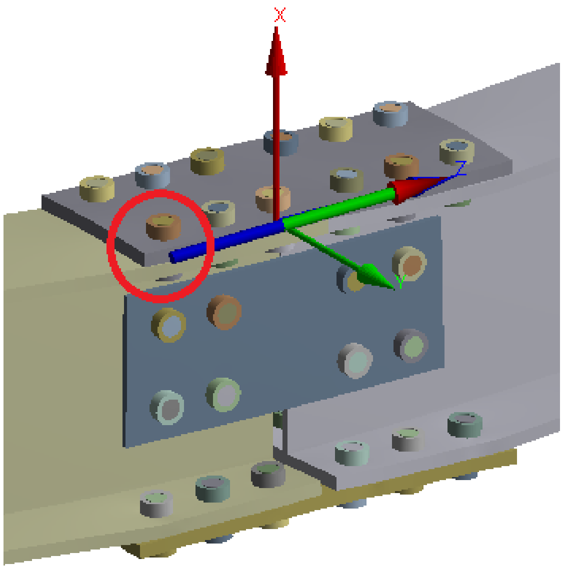


Figure 4.24. *Flange and flange plate meshing.*

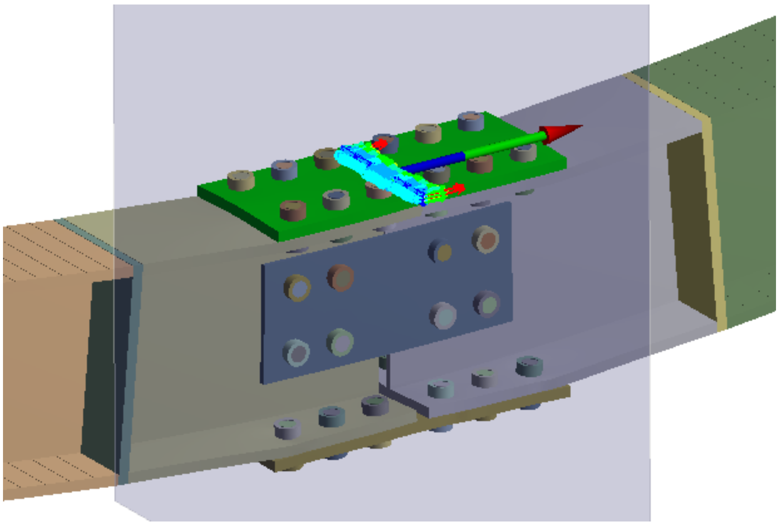
Using the specimen “Non-bearing – My” as an example, the bolt shear forces were practically the same between flanges consisting of 2 and 3 elements through the flange thickness, see figure 4.25.



Time	Splice load	Bolt shear force		Diff.
		2 elem.	3 elem.	
	My	X	X	
s	kNm	kN	kN	%
0,5	125	46	46	0,2
1,0	250	91	92	0,7
1,5	375	138	139	0,6
2,0	500	182	184	1,0
2,5	625	218	221	1,3

Figure 4.25. *The difference of the shear forces in the flange bolt (inside of the red circle) with 2 and 3 elements through the flange thickness*

Also, the force reaction in the flange plate was the same between 2 and 3 element model, as can be seen in figure 4.26.



Time	Splice load My	Force reaction		Diff.
		2 elements	3 elements	
s	kNm	kN	kN	%
0,5	125	294	294	0,0
1,0	250	585	585	0,0
1,5	375	877	877	0,0
2,0	500	1166	1167	0,0
2,5	625	1459	1460	0,1

Figure 4.26. *The difference of the force reaction in the flange plate with 2 and 3 elements through the flange thickness*

All specimen were analyzed with a mesh consisting of

- 3 elements per flange thickness,
- 2 elements per web thickness and
- 3 elements per flange and web plate thicknesses,

except “Non-bearing – Mz” where was 2 elements through all thicknesses mentioned above.

4.3.2 Support reactions

Using the specimen “Non-bearing - N My Mz” as an example, the support reactions were checked by comparing both vertical support reactions to each other and to the loads. The normal force N is 600 kN, which is equal to the support reaction in the left end of the beam. The left support of the beam was fixed in the z-axis direction (in FEA coordinate system). Normal force and beam support is shown in figure 4.27.

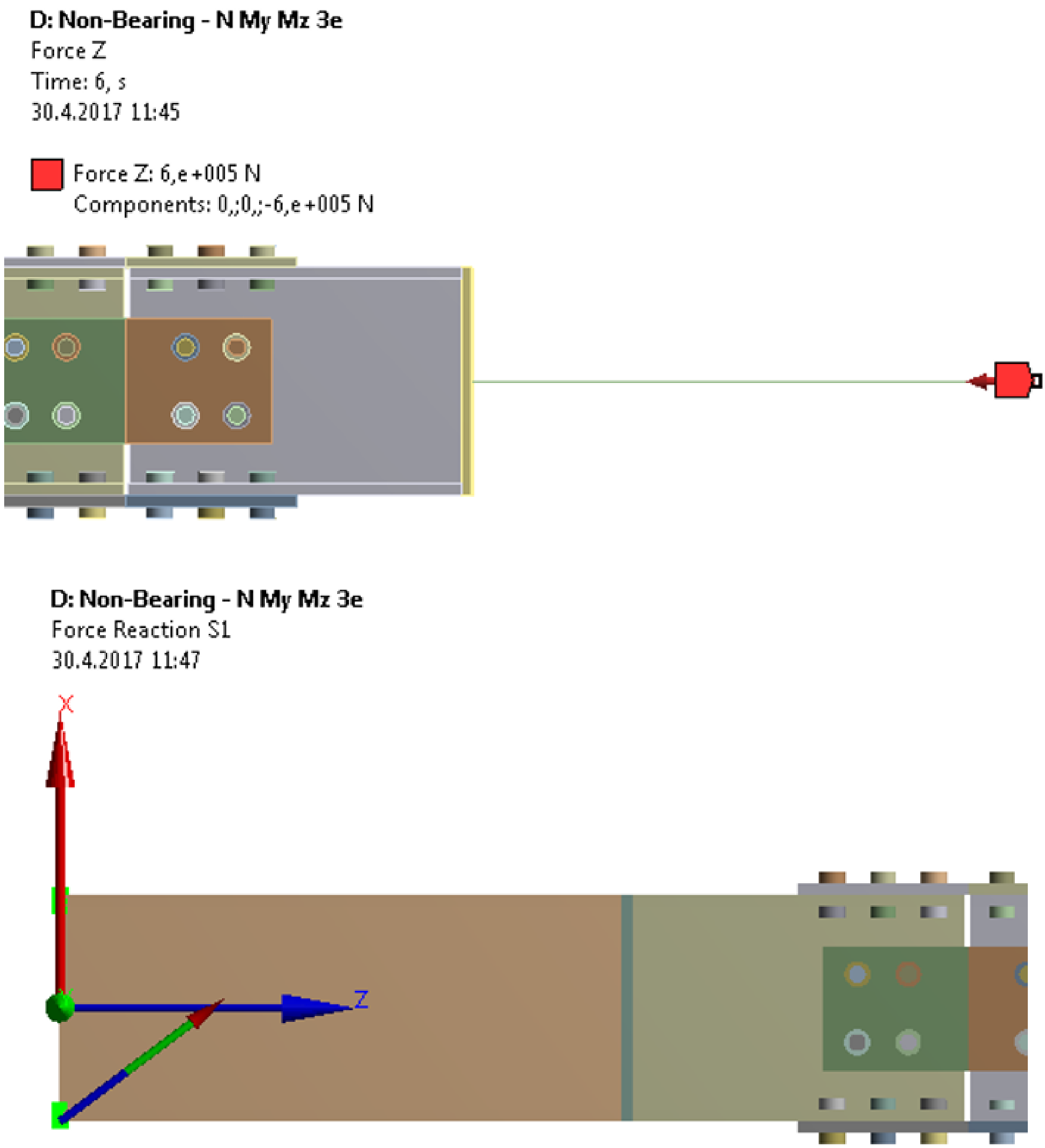
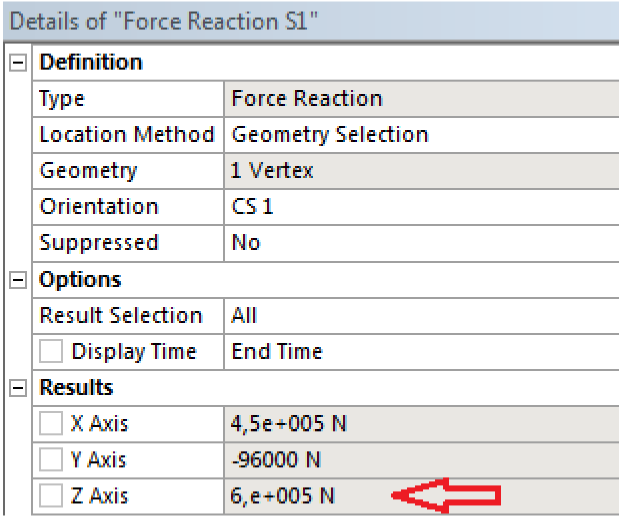


Figure 4.27. Support reaction in z-axis direction (below) by the normal load N (above).

The support reaction can be seen in the “Details” -dialog, shown in figure 4.28.



Details of "Force Reaction S1"

Definition	
Type	Force Reaction
Location Method	Geometry Selection
Geometry	1 Vertex
Orientation	CS 1
Suppressed	No
Options	
Result Selection	All
Display Time	End Time
Results	
X Axis	4,5e+005 N
Y Axis	-96000 N
Z Axis	6,e+005 N

Figure 4.28. *Support reaction in z-axis direction by the normal load N.*

4.3.3 Bending moment

The force F in z-z axis direction (see figure 4.29) was 450 kN in both end plates. As the beam end rotation about y-y axis is released at the supports, the theoretical bending moment between loading points can be calculated with the formula

$$M = Fa$$

where

M = bending moment

F = point load

a = length between the support and the load.

A free-body diagram of the bending about z-z axis is shown in figure 4.30. Because the rotation of the support can be released only in one direction at the same time in Ansys, the rotation about z-z axis is fixed and the bending must be calculated by the formula

$$M = \frac{Fa^2}{L}$$

where

M, F, a see previous formula

L = beam span.

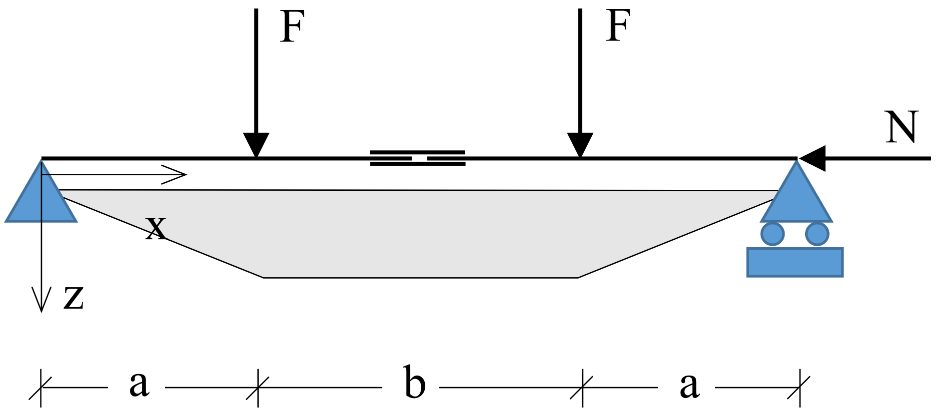


Figure 4.29. A free-body diagram, bending about y-y axis.

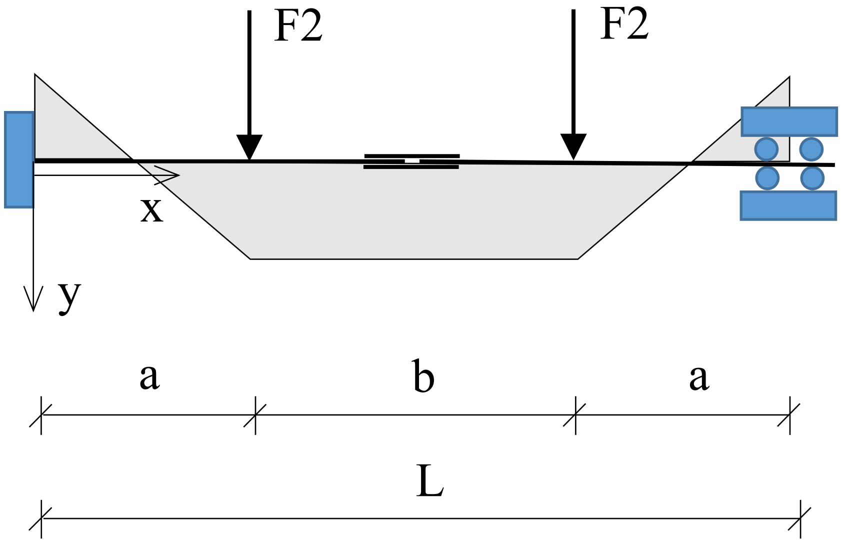


Figure 4.30. A free-body diagram, bending about z-z axis.

Because of the fixed rotation, the bending about z-z axis is more sensible for the distractions in the analysis, and the bending moment can differ a little from the theoretical value. In the specimen 6 (Non-bearing - N My Mz), the end load was 96 kN, thus the moment should be 30 kNm but in the end of the analysis it was 27,9 kNm (-7%) as shown in figure 4.32. In Mathcad calculations, FEA bending moments were used at each load step to ensure the compatibility of the results.

The bending moment was found as a moment reaction of the splice plates about y-y and z-z axis (y-y and x-x axis in FEA global coordinate system, respectively), see figure 4.31.

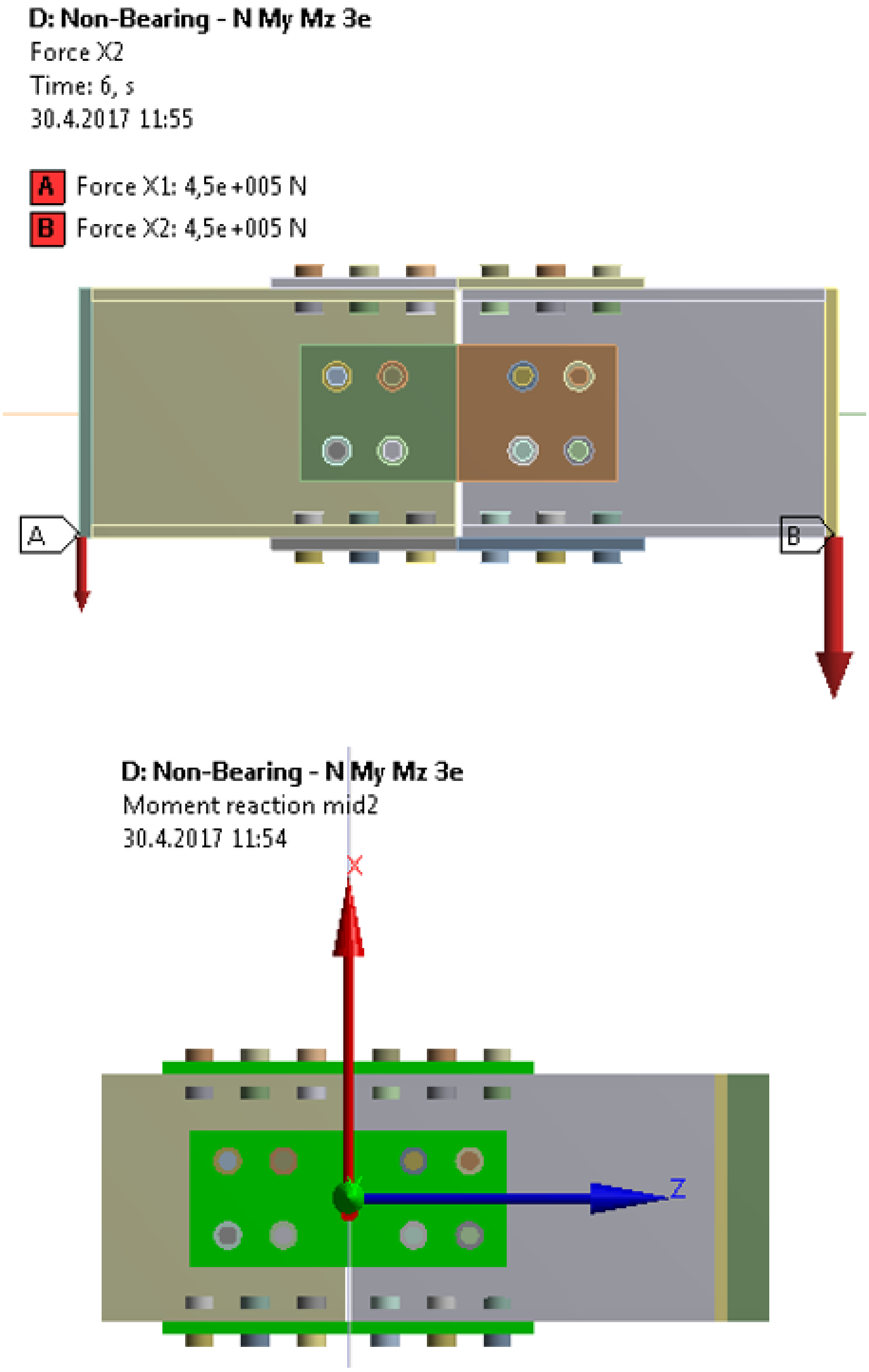
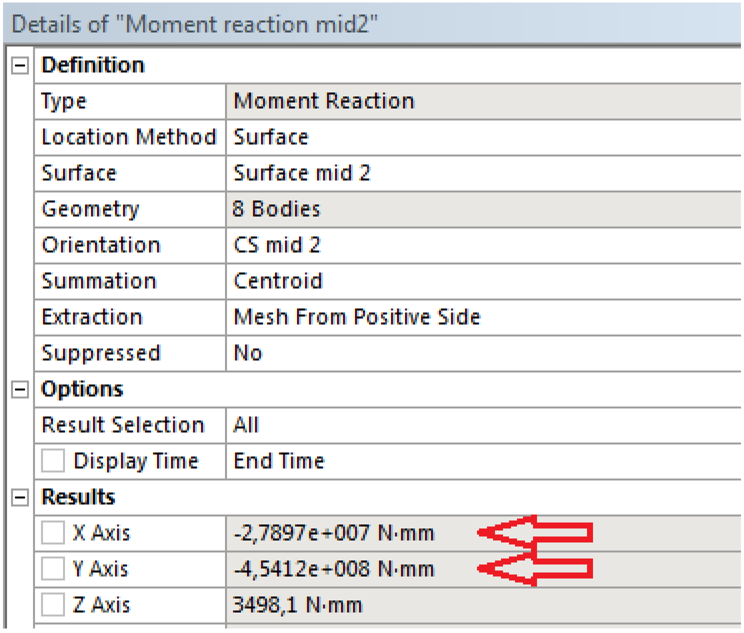


Figure 4.31. *Splice plates subjected to bending moment (below) by the design load (above). A local coordinate system of the analysis model is shown in figure.*

Moment reactions of the splice plates can be seen from the “Details” -dialog, see figure 4.32. As mentioned above, the bending about x-x axis in analysis model coordinate system in figure 4.32 is analogous to the bending about z-z axis in the further calculations.



Details of "Moment reaction mid2"

Definition	
Type	Moment Reaction
Location Method	Surface
Surface	Surface mid 2
Geometry	8 Bodies
Orientation	CS mid 2
Summation	Centroid
Extraction	Mesh From Positive Side
Suppressed	No
Options	
Result Selection	All
Display Time	End Time
Results	
X Axis	-2,7897e+007 N·mm
Y Axis	-4,5412e+008 N·mm
Z Axis	3498,1 N·mm

Figure 4.32. *Moment reactions from the bending about x-x and y-y axis.*

4.3.4 Bolt shear force reaction

Using the specimen “Non-bearing – My”, bolt no. 2 as an example, shear force reaction of the bolt contact surface inside the flange was compared to the equivalent force reaction inside the flange plate. The bolt shaft contact surface concerned is shown as red color in figure 4.33.

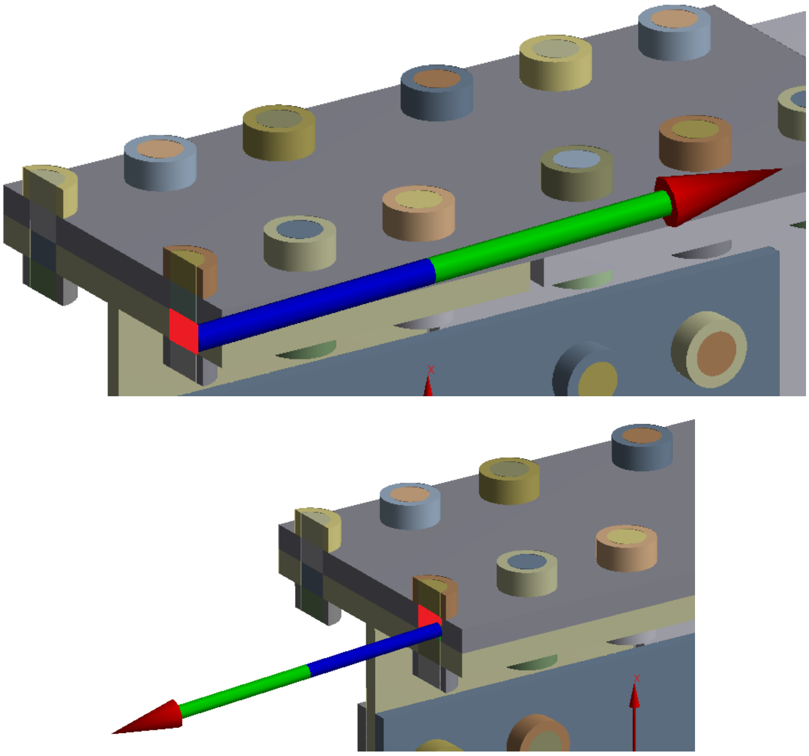


Figure 4.33. Bolt shaft shear force reaction in the flange (above) and flange plate (below).

The results are shown in table 4.4. No significant difference in the results was detected.

Table 4.4. Bolt shear force reactions, flange vs. flange plate.

Time	Splice load	Bolt shear force		Diff.
		Flange	Plate	
	My	X	X	
s	kNm	kN	kN	%
0,5	125	46	45	-2,0
1,0	250	92	91	-1,2
1,5	375	139	138	-0,4
2,0	500	184	184	0,1
2,5	625	221	223	0,9

5. RESULTS AND DISCUSSION

5.1 General

Coordinate system used in the results is analogical to EN 1993-1-1: 2005 conventions for member axes [1, p. 20], which is also used in Mathcad calculations. Bolt numbering system is the same through all tests with non-bearing and bearing type splices. The coordinate system and the flange/web bolt numbering system is shown in figure 5.1. Bottom flange bolts are in the same order as the top flange bolts. As can be expected, the bolt shear forces were approximately equal between corresponding bolts on the other side of the splice (light grey numbers in figure 5.1) in all specimens. Therefore, only the results from the left side (numbered bolts) of the splice are reported.

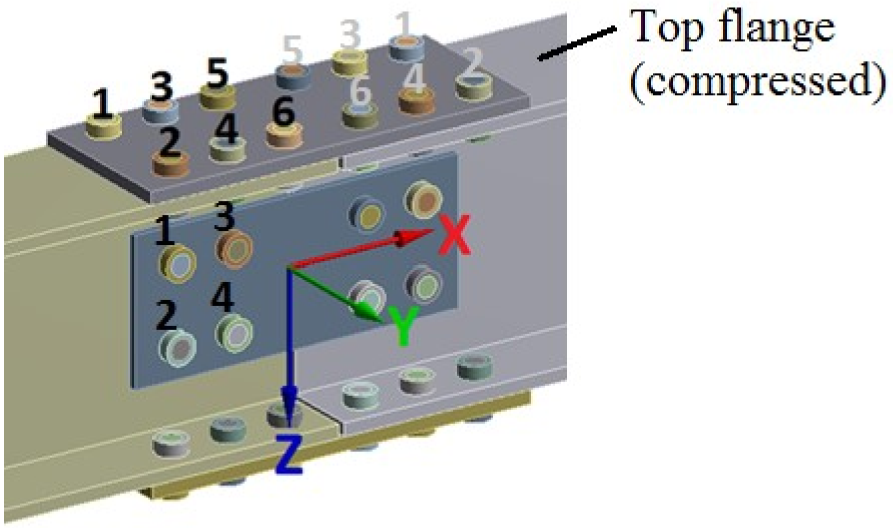


Figure 5.1. *Flange and web bolt numbers.*

Shear forces of the flange bolts in FEA model were measured from the part of the bolt shaft inside the flange, see figure 5.2. The forces were measured separately from each bolt shaft, though in figure 5.2 the force resultant of all bolts is shown.

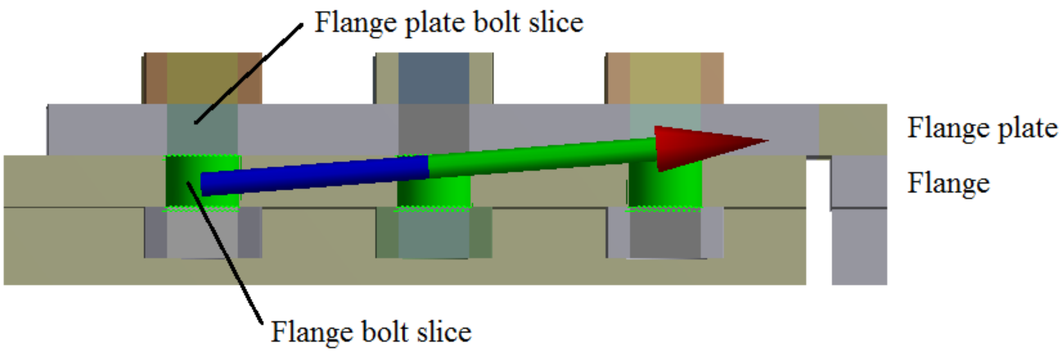


Figure 5.2. *Part of the bolt shaft through the flange.*

Shear forces of the web bolts in Ansys model were measured from the bolt shaft slice contact surface inside the web, see figure 5.3.

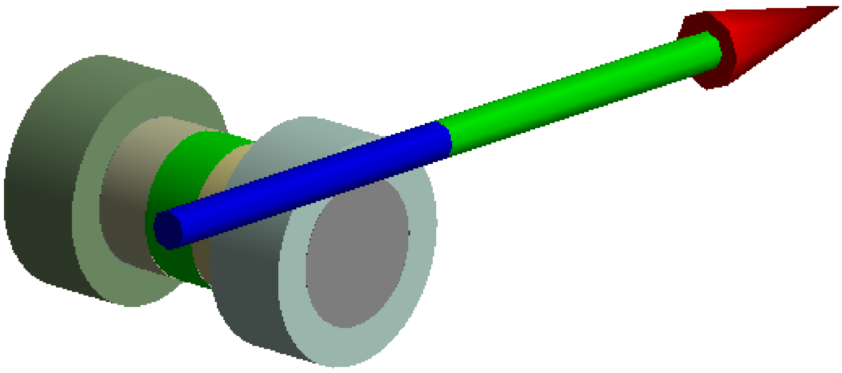


Figure 5.3. *Web bolt shaft shear force resultant in the middle slice.*

5.2 Non-bearing type splice

Six specimens were analyzed with different loads or load combinations shown in table 5.1:

Table 5.1. *Loads and load combinations of the non-bearing splice analysis.*

Specimen no.	Load / load combination
1	N
2	My
3	Mz
4	Vz
5	My + Mz
6	N + My + Mz

The specimen no. 5 includes the primary load case N (normal force), which effects alone during the first 3 seconds and can be analyzed separately as the specimen 1.

5.2.1 Specimen no. 1: Normal force N

In the specimen no. 1, the splice was loaded at the end of the beam element (shown as a single line) with a compressive force in the x-x axis direction during the first 3 load steps, 1 second / step, see figure 5.4. The load was increased 200 kN every step, the final load being 600 kN. Analysis ended to a converged solution.

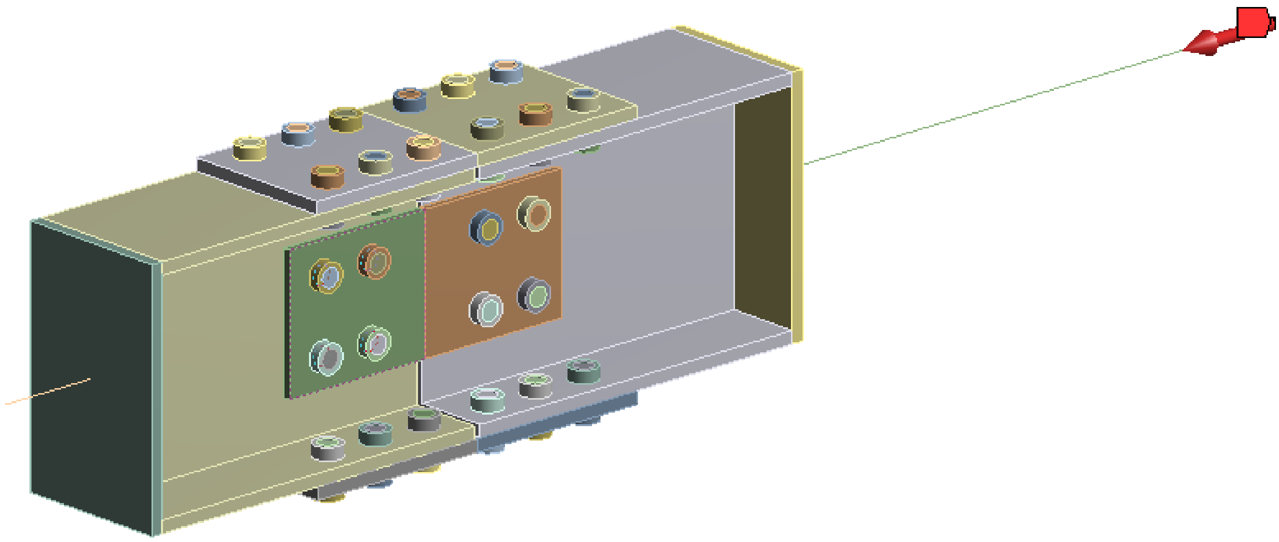


Figure 5.4. *Compressive normal force at the end of the beam element.*

Flange / flange plate

Flange compression in Mathcad was compared to the flange plate force reaction in FEA. Top flange plate force reaction in FEA is shown in figure 5.5.

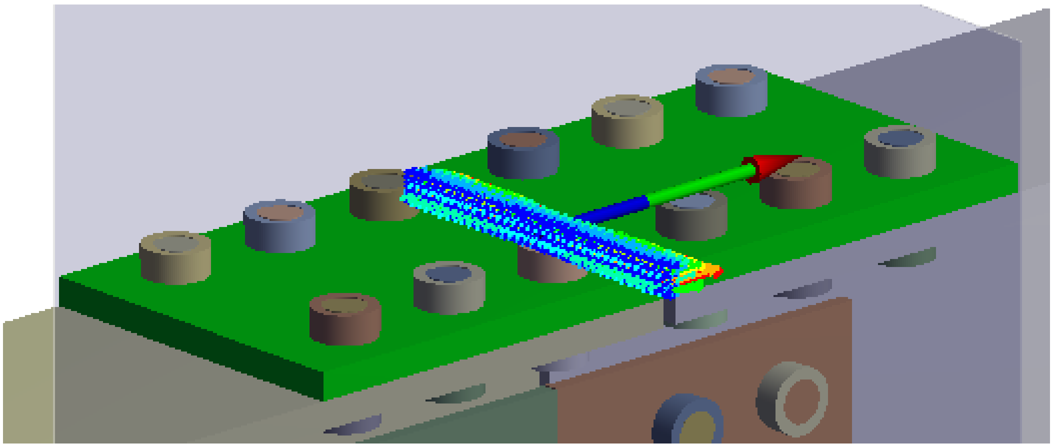


Figure 5.5. Top flange plate axial force resultant at the end of the load step 3.

The force reactions are shown in table 5.2 and the chart in figure 5.6. The difference (%) indicates, how much bigger or smaller the result in Mathcad is comparing to the result in FEA. Flange compression in Mathcad was quite equal to the flange plate compression in FEA.

Table 5.2. Flange (Mathcad) and flange plate (FEA) compression.

Time	Splice load	Force reaction		Diff.
	Fx	Ansys	Mathcad	
s	kN	kN	kN	%
1,0	200	71	70	-1,4
2,0	400	142	140	-1,4
3,0	600	213	209	-1,4

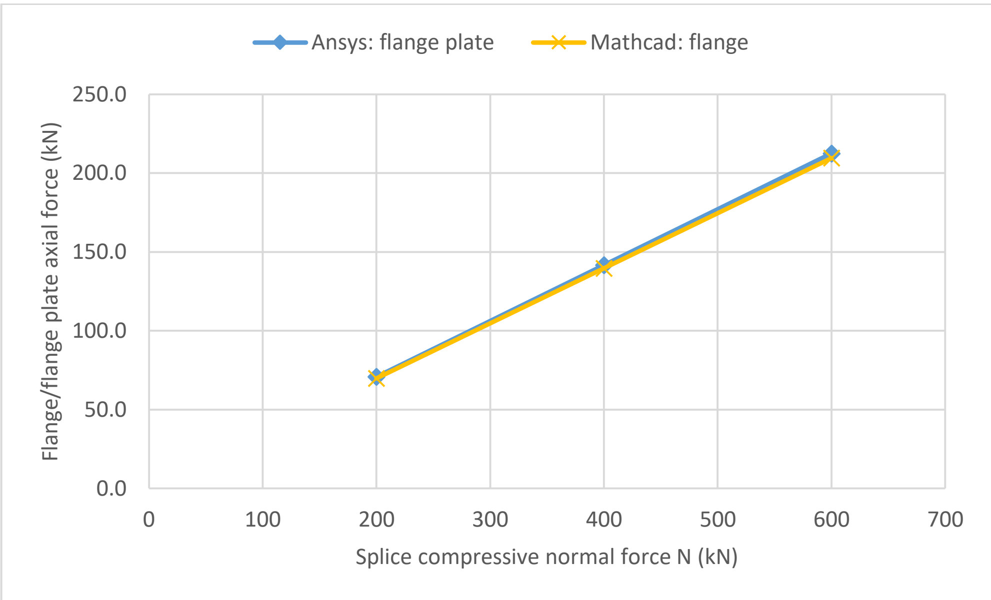


Figure 5.6. Flange / flange plate compression.

5.2.1.1 Flange bolts

Top flange bolt shear forces were studied from the flange bolts no. 1-6 in FEA and the average shear force is shown. At time step 3 in FEA, the shear forces varied from 27,4 kN (bolts 3 and 4) to 31,9 kN (bolts 1 and 2). Bolt shear force in x-x axis direction for the flange bolts were calculated in Mathcad. Shear force results are shown in table 5.3 and in figure 5.7.

Table 5.3. *Flange bolt shear forces in x-x axis direction.*

Time	Splice load	Bolt shear force		Diff.
		Ansys	Mathcad	
	Fx	X	X	
s	kN	kN	kN	%
1,0	200	10	12	17,0
2,0	400	20	23	16,9
3,0	600	30	35	16,9

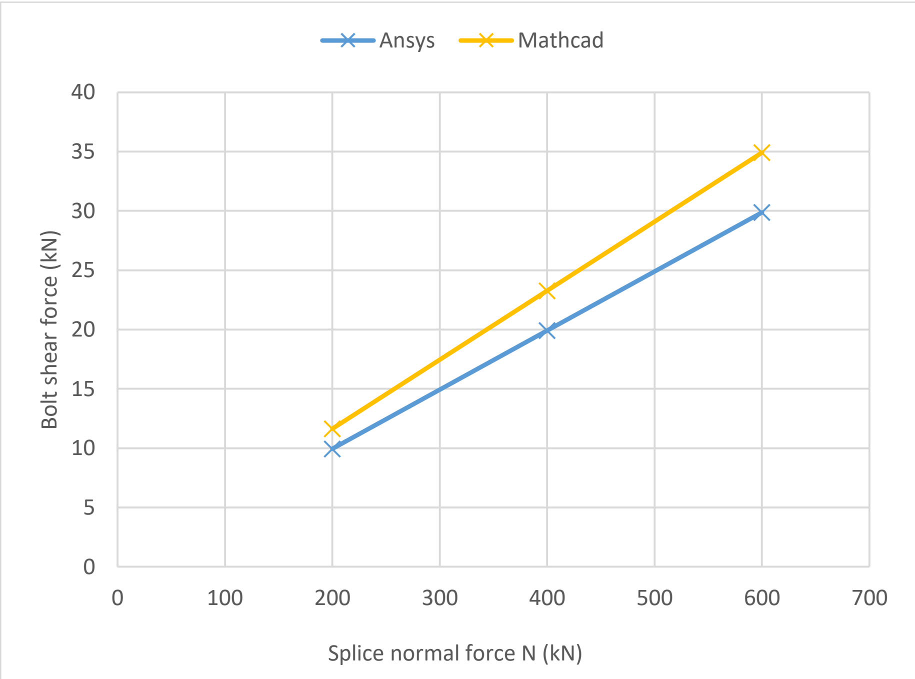


Figure 5.7. *Flange bolt shear forces.*

5.2.1.2 Web / web plates

Web force in Mathcad was compared to the web plates combined compression in FEA, because there were not results available for the web alone in FEA. The force reactions are shown in figure 5.8, table 5.4 and graphics in figure 5.9. No significant difference was detected.

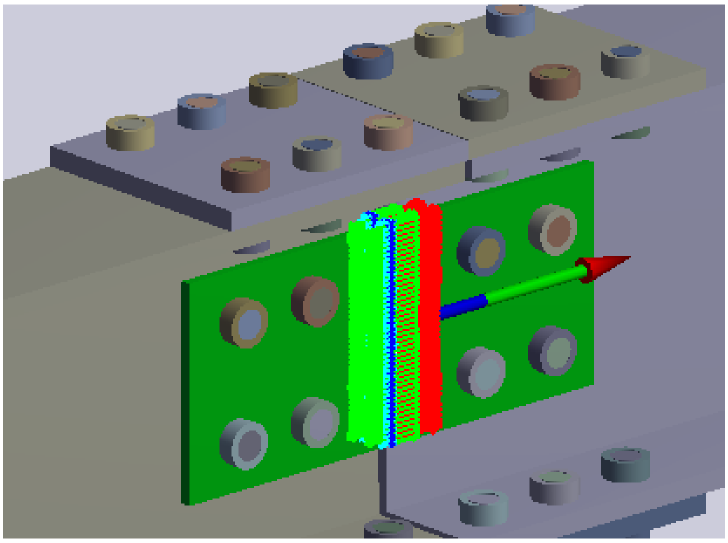


Figure 5.8. Web plates combined compression resultant at the end of the load step 3.

Table 5.4. Web (Mathcad) and web plates combined (FEA) compression.

Time	Splice load N	Force reaction		Diff.
		Ansys	Mathcad	
s	kN	kN	kN	%
1,0	200	58	60	3,3
2,0	400	117	121	3,4
3,0	600	175	181	3,4

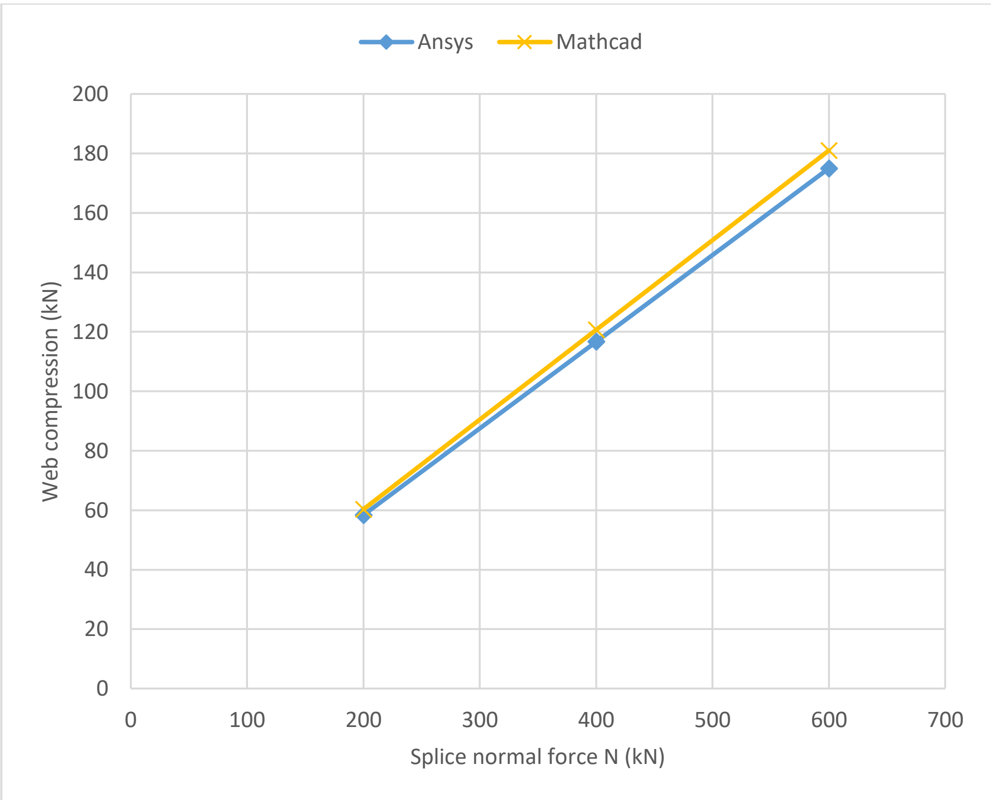


Figure 5.9. Web / web plates compression.

5.2.1.3 Web bolts

Web bolt shear forces were studied for the web bolts no. 1-4 in FEA and the average shear force is shown. At time step 3 in FEA, the shear force varied from 37,9 kN (bolts 3 and 4) to about 40 kN (bolts 1 and 2). Both FEA and Mathcad web bolt shear force results are shown in table 5.5 and in figure 5.10.

Table 5.5. *Web bolt shear forces in x-x axis direction.*

Time	Splice load	Bolt shear force		Diff.
		Ansys	Mathcad	
	N	X	X	
s	kN	kN	kN	%
1,0	200	13	15	16,0
2,0	400	26	30	16,2
3,0	600	39	45	16,2

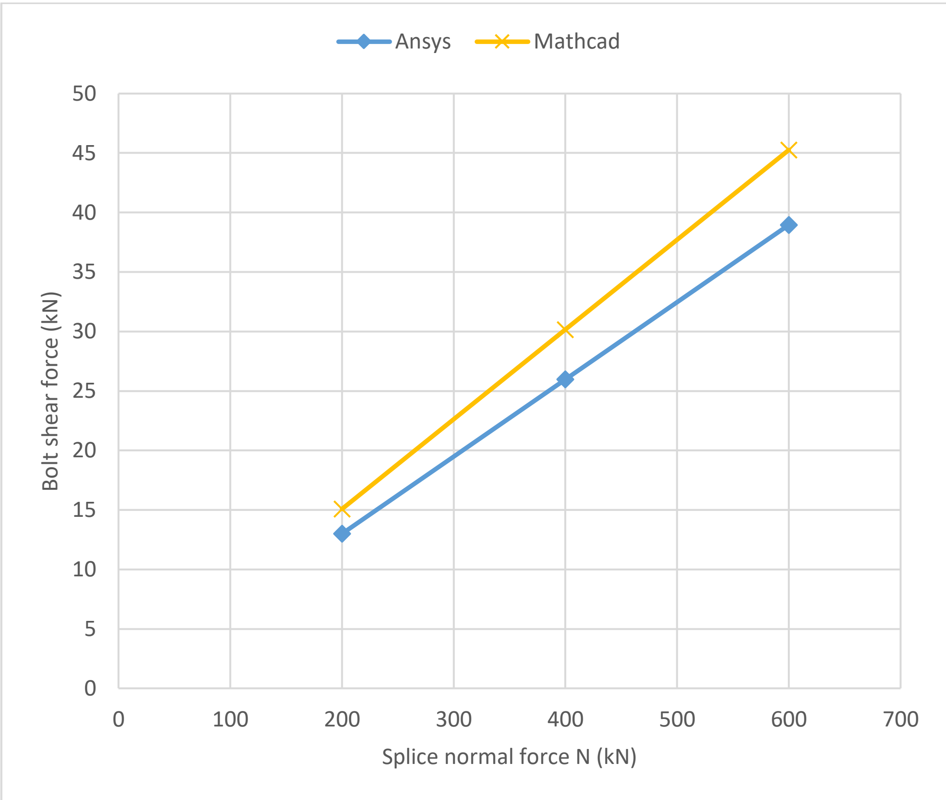


Figure 5.10. *Web bolt shear forces by splice normal force N.*

Force reaction of the flange and web plates in FEA was 2*212,5 kN (flange plates) + 175 kN (web plates). The ratio of the flange plate reaction to the web plate reaction is 2*212,5 / 175 = 2,43, while the ratio of the cross-section areas of two flanges and web is 2*50 cm^2 / 43,2 cm^2 = 2,31. Thus, the compression transmitted via flanges in FEA is 12% greater than the force in Mathcad, where the flange axial force is based on the ratio of the cross-section areas. Therefore, the bolt shear forces in FEA should be higher than in Mathcad.

There was about 16-17% difference in the bolt shear forces between FEA and Mathcad, although the flange and web plate forces were nearly equal. With a normal force 600 kN in the splice, the flange bolt shear force varied between 27,4 – 31,9 kN and the sum of all shear forces were 179,2 kN, while the flange plate axial force was 213 kN. The difference was 213-179,2 = 33,8 kN (-15,9%). As told in the chapter 4.2.6, the contact between the profile and the plate was frictionless. The reason for the difference was not solved.

5.2.2 Specimen no. 2: Bending M_y

In the specimen no. 2, the splice was loaded with vertical loads from the bottom of the profile end plates, see figure 5.11. The load was increased 250 kN in 3 load steps, 1 second / step, the final load being 750 kN. The load caused a bending moment about y-y axis, which can be calculated by the formula M = F a, see ch. 4.3.3. Results were collected in every 0,5 seconds. The last reported time is 2,5 s., because the analysis ended to an unconverged solution when the structure yielded at time 2,7 s. with the moment 670 kNm. The exact reason of the yielding is ignored in this research.

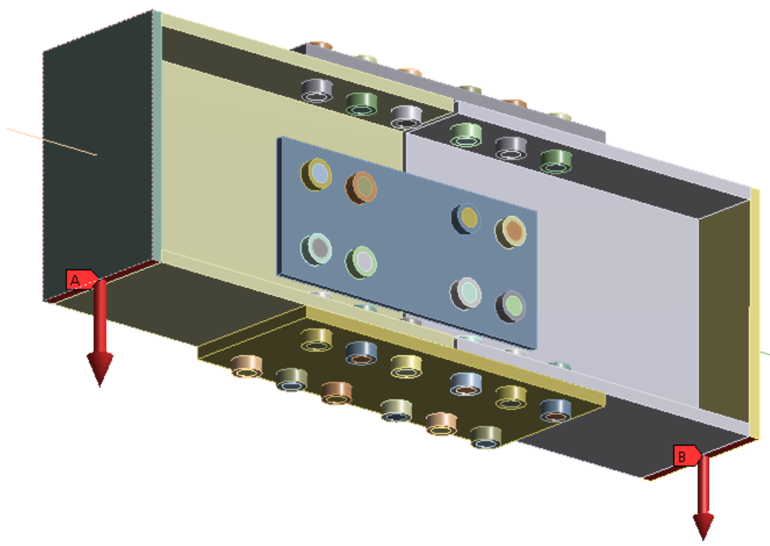


Figure 5.11. *Vertical loads at the bottom side of the profile end plates.*

5.2.2.1 Flange / flange plate

Compressed (top) flange plate axial force in Mathcad was compared to the flange plate compression in FEA. Plate axial force reactions are shown in table 5.6.

Table 5.6. *Flange (Mathcad) and flange plate (FEA) compression.*

Time	Splice load My	Force reaction		Diff.
		Ansys	Mathcad	
s	kNm	kN	kN	%
0,5	125	294	291	-1,1
1,0	250	585	582	-0,5
1,5	375	877	873	-0,5
2,0	500	1167	1164	-0,2
2,5	625	1460	1455	-0,3

The chart of the flange/flange plate axial forces is shown in figure 5.12. The values were equal.

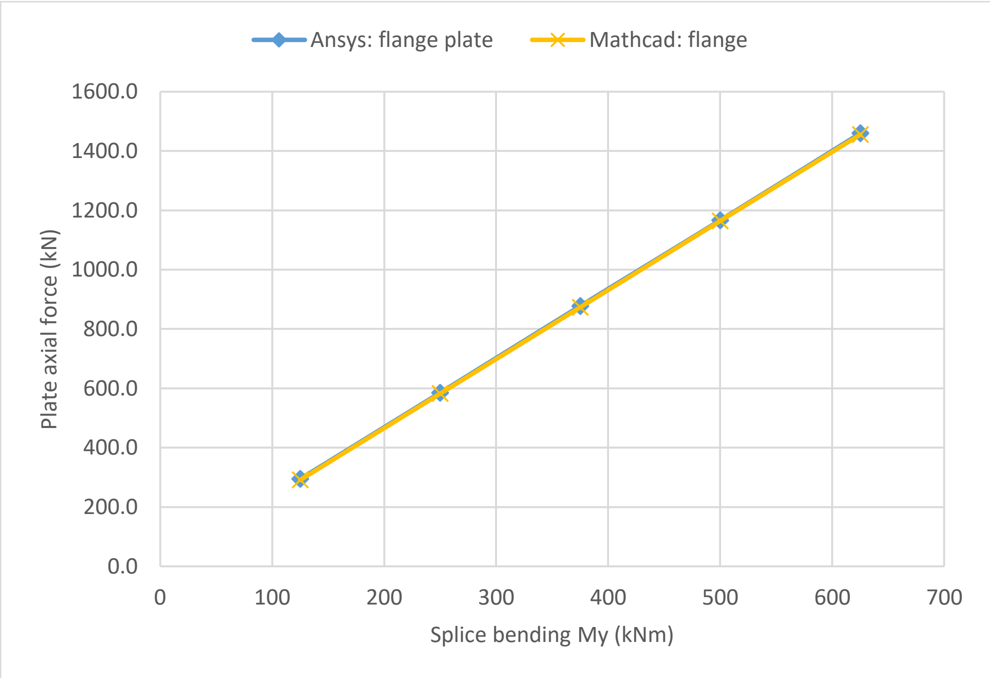


Figure 5.12. *Flange / flange plate compression.*

Tensioned flange plate axial force in FEA was compared to the tensioned flange force in Mathcad. As can be seen in table 5.7 and figure 5.13, the axial force in the compression side is about 5-8 % greater than in the tensioned side in FEA.

Table 5.7. *Flange (Mathcad) and flange plate (FEA) tension.*

Time	Splice load My	Force reaction Ansys	Force reaction Mathcad	Diff.
s	kNm	kN	kN	%
0,5	125	278	291	4,6
1,0	250	553	582	5,2
1,5	375	830	873	5,2
2,0	500	1098	1164	6,1
2,5	625	1349	1455	7,9

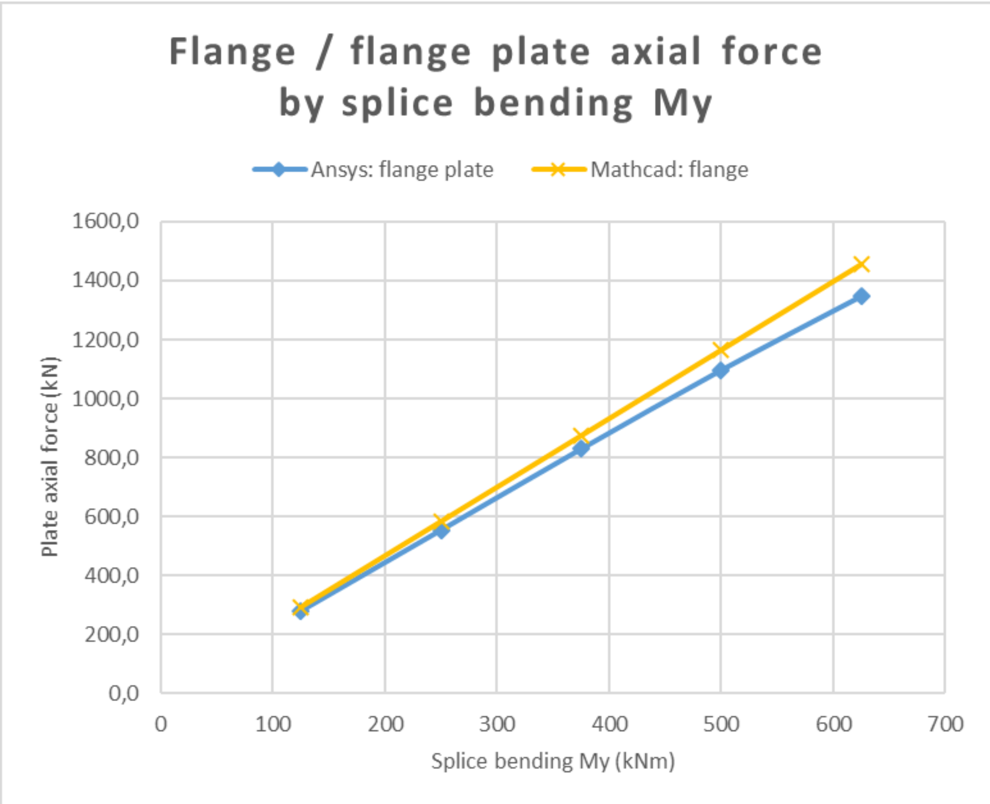


Figure 5.13. *Flange and flange plate tension.*

5.2.2.2 Flange bolts

Top flange bolt shear forces were studied in FEA from the bolts no. 1-6. At time step 3 in FEA, the bolt shear forces varied between 221 kN (bolts 1 and 2) and 216 kN (bolts 5 and 6). The average bolt shear force in FEA together with maximum shear force of the flange bolt in Mathcad are shown in table 8.5 and in figure 5.14.

Table 5.8. Flange bolt shear forces in x-x axis direction.

Time	Splice load	Bolt shear force		Diff.
		Ansys	Mathcad	
	My	X	X	
s	kNm	kN	kN	%
0,5	125	42	49	19,2
1,0	250	83	97	16,5
1,5	375	127	146	14,1
2,0	500	172	194	12,6
2,5	625	218	243	11,1

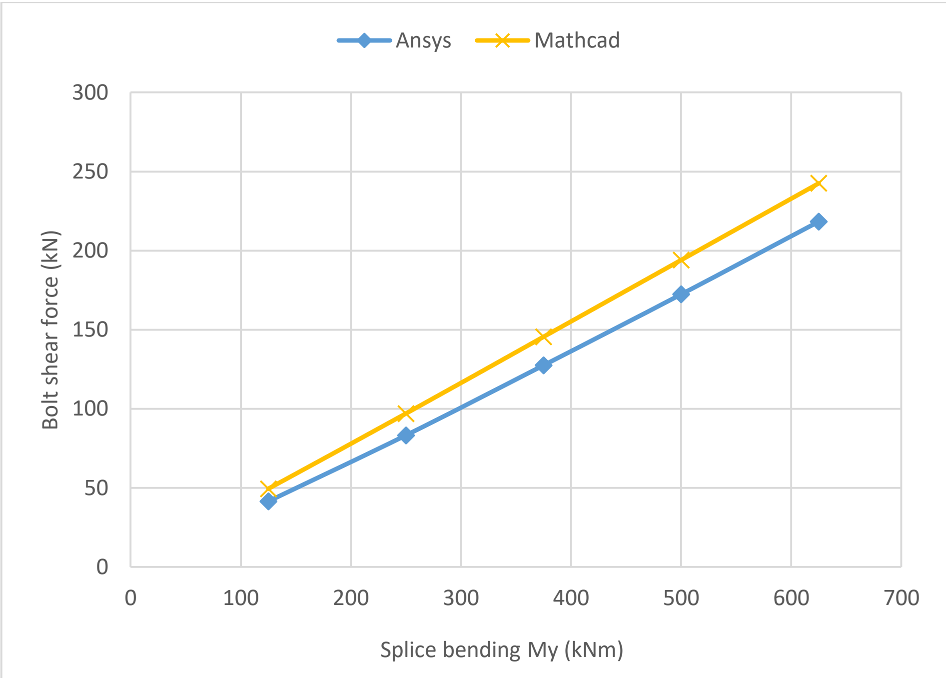


Figure 5.14. Flange bolt shear forces.

5.2.2.3 Flange bolt tension force in the bolt axis direction

The tension force of the bolt was not in the scope of this work. However, it was noticed that there was a significant tension force along bolt axis at yield point of the FE-model in this load case. Initially, the bolts were not pre-tensioned, thus in the beginning of the loading the bolt tension is 0 kN. At time 2,588 s. the tension force was at the top, 94 kN, see blue arrow in figure 5.15. At time 2,692 s., when the failure occurred, the shear and axial forces of the flange bolt no. 6 was as follows:

- shear force resultant from the shear force components in the x-x and y-y axis direction (z- and y- axis in FEA): $\sqrt{235^2 + 16^2} = 236\ kN$
- tension force along the bolt axis: 85 kN

The utilization rate (U) for the combined shear and tension according to [3] table 3.4 for

- class 8.8 M30 bolt
- 20 mm flange, S355
- 20 mm flange plate S355

with the given forces is 1,06, thus, at the time of the collapse the combined shear and tension resistance of the bolt no. 6 was just exceeded. This was the most tensioned bolt in the top flange. The behavior of the tension force is shown graphically in figure 5.15. Calculating the resistances separately, the shear $F_{v,Rd}$ resistance is 271 kN (U = 236 / 271 = 0,87) and the design bearing resistance $F_{b,Rd}$ is 371 kN (U = 236 / 371 = 0,64) [3, table 3.4], which are clearly below 1.

The reason for the structure failure was not studied in this work. However, there could be a need for discussion of the following topics: Is there a situation, that the bolt tension force becomes ruling in designing the splice? What is the effect of the profile height, flange thickness and flange plate thickness for the axial tension of the bolt? In this example, the profile height was quite small comparing to the width, and the flange and flange plate were relatively thick, which can be the reason for the significant growing of the bolt tension force.

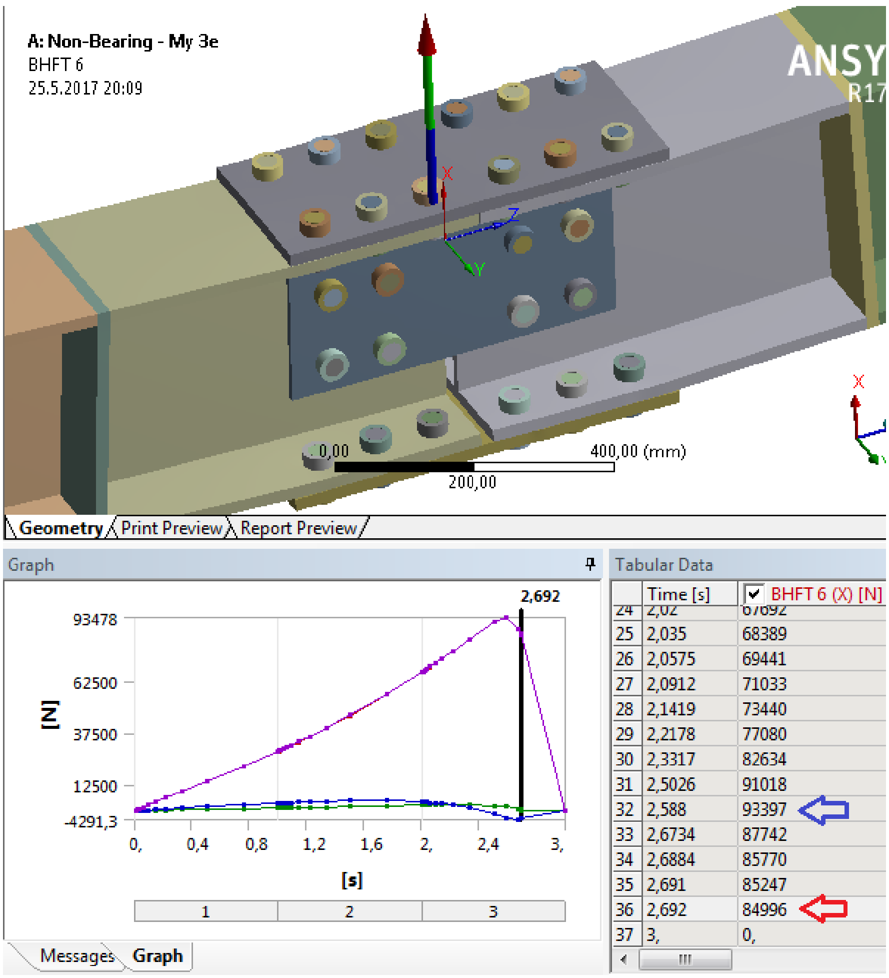


Figure 5.15. Flange bolt no. 6 axial force at the time of the failure

5.2.2.4 Web / web plates

Web bending moment in Mathcad was compared to the web plates total bending moment about y-y axis in FEA. The force reaction of the web plates is shown in the figure 5.16. Moment reactions are shown in table 5.9 and the chart in figure 5.17.

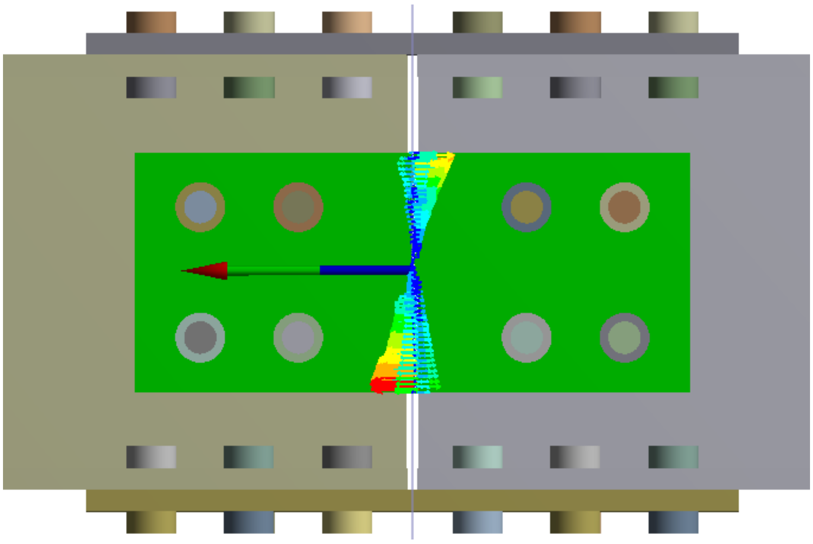


Figure 5.16. *Force reaction of the web plates, bending about y-y axis.*

Table 5.9. *Web (Mathcad) and web plates combined (FEA) bending about y-y axis.*

Time	Splice load My	Moment reaction		Diff.
		Ansys	Mathcad	
s	kNm	kNm	kNm	%
0,5	125,0	6	14	153
1,0	250,0	11	29	153
1,5	375,0	18	43	145
2,0	500,0	25	57	133
2,5	625,0	35	71	105

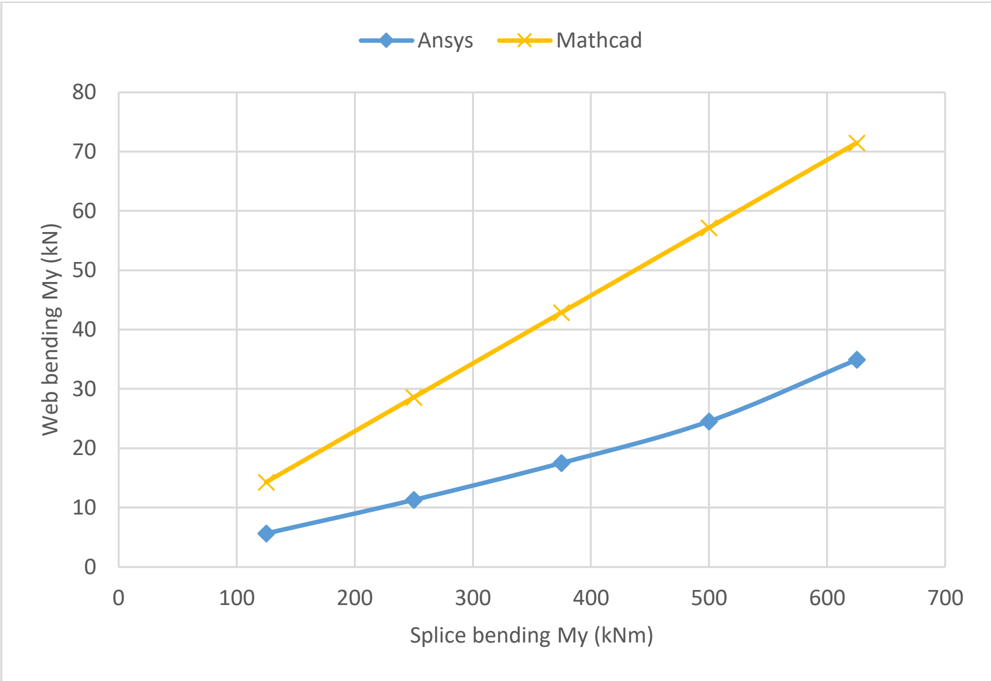


Figure 5.17. Web / web plates bending.

5.2.2.5 Web bolts

Web bolt shear forces were studied from the web bolts no. 1-4 in FEA (see figure 5.18). The shear force components in the x- and z-axis directions are calculated as an average of the component absolute values. Components X and Z and their resultant are shown in table 5.10 and in figure 5.19.

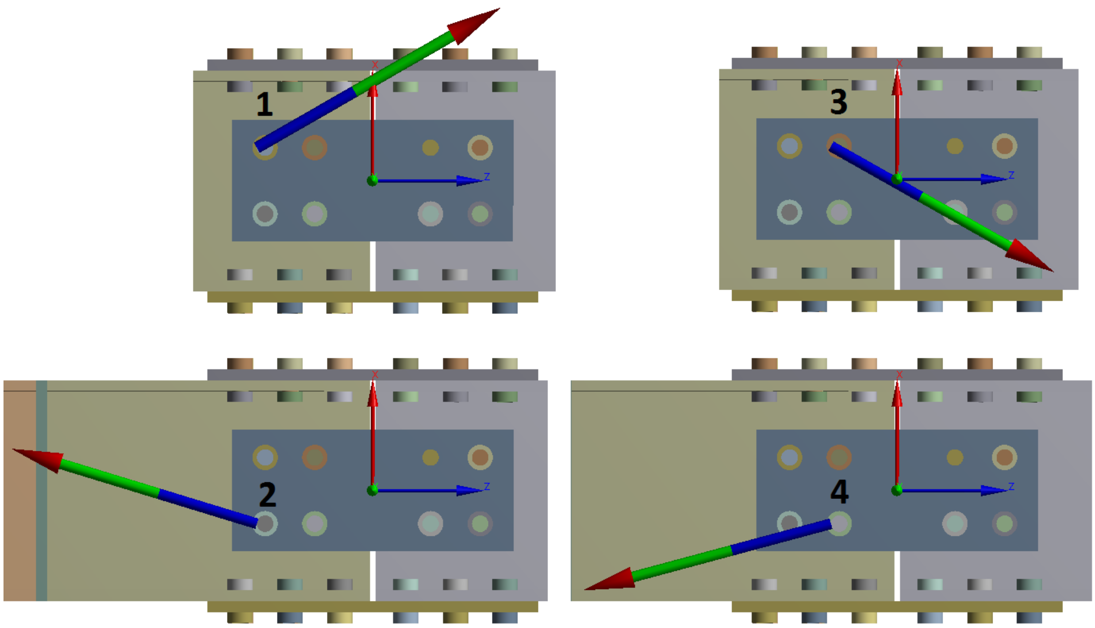


Figure 5.18. Shear force resultant of the web bolts at time 3 s.

Table 5.10. Web bolt shear force components (X and Z) and resultants.

Time	Splice load	Bolt shear force						Diff.
		Ansys			Mathcad			
	My	X	Z	Res.	X	Z	Res.	Res.
s	kNm	kN			kN			%
0,5	125	17	5	18	38	29	48	168,9
1,0	250	34	10	35	76	57	95	169,1
1,5	375	52	17	55	114	86	143	161,1
2,0	500	72	24	76	152	114	191	149,9
2,5	625	100	39	107	191	143	238	122,7

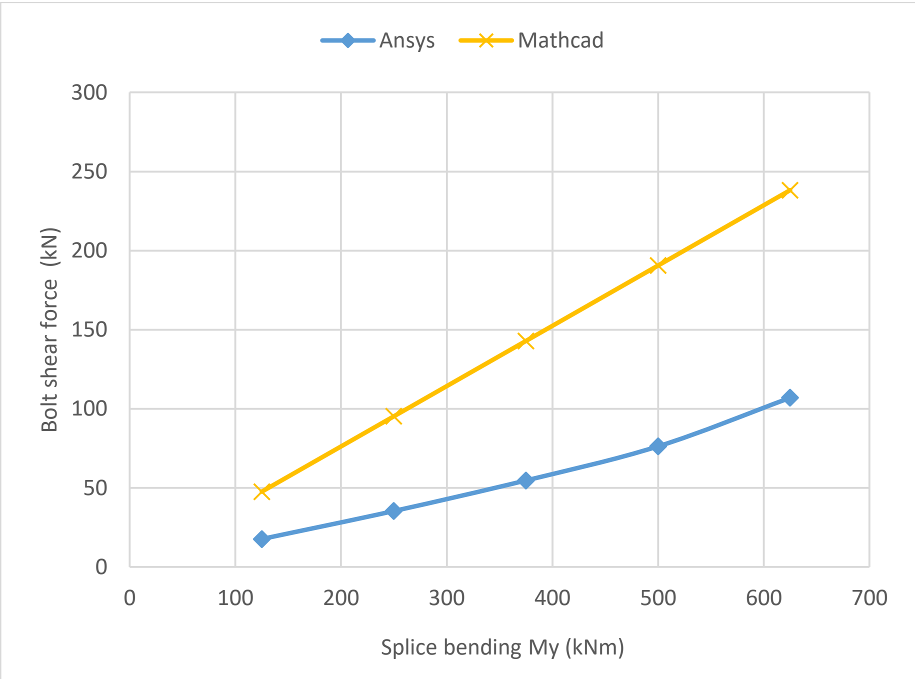


Figure 5.19. Web bolt shear force resultants.

A significant difference between Mathcad and FEA results in the web and web bolt shear forces can be found from the results. This was due to the difference of the force distribution between flanges and web in bending about y-y axis. The real bending force in the web is not divided as a ratio of the whole cross-section area of the web.

5.2.3 Specimen no. 3: Bending M_z

In the specimen no. 3, the splice was loaded with lateral loads from the side of the profile end plates, see figure 5.20. The load was increased 50 kN in 3 load steps, 1 second / step, the final load being

150 kN. The load caused a bending moment about z-z axis, which can be calculated basically by the formula $M = P a^2 / L$, see chapter 4.3.3. The real bending moments of the FEA model are used, which are about 4% below theoretical bending moments. Results are collected in every 0,5 seconds and last reported time is 3,0 s. Analysis ended to a converged solution.

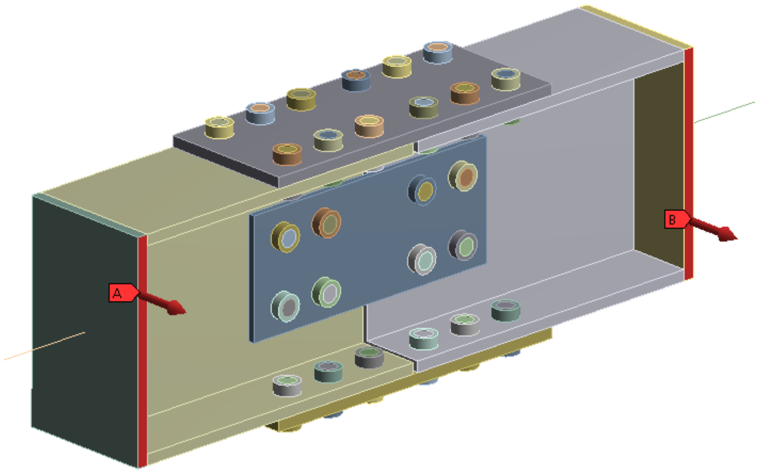


Figure 5.20. *Lateral loads at the other side of the profile end plates.*

5.2.3.1 Flange / flange plate

Flange bending moment about z-z axis in Mathcad was compared to the flange plate bending moment in FEA. Bending moment reactions are shown in table 5.11 and the chart in figure 5.21. The bending moments were equal.

Table 5.11. *Flange (Mathcad) and flange plate (FEA) bending about z-z axis.*

Time	Splice load Mz	Moment Mz		Diff.
		Ansys	Mathcad	
s	kNm	kNm	kNm	%
0,5	7,5	3,7	3,8	0,5
1,0	15,0	7,4	7,5	0,5
1,5	22,5	11,2	11,2	0,5
2,0	29,9	14,9	14,9	0,5
2,5	37,4	18,6	18,7	0,5
3,0	44,9	22,3	22,4	0,5

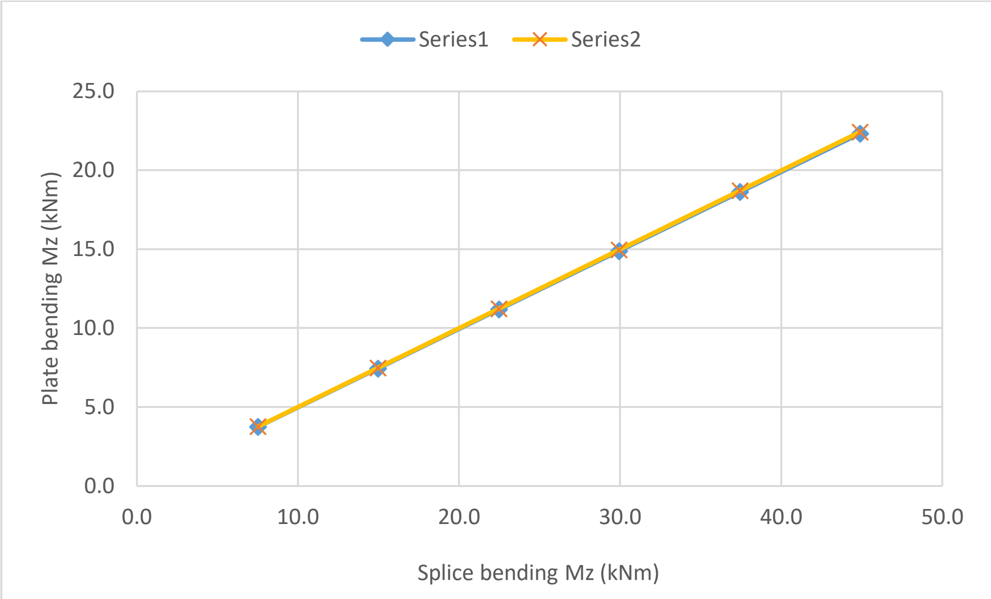


Figure 5.21. *Flange / flange plate axial forces.*

5.2.3.2 Flange bolts

Bolts no. 1, 2, 5 and 6 were the most stressed flange bolts by bolt shear force. At time step 3 in FEA, the bolt shear force resultants varied between 31 kN (bolts 2 and 6) and 33-34 kN (bolts 5 and 6). The bolts shear force resultants are shown in the figure 5.22. The average bolt shear force components in x- and y-axis direction and their resultants were calculated in FEA from the bolts named, using the absolute values of the force components. The most stressed bolt shear force components in x- and y-axis direction and their resultants were calculated in Mathcad. The results are shown in table 5.12 and in figure 5.23.

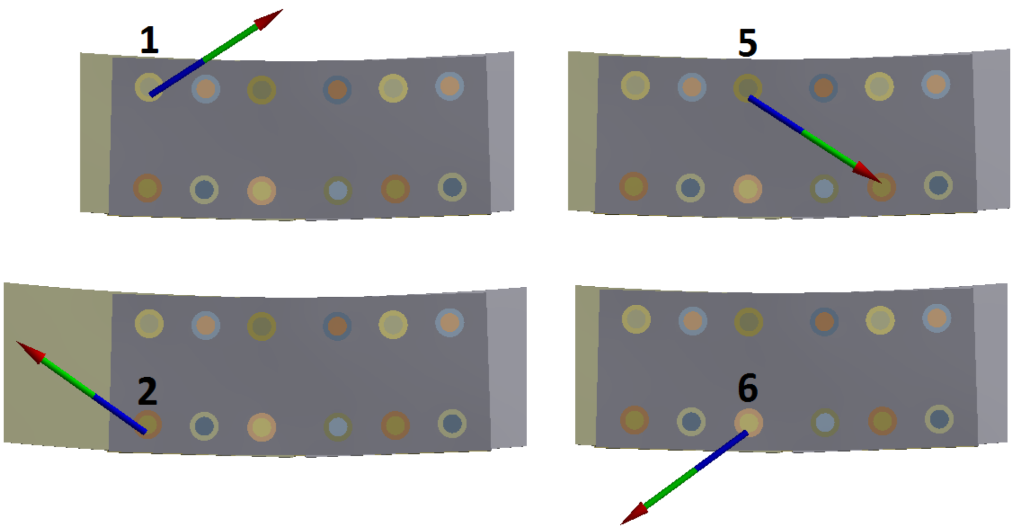


Figure 5.22. *Shear force resultant of the flange bolts no. 1, 2, 5 and 6 at time 3 s.*

Table 5.12. Flange bolt shear force components (X and Y) and their resultants.

Time	Splice load	Bolt shear force						Diff.
		Ansys			Mathcad			
	Mz	X	Y	Res.	X	Y	Res.	Res.
s	kNm	kN			kN			%
0,5	7,5	4	3	5	4	5	6	17,9
1,0	15,0	9	6	11	8	10	13	17,9
1,5	22,5	13	9	16	13	14	19	17,9
2,0	29,9	18	12	22	17	19	25	18,0
2,5	37,4	22	15	27	21	24	32	18,0
3,0	44,9	27	18	32	25	29	38	18

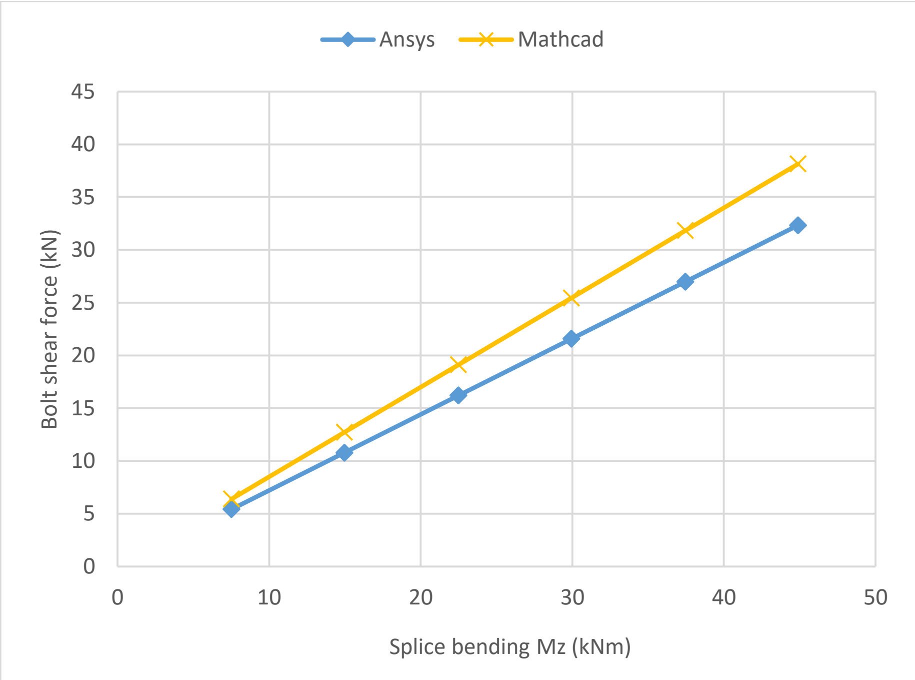


Figure 5.23. Flange bolt shear forces.

5.2.4 Specimen no. 4: Shear V_z

In the specimen no. 4, the splice was loaded with vertical loads from the top of the left end plate and from the bottom of the right end plate, see figure 5.24. The load was increased 100 kN in 3 load steps, 1 second / step, the final load being 300 kN. In the area of the splice, the load caused a shear force along z-z axis, which can be calculated by the formula

$$V = \frac{1m}{1{,}6m} \cdot F$$

where

V = shear force

F = vertical load per end plate

$\frac{1m}{1{,}6m}$ = following distances: 1m = from support to end plate centerline, 1,6m = from support to splice center, see figure 4.7 in chapter 4.2.2.

The shear force resultants of the splice plates in FEA model were equal with the theoretical shear forces in each load steps. Results are collected in every 0,5 seconds and last reported time is 3,0 s. Analysis ended to a converged solution.

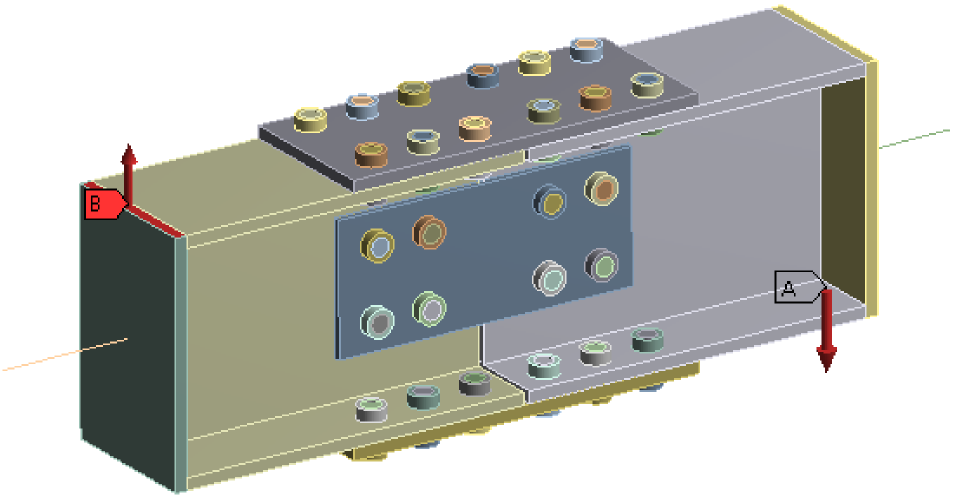


Figure 5.24. *Vertical loads at the top and the bottom side of the profile end plates.*

5.2.4.1 Web / web plates

Web plates shear force resultant is shown in the figure 5.25. Web shear force in Mathcad was compared to the web plates total shear force along z-z axis in FEA. Force reactions are shown in table 5.13 and the chart in figure 5.26.

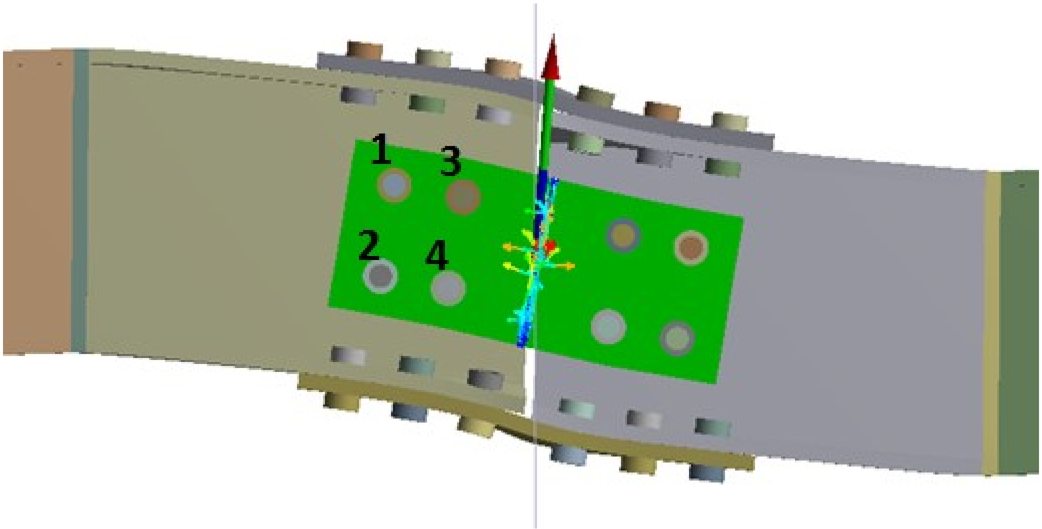


Figure 5.25. *Combined shear force resultant of the web plates.*

Table 5.13. *Web (Mathcad) and web plates combined (FEA) shear along z-z axis.*

Time	Splice load My	Moment reaction		Diff.
		Ansys	Mathcad	
s	kNm	kNm	kNm	%
0,5	31,3	18	31	70
1,0	62,5	37	63	71
1,5	93,8	55	94	70
2,0	125,0	73	125	71
2,5	156,3	92	156	70
3,0	187,5	110	188	71

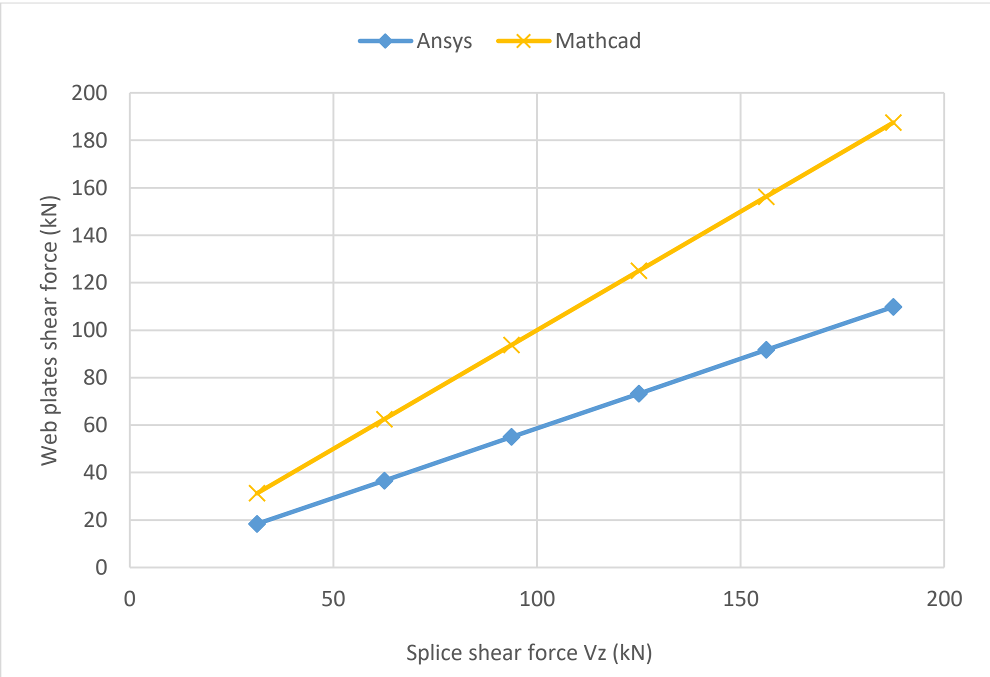


Figure 5.26. *Web / web plates shear force.*

Web shear force in FEA is about 70% smaller than the combined shear force of the web plates. In Mathcad, the whole shear force, 187,5 kN at time 3s., is directed to the web, while in FEA, the combined shear force of the web plates is about 110 kN at time 3s. It was also checked from the analysis, that the shear force resultant of the flange plates was 77,7 kN, which was exactly the remaining part of the total shear force (109,8 + 77,7 = 187,5 kN).

In other words, about 41% of the shear force is distributed to the flange plates according to the FEA results. Analogous observation has been made in the experimental tests by Firas. According to him, "*Flange splices, if not fully yielded, carry a portion of the total shear. This shear is a function of the ratio of the applied moment to moment capacity of the flange splices, gap clearance in the beam, and end distance of the flange bolts*" [10, p. 114]. In the same context, he continues that "*To simplify the design process, the shear carried by the flange splices can be conservatively ignored and the web splice can be assumed to carry the total shear.*" However, it could be worth considering to calculate the distribution of the shear forces more exactly in some cases.

5.2.4.2 Web bolts

Web bolt shear forces were studied from the web bolts no. 1-4 in FEA (see figure 5.27). The shear force components in the x-x and z-z axis directions are calculated as an average of the component absolute values. Components X and Z and their resultant are shown in table 5.14 and in figure 5.28.

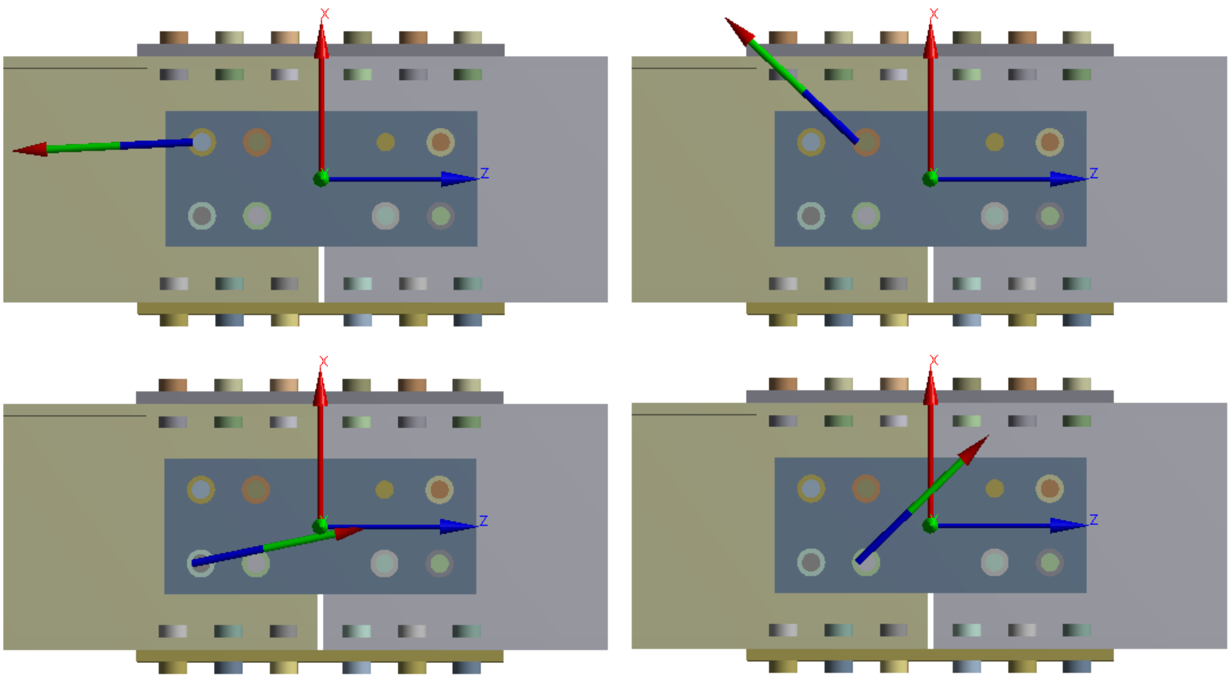


Figure 5.27. *Shear force resultant of the web bolts at time 3 s.*

Table 5.14. Web bolt shear force components (X and Z) and resultants.

Time	Splice load	Bolt shear force						Diff.
		Ansys			Mathcad			
	Vz	X	Z	Res.	X	Z	Res.	Res.
s	kN	kN			kN			%
0,5	31,3	8	4	9	13	17	21	144,5
1,0	62,5	15	9	17	25	34	43	145,7
1,5	93,8	23	13	26	38	52	64	145,2
2,0	125,0	30	17	35	50	69	85	145,7
2,5	156,3	38	21	43	63	86	106	145,5
3,0	187,5	45	25	52	75	103	128	146

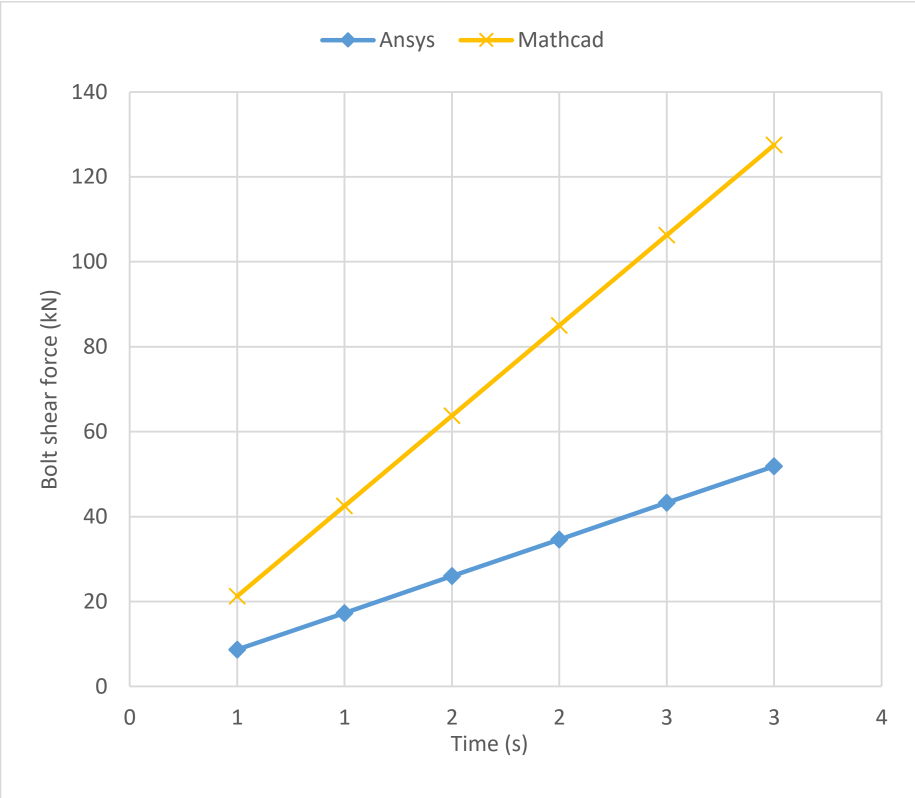


Figure 5.28. Web bolt shear force resultants.

Because of the greater shear force in the web in Mathcad, also the bolt shear forces are greater than in FEA, the difference being about 145%. Adjusting the shear force in Mathcad to the same value than the web plates combined shear in FEA, the bolt shear forces comes closer to FEA results, as can be seen in figure 5.29:

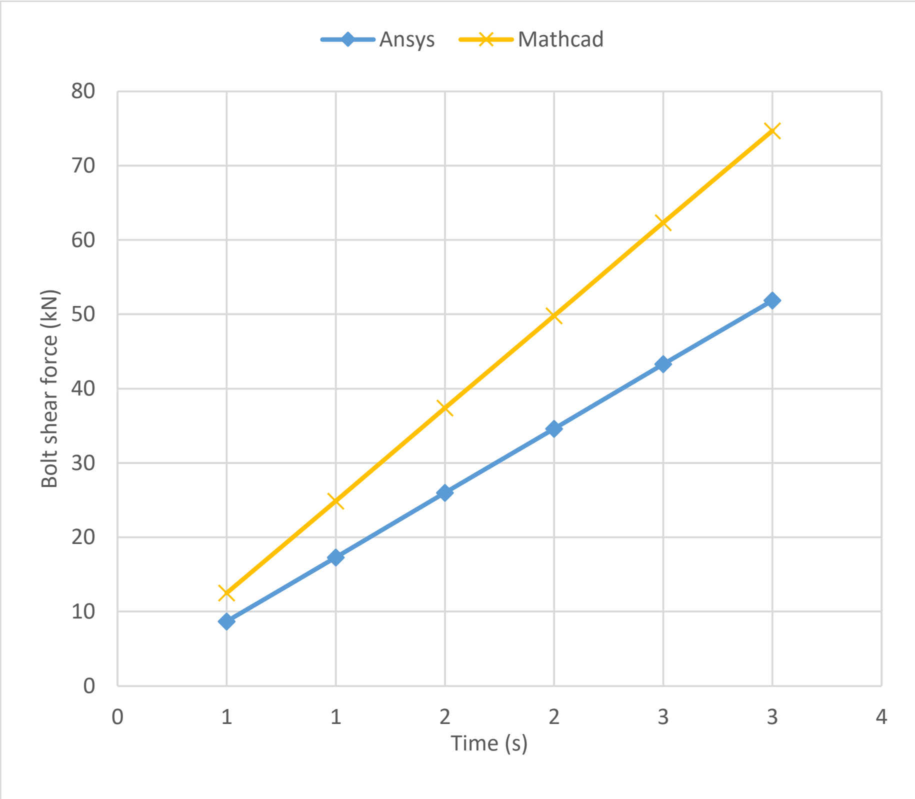


Figure 5.29. *Web bolt shear force resultants. Shear force in Mathcad is equal to the FEA web plates shear force*

As can be seen in figure 5.27, the shear force resultant of the bolts no. 1 and 2 in FEA is quite horizontal. X-components of the shear force of these bolts are 41 and 44 kN and the z-component 2 and 9 kN, respectively. Bolts no. 3 and 4 are the most loaded bolts, x-component being 46 and 50 kN and z-component 43 and 48 kN, respectively. If only the most loaded bolts (no. 3 and 4) are taken into account, the results are closer to the each others, as can be seen in figure 5.30:

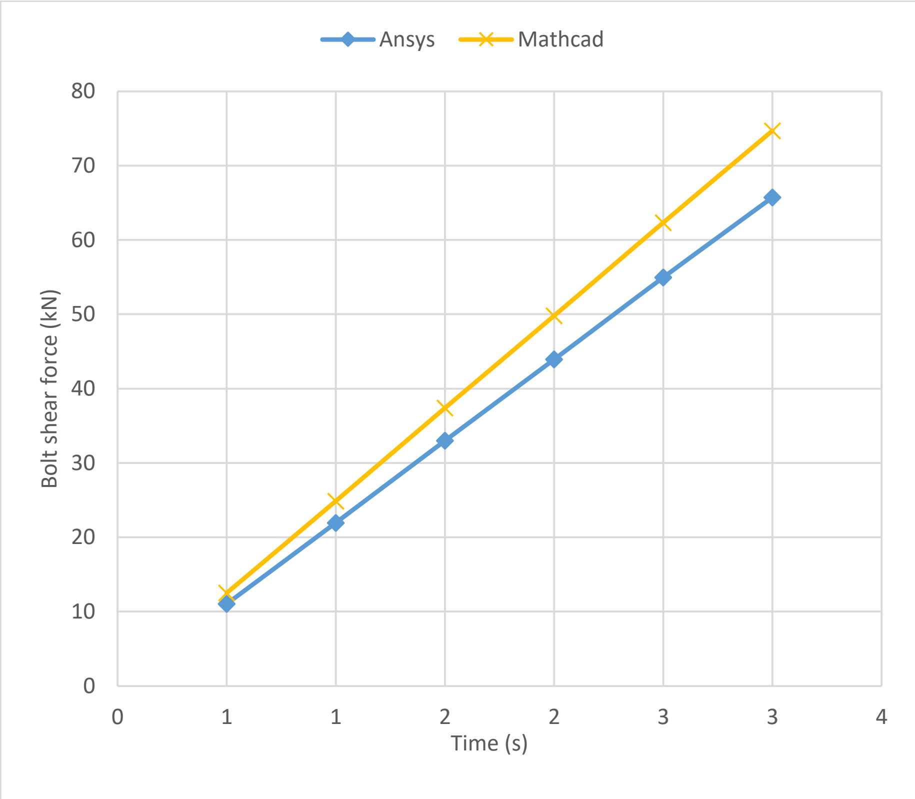


Figure 5.30. *Web bolt shear force resultants. Shear force in Mathcad is equal to the FEA web plates shear force. Only bolts no. 3 and 4 are considered in FEA.*

5.2.5 Specimen no. 5: Load combination M_y + M_z

In the specimen no. 5, the splice was loaded with vertical and lateral loads from the sides of the profile end plates, see figure 5.31. In vertical direction, the load was increased 150 kN in 3 load steps, the final load being 450 kN and theoretical bending moment 450 kNm. In horizontal direction, the load was increased simultaneously 32 kN in 3 load steps, the final load being 96 kN and theoretical bending moment 30 kNm. The real bending moments about z-z axis of the FEA model are used, which are 4-10 % below the theoretical bending moment values, growing towards the end of the analysis. Results are collected in every 0,5 seconds and last reported time is 3,0 s. Analysis ended to a converged solution.

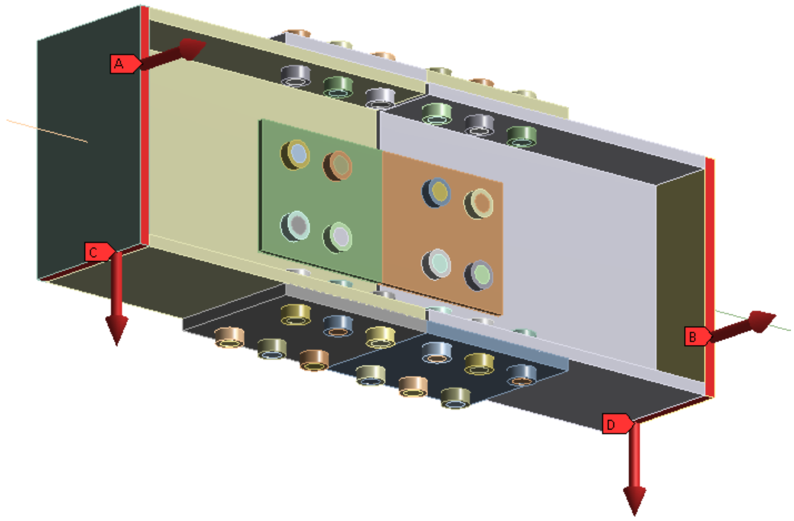


Figure 5.31. Vertical and lateral loads at the sides of the profile end plates.

5.2.5.1 Flange bolts

Bolts no. 1, 2, 5 and 6 were the most stressed flange bolts by bolt shear force. At time step 3 in FEA, the bolt shear forces varied between 132 kN (bolt 6) and 188 kN (bolt 1). The average bolt shear force components in x- and y-axis direction and their resultants were calculated in FEA from the named bolts, using the absolute values of the force components. The most stressed bolt shear force components in x- and y-axis direction and their resultants in FEA model can be seen in the figure 5.32. Shear forces were calculated in Mathcad. The comparison of the results is shown in table 5.15 and in figure 5.33.

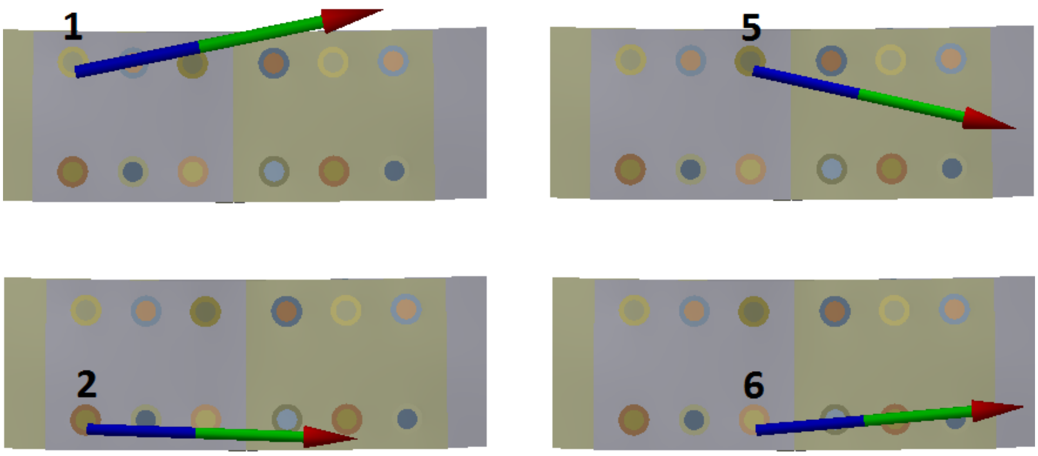


Figure 5.32. Shear force resultant of the flange bolts no. 1, 2, 5 and 6 at time 3 s.

Table 5.15. Flange bolt shear forces in the x-x axis direction.

Time	Splice load combination		Bolt shear force						Diff.
			Ansys			Mathcad			
	My	Mz	X	Y	Res.	X	Y	Res.	Res.
s	kNm		kN			kN			%
0,5	75	5	26	4	26	32	3	32	22,3
1,0	150	10	52	7	52	64	6	64	22,4
1,5	225	14	78	11	79	96	9	96	21,7
2,0	300	19	105	15	106	127	12	128	20,6
2,5	375	24	132	19	133	159	15	160	19,6
3,0	450	27	159	23	160	190	17	190	19

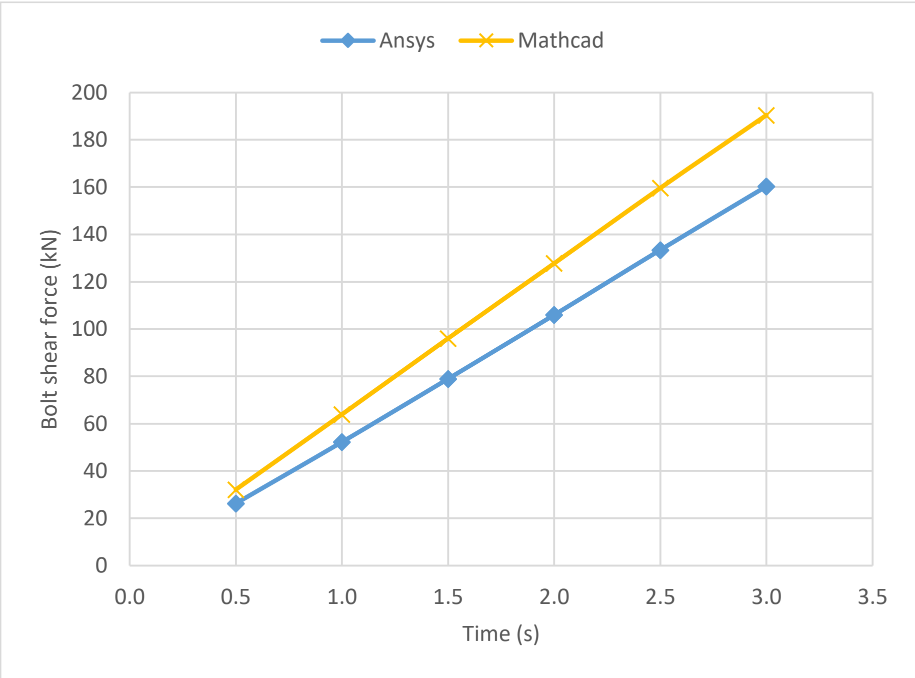


Figure 5.33. Flange bolt shear forces by splice load My+Mz.

5.2.5.2 Web bolts

Web bolt shear forces were studied from the web bolts no. 1-4 in FEA. The shear force components in x- and y-axis direction and their resultant were calculated in FEA and in Mathcad. The results are shown in table 5.16 and in figure 5.34.

Table 5.16. Web bolt shear force components and resultants.

Time	Splice load		Bolt shear force						Diff.
			Ansys			Mathcad			
	My	Mz	X	Z	Res.	X	Z	Res.	Res.
s	kNm	kNm	kN			kN			%
0,5	75	5	10	3	11	23	17	29	169,8
1,0	150	10	20	6	21	46	34	57	169,9
1,5	225	14	31	9	32	69	52	86	168,9
2,0	300	19	41	13	43	91	69	114	165,2
2,5	375	24	53	17	55	114	86	143	159,2
3,0	450	27	65	21	69	137	103	171	149,9

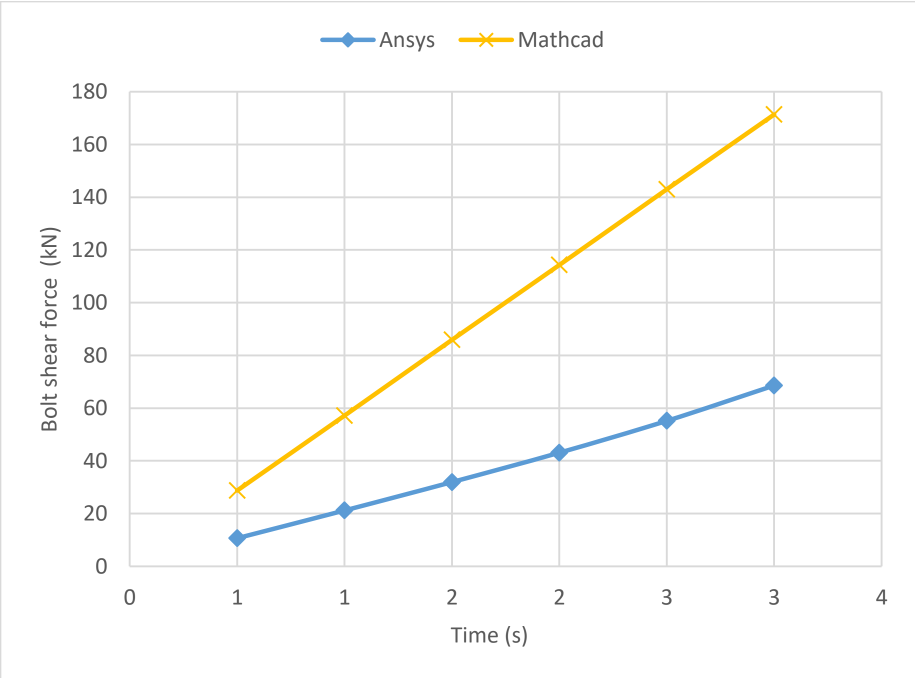


Figure 5.34. Web bolt shear forces.

As noticed in the specimen 2, there is a significant difference between Mathcad and FEA results in the web and web bolt shear forces due to the difference of the force distribution between flanges and web.

5.2.6 Specimen no. 6: Load combination N + M_y + M_z

In the specimen no. 6, the splice was loaded with compressive axial force in the end of the other beam element (shown as a single line) and vertical and lateral loads from the sides of the profile end plates, see figure 5.35. There were 6 load steps in all. The axial (X) force was increased 200 kN in first 3 load steps, the final load being 600 kN through the load steps 3-6. At load step 4, the vertical load (Y) was increased 150 kN in every 3 load steps, the final load being 450 kN. At the same time, the horizontal load (Z) was increased 32 kN in 3 load steps, and the final load was 96 kN. The load chart is shown in the table 5.17. The real bending moments of the FEA model are used, which differs a little from the theoretical values. Results are collected in every 0,5 seconds and last reported time is 6,0 s. Analysis ended to a converged solution.

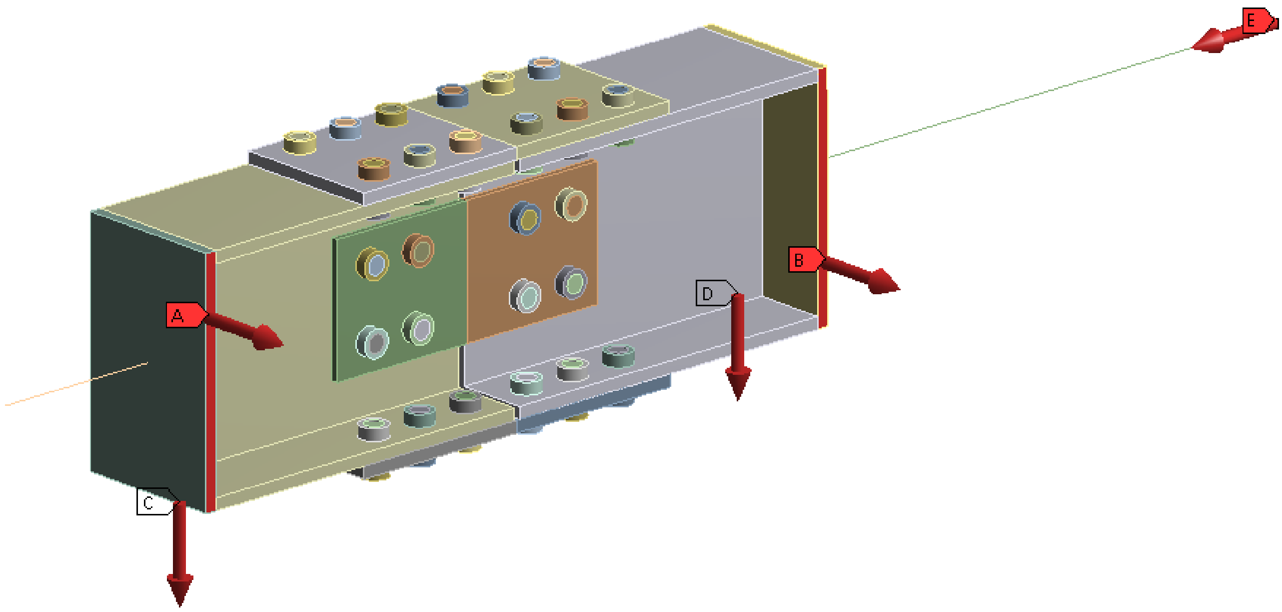


Figure 5.35. *Axial, vertical and lateral loads at the sides of the profile end plates.*

Table 5.17. *Loads in FE-analysis.*

Step	Time (s)	X (kN)	Y (kN)	Z (kN)
0	0	0	0	0
1	1	-200	0	0
2	2	-400	0	0
3	3	-600	0	0
4	4	-600	150	32
5	5	-600	300	64
6	6	-600	450	96

5.2.6.1 Flange bolts

Bolt no. 1 (see figure 5.36) was the most stressed flange bolt by shear force. The bolt shear force components in x- and y-axis direction and their resultant were calculated in FEA and in Mathcad. The results are shown in table 5.18 and in figure 5.37.

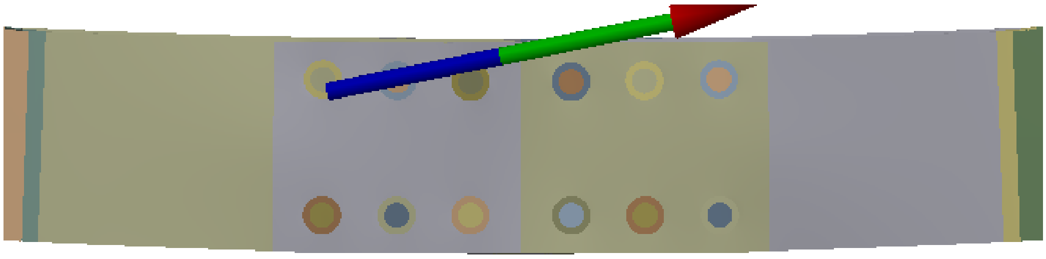


Figure 5.36. *Shear force resultant of the flange bolt no. 1 at time 6 s.*

Table 5.18. *Flange bolt shear forces in the x-x axis direction.*

Time	Splice load combination			Bolt shear force						Diff.
				Ansys			Mathcad			
	N	My	Mz	X	Y	Res.	X	Y	Res.	Res.
s	kN	kNm		kN			kN			%
0,5	100	0	0	5	1	5	6	0	6	8,2
1,0	200	0	0	11	1	11	12	0	12	8,6
1,5	300	0	0	16	2	16	17	0	17	8,4
2,0	400	0	0	21	3	21	23	0	23	8,5
2,5	500	0	0	27	3	27	29	0	29	8,4
3,0	600	0	0	32	4	32	35	0	35	8,5
3,5	600	76	5	62	9	63	67	3	67	6,8
4,0	600	151	10	94	15	95	99	6	99	4,4
4,5	600	228	15	126	21	128	132	9	132	3,3
5,0	600	303	20	156	27	159	163	12	164	3,3
5,5	600	379	24	185	34	188	196	15	196	4,6
6,0	600	454	28	206	41	210	227	18	228	8,4

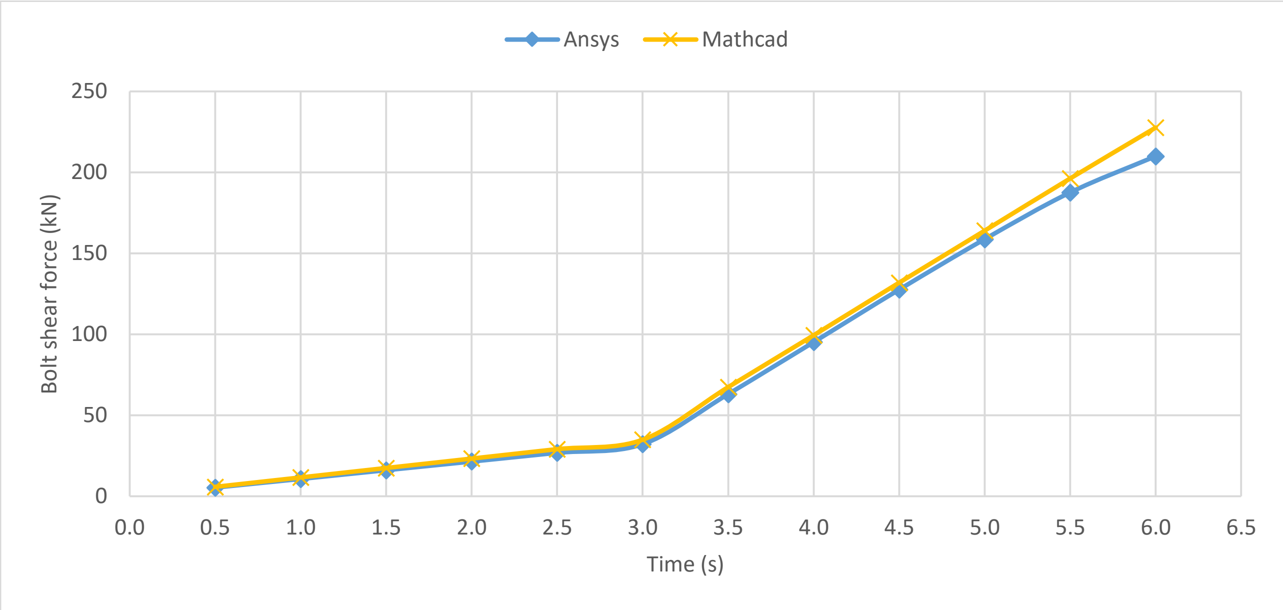


Figure 5.37. *Flange bolt shear forces.*

5.2.6.2 Web bolts

Web bolt shear forces were studied from the bolts no. 1 and 3 in the compressed side of the web, which are shown in figure 5.38. The shear force components in x- and y-axis direction and their resultant were calculated in FEA and in Mathcad. The results are shown in table 5.19 and in figure 5.39.

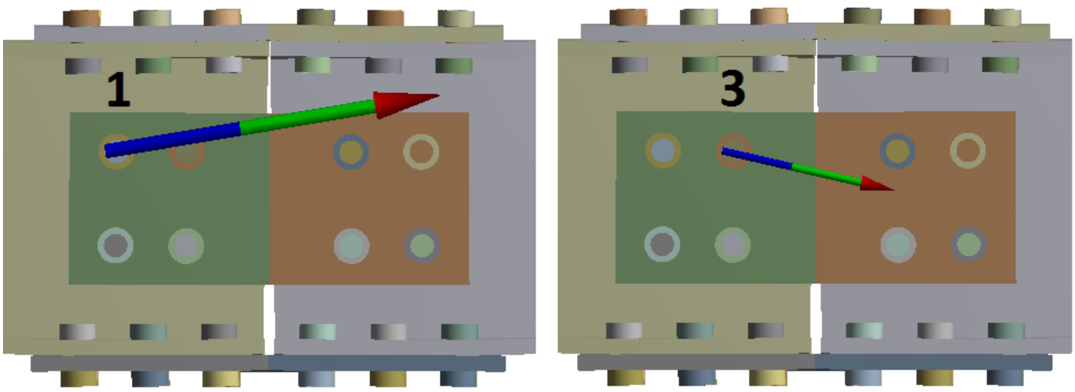


Figure 5.38. *Shear force resultant of the web bolts no. 1 and 3 at time 6 s.*

Table 5.19. *Web bolt shear force components and resultants.*

Time	Splice load			Bolt shear force						Diff.
				Ansys			Mathcad			
	N	My	Mz	X	Z	Res.	X	Z	Res.	Res.
s	kN	kNm	kNm	kN			kN			%
1,0	200	0,0	0,0	13	0	13	15	0	15	16,0
2,0	400	0,0	0,0	26	1	26	30	0	30	16,2
3,0	600	0,0	0,0	39	1	39	45	0	45	16,2
4,0	600	151,4	9,8	59	6	59	91	35	98	65,8
5,0	600	302,8	19,6	78	12	79	138	69	154	94,9
6,0	600	454,1	27,9	102	20	104	184	104	211	103,8

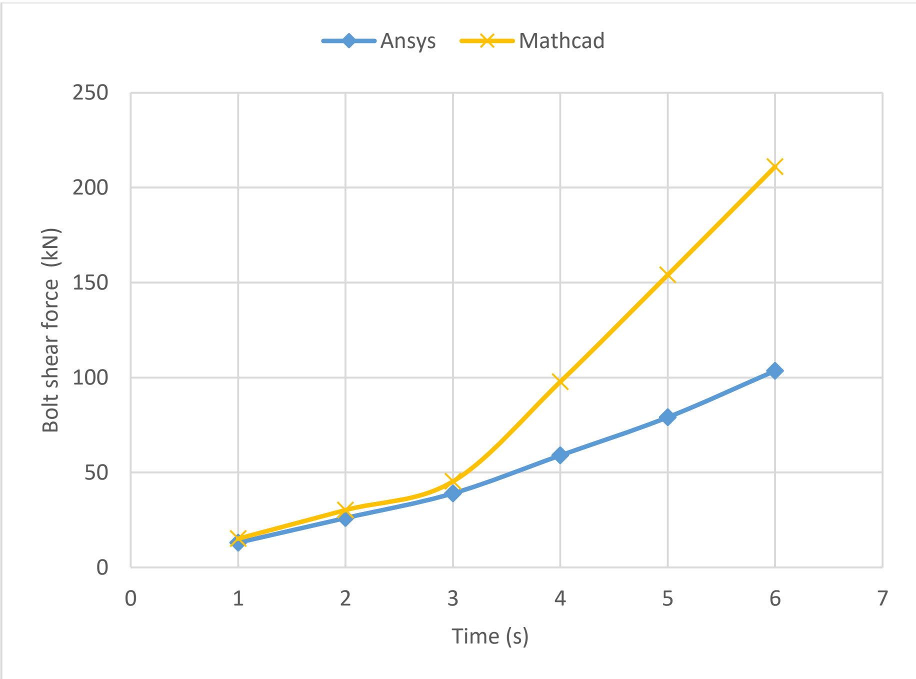


Figure 5.39. *Web bolt shear forces.*

When the moment about y-y axis begins to grow at the time 3 s., the results begin to diverge strongly. According to the results, the Mathcad result is clearly on the safe side at the end in the specimen no. 2, 5 and 6.

5.3 Bearing type splice

Five specimens were analyzed with different loads or load combinations shown in the table 5.20:

Table 5.20. *Loads and load combinations of the bearing splice analysis.*

Specimen no.	Load / load combination
7	N
8	My
9	Mz
10	My + Mz
11	N + My + Mz

The specimen no. 11 includes the primary load case N (normal force), which effects alone during the first 3 seconds and can be analyzed separately as the specimen 7.

5.3.1 Specimen no. 7: Normal force N

In the specimen no. 7, the splice was loaded at the end of the beam element with a compressive force in the x-x axis direction during the first 3 load steps, 1 second / step. The load was increased 250 kN every step, the final load being 750 kN. Analysis ended to a converged solution.

5.3.1.1 Flange plate

Flange plates compression was compared between Mathcad and FEA. As described in chapter 3.4.4, the flange plate axial force is calculated by multiplying the design normal force N_{Ed} with the ratio of the plate cross-section area and the total splice cross-section area. Top flange plate force reaction in FEA is shown in figure 5.40.

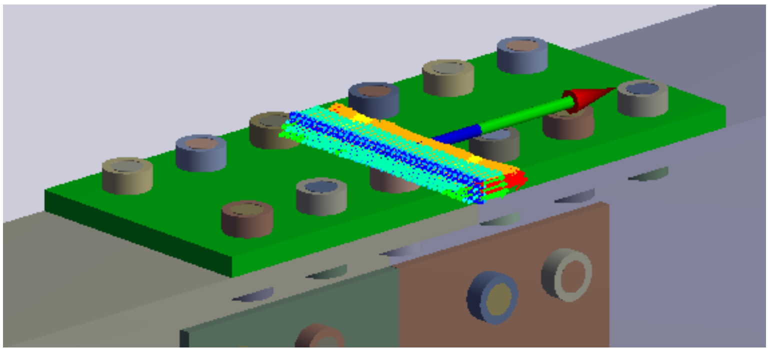


Figure 5.40. Top flange plate axial force resultant at the end of the load step 3.

Top and bottom flange plate force reaction were equal in FEA. Flange plate axial force reactions are shown in table 5.21 and the chart in figure 5.41.

Table 5.21. Flange plate compression.

Time	Splice load Fx	Force reaction Ansys	Force reaction Mathcad	Diff.
s	kN	kN	kN	%
0,5	125	16	21	35,9
1,0	250	31	42	35,5
1,5	375	47	63	34,9
2,0	500	63	84	34,9
2,5	625	78	106	34,6
3,0	750	94	127	34,7

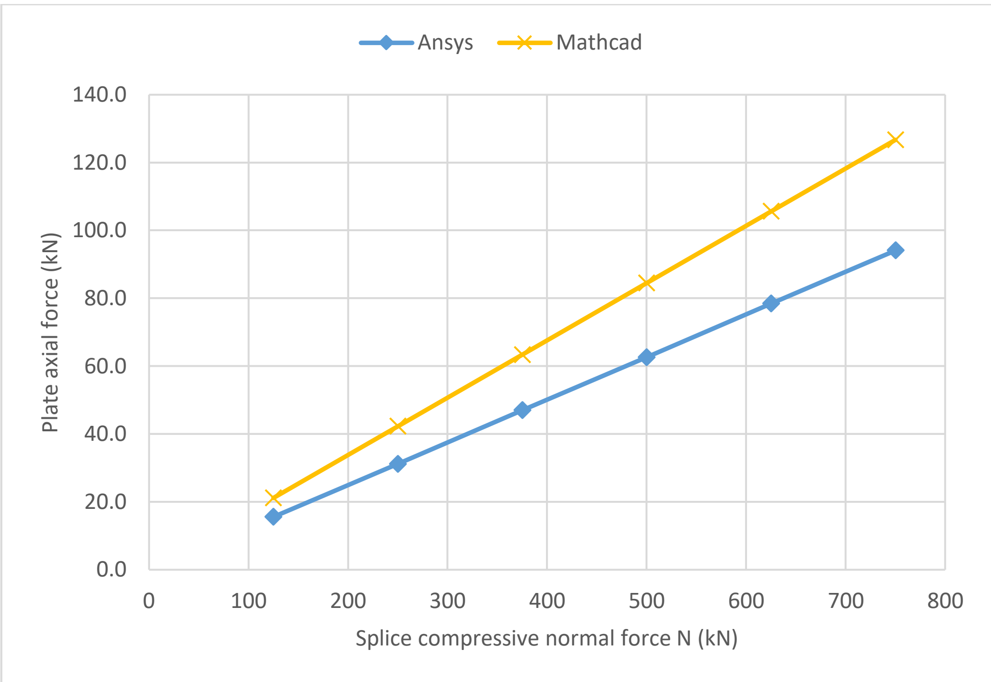


Figure 5.41. Flange plate compression.

5.3.1.2 Flange bolts

Top flange bolt shear forces were studied from the flange bolts no. 1-6 in FEA and the average shear force is shown. At time step 3 in FEA, the shear forces varied from 5 kN (bolts 5 and 6) to 22 kN (bolts 1 and 2). Bolt shear force in x-x axis direction for the flange bolts were calculated in Mathcad. Both shear force results are shown in table 5.22 and in figure 5.42.

Table 5.22. *Flange bolt shear forces in x-x axis direction.*

Time	Splice load	Bolt shear force		Diff.
		Ansys	Mathcad	
	Fx	X	X	
s	kN	kN	kN	%
0,5	125	2	4	59,1
1,0	250	4	7	58,7
1,5	375	7	11	58,0
2,0	500	9	14	58,0
2,5	625	11	18	57,7
3,0	750	13	21	57,8

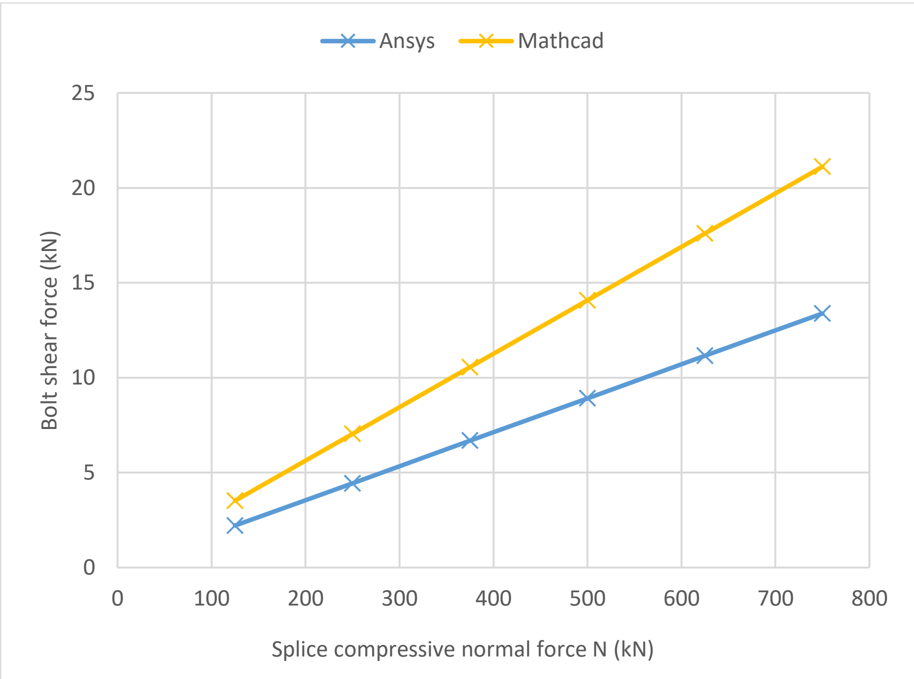


Figure 5.42. *Flange bolt shear forces, bolts no. 1-6.*

The distance between the centers of the end fasteners (480 mm) is slightly above 15*bolt diameter (15*30mm = 450 mm), which is the limit for the long joint [3, p. 29]. Because of the long joint, the distribution of the bolt shear forces within the bolt group in bearing type splice is quite uneven, as shown in table 5.23:

Table 5.23. Flange bolt shear forces in x-x axis direction, bolts no. 1-6.

Time (s)	Bolt No. / Shear force (kN)					
	1	2	3	4	5	6
0,5	4	4	2	2	1	1
1	7	7	4	4	2	2
1,5	11	11	6	6	3	3
2	15	15	8	8	4	4
2,5	18	18	10	10	5	5
3	22	22	13	13	5	5

The shear forces of the bolts are though relatively small. Using only the end bolt shear forces (bolts no. 1 and 2) in FEA, the results are closer to each other as shown in figure 5.43:

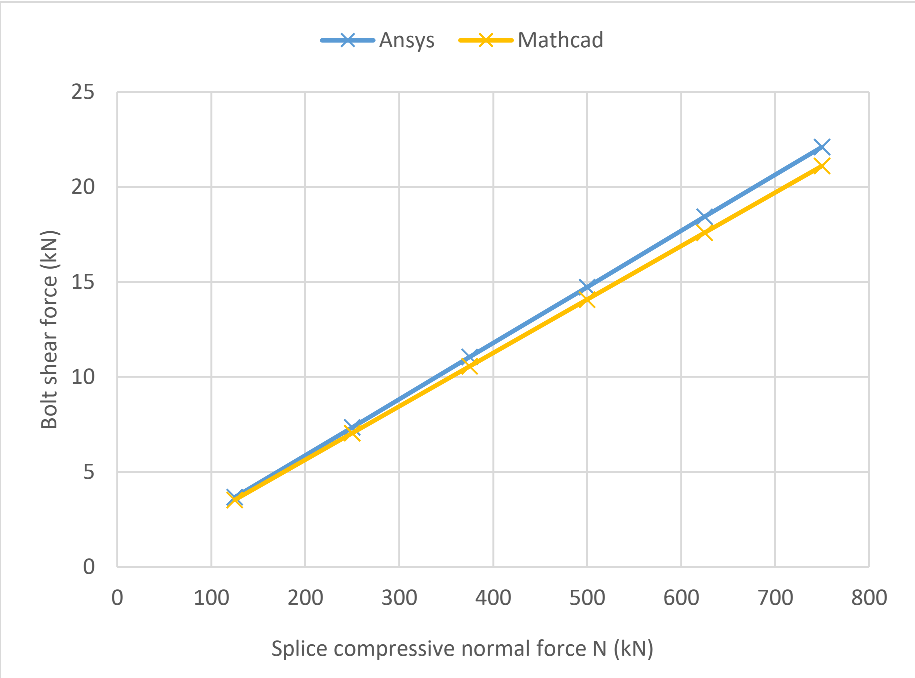


Figure 5.43. Flange bolt shear forces, bolts no. 1 and 2 in FEA model.

5.3.1.3 Web plates

Web plates compression was compared between Mathcad and FEA. The force reactions are shown in table 5.24 and graphics in figure 5.44. As described in chapter 3.5.4, the web plate axial force is calculated by multiplying the design normal force N_{Ed} with the ratio of the plate cross-section area and the total splice cross-section area.

Table 5.24. Web plates combined bending about y-y axis.

Time	Splice load	Force reaction		Diff.
	N	Ansys	Mathcad	
s	kN	kN	kN	%
1,0	250	29	36	27,5
2,0	500	57	73	27,2
3,0	750	86	109	27,1

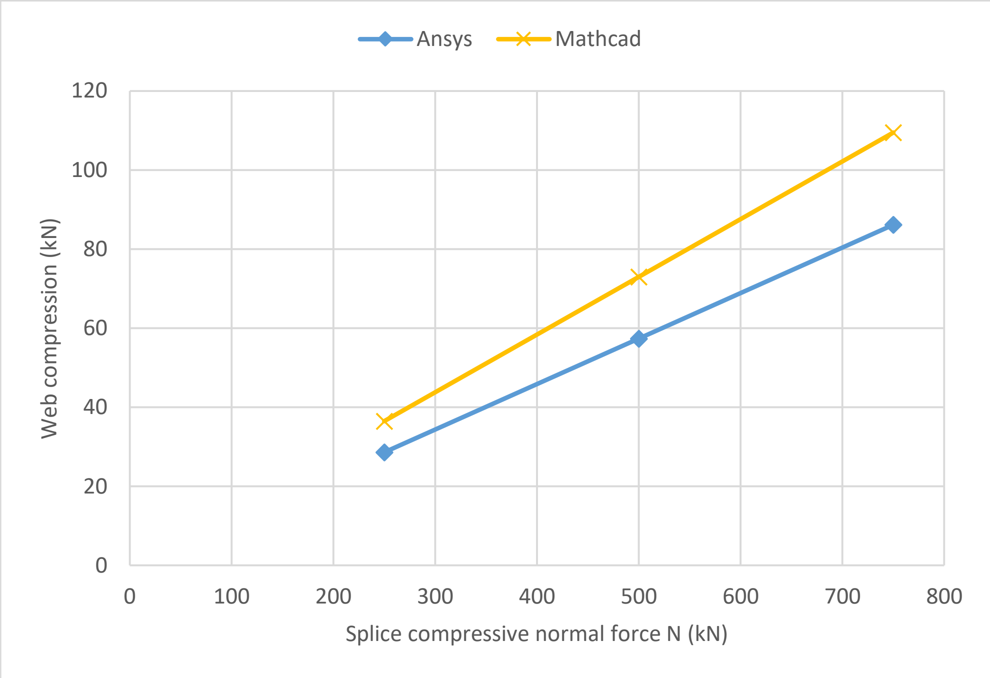


Figure 5.44. Web plates combined bending about y-y axis.

The theory, that stress in the whole web cross-section area is directed to the web plates, leads about 27% higher stress values in Mathcad comparing to results in FEA.

5.3.1.4 Web bolts

Web bolt shear forces were studied for the web bolts no. 1-4 in FEA and the average shear force is shown. At time step 3 in FEA, the shear force varied from 12,5 kN (bolts 3 and 4) to 25,7 kN (bolts 1 and 2). Both FEA and Mathcad web bolt shear force results are shown in table 5.25 and in figure 5.45.

Table 5.25. Web bolt shear forces in x-x axis direction.

Time	Splice load	Bolt shear force		Diff.
		Ansys	Mathcad	
	N	X	X	
s	kN	kN	kN	%
1,0	250	6	9	43,9
2,0	500	13	18	43,5
3,0	750	19	27	43,4

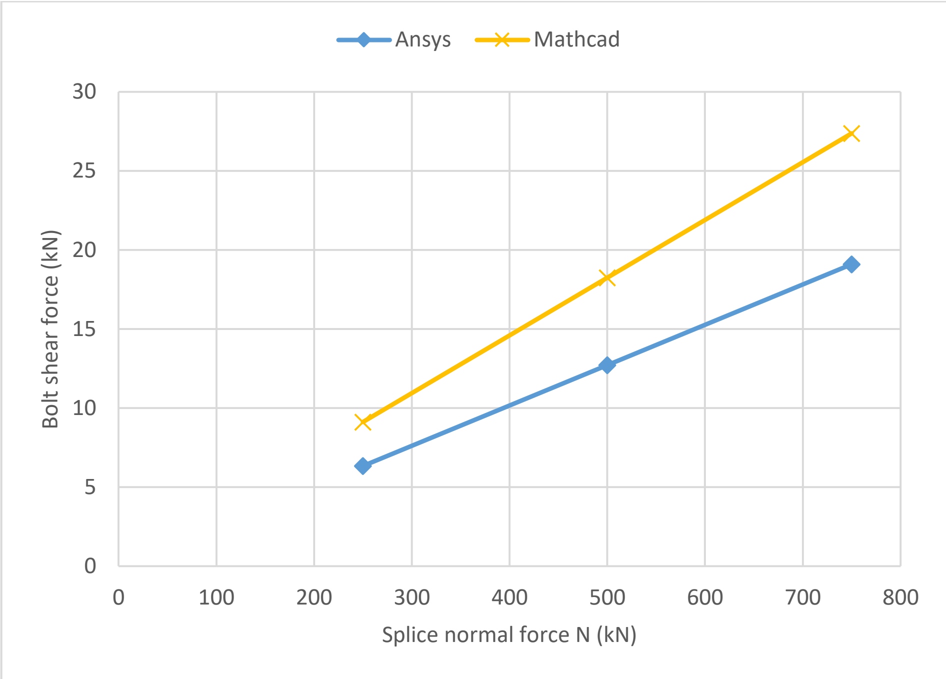


Figure 5.45. Web bolt shear forces.

The ratio of highest/lowest shear force value in FEA was 25,7/12,5 ≈ 2. The difference between shear forces, about 44%, is partly because the theoretical web plates compression in Mathcad is higher than the equivalent force in FEA.

Using the bolt shear forces only from the bolts no. 1 and 2 in FEA, the results are as shown in figure 5.46:

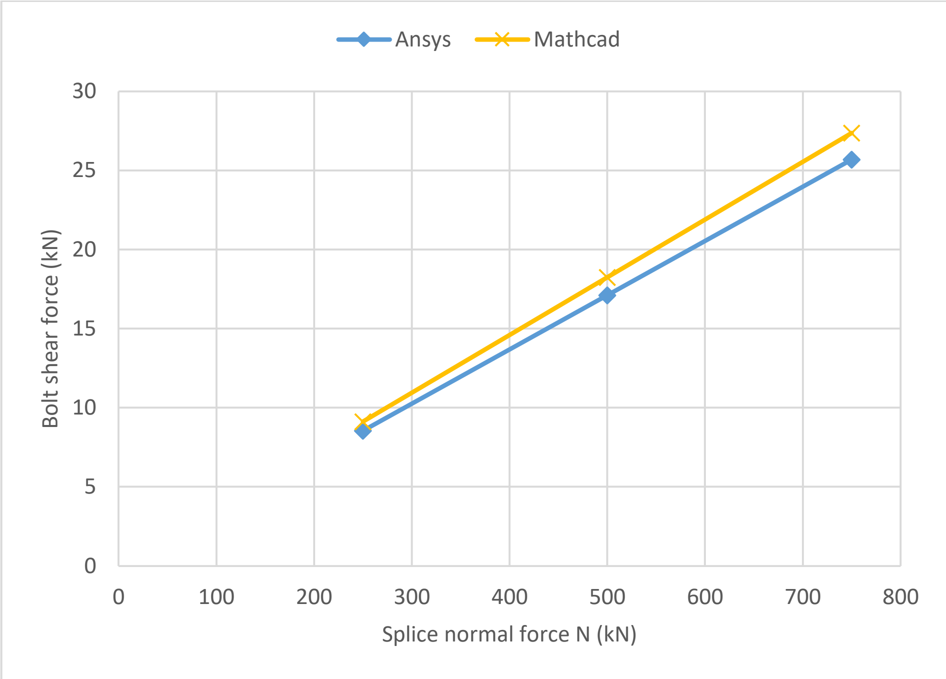


Figure 5.46. *Web bolt shear forces including bolts no. 1 and 2 in FEA model.*

5.3.2 Specimen no. 8: Bending M_y

In the specimen no. 8, the splice was loaded with vertical loads from the bottom of the profile end plates as in the specimen 2. The load was increased 200 kN in 3 load steps, the final load being 600 kN and theoretical bending moment 600 kNm. Results were collected in every 0,5 seconds and last reported time is 3,0 s. Analysis ended to a converged solution.

5.3.2.1 Flange plate

Compressed (top) flange plate axial force was compared between Mathcad and FEA. Plate axial force reactions are shown in table 5.26 and the chart in figure 5.47.

Table 5.26. Flange plate compression.

Time	Splice load	Force reaction		Diff.
	My	Ansys	Mathcad	
s	kNm	kN	kN	%
0,5	100	97	131	36,1
1,0	200	192	261	35,9
1,5	300	289	393	35,7
2,0	400	386	523	35,5
2,5	500	484	654	35,2
3,0	600	584	784	34,2

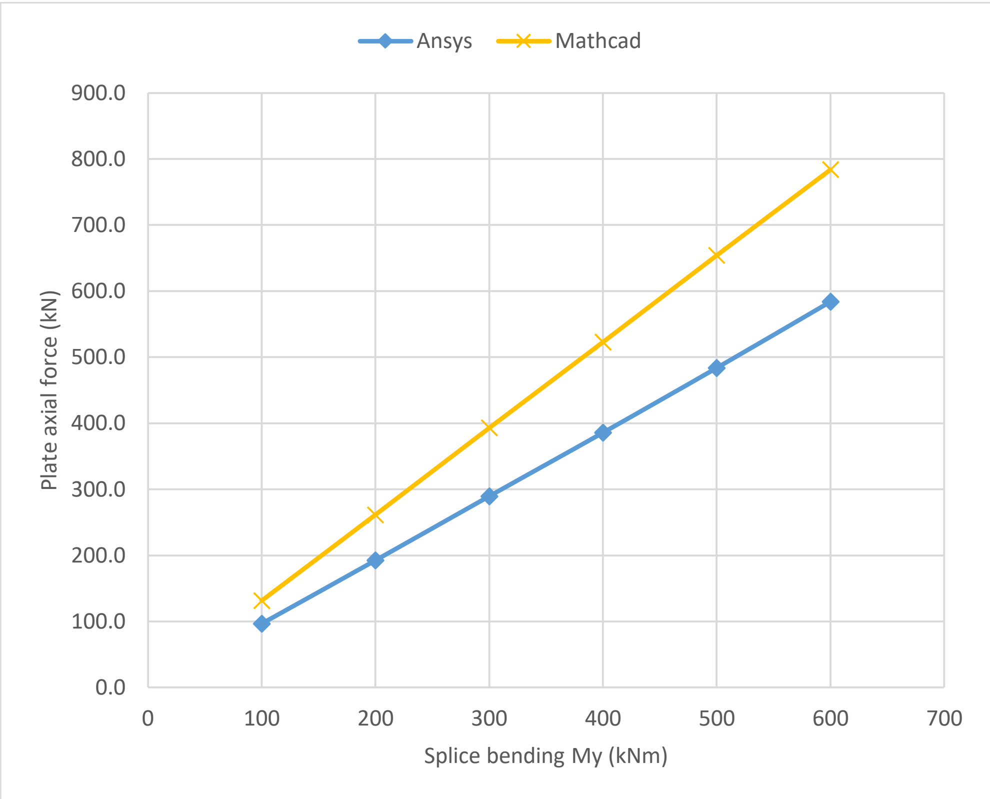


Figure 5.47. Flange plate compression.

The flange compression forces are about 35% on the safe side with the corresponding results of the FEA. This indicates, that the compression force is not moved wholly from the flange into the flange plate via bolts.

The tensioned (bottom) flange plates were compared between Mathcad and FEA. Plate axial force reactions are shown in table 5.27 and the chart in figure 5.48.

Table 5.27. Flange plate tension.

Time	Splice load My	Force reaction		Diff.
		Ansys	Mathcad	
s	kNm	kN	kN	%
0,5	100	217	216	-0,2
1,0	200	431	430	-0,2
1,5	300	646	646	0,0
2,0	400	857	860	0,3
2,5	500	1066	1076	0,9
3,0	600	1263	1289	2,1

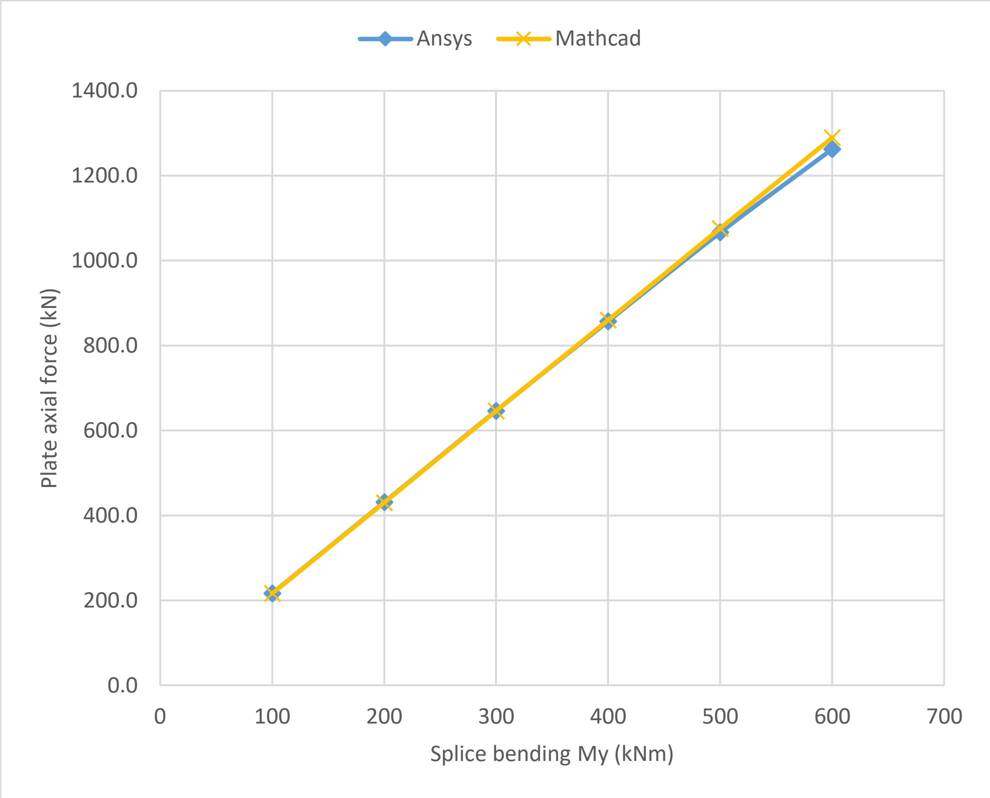


Figure 5.48. *Flange plate tension.*

5.3.2.2 Flange bolts

Top flange bolt shear forces were studied in FEA from the bolts no. 1-6. At time step 3 in FEA, the bolt shear forces varied between 134 kN (bolts 1 and 2) and 38 kN (bolts 5 and 6). The average bolt shear force in FEA together with maximum shear force of the flange bolt in Mathcad are shown in table 5.28 and in figure 5.49.

Table 5.28. *Flange bolt shear forces in the x-x axis direction.*

Time	Splice load	Bolt shear force		Diff.
		Ansys	Mathcad	
	My	X	X	
s	kNm	kN	kN	%
0,5	100	14	22	58,9
1,0	200	27	44	58,8
1,5	300	41	65	58,6
2,0	400	55	87	57,8
2,5	500	70	109	56,5
3,0	600	85	131	54,5

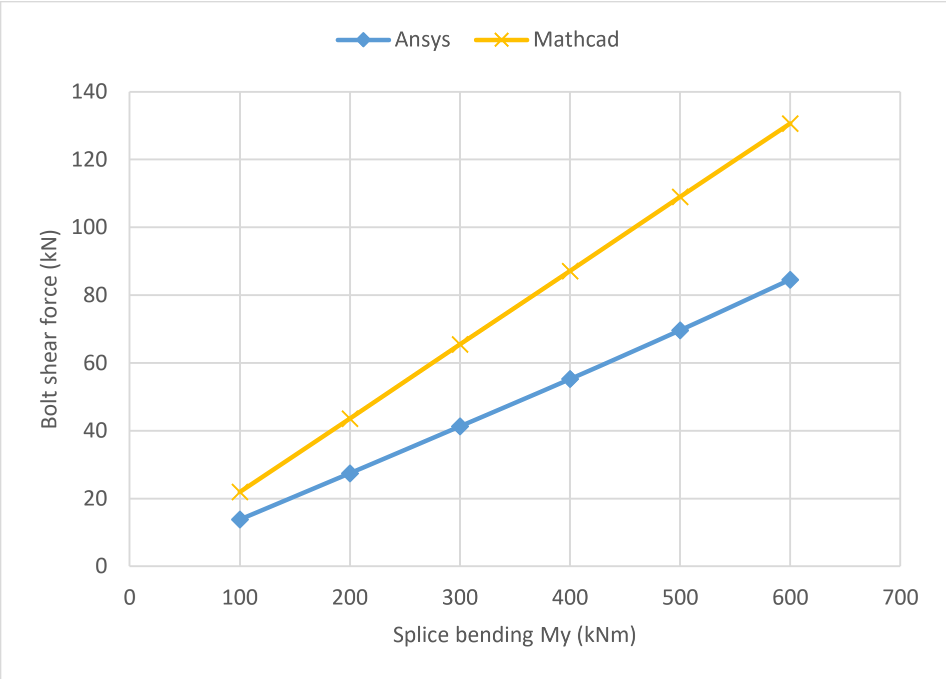


Figure 5.49. *Flange bolt shear forces.*

It was noticed in the FEA, that the maximum bolt shear force (bolts 1 and 2) was 3,5 times the minimum bolt shear force (bolts 5 and 6). The figure 5.50 illustrates the average shear force only from the bolts no. 1 and 2 together with the same Mathcad shear force as in figure above.

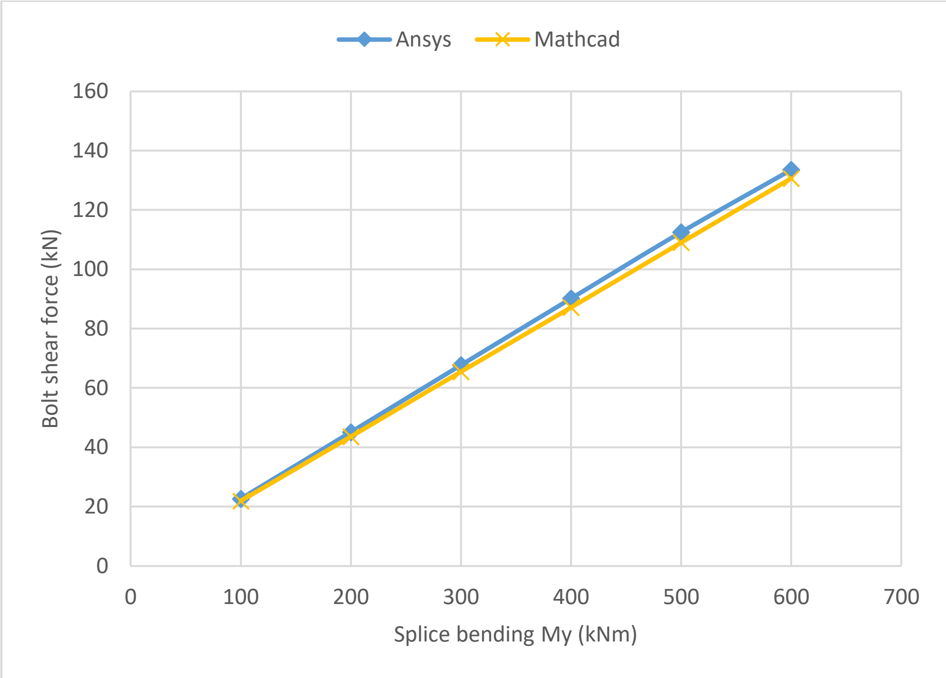


Figure 5.50. *Flange bolt shear forces, bolts no. 1 and 2.*

Bottom flange bolt shear forces were studied in FEA from the bolts no. 1-6. At time step 3 in FEA, the bolt shear forces varied between 190 kN (bolts 1 and 2) and 187 kN (bolts 3 and 4). The average bolt shear force in FEA together with maximum shear force of the flange bolt in Mathcad are shown in table 5.29 and in figure 5.51.

Table 5.29. *Flange bolt shear forces in the x-x axis direction.*

Time	Splice load	Bolt shear force		Diff.
		Ansys	Mathcad	
	My	X	X	
s	kNm	kN	kN	%
0,5	100	31	36	17,8
1,0	200	61	72	17,8
1,5	300	92	108	17,0
2,0	400	124	143	15,4
2,5	500	157	179	14,2
3,0	600	188	215	14,1

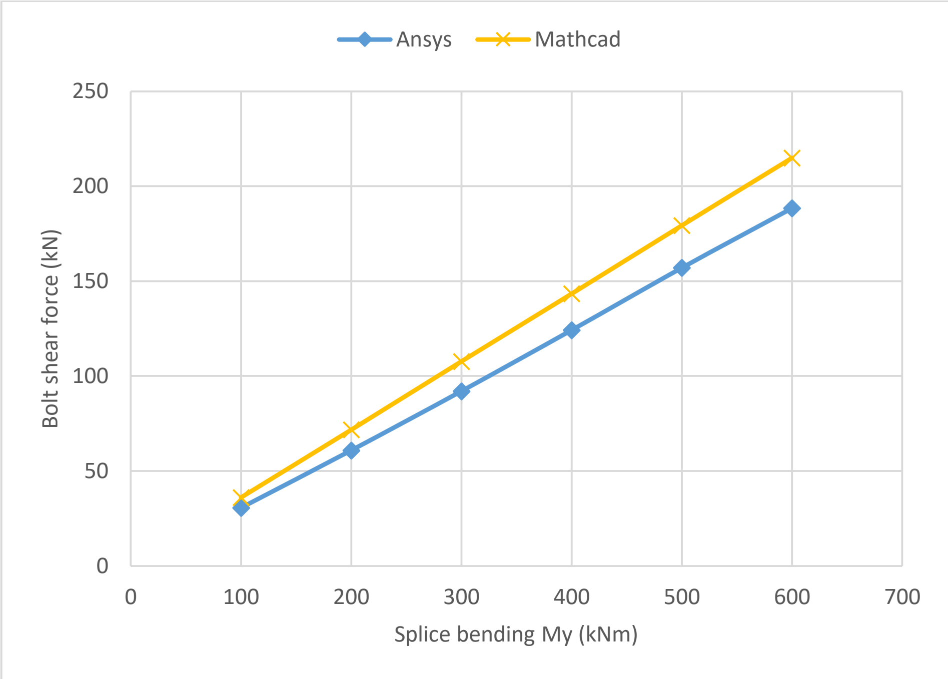


Figure 5.51. Flange bolt shear forces in the x-x axis direction.

Table 5.30 illustrates the difference between the tensioned flange bolt shear forces in the bearing and non-bearing cases. According to the results, the shear force is about 8-9% smaller in the bearing type splice with the same splice bending value (500 kNm).

Table 5.30. The difference in flange bolt shear forces between non-bearing and bearing type splices, bending 500 kNm about y-y axis.

Splice type	Splice load	Bolt shear force	
		Ansys	Mathcad
	My	X	X
	kNm	kN	kN
Non-bearing	500	172	194
Bearing	500	157	179
Difference		-8,9 %	-7,6 %

5.3.2.3 Web plates

Web plates bending about y-y axis was compared between Mathcad and FEA. The moment reactions of the plates are shown in table 5.31 and the chart in figure 5.52.

Table 5.31. Web plates combined bending about y-y axis.

Time	Splice load My	Moment reaction		Diff.
		Ansys	Mathcad	
s	kNm	kNm	kNm	%
0,5	100,0	3	6	91
1,0	200,0	6	12	91
1,5	300,0	9	17	89
2,0	400,0	12	23	88
2,5	500,0	15	29	89
3,0	600,0	18	35	90

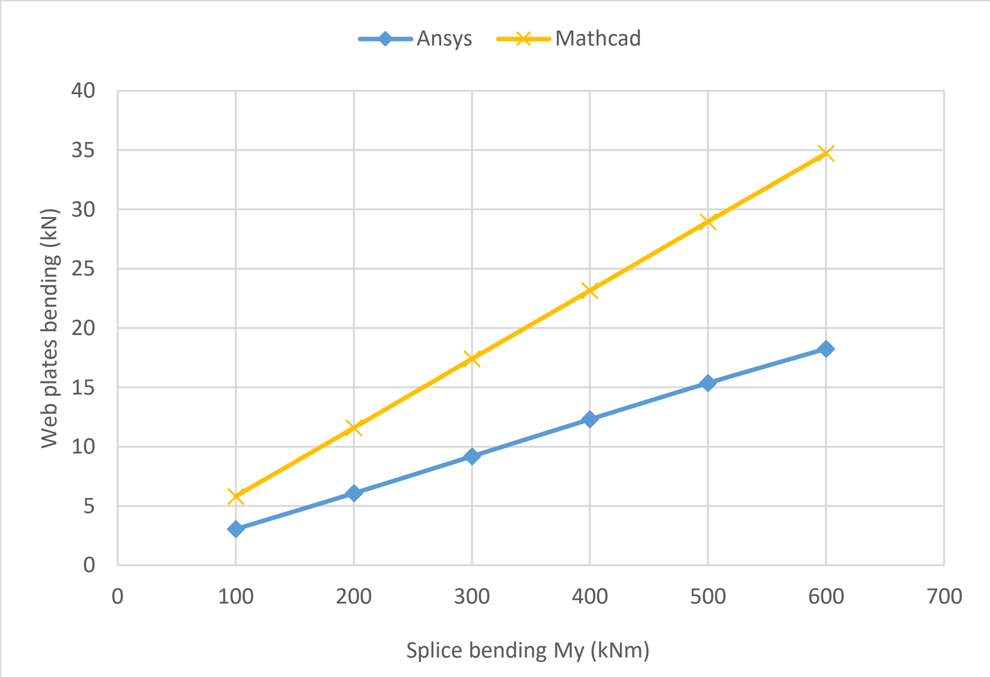


Figure 5.52. Web plates combined bending.

According to the results, the bending moment is clearly on the safe side in Mathcad when calculating with the method shown in chapter 3.5.2.

5.3.2.4 Web bolts

Web bolt shear forces were studied from the web bolts no. 2 and 4 in FEA (see figure 5.53), which were the most stressed bolts in the bolt group. In Mathcad, the maximum bolt shear force is calculated either from the compression side (bolts 1 and 3) or tension side (bolts 2 and 4) of the web plate, whichever causes a bigger force.

In FEA, the shear force components in the x- and z-axis directions are calculated as an average of the component absolute values. In Mathcad, the bolt shear force is calculated only in the x-x axis direction, see ch. 3.4.6. Bolt shear force X- and Z- components and their resultants in FEA are shown in table 5.32 and in figure 5.54, together with Mathcad bolt shear force X-component.

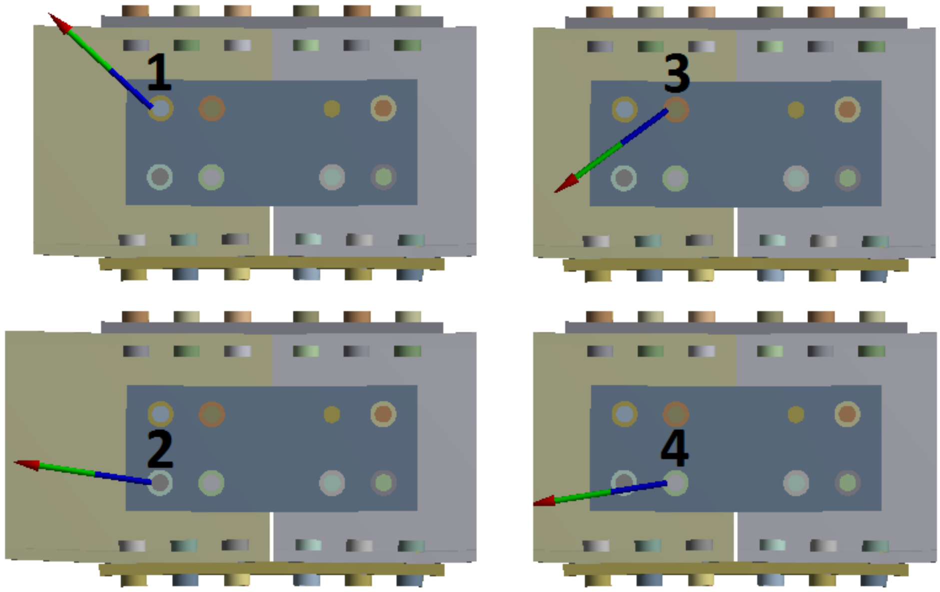


Figure 5.53. *Shear force resultant of the web bolts at time 3 s.*

Table 5.32. *Web bolt shear force components (X and Z) and their resultants in FEA, bolt shear force X-component in Mathcad.*

Time	Splice load	Bolt shear force				Diff.
		Ansys			Mathcad	
	My	X	Z	Res.	X	
s	kNm	kN		kN	kN	%
0,5	100	20	3	21	25	21,5
1,0	200	40	6	41	50	21,7
1,5	300	61	10	62	75	20,5
2,0	400	83	13	84	99	18,8
2,5	500	105	16	106	124	16,7
3,0	600	130	20	132	149	12,9

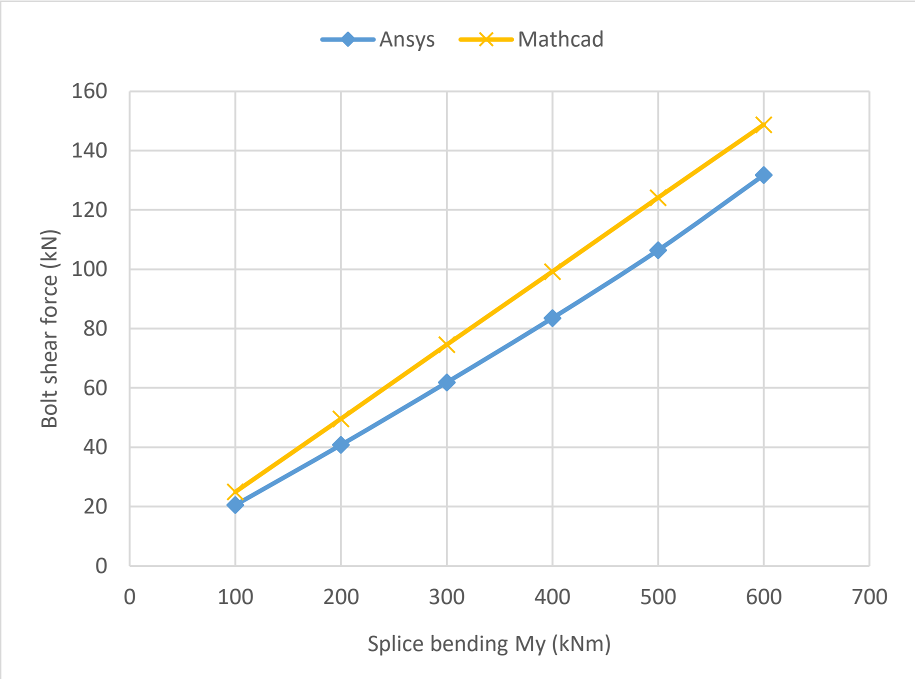


Figure 5.54. *Web bolt shear forces.*

Calculating web bolt shear forces as shown in chapter 3.5.6 produces more accurate results than in the non-bearing case.

5.3.3 Specimen no. 9: Bending M_z

In the specimen no. 9, the splice was loaded with lateral loads from the side of the profile end plates, as in the specimen 3. In this case the beam end rotation about z-z axis was released in supports, thus the theoretical bending moment is calculated by the formula

$$M = F\,a$$

where F is nodal force and *a* is the length of the beam element, 1,0 m. The load was increased 50 kN in 3 load steps, 1 second / step, the final load being 150 kN and theoretical bending moment 150 kNm. The real bending moments of the FEA model are in-line with the theoretical bending moments. Results are collected in every 0,5 seconds and last reported time is 3,0 s. Analysis ended to a converged solution.

5.3.3.1 Flange plate

Flange bending moment about z-z axis in Mathcad was compared to the flange plate bending moment in FEA. Bending moment reactions are shown in table 5.33 and the chart in figure 5.55.

Table 5.33. *Flange plate compression.*

Time	Splice load	Moment reaction		Diff.
	My	Ansys	Mathcad	
s	kNm	kNm	kNm	%
0,5	25,0	8,5	9,5	12,0
1,0	50,0	16,8	18,8	12,0
1,5	75,0	25,3	28,3	12,0
2,0	100,0	33,6	37,7	12,0
2,5	125,0	42,0	47,1	12,3
3,0	150,0	50,1	56,5	12,8

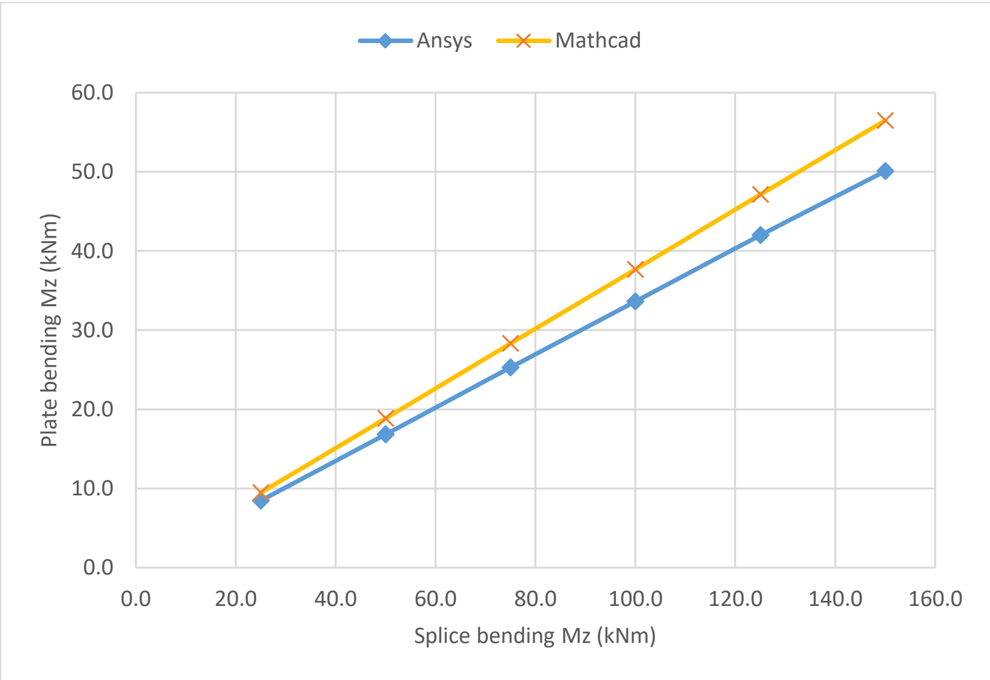


Figure 5.55. *Flange plate compression.*

5.3.3.2 Flange bolts

Bolt no. 2 (see figure 5.56) was the most stressed flange bolts by bolt shear force. The shear force components in x- and y-axis direction and their resultants were calculated in FEA and in Mathcad. The results are shown in table 5.34 and in figure 5.57.

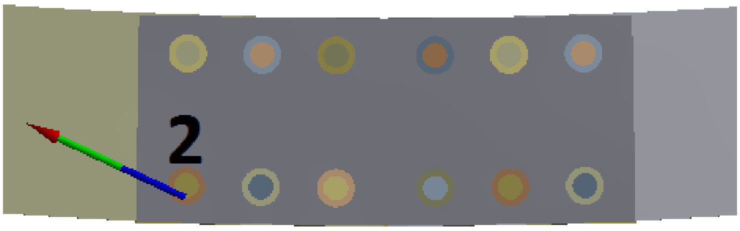


Figure 5.56. Shear force resultant of the flange bolt no. 2 at time 3 s.

Table 5.34. Flange bolt shear forces in the x-x axis direction.

Time	Splice load	Bolt shear force						Diff.
		Ansys			Mathcad			
	Mz	X	Y	Res.	X	Y	Res.	Res.
s	kNm	kN			kN			%
0,5	25	15	8	17	11	16	20	16,0
1,0	50	29	16	33	21	32	39	16,0
1,5	75	44	24	50	32	49	58	16,0
2,0	100	59	32	67	43	65	78	16,6
2,5	125	73	39	83	53	81	97	17,6
3,0	150	85	40	94	64	97	116	24

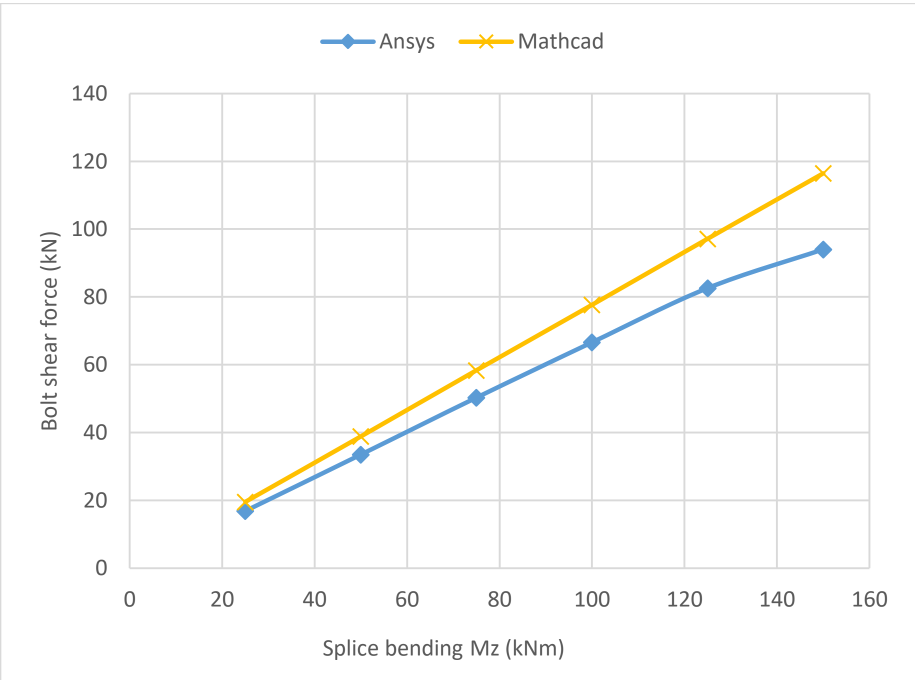


Figure 5.57. Flange bolt shear forces.

5.3.3.3 Web plates

In the bearing type splice, the bending moment Mz is supposed to cause tension for the web plates, as is stated in chapter 3.4.3. The force reactions of the web plates in Mathcad and in FEA are shown in table 5.35 and graphics in figure 5.58. The behavior of the web was slightly non-linear in the FEA model.

Table 5.35. *Web plates combined tension.*

Time	Splice load	Force reaction		Diff.
	Mz	Ansys	Mathcad	
s	kNm	kN	kN	%
1,0	50	45	45	-0,4
2,0	100	90	89	-1,2
3,0	150	152	134	-12,3

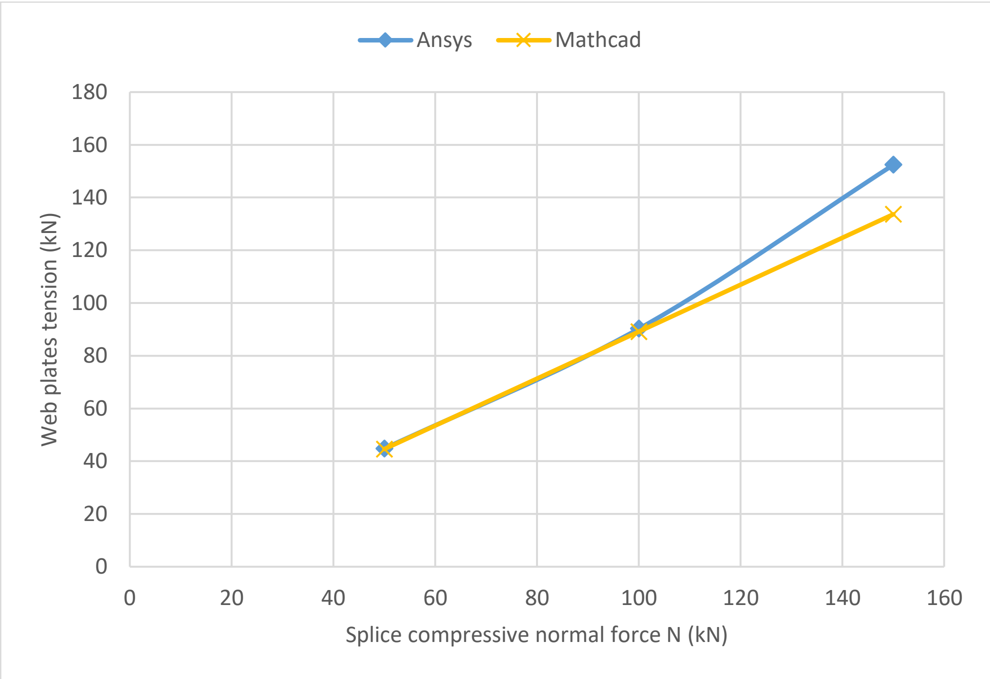


Figure 5.58. *Web plates combined tension.*

5.3.3.4 Web bolts

Web bolt shear forces were studied in FEA from the bolts no. 1-4. At time step 3 in FEA, the bolt shear forces varied between 34,2 kN (bolts 1 and 2) and 35 kN (bolts 3 and 4). The average bolt shear force in FEA together with maximum shear force of the flange bolt in Mathcad are shown in table 5.36 and in figure 5.59. As with the web plate, the behavior of the web bolt was slightly non-linear.

Table 5.36. *Web bolt shear forces in the x-x axis direction.*

Time	Splice load	Bolt shear force		Diff.
		Ansys	Mathcad	
	N	X	X	
s	kN	kN	kN	%
0,5	25	5	6	9,9
1,0	50	10	11	9,9
1,5	75	15	17	9,8
2,0	100	20	22	8,9
2,5	125	26	28	6,4
3,0	150	35	33	-3,4

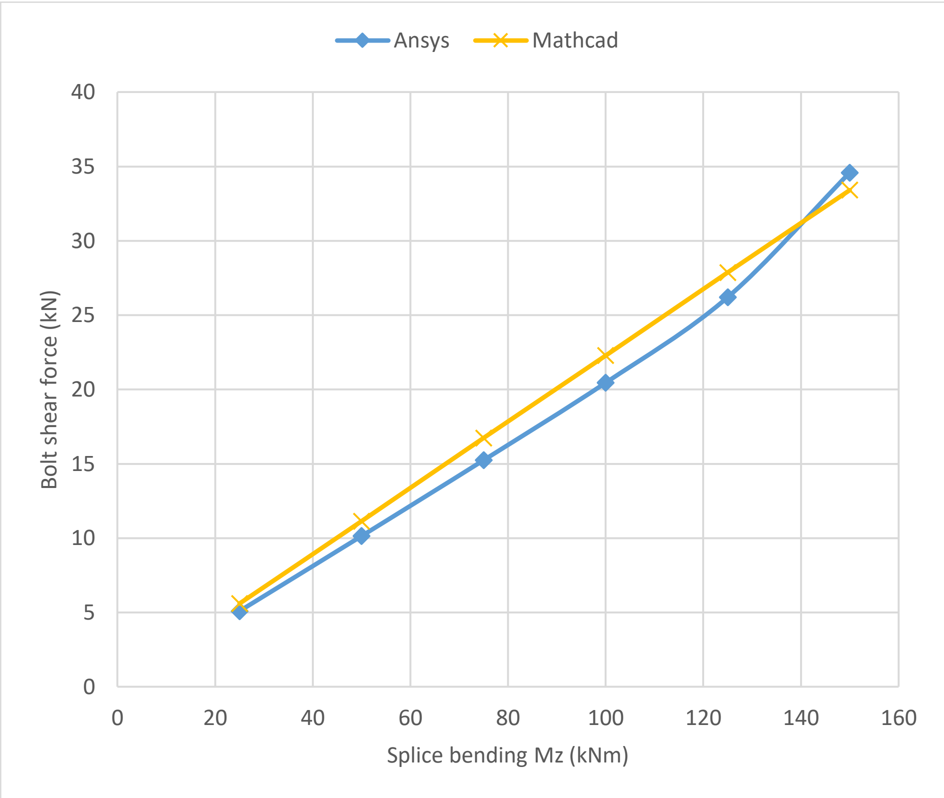


Figure 5.59. *Web bolt shear forces.*

As can be seen from the figure 5.57, there was an equivalent behavior with the flange bolt but into the other direction. It seems, thus, that the force moved more to the web bolts after the bending exceeded 120 kNm near the end. Another reason is probably, that there exists impose forces due to secondary deformations in the web plates area. In the figure 5.60 the beam is shown as splitted in horizontal direction. The figure illustrates a 49x deformation of the splice at the end of the test (3 s.). The web plate tension in the outer side of the web is 99 kN and in the inner side 53 kN, which causes a tilt for the web bolts and in that way, additional forces for the bolts. The more exact study of this issue is ignored in this research.

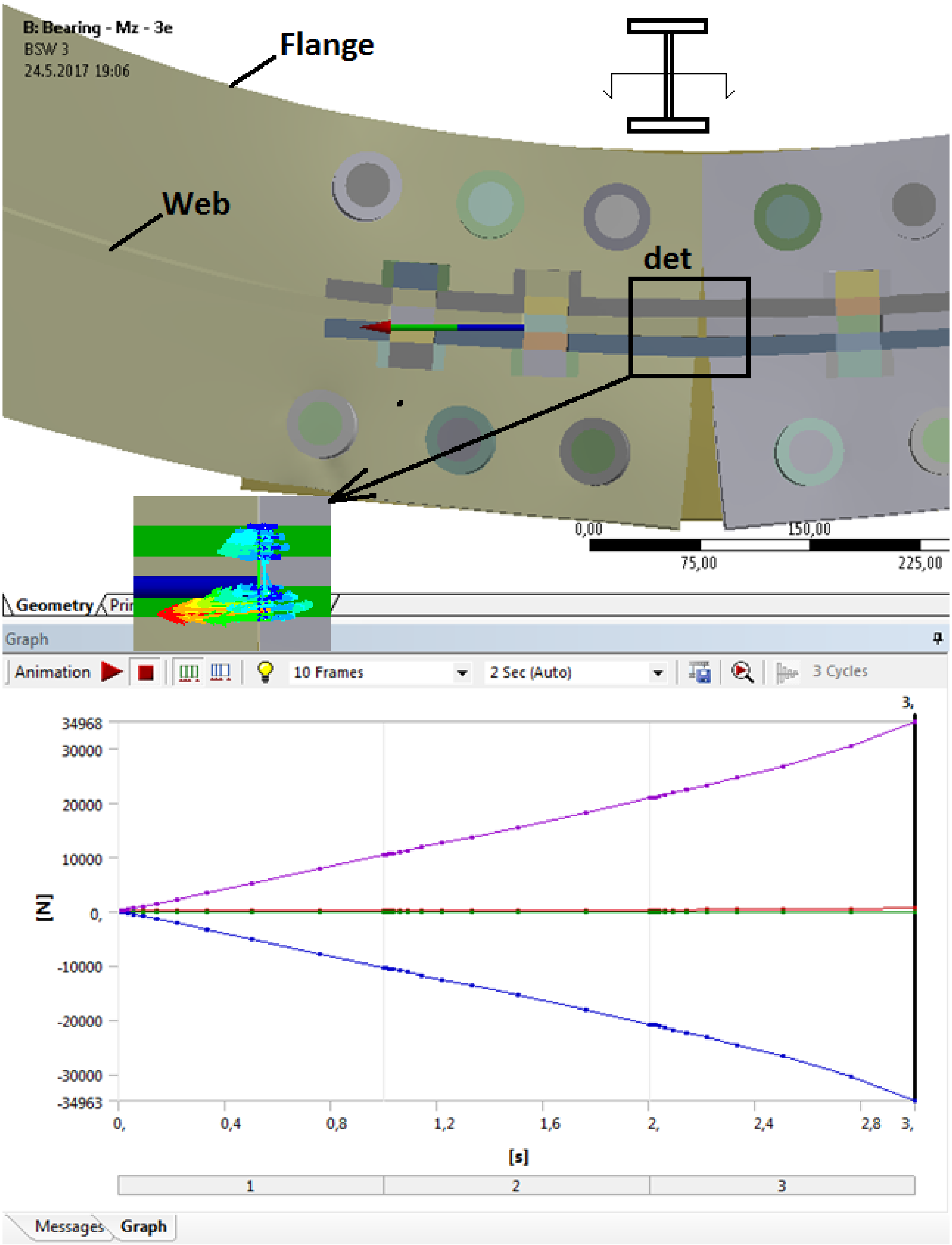


Figure 5.60. Web deformation at time 3 s. (top), shear force graph of the bolt no. 3.

5.3.4 Specimen no. 10: Load combination $M_y + M_z$

In the specimen no. 10, the splice was loaded with vertical and lateral loads from the sides of the profile end plates, as in the specimen no. 5. In vertical direction, the load was increased 200 kN in 3 load steps, the final load being 600 kN and theoretical bending moment 600 kNm. In horizontal direction, the load was increased simultaneously 32 kN in 3 load steps, the final load being 96 kN and theoretical bending moment 30 kNm. The real bending moments about z-z axis of the FEA model are used, which are 0-18 % below the theoretical bending moment values, growing towards the end of the analysis. Results are collected in every 0,5 seconds and last reported time is 3,0 s. Analysis ended to a converged solution.

5.3.4.1 Flange bolts

Bolt no. 6 (see figure 5.61) in tensioned (bottom) flange was the most stressed bolt by bolt shear force. The shear force components in x- and y-axis direction and their resultants were calculated in FEA and in Mathcad. The results are shown in table 5.37 and in figure 5.62.

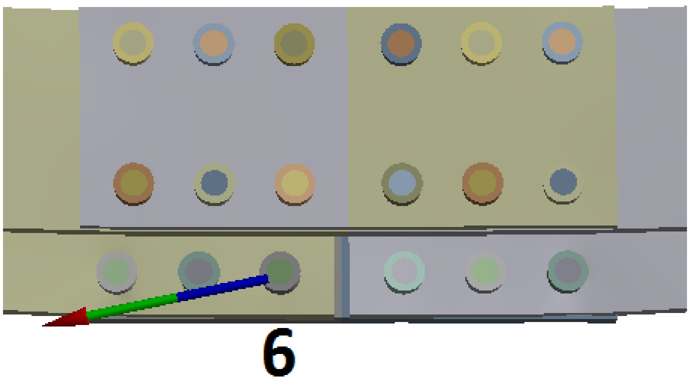


Figure 5.61. *Shear force resultant of the bottom flange bolt no. 6 at time 3 s.*

Table 5.37. *Flange bolt shear force components and resultants.*

Time	Splice load combination		Bolt shear force						Diff.
			Ansys			Mathcad			
	My	Mz	X	Y	Res.	X	Y	Res.	Res.
s	kNm		kN			kN			%
0,5	101	5	33	8	34	39	2	39	16,3
1,0	200	10	66	15	67	78	5	78	16,4
1,5	300	15	99	23	102	117	7	118	15,5
2,0	400	20	133	30	136	156	10	157	14,8
2,5	500	24	165	34	168	195	11	195	16,1
3,0	599	25	192	33	195	231	12	231	19

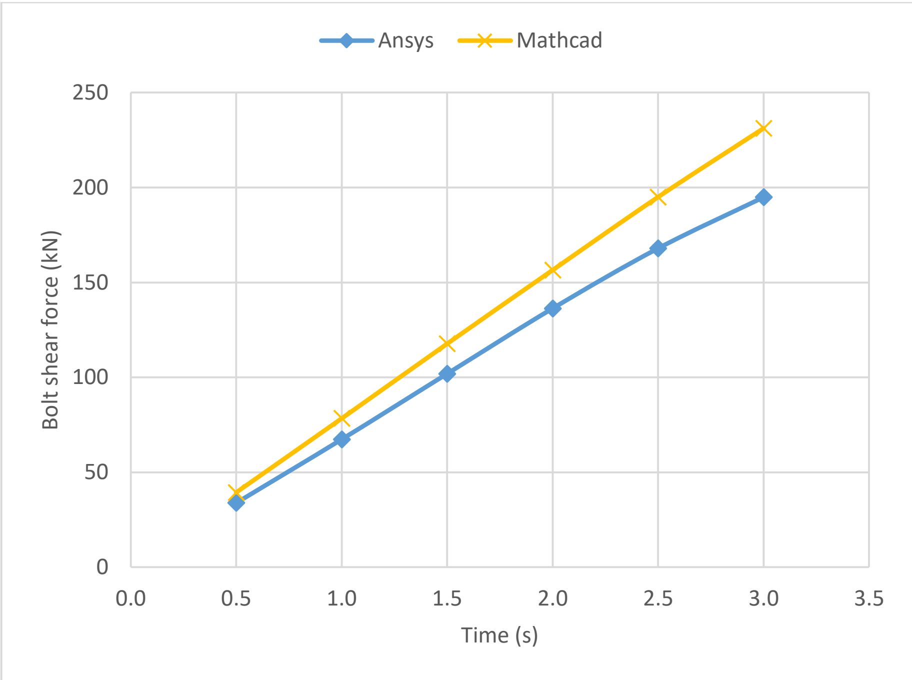


Figure 5.62. *Flange bolt shear forces.*

5.3.4.2 Web bolts

Web bolt shear forces were studied from the web bolts no. 2 and 4 in FEA. The shear force components in x-x and y-y axis direction and their resultant were calculated in FEA and in Mathcad. The results are shown in table 5.38 and in figure 5.63.

Table 5.38. Web bolt shear force components (X and Z) and their resultants.

Time	Splice load		Bolt shear force						Diff.
			Ansys			Mathcad			
	My	Mz	X	Z	Res.	X	Z	Res.	Res.
s	kNm	kNm	kN			kN			%
0,5	101	5	20	1	20	26	0	26	28,3
1,0	200	10	40	1	40	52	0	52	28,5
1,5	300	15	61	2	61	78	0	78	27,1
2,0	400	20	83	2	83	104	0	104	24,8
2,5	500	24	107	1	107	129	0	129	20,9
3,0	599	25	132	1	132	154	0	154	17

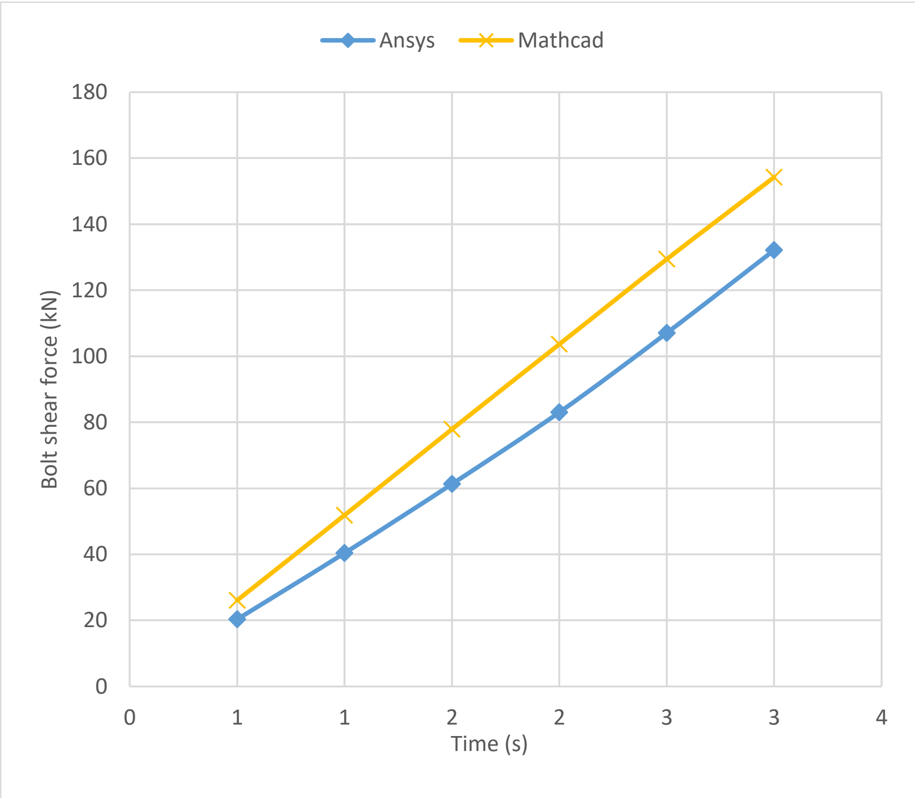


Figure 5.63. Web bolt shear forces.

5.3.5 Specimen no. 11: Load combination N + M_y + M_z

In the specimen no. 11, the splice was loaded with compressive axial force in the end of the other beam element and vertical and lateral loads from the sides of the profile end plates, as in the specimen no. 6. There were 6 load steps in all. The axial (X) force was increased 250 kN in first 3 load steps, the final load being 750 kN through the load steps 3-6. At load step 4, the vertical load (Y) was increased 150 kN in every 3 load steps, the final load being 450 kN. At the same time, the horizontal load (Z) was increased 32 kN in 3 load steps, and the final load was 96 kN. The load chart is shown in table 5.39. The real bending moments of the FEA model are used, which differs a little from the theoretical values. Results are collected in every 0,5 seconds and last reported time is 6,0 s. Analysis ended to a converged solution.

Table 5.39. *Loads in FE-analysis.*

Step	Time (s)	X (kN)	Y (kN)	Z (kN)
0	0	0	0	0
1	1	-250	0	0
2	2	-500	0	0
3	3	-750	0	0
4	4	-750	150	32
5	5	-750	300	64
6	6	-750	450	96

5.3.5.1 Flange bolts

Bolt no. 1 (see figure 5.64) was the most stressed flange bolt by shear force. The bolt shear force components in x- and y-axis direction and their resultant were calculated in FEA and in Mathcad. The results are shown in table 5.40 and in figure 5.65.

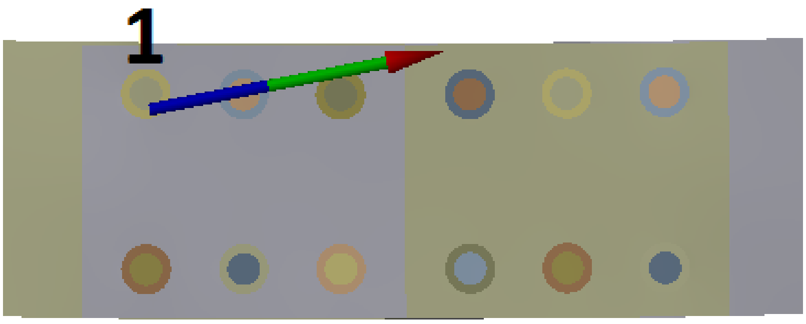


Figure 5.64. *Shear force resultant of the flange bolt no. 1 at time 6 s.*

Table 5.40. Flange bolt shear forces in the x-x axis direction.

Time	Splice load combination			Bolt shear force						Diff.
				Ansys			Mathcad			
	N	My	Mz	X	Y	Res.	X	Y	Res.	Res.
s	kN	kNm		kN			kN			%
0,5	125	0	0	4	0	4	4	0	4	-4,7
1,0	250	0	0	7	1	7	7	0	7	-4,9
1,5	375	0	0	11	1	11	11	0	11	-5,3
2,0	500	0	0	15	2	15	14	0	14	-5,3
2,5	625	0	0	18	2	19	18	0	18	-5,4
3,0	750	0	0	22	3	22	21	0	21	-5,4
3,5	750	76	5	41	6	41	40	3	40	-2,4
4,0	750	152	10	60	10	61	59	5	59	-3,5
4,5	750	228	15	80	13	81	77	7	78	-4,5
5,0	750	303	21	100	17	101	96	10	96	-4,5
5,5	750	379	26	118	21	119	115	12	115	-3,4
6,0	750	455	30	131	25	133	133	15	134	0,4

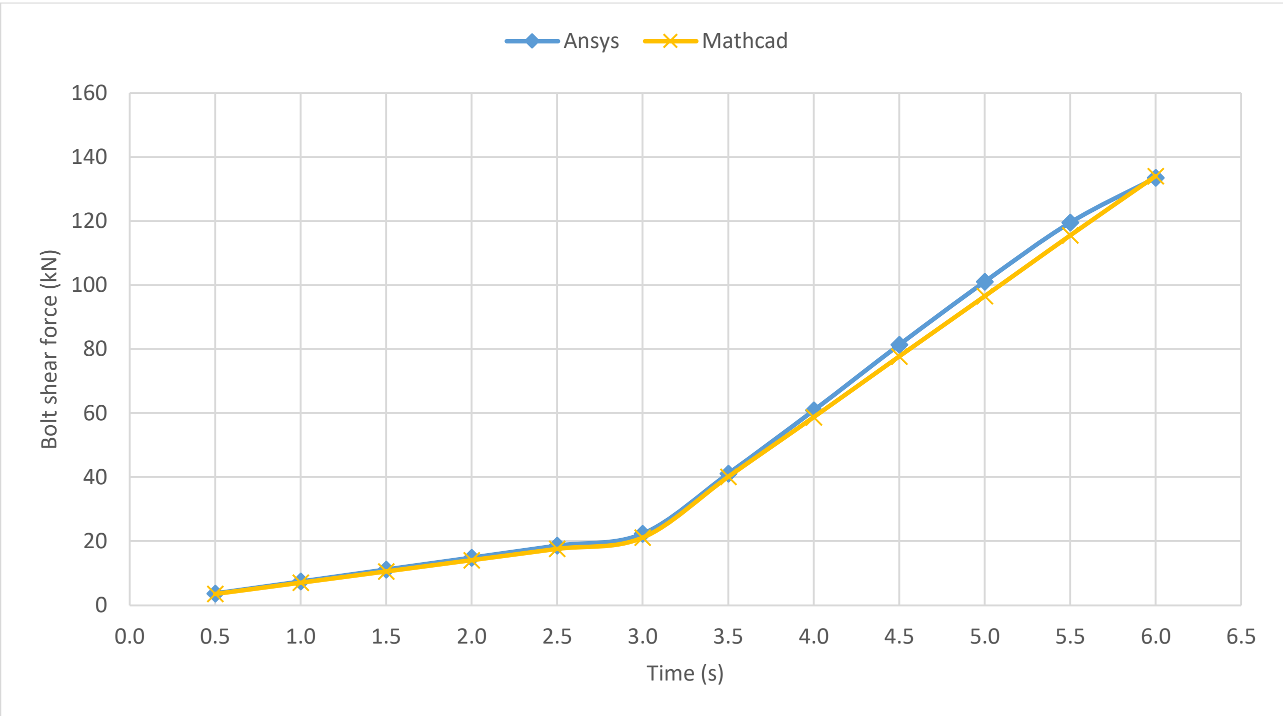


Figure 5.65. Flange bolt shear forces.

5.3.5.2 Web bolts

Web bolt shear forces were studied from the web bolts no. 2 and 4 in FEA (see figure 5.66), which were the most stressed bolts in the bolt group. In Mathcad, the maximum bolt shear force is calculated either from the compression side (bolts 1 and 3) or tension side (bolts 2 and 4) of the web plate, whichever causes a bigger force.

In FEA, the shear force components in the x- and z-axis directions are calculated as an average of the component absolute values. In Mathcad, the bolt shear force is calculated only in the x-x axis direction, see chapter 3.5.6. Bolt shear force X- and Z- components and their resultant in FEA are shown in table 5.41 and in figure 5.67, together with Mathcad bolt shear force X-component.

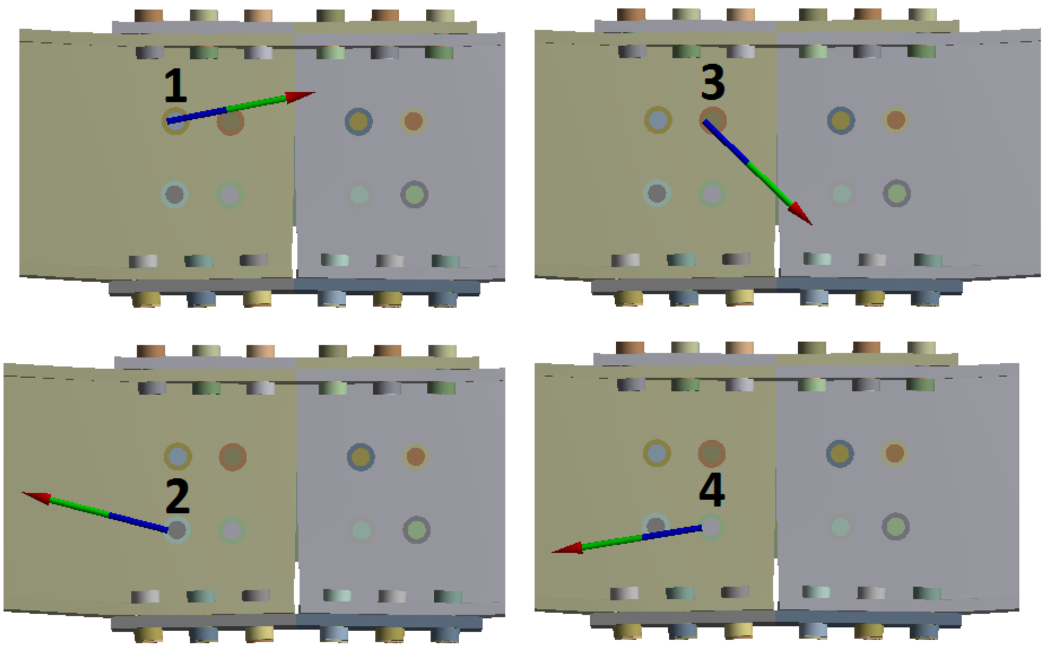


Figure 5.66. *Shear force resultant of the web bolts at time 3 s.*

Table 5.41. Web bolt shear force components and resultants.

Time	Splice load			Bolt shear force						Diff.
				Ansys			Mathcad			
	N	My	Mz	X	Z	Res.	X	Z	Res.	Res.
s	kN	kNm	kNm	kN			kN			%
0,5	125	0,0	0,0	3	0	3	5	0	5	43,4
1	250	0,0	0,0	6	-1	6	9	0	9	43,4
1,5	375	0,0	0,0	10	-1	10	14	0	14	42,9
2	500	0,0	0,0	13	-1	13	18	0	18	43,0
2,5	625	0,0	0,0	16	-1	16	23	0	23	42,8
3	750	0,0	0,0	19	-2	19	27	0	27	43
3,5	750	76,2	5,4	15	-2	15	7	0	7	-51
4	750	151,6	10,2	7	-2	8	-13	0	-13	66
4,5	750	227,8	15,4	-9	0	-9	-33	0	-33	279
5	750	303,2	20,6	-23	1	-23	-53	0	-53	127
5,5	750	379,4	25,8	-38	1	-38	-73	0	-73	89
6	750	454,8	30,4	-54	2	-55	-92	0	-92	69

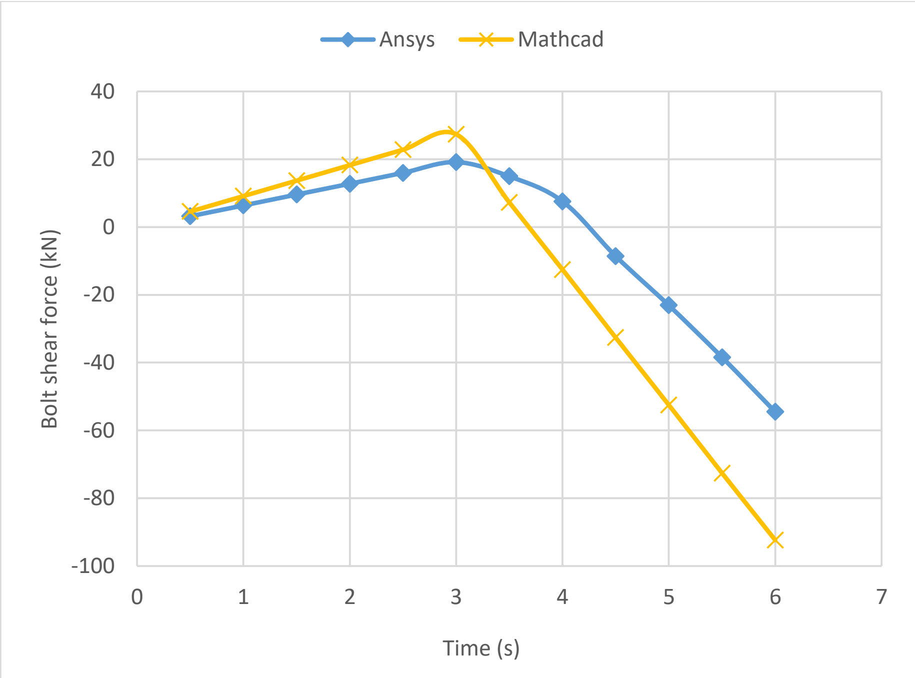


Figure 5.67. Web bolt shear forces.

6. WORKED EXAMPLE

6.1 A comparison between the example in SCI P398 and Mathcad

An example of the non-bearing, bolted beam splice has been calculated by SCI and BCSA in the publication P398 [6, pp. 127-140]. A comparison between the example D.1 in the publication and Mathcad calculation for the similar joint was made. Some specifications of the profile and bolt group used in the calculations can be found in table 6.1. Some minor differences come from the rounding of the values in P398:

Table 6.1. *Profile and bolt group specifications*

	P398	Mathcad	Unit	Description
A	85,5	85,5	cm^2	Profile cross-section area
Aw	36,4	36,4	cm^2	Web cross-section area
I_y	29400	29400 (a_w = 4,77 mm)	cm^4	Profile
$I_{w,y}$	5550	5554	cm^4	Web, welds not included
$I_{p,wb}$	68400	68438	cm^4	Web bolt group

Flange axial forces from the normal force N_{Ed} and bending $M_{y,Ed}$ and their combinations in the compressed and the tensioned side of the joint are specified in table 6.2:

Table 6.2. *Flange forces*

	P398	Mathcad	Unit	
$F_{f,x,N}$	43	43	kN	Axial force from N_{Ed}
$F_{f,x,My}$	368	362	kN	Axial force from $M_{y,Ed}$
$F_{f,c,Ed}$	368+43 = 411	362+43 = 405	kN	Force combination in the compression side
$F_{f,t,Ed}$	368-43 = 325	362-43 = 319	kN	Force combination in the tension side

Flange bolt shear forces in the compressed and the tensioned flange are compared in table 6.3. Only minor differencies can be seen:

Table 6.3. *Flange bolt shear forces*

	P398	Mathcad	Unit	
$V_{fb,x,c,Ed}$	411/6 = 68,5	405/6 = 67,5	kN	Bolt shear force, compression side
$V_{fb,x,t,Ed}$	325/6 = 54,2	319/6 = 53,2	kN	Bolt shear force, tension side

Web axial force from the normal force N_{Ed}, shear $V_{z,Ed}$ and bending $M_{y,Ed}$ and their combination are specified in table 6.4:

Table 6.4. *Web forces*

	P398	Mathcad	Unit	
$F_{w,x,N}$	63,9	63,8	kN	Axial force from N_{Ed}
$V_{w,Ed}$	150	150	kN	Shear force from V_{Ed}
$M_{w,y,My}$	37,8	37,8	kNm	Portion of the bending $M_{y,Ed}$
$M_{w,y,Vz}$	16,9	16,9	kNm	Portion of the eccentricity of the $V_{z,Ed}$
$M_{w,y,Ed}$	37,8+16,9 = 54,7	37,8+16,9 = 54,7	kNm	Total bending of the web

Web bolt shear forces in the compressed and the tensioned flange are compared in table 6.5. The results are equal in practice:

Table 6.5. *Web bolt shear forces*

	P398	Mathcad	Unit	
$F_{w,x,N}$	10,7	10,6	kN	Normal force N_{Ed}
$F_{w,x,My}$	95,4	95,8	kN	From $M_y + V_z$ in the compression side
$F_{w,x,Ed}$	10,7+95,4 = 106,1	10,6+95,8 = 106,4	kN	Force combination in the compression side
$F_{w,z,V}$	25	25	kN	Shear force V_z
$F_{w,z,V,ecc}$	33,8	33,9	kN	The eccentricity of the shear force V_z
$F_{w,z,Ed}$	25+33,8 = 58,8	25+33,9 = 58,9	kN	Force combination
$F_{wb,Ed}$	$\sqrt{(106,1^2 + 58,8^2)}$ = 121,3	$\sqrt{(106,4^2 + 58,9^2)}$ = 121,6	kN	Bolt shear force

7. SUMMARY AND CONCLUSIONS

7.1 Non-bearing type splice

A summary of the test results in chapter 5 is showed in tables below. The average value of the differences of all load steps is shown for each specimen. For example, in the specimen 2, the average value of the differences in the flange bolt shear forces is 14,7% as shown in table 7.1.

Table 7.1. *An example: average value of the differences in the flange bolt shear forces.*

Time	Splice load	Bolt shear force		Diff.
		Ansys	Mathcad	
s	My kNm	X kN	X kN	%
0,5	125	42	49	19,2
1,0	250	83	97	16,5
1,5	375	127	146	14,1
2,0	500	172	194	12,6
2,5	625	218	243	11,1
			Avg.	14,7

The difference (%) indicates, how much bigger or smaller the result in Mathcad is comparing to the result in FEA. If a result is marked with "-" in table, it is not calculated. Because the flange forces were not available separately in FEA, the flange force in Mathcad is compared to the flange plates combined force in FEA. The results are shown in table 7.2. In the specimen 2, compression (c) and tension (t) sides of the splice are shown separately.

Table 7.2. *Flange forces / flange bolt shear forces*

Specimen no.	Load / load combination	Difference, flange axial force/bending (%)	Difference, flange bolt shear force (%)
1	N	-1,4	16,9
2	My	-0,5 (c) / 5,8 (t)	14,7 (c) / 22,2 (t)
3	Mz	0,5	17,9
4	Vz	-	-
5	My + Mz	-	20,9
6	N + My + Mz	-	5,1

Respectively, the web force in Mathcad is compared to the web plates combined force in FEA. The results are shown in table 7.3.

Table 7.3. *Web forces / web bolt shear forces*

Specimen no.	Load / load combination	Difference, web axial force/bending (%)	Difference, web bolt shear force (%)
1	N	3,4	16,1
2	My	137,8	154,3
3	Mz	-	-
4	Vz	70,6	43,9
5	My + Mz	-	163,8
6	N + My + Mz	-	88,2

Based on the results of the 6 specimens analyzed with 4 load cases and 2 load combinations, the following conclusions are made:

Flange, table 7.2:

- In the specimen 1, 2 and 3, flange axial forces and bending moment about z-z axis are in-line with the corresponding results of the flange plate in FEA. The difference between the flange bolt shear forces varies between 14,7-22,2 % and are on the safe side.
- In the specimen 5 and 6, the difference between flange bolt shear forces varies between 5,1-20,9%, being on the safe side.
- The results can be kept acceptable otherwise, but the 20% excess can be too much in some cases.

Web, table 7.3:

- In the specimen 1, the web axial force is in-line with the results of the web plates axial force in FEA. Web bolt shear force in the same specimen is 16,1% bigger in Mathcad calculation.
- In the specimen 2, 4, 5 and 6, a significant difference between Mathcad and FEA results in the web and web bolt shear forces can be found. This was due to the difference of the force distribution between flanges and web in bending about y-y axis. According to the results, the real bending force in the web is not divided as a ratio of the whole cross-section area of the web.
- Flange forces and flange bolt shear forces can be kept quite realistic. Being on the safe side, Mathcad calculation results are acceptable. On the other hand, the web forces and web bolt shear forces are very conservative and, it that way, does not correspond to the results of the FEA. An additional research is needed for finding the more accurate results for web forces.

7.2 Bearing type splice

Flange and web plate forces and bending are compared between Mathcad and FEA. The results are shown in tables 7.4 and 7.5. In the specimen no. 8, compression (c) and tension (t) sides of the splice are shown separately.

Table 7.4. *Flange forces / flange bolt shear forces*

Specimen no.	Load / load combination	Difference, flange axial force/bending (%)	Difference, flange bolt shear force (%)
7	N	35,1	58,2
8	My	35,4 (c) / 0,5 (t)	57,5 (c) / 16 (t)
9	Mz	12,2	17,1
10	My + Mz	-	16,3
11	N + My + Mz	-	-3

Table 7.5. *Web forces / web bolt shear forces*

Specimen no.	Load / load combination	Difference, web axial force/bending (%)	Difference, web bolt shear force (%)
7	N	27,3	6,7
8	My	89,7	18,7
9	Mz	-4,6	6,9
10	My + Mz	-	24,4
11	N + My + Mz	-	96,5

Based on the results of the 5 specimens analyzed with 3 load cases and 2 load combinations, the following conclusions are made:

Flange, table 7.4:

- In the specimen 7 and 8, the flange compression forces are about 35% on the safe side with the corresponding results of the FEA, and, therefore, also bolt shear forces are significantly higher in Mathcad calculation. This indicates, that the compression force is not moved wholly from the flange into the flange plate via bolts.

Web, table 7.5:

- In the specimen 8, the web bending about y-y axis is almost 90% bigger in the Mathcad calculation. The portion of the moment for the web is too big when calculating with the method shown in chapter 3.5.2, so it must be studied more to achieve better results.

- In the specimen 9 the difference of the web axial force was negative by way of exception, and grew towards the end of the test. However, the difference was quite small. The possibly reasons for the growing of the force is explained more in the chapter 5.3.3.
- In the specimen 7-10, the web bolt shear forces are calculated with a method, which produces quite accurate results in this case.
- In the specimen 11 the shear forces are relatively small during the first 5 seconds, but their relative difference is big as the values varies from positive to negative side at different times. The difference in the end of the specimen is 69%, which is still very conservative value but analogous to the web bending.

Topics for the future research by FEA for both the non-bearing and bearing type splice could be as follows:

- deformations of the profile, plates and bolts during the load increment,
- the development of the bolt tension force during the load increment,
- the effect of the imposed loads because of the deformations of the splice members for the bolt shear forces,
- determining the stiffness for the bolt and bolt group for the calculations,
- the effect of the bolt (group) stiffness for the stress distribution, especially between the flange and flange plate in the bending about y-y axis,
- determining the moment for the web more accurately in bending about y-y axis,
- considering the effect of the friction between profile and plates in analysis and
- the capacity and behavior of the splice in ultimate stress, especially the bearing type splice under biaxial bending.

In the future, splice could be researched more closely for to study both the linear and nonlinear behavior of the splice members, as the researches or tests of the biaxially loaded splice discussed in this thesis is very little available.

The calculation method can be developed further to achieve more accurate results. The variety of the bolt assembly must be expanded to include more than 2 bolt rows in the beam longitudinal distance. Finally, the splice must be tested with a wide variety of the beam sizes.

The main purpose of this work, to find joint stresses and bolt shear forces by calculations, seems to be fulfilled, when talking about the non-bearing splice. In the question of the bearing type splice, the work was partially successful. The calculation method shown in this research acts as one kind of basis for the future developing of the splice design program. All results are not acceptable, but with adjusting certain fields in the theory, the useful calculation can be achieved.

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