Suppressing Torsional Buckling Effects of Angle Members

Application on lattice towers

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Preface

This thesis was made in collaboration with the Department of Civil, Environmental and Natural recourses engineering - Institute of steel construction at Luleå Technical University.

We wrote this thesis to further develop our knowledge of steel and the finite element method. Our hope is that the idea presented in this project will be developed and used practically in the future.

We want to extend our gratitude to senior lecturer Efthymios Koltsakis and PhD Panagiotis Manoleas whom have given us a presentation to this field of work. We are very grateful for their help and guidance throughout the project.

Luleå, June 2017.
Abstract

Wind towers are a today under a global development and many countries put more focus on this environmentally friendly way of producing electricity. The performance requirement increase and at the same time the wind towers should be economical. One way of achieving better performance is to build higher towers which increase the harvesting efficiency. One way of achieving high towers is to use a lattice structure. High lattice towers require more material and have a more demanding structural design. By using cold form steel angles as columns for the lattice tower the aim is to achieve a high utilization ratio of the steel angels. Angle members are susceptible to torsional buckling, which is often the critical mode. It is thus essential to enhance their torsional response.

The four columns in a lattice tower are restrained against sideway displacements by the braces and diagonals, which limits their flexural bucking length. In contrast, restraining the torsional rotations is challenging. As angels are susceptible to torsion and the flexural buckling length is decreased, the flexural-torsional interaction becomes significant.

The objective of this study is to investigate thin walled angle members under compression. The idea for this project is to increase the torsional properties of an angle by lacing together the free ends of its two legs. If the lacing acts like a plate the angle columns can behave similar to a closed section. The aim will be to increase the buckling resistance of the angle column. The design is assessed through GMNIA investigations in the FEM program Abaqus and compare laced columns to their unlaced counterparts. Using this method the result will show how the buckling resistance and buckling mode is affected by the lacing.

The results of this study showed that lacing had a positive effect on columns in cross-section class 4. Columns in these two classes reached a higher buckling resistance and the buckling mode shifted from torsional buckling to localized buckling. The result showed increased effect by using a higher density of lacing.
## Notations

**Latin capital letters**

- \( A \)  
  Cross-sectional area  
  [mm\(^2\)]
- \( A_{eff} \)  
  Effective cross-sectional area  
  [mm\(^2\)]
- \( C \)  
  Centroid of the cross-section  
  [mm]
- \( E \)  
  Modulus of elasticity  
  [N/mm\(^2\)]
- \( I \)  
  Moment of inertia  
  [mm\(^4\)]
- \( I_t \)  
  Uniform torsion section constant  
  [mm\(^4\)]
- \( G \)  
  Modulus of rigidity  
  [Pa]
- \( L \)  
  Length of column  
  [mm]
- \( L_{cr} \)  
  Critical length of column  
  [mm]
- \( N_{b,Rd} \)  
  Design buckling resistance  
  [kN]
- \( N_{cr} \)  
  Euler critical buckling load

**Latin small letters**

- \( c \)  
  Length of column leg without radius  
  [mm]
- \( f_y \)  
  Yield strength  
  [MPa]
- \( i \)  
  Radius of gyration  
  [mm]
- \( k \)  
  Euler coefficient  
  [-]
- \( l_{leg} \)  
  Length of the leg including the radius  
  [mm]
- \( t \)  
  Plate thickness  
  [mm]

**Greek small letters**

- \( \alpha \)  
  Imperfection factor  
  [-]
- \( \gamma_{m1} \)  
  Partial factor  
  [-]
- \( \varepsilon \)  
  Strain  
  [-]
- \( \bar{\lambda} \)  
  Non-dimensional slenderness ratio  
  [-]
- \( \sigma \)  
  Stress  
  [N/mm\(^2\)]
- \( \chi \)  
  Reduction factor for buckling resistance  
  [-]
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1 Introduction

In this chapter a background to the use of angle members is presented. Different types of wind towers are introduced and the buckling phenomena are elaborated on regarding the use of angle members as wind towers. The problem is explained and the objective and limitations of the thesis are presented.

1.1 Background

Throughout history mankind has used wind power to actuate mills and propel sail boats. Windmills have been used for at least 3000 years, originally for grinding grain and pumping water. Today's wind turbines are mainly used to produce electricity. The first wind mills to produce electricity were made in the late nineteenth century. These mills could generate 12 kW, today's wind turbines can generate around 8 MW (Wind, 2014). This technique is still being improved and with more research better results might be achieved in the coming years. (Burton et al., 2011).

The European Union runs the project HISTWIN, High-Strength steel Tower for Wind Turbines, with the aim of developing and expanding the ways of building steel wind towers. The new towers should be cheaper with increased power efficiency. Development regarding the wind turbine and their power output has made large progress in the recent decades, whereas improvements can still be made concerning the towers. One important issue of the tubular wind towers is the connections between parts to make the structure erected (Olga Garzon, 2013). This problem differs for the lattice construction where the connections are made for each and every node.

Compared to fossil and nuclear energy wind turbines have the advantage of low emission of carbon dioxide, CO₂, when producing electricity. Because of the current environmental situation large research and resources within Europe have been focused on wind power production (Olga Garzon, 2013). The total capacity of installed wind power was 9 MW in 2011 in Europe while in 2016, the amount was 153,7 GW, an increase of approximately 153,6 GW in 4 years (EWEA, 2017). One reason to this development is the increase in height of the wind tower. Higher towers provide an important increase of the harvesting efficiency, decreasing the unit cost of generated electricity. This is due to the wind being more constant and stable at higher altitudes. (Olga Garzon, 2013).

1.2 Wind towers

The purpose of the wind tower is to support the wind turbine. The wind tower can be built in a variety of ways. New methods are still being developed. The most common towers today are lattice- and tubular towers.

1.2.1 Lattice towers

A lattice tower, also known as truss tower, is a three-dimensional truss structure. Lattice towers have the advantage transportation in small parts. In early years of wind energy lattice towers were generally used for small turbines. As the sizes of turbine towers increased the tubular tower replaced the lattice towers, with the reference to their aesthetic.
Lately the interest for lattice towers has done a comeback, especially for towers of heights greater than 100 meters. One disadvantage is their number of bolts and connections, and the on-site assembly compared to tubular towers. However, with a given height and stiffness the expenditure of material is less for lattice towers than the tubular ones. The mass of the structure can be less by up to 40%. This is a big profit for economic aspects due material consumption. (Hau, 2006)

1.2.2 Tubular towers

The free-standing steel tube tower is the most common tower type currently being used. A reason for this is a short on-site assembly and erection time. Higher towers up to 100 m are made of several sections which are bolted together. This means that no welding is required on-site. This results in a short one-site assembly and erection time. (Olga Garzon, 2013)

1.3 Problem

Diagonals and braces secure the four columns of the lattice tower from sideways displacements, effectively reducing the flexural buckling length to a node-to-node distance ($L_F$ on Figure 1: Sinusoidal buckling of a lattice tower). On the contrary, the torsion of the columns is not adequately restrained, which leads to much larger torsional buckling lengths, equivalent to the entire length of the columns, $L_T$.

Torsion of angles is described only by the Saint-Venant while there is no warping ($I_w = 0$). This means that the torsional critical load is not related to the buckling length, see Eq. 3, chapter 2.7.1. Angles are susceptible to torsion, hence as the flexural buckling length is decreased, flexural-torsional interaction becomes significant.

![Figure 1: Sinusoidal buckling of a lattice tower](image)
1.4 Objective and research questions

By lacing an angle member according to Figure 2 the lacing is assumed to act similar to a plate and thus increasing the torsional buckling resistance. The hope is that the torsional buckling resistance can be increased by the lacing; flexural torsional interaction load could also be increased.

In Figure 3 the expected result by applying the lacing is illustrated. A laced column will have a higher torsional buckling resistance \( N_{cr,T} \) compared to an unlaced. The expected buckling modes are also illustrated in the figure.

The aim of this thesis is to investigate the use of thin walled angle members under compression. The legs of the column are continuously laced and compared to an unlaced counterpart. The design methods are assessed by making finite element models (FEM) in Abaqus and comparing to Eurocode (EC) with the aim to increase the buckling resistance of the column with regard to torsional, flexural and local buckling.

The questions and objective presented in the thesis are:

- In what interval of flexural- and local slenderness is the lacing technique suitable?
- How do calculations of the Eurocodes compare to results from finite element method?
- How do the unlaced and laced columns buckle with regard to torsional buckling?
- What resistance gains can be achieved by properly lacing the angles?
- How does the Eurocode imperfections compare with reduced imperfections?
1.5 Limitations

In this investigation the column is subjected to pure compression. Residual stresses at the bended region of the cross-section are neglected in the calculations. Thus the radius has the same steel grade as the rest of the cross-section. All models that are calculated have the same steel grade based on a coupon test of steel grade S650.

All Eurocode calculated buckling resistances are for unlaced columns.

Economical and practical factors, such as attachment of the lacing rods, are not taken into account for this thesis.
2 Literature review

The literature review aims to give the reader an insight in the manufacturing process of cold-formed steel and the effects this gives to the material properties. The buckling phenomena are further explained and how a finite element analysis is conducted according to Eurocode is explained.

2.1 Cold-formed steel

Steel constructions have two different main families of structural members. The most familiar group is the hot-rolled shapes and members built up of plates. The second group is the cold-formed steel built up of steel sheet, strip, plate, or flat bars formed at room temperature. Cold-formed steel is less familiar than hot-rolled but is of growing importance. (Yu and LaBoube, 2010)

The cold-forming of steel profiles originates from the United States and during the Second World War the development accelerated. During the 1970s the technique was transferred to Europe and Sweden. (Höglund and Strömberg, 2006)

2.1.1 Methods of forming

The manufacturing of cold-formed steel sections is generally divided in three methods; cold roll forming, press brake operation and bending brake operation.

Cold-rolling is often used for the production of components used in construction such as structural members, roofs, floors and wall panels. The machine used for this type of forming consists of a pair of rolls. Whenever the steel is passing the rolls the material is formed into the required shape, see Figure 4. How many rolls the machine is using depends of the complexity of the required shape. Created a simple section may require as few as six rolls, a complex section may need as many as 15 sets of rolls. The speed capacity of a machine ranges from 6 m/min to 92 m/min. Usually the speed is in the range of 23-46 m/min. (Yu and LaBoube, 2010)

![Figure 4: Cold-forming machine](image)

The machine used for press brake operations consists mainly of a moving top beam and a stationary bottom bed. The bottom bed is configured such as when the machine is pressing the steel plate the required shape is created. This method of forming is usually used for simple
section as angles, channels and Z-sections. The sections are produced by pressing a sheet, strip, plate or bar see Figure 5.

![Figure 5: Steel sheets are given an angle by a press brake operation](image)

The bending brake operation method reminds of the press brake operation in execution. The steel is placed in the machine and the machine bends the steel in a motion. This method is also used for simple sections. (Yu and LaBoube, 2010)

2.1.2 Use of cold-formed steel

A designer has many aspects to take into account. Beside strength and dimensional requirements the designer should also consider highly relevant factors as cost, availability of material, capacity, cost of manufacturing equipment etc. Especially, economical aspect in building construction is very important. The cost of a product depends often on the manufacturing process used in the production. Because of this, cold-formed steel section can be produced more economically than hot-rolled steel. Another notable advantage is the favourable strength-to-weight ratios can be achieved with cold-formed steel. (Yu and LaBoube, 2010)

The three relevant metallurgical phenomena occurring during cold forming of steel are strain hardening, strain ageing and Bauschinger effect. The basis of these phenomena is in plastic deformation, slip and dislocation movement and interaction at an atomic level. The Bauschinger effect can simply be explained as the tensile yield strength of the steel is increasing while the initial compressive yield strength is decreased. This means that it requires less stress to deform the steel in the direction opposite to the original slip. (Sloof and Schuster, 2000)

If the $\sigma_f$ are the forward stress and $\sigma_r$ shows reverse stress then $\sigma_r < \sigma_f$ for the strain $\varepsilon$. See Figure 6.

![Figure 6: Explanation of Bauschunger phenomenon](image)
Strain hardening occurs because of dislocation of the nuclear structure in the material during tensile stresses. As the steel is undergoing strain hardening and ageing the yield strength is increased and ductility is decreased.

A summary of these three effects is shown in Figure 7. Elastic and plastic behaviour is shown with the curve A to the point B. The figure also shows unloading path after plastic strains have developed (curve C). Point B shows the start of increasing yield stress due to strain hardening and curve D shows the behaviour of the steel due to steel ageing. (Sloof and Schuster, 2000)

![Figure 7: Stress and Strain](image)

### 2.2 Buckling strength

Cold-formed steel sections can undergo four generic buckling types, usually called local, global, and distortional and shear (Dubina, Ungureanu and Landolfo, 2012). Cold-formed profiles often come in several non-symmetric cross-sections where the shear centre doesn’t coincide with the centroid. Therefore, consideration should also be given to some other buckling mode as torsional and flexural-torsional failure modes. (Yu and LaBoube, 2010)

When calculating the buckling resistance of a column the following parameters should be considered according to Eurocode, depending on the type of section, plate slenderness and flexural slenderness.

- Yield strength
- Overall column buckling
  - Flexural buckling mode
  - Torsional buckling mode
  - Flexural-torsional buckling mode
- Local buckling
- Distortional buckling
2.3 Flexural buckling

A slender column under compression load buckles in an overall flexural bucking mode. This happens if the cross section of the column is:

- Doubly symmetric (Double T-sections, RHS, QHS, CHS)
- Point-symmetric shape (Z-shape or cruciform)

For singly symmetric shapes, as angles and channels, flexural buckling is one of the possible buckling modes but is often combined with torsional buckling (Yu and LaBoube, 2010)

2.4 Torsional buckling and flexural-torsional buckling

Usually, closed sections don’t buckle torsionally under compression loads due to their large torsional rigidity. There are three modes of overall buckling for open thin-walled cross-sections;

- Flexural buckling
- Torsional buckling
- Flexural-torsional buckling

In a flexural-torsional buckling mode, the columns get an overall bending and twisting at the same time, see Figure 9 (Yu and LaBoube, 2010)
2.4.1 St. Venant's torsion

As a structural member is under torsional buckling, the cross-section of the member may undergo warping due to twisting. If the member is free to warp, the applied torsion is resisted only by torsional shear stresses, also called St. Venant's torsional shear stress. If the member can't warp freely, the torsion is resisted by St. Venant's torsional shear stresses and warping torsion. That phenomena is called non-uniform torsion. (Trahair et al., 2007)

2.5 Local buckling

The mode of local buckling is characterized by the relatively short wave lengths of the plate elements (Dubina, Ungureanu and Landolfo, 2012).

This means that local buckling will occur individually for the components in the structure before the applied load reaches the overall collapse load of the column. The overall bucking resistance strength of the column will be reduced due to the interaction effect between the local - and overall buckling. (Yu and LaBoube, 2010)

2.5.1 Localized buckling

Localized buckling can simply be described as deflection in a limited small part of a column (Coman, 2006).

There are multiple local buckling modes, which are characterized by half wave lengths, for thin-walled sections and these buckling modes may occur simultaneously. In case of slender columns these local buckling modes may interact with each other and contribute to a post-critical behaviour called localization of the buckling pattern. The localized buckling is the first iteration, which leads to an overall buckling mode of a member. When there is a localized buckling pattern, the buckled member is characterized with large local displacements in a plastic range. The consequence of this phenomenon is local plastic folding of the thin-walled steel member. The localized buckling failure depends on the yield strength, local slenderness and the size of geometrical imperfection. (Loughlan, 2004)
2.6 Distortional buckling

Distortional buckling, also known as local-torsional buckling is a buckling failure mode characterized by rotation of the flanges, in this case legs, at the web and flange junction in members with stiffed edges. Distortional buckling can be described as the buckling that distorts the profile shape, meaning that the relative positions of the nodes change. (Schafer, 2000)

A finite element strip analysis of lipped C-profiles conducted by (Schafer, 2000) shows the buckling behaviour of such profiles in Figure 10. For this kind of sections local buckling usually occurs before distortional buckling is reached. In this case distortional buckling can be ignored. By doing a similar investigation for other cross-section, the distortional behaviour of a member can be determined.

![Figure 10: Buckling mode behaviour of a lipped C section is investigated by finite strip analysis](image)

2.7 Angle compression members

Single angle members can be used in a variety of applications, such as web members in steel joints and trusses. Single angle members are popular since they can easily be connected to other structural members. Angel members can be connected eccentrically at their ends. This means that a load is applied through one leg only. This connection introduces an eccentricity to the member. Due to the asymmetry of the cross-section the compression capacity is complex under such conditions. The eccentricity causes a biaxial flexural deformation of the member at any given load. (Galambos, 1998)

Finite element analysis can be used as a general tool to determine the load carrying capacity of eccentrically loaded members. The analysis can be made using two different models. The column and its connections can be modelled using plate elements. This method has the advantage of including local plate buckling and cross-sectional distortion effects. The second type of modelling is using the beam-column theory of open cross-sections. For this method beam elements are used which has the advantage of using relatively large frame assemblies with small model and calculation efforts. (Galambos, 1998)
2.7.1 Elastic behaviour

Stability of thin-walled members is a special case according to elastic behaviour because of the location of the shear centre. The shear centre is found in the intersection of the two angle legs. This makes the warping practically equal to zero, therefore the warping constant $I_w$ zero. (Galambos, 1998)

Compression will cause buckling around the minor axis:

$$N_{cr,x} = \frac{\pi^2 E I_z}{k L_{cr,x}^2}$$

(1)

Or the major axis

$$N_{cr,y} = \frac{\pi^2 E I_z}{k L_{cr,y}^2}$$

(2)

Thin-walled open section, with a compressive axial load, may also buckle by twisting about the longitudinal axis or by combined bending and twisting, see Figure 11.

![Figure 11: Torsional buckling of a section](image)

The torsional critical load is given as

$$N_{cr,T} = \frac{1}{I_0^2} \left( G I_t + \frac{\pi^2 E I_w}{L_{cr,T}^2} \right)$$

(3)
Where $GI_1$ is the torsional rigidity, $EI_w$ is the warping rigidity, and $L_{cr,T}^2$ is the length between the inflexion points of the twisted part of the column. $i_0^2$ is defined by

$$i_0^2 = i_p^2 + y_0^2 + z_0^2$$  

Where $y_0$ and $z_0$ are the distances to the shear center of the column. This means that $z_0$ and $y_0$ are zero for a double symmetric section and $i_p$ is the polar radius of gyration, given by

$$i_p = \sqrt{\frac{I_y + I_z}{A}}$$  

In many cases the torsional buckling load, $N_{cr,T}$, is higher than the minor axis buckling load, $N_{cr,Z}$, and the case of torsional buckling can be ignored. For a short member with low torsional and warping rigidities the torsional buckling should be checked.

As previously stated, flexural and torsional buckling can interact. A combined form of twisting and deflecting may occur for mono-symmetric and asymmetric section members, such as thin-walled tees and angles and is termed as flexural-torsional buckling. This happens due to the action of twist, along the shear centre, not coinciding with the centroid where the load is applied.

For simply supported member the critical flexural-torsional load, $N_{cr}$, is obtained by the lowest root of the cubic equation, see Eq. 6.

$$N_{cr}^3 (i_0^2 - y_0^2 - z_0^2) - N_{cr}^2 \left\{(N_{cr,y} + N_{cr,z} + N_{cr,T})i_0^2 - N_{cr,z}y_0^2 - N_{cr,z}z_0^2\right\}$$
\[+ N_{cr}i_0^2\left\{N_{cr,y}N_{cr,z} + N_{cr,z}N_{cr,T} + N_{cr,T}N_{cr,y}\right\}\]
\[- N_{cr,y}N_{cr,z}N_{cr,T}i_0^2 = 0\]  

As an example, $N_{cr}$ for a compressive loaded pin-ended unequal angle is less than any of $N_{cr,Z}$, $N_{cr,y}$ and $N_{cr,T}$. See Figure 12 and Figure 13. (Trahair et al., 2007)
2.8 Buckling resistance according to EC

Eurocode classifies cross-sections into four different classes for determining the cross-sectional resistance. A cross-section with slender flanges and webs, legs in the case of an angle member, will be more susceptible to local buckling. This means that the member will fail before the design strength is reached. By introducing classification, Eurocode takes the effect of local buckling into account. The description below is taken from Eurocode 1993-1-1 chapter 5.5.

- Class 1 cross-sections are those which can form a plastic hinge with the rotation capacity required from plastic analysis without reduction of the resistance.
- Class 2 cross-sections are those which can develop their plastic moment resistance but have limited rotation capacity because of the local buckling
- Class 3 cross-sections are those in which the stress in the extreme compression fibre of the steel member assuming an elastic distribution of stresses can reach the yield strength, but local buckling is liable to prevent development of the plastic moment resistance.
- Class 4 cross-sections are those in which local buckling will occur before the attainment of the yield stress in one or more parts of the cross-section.

The classification of a cross-section depends mainly on the yield strength of the steel and the width-to-thickness ratio. The classes are found in table 5.2 in SS-EN 1993-1-1. Classification of angle section is shown in Table 1. According to the table all cross-sections until local slenderness 15 are in class 3. For local slenderness above 15 the profiles are in class 4.

Table 1: Classification of angle section according to table 5.2 in SS-EN 1993-1-1

<table>
<thead>
<tr>
<th>Class</th>
<th>Section in compression</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>h/t ≤ 15, b + h ≤ 11.5t</td>
</tr>
</tbody>
</table>

Refer also to “Outstand flanges” (see sheet 2 of 3)
2.8.1 Design buckling resistance

According to Eurocode 1993-1-1 chapter 6.3, the Buckling resistance of a compressed member should be confirmed by

\[
\frac{N_{Ed}}{N_{b,Rd}} \leq 1,0 \quad (7)
\]

Where \(N_{Ed}\) the design value of the compression is load and \(N_{b,Rd}\) is the buckling resistance of the compression member.

\(N_{b,Rd}\) are calculated as follows

\[
N_{b,Rd} = \frac{\chi \cdot A \cdot f_y}{\gamma_{m1}} \quad \text{for cross – section class 1,2 and 3} \quad (8)
\]

\[
N_{b,Rd} = \frac{\chi \cdot A_{eff} \cdot f_y}{\gamma_{m1}} \quad \text{for cross – section class 4} \quad (9)
\]

The \(\chi\) is a reduction factor for the buckling mode, given by

\[
\chi = \frac{1}{\Phi + \sqrt{\Phi^2 - \lambda^2}} \quad \text{but} \quad \chi \leq 1,0 \quad (10)
\]

Where

\[
\Phi = 0,5 \left[ 1 + \alpha (\bar{\lambda} - 0,2) + \bar{\lambda}^2 \right] \quad (11)
\]

\(\bar{\lambda}\) is the non-dimensional flexural slenderness ratio and is defined by

\[
\bar{\lambda} = \frac{A_{fy}}{\sqrt{N_{cr}}} \quad \text{for class 1,2 and 3 cross – sections} \quad (12)
\]

\[
\bar{\lambda} = \frac{A_{eff} f_y}{\sqrt{N_{cr}}} \quad \text{for class 4 cross – sections} \quad (13)
\]
The reduction factor $\alpha$ is taking into account due to initial imperfections and can be obtained using table 6.1 and 6.2 in SS-EN 1993-1-1.

**Table 2: Buckling curves**

<table>
<thead>
<tr>
<th>Buckling curve</th>
<th>$a_0$</th>
<th>$a$</th>
<th>$b$</th>
<th>$c$</th>
<th>$d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imperfection factor $\alpha$</td>
<td>0,13</td>
<td>0,21</td>
<td>0,34</td>
<td>0,49</td>
<td>0,76</td>
</tr>
</tbody>
</table>

Where curve b should be used for L-sections according to table 6.2 in SS-EN 1993-1-1.

**Table 3: Parameters for buckling curves**

![Buckling curves diagram]

2.8.2 Slenderness for flexural buckling

According to SS-EN 1993-1-1 chapter 6.3, the non-dimensional slenderness ratio is given by

$$\bar{\lambda} = \frac{\sqrt{A_f}}{N_{cr} \frac{L_{cr}}{i \lambda}} \frac{1}{\lambda_1} \quad \text{for class 1,2 and 3 cross-sections}$$  \hspace{1cm} (14)
\[ \bar{\lambda} = \frac{A_{eff} f_y}{N_{cr}} = \frac{L_{cr}}{i} \sqrt{\frac{A_{eff}}{\lambda_1}} \text{ for class 4 cross-sections} \]  \hfill (15)

Where \( L_{cr} \) is the buckling length and \( i \) is the radius of gyration about the axis of interest. These operators are determined by using the gross cross-section properties.

\( \lambda_1 \) is given

\[ \bar{\lambda}_1 = \pi \sqrt{\frac{E}{f_y}} = 93.9 \varepsilon \]  \hfill (16)

and

\[ \varepsilon = \sqrt{\frac{235}{f_y}} \text{ and } f_y \text{ in N/mm}^2 \]  \hfill (17)

2.8.3 Slenderness for torsional and torsional-flexural buckling

The information in Eurocode dealing with elastic torsional-flexural behaviour of angle compression member is based on the information given in chapter 2.7.1. However, according to SS-EN 1993-1-1 chapter 6.3, the non-dimensional slenderness ratio is given by

\[ \bar{\lambda}_T = \frac{A f_y}{N_{cr}} \text{ for class 1,2 and 3 cross-sections} \]  \hfill (18)

\[ \bar{\lambda}_T = \frac{A_{eff} f_y}{N_{cr}} \text{ for class 4 cross-sections} \]  \hfill (19)

Where \( N_{cr} = N_{cr,TF} \) but \( N_{cr} < N_{cr,T} \) and

\( N_{cr,TF} \) is the elastic torsional-flexural buckling load.

\( N_{cr,T} \) is the elastic torsional buckling load.
2.9 Finite element method of analysis


**Table 4: C1 in SS-EN 1993-1-5**

<table>
<thead>
<tr>
<th>No</th>
<th>Material behaviour</th>
<th>Geometric behaviour</th>
<th>Imperfections, see section C.5</th>
<th>Example of use</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>linear</td>
<td>linear</td>
<td>no</td>
<td>elastic shear lag effect, elastic resistance</td>
</tr>
<tr>
<td>2</td>
<td>non linear</td>
<td>linear</td>
<td>no</td>
<td>plastic resistance in ULS</td>
</tr>
<tr>
<td>3</td>
<td>linear</td>
<td>non linear</td>
<td>no</td>
<td>critical plate buckling load</td>
</tr>
<tr>
<td>4</td>
<td>linear</td>
<td>non linear</td>
<td>yes</td>
<td>elastic plate buckling resistance</td>
</tr>
<tr>
<td>5</td>
<td>non linear</td>
<td>non linear</td>
<td>yes</td>
<td>elastic-plastic resistance in ULS</td>
</tr>
</tbody>
</table>

By taking imperfection into account the analysis will be more realistic. SS-EN 1993-1-5 recommends using imperfection. An equivalent geometric imperfection is given in table C.2.

**Table 5: C2 in SS-EN 1993-1-1**

<table>
<thead>
<tr>
<th>Type of imperfection</th>
<th>Component</th>
<th>Shape</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>global</td>
<td>member with length ( l )</td>
<td>bow</td>
<td>see EN 1993-1-1, Table 5.1</td>
</tr>
<tr>
<td>global</td>
<td>longitudinal stiffener with length ( a )</td>
<td>bow</td>
<td>min ((a/400, b/400))</td>
</tr>
<tr>
<td>local</td>
<td>panel or subpanel with short span ( a ) or ( b )</td>
<td>buckling shape</td>
<td>min ((a/200, b/200))</td>
</tr>
<tr>
<td>local</td>
<td>stiffener or flange subject to twist</td>
<td>bow twist</td>
<td>(1/50)</td>
</tr>
</tbody>
</table>

One way to satisfy the recommendations of Eurocode is using geometrically and materially non-linear analysis (GMNIA). GMNIA is currently the most sophisticated and perspective numerical structural analysis for verification of buckling strength capacity of a structure. (Schneider, 2006)
3 Method

A parametric study is the basis for this thesis. The simulations are conducted in the FEM-program Abaqus. This chapter describes how the thesis is conducted and the approach is motivated. The input of the script that is run in Abaqus is explained and how it affects a FEM-model.

The entire script can be seen in Annex A.

3.1 Material

The stress-strain curve is determined by a coupon test from hot rolled plate steel S650. Results taken from the test are used to describe the plastic behaviour of the material in Abaqus. Five points from the test are selected, see Table 6. The last value is selected to give a small inclination to Abaqus as possible, see Diagram 1.

<table>
<thead>
<tr>
<th>ε [%]</th>
<th>σ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>800</td>
</tr>
<tr>
<td>0,03</td>
<td>837,01</td>
</tr>
<tr>
<td>0,06</td>
<td>878,55</td>
</tr>
<tr>
<td>0,10</td>
<td>902,55</td>
</tr>
<tr>
<td>0,18</td>
<td>902,65</td>
</tr>
</tbody>
</table>

Table 6: Abaqus plastic behaviour

Diagram 1: Coupon test of S650

3.2 Profile

The comparisons of a laced and unlaced column are the basis for the study. The laced and the unlaced column are cross compared to each other.
3.2.1 Cross-section

The section is an angle member with legs of equal lengths. The angle between the legs is 90 degrees. See the cross-section with applied lacing in Figure 14. The bending radius is defined as a ratio to the shell thickness. The radius is always three times the value of the thickness.

![Cross-section with lacing](image)

Figure 14: Profile cross-section with lacing

3.2.2 Lacing

The lacing is made of circular tubes attached according to Figure 15, highlighted in red. Truss elements are used to create the lacing, meaning they have three translational degrees of freedom at each end.

![Laced column](image)

Figure 15: Laced column

The cross-sectional area of those elements is equal to a circular hollow section with a flexural slenderness equal to one and

\[ \frac{c}{\varepsilon \cdot t} = 70 \]

(20)

Where

\[ c = l_{\text{leg}} - r_{\text{bend}} \]

(21)
The lacing is placed on the column by a ratio to the leg length. This means that the density of the laces stays the same regardless of the length of the column.

### 3.3 Parameters

The five parameters of the study are given in the script as input variables:

1. The length of the legs is changed via an input value. The $l_{leg}$ input includes the radius connecting the two legs according to Figure 14. The radius, $r_{bend}$, is always three times the plate thickness.

2. Cross-section class. According to EC3-1-1 table 5.1 sheet 3 for angles the class is calculated as follows:

$$
\frac{c}{\varepsilon * t} \leq 15 \text{ for cross-section class 3} \tag{22}
$$

Thus the following input will result in the following values, see Table 7:

<table>
<thead>
<tr>
<th>$l_{leg}$</th>
<th>$\frac{c}{\varepsilon * t}$</th>
<th>$t$</th>
<th>Rounded t</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>10</td>
<td>5.84</td>
<td>6</td>
</tr>
<tr>
<td>100</td>
<td>11</td>
<td>5.30</td>
<td>5</td>
</tr>
<tr>
<td>100</td>
<td>12</td>
<td>4.86</td>
<td>5</td>
</tr>
<tr>
<td>100</td>
<td>13</td>
<td>4.49</td>
<td>4</td>
</tr>
<tr>
<td>100</td>
<td>14</td>
<td>4.17</td>
<td>4</td>
</tr>
</tbody>
</table>

3. The flexural slenderness input is used both with regards to cross-section class 1-3 and 4. The following is an example of how the flexural slenderness is used in the script. Using Eq. 1 and 12 an expression for the column length can be expressed, see equation 23

$$
L_{cr} = \frac{\lambda \pi}{E * l_{f}} \frac{\sqrt{A * f_y}}{A * f_y} \tag{23}
$$

The column is pinned at both ends. This means the buckling length is equal to the columns entire length. The length is given by Eq. 23. The moment of inertia is calculated according to Steiner's theorem. The weak principal axis is 135° from the x-axis. An example of input values can be seen in Table 8.

<table>
<thead>
<tr>
<th>$l_{leg}$</th>
<th>$\frac{c}{\varepsilon * t}$</th>
<th>$\lambda_{flexural}$</th>
<th>L [mm]</th>
<th>L [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>12</td>
<td>0.4</td>
<td>416</td>
<td>0.42</td>
</tr>
<tr>
<td>100</td>
<td>12</td>
<td>0.6</td>
<td>623</td>
<td>0.62</td>
</tr>
<tr>
<td>100</td>
<td>12</td>
<td>0.8</td>
<td>831</td>
<td>0.83</td>
</tr>
</tbody>
</table>
4. The number of laces is defined by rounding up the division of the total column length to the requested lacing length. The lacing length is input as a ratio to the leg length.

5. Three different imperfections are imposed on the columns. All three have the same amplitude, \( I/200 \) according to EC 1090-2. \( I/400 \) is also tested to compare the results with decreased deformations. The buckling length, \( l \), differs for the three types of imperfection.

A sinusoidal imperfection along the lips at the end of the legs is applied. In this case the buckling length is equal to the distance between the laces, see Figure 16 a).

For the torsional and flexural imperfection the buckling length is equal to the entire length of the column, see Figure 16 b) and c).

![Figure 16: Imposed imperfections](image)

### 3.4 Finite element analysis

The following properties are used in the finite element analysis in Abaqus.

#### 3.4.1 Shell element

A shell element is used in the analysis due to following advantages. Shell elements has the advantage to save time since they typically requires fewer elements while modelling with thin structures. Another advantage is that shell elements are easier to mesh than solid elements. There are some other advantages as well. (Bari, 2015)
• Modelling with solid elements requires large disk spaces. This can be a problem in non-linear and big models. In this case it’s better with shell elements
• The processing time of the analysis is faster with shell elements compared to solid elements due to fewer degrees of freedom

3.4.2 Boundary conditions
Reference points are created at both ends of the column on the profile’s centroid. Both reference points are coupled to the edges of the cross-section. Hinge boundary conditions are added on the reference points. Torsion is constrained on one of the two ends for stabilisation.

![Figure 17: Reference point and coupling at the ends](image)

The following boundary conditions are used:

<table>
<thead>
<tr>
<th></th>
<th>Top</th>
<th>Bottom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Translation - X</td>
<td>Constrained</td>
<td>Constrained</td>
</tr>
<tr>
<td>Translation - Y</td>
<td>Constrained</td>
<td>Constrained</td>
</tr>
<tr>
<td>Translation - Z</td>
<td>Free</td>
<td>Constrained</td>
</tr>
<tr>
<td>Rotation - X</td>
<td>Free</td>
<td>Free</td>
</tr>
<tr>
<td>Rotation - Y</td>
<td>Free</td>
<td>Free</td>
</tr>
<tr>
<td>Rotation - Z</td>
<td>Free</td>
<td>Constrained</td>
</tr>
</tbody>
</table>

Translational boundary condition in Z-direction is free to translate at the top due to displacement under compression load.

3.4.3 Load
One load case will be analysed in this investigation. The beam will be subjected to pure compression. A reference point is created in the centroid of the cross-sections at the top of the beam, the same reference point as for the boundary condition. The reference point is coupled to the edges of the cross-section.

The laced column is loaded with the design bucking resistance according to Eurocode rules a typical unlaced column. The procedure is presented in chapter 2.8. By using this method, the utilization ratio of the laced column compared to an unlaced column can be expressed.
3.4.4 Mesh

The mesh is created in the independent assembly instance in Abaqus with a global size of mesh shown in Eq. 23. A structured mesh technique is used, this technique generates a uniformly mesh of quads.

\[
\text{Global mesh size} = \frac{l_{efg}}{10}
\]

(24)

3.4.5 Step and procedure

The deformed shape for the initial imperfections is directly imposed as displacement functions over the nodes of the column. Thereafter the Riks analysis is carried out directly on the imperfect shape.

3.5 Investigation procedure

The stated parameters are run in the script. Key parameters are picked up by looking at preliminary tests. One such parameter is the flexural slenderness. An interesting point to locate is where the buckling mode changes from torsional to flexural buckling for an unlaced column. This preliminary test is similar to the one conducted by Trahair et al., 2007, see Figure 13.

When the interval of flexural slenderness is known, the buckling resistance of the columns is calculated with respect to local slenderness, flexural slenderness and the density of the lacing. These results are cross compared to the unlaced columns calculated according to Eurocode. Two different amplitudes of imperfections are tested, these are also compared respectively.

It is difficult to categorise the failure mode automatically for the script in Abaqus, this means all results are visually checked and noted to determine the buckling mode of each specimen, see Figure 18.

![Figure 18: Analyzed buckling modes](image)

Modes: a) Flexural buckling, b) Flexural-torsional buckling, c) Torsional buckling, d) Localized buckling
4 Results

In the following chapter the simulated results from Abaqus run by the script are presented. The table values used to plot the graphs can be seen in Annex B.

4.1 Unlaced columns

Figure 19 shows the results for unlaced columns with regard to local- and flexural slenderness. The imperfections used are $t/200$ for all three imposed imperfections, see heading 3.3.

![Figure 19: Unlaced columns; Imperfection 1/200](image)

The results show that the utilization ratio between $N_{ABQ}$ and $N_{b,Rd}$ is equal to one or below one for local slenderness 10. The lowest utilization ratio occurs with local slenderness 10 and flexural slenderness 0.9. For local slenderness 10 only flexural buckling failures occur.

For local slenderness 15 – 25 only torsional buckling failures occur. The highest utilization ratio is found in cross-section class 4 when the column has a flexural slenderness of 0.4.
Figure 20 shows the results for unlaced columns with regard to local- and flexural slenderness. The imperfections used are $l/400$ for all three imposed imperfections, see heading 3.3.

![Figure 20: Unlaced columns; Imperfection 1/400](image)

The results show that the utilization ratio between $N_{ABQ}$ and $N_{b,Rd}$ is above one for all specimen. The lowest utilization ratio occurs for local slenderness 10 and flexural slenderness 0.9. For local slenderness 10 only flexural buckling failures occur.

Local slenderness 15 has both torsional buckling failures and flexural-torsional buckling failures. Flexural-torsional buckling failure occurs for flexural slenderness from 0.7 to 0.9.

For cross-sections class 4 only torsional buckling failures occur. The highest utilization ratio is found for local slenderness 25 when the column has a flexural slenderness of 0.4.
4.2 Laced columns - Step: 1.25

Figure 21 shows the results for laced columns with regard to local- and flexural slenderness. The
imperfections used are \( l/200 \) for all three different imposed imperfections, see heading 3.3. The used lace step is 1.25.

![IMP:200 - Laced: Step 1.25](image)

Figure 21: Laced column, Lace step 1.25; Imperfection 1/200

The results show that the utilization ratio between \( N_{ABQ} \) and \( N_{b,Rd} \) is equal to one or below for
local slenderness 10. The lowest utilization ratio occurs with local slenderness 10 with flexural
slenderness 0.9. For local slenderness 10 only flexural buckling failures occur.

Local slenderness 15 has three different buckling failure modes, Localized failure, torsional
failure and flexural-torsional failure.

Local slenderness 20 has two buckling failures, localized failure and torsional failure. Torsional
failure is dominant for this cross-section.

In local slenderness 25 torsional buckling occurs for all typed of flexural slenderness. The
highest utilization ratio is in local slenderness 25 and when the column has a flexural
slenderness of 0.4.
Figure 22 shows the results for laced columns with regard to local- and flexural slenderness. The imperfections used are \( l/400 \) for all three different imposed imperfections, see heading 3.3. The used lace step is 1.25.

The results show that the utilization ratio between \( N_{ABQ} \) and \( N_{b,Rd} \) is slightly above one for local slenderness 10. The lowest utilization ratio occurs with local slenderness 10 with flexural slenderness 0.9. For local slenderness 10 only flexural buckling failures occur.

For local slenderness 15 there are two different buckling modes, localized failure flexural-torsional failure.

For local slenderness 20 only localized buckling failures occur.

For local slenderness 25 torsional buckling is the dominated failure mode. The highest utilization ratio is in local slenderness 25 when the column has a flexural slenderness of 0.4.
4.3 Laced columns - Step: 1.0

Figure 23 shows the results for laced columns with regard to local- and flexural slenderness. The imperfections used are $l/200$ for all three different imposed imperfections, see heading 3.3. The used lace step is 1.0.

![Figure 23: Laced column, Lace step 1.0; Imperfection 1/200](image)

The results show that the utilization ratio between $N_{ABQ}$ and $N_{b,Rd}$ is equal to one or below for local slenderness 10. The lowest utilization ratio occurs with local slenderness 10 with flexural slenderness 0.9. For local slenderness 10 only flexural buckling failures occur.

For local slenderness 15 there are three different buckling failure modes, Localized failure, torsional failure and flexural-torsional failure.

For local slenderness 20 there are two buckling modes, localized failure and torsional failure.

For local slenderness 25 torsional buckling occurs when the flexural slenderness is in the interval 0.4-0.7 making torsion the dominant buckling mode for this local slenderness. The highest utilization ratio is for local slenderness 25 and when the column has a flexural slenderness of 0.4.
Figure 24 shows the results for laced columns with regard to local- and flexural slenderness. The imperfections used are $l/400$ for all three different imposed imperfections, see heading 3.3. The used lace step is 1.0.

![Figure 24: Laced column, Lace step 1.0; Imperfection 1/400](image)

The results show that the utilization ratio between $N_{ABQ}$ and $N_{Rd}$ is slightly above one for local slenderness 10. The lowest utilization ratio occurs with local slenderness 10 and flexural slenderness 0.9. For local slenderness 10 only flexural buckling failures occur.

For local slenderness 15 there are two different buckling modes, localized failure flexural-torsional failure.

For local slenderness 20 only localized buckling failures occur.

For local slenderness 25 localized buckling is the dominated failure mode. The highest utilization ratio is for local slenderness 25 when the column has a flexural slenderness of 0.4.
4.4 Laced columns - Step: 0.75

Figure 25 shows the results for laced columns with regard to local- and flexural slenderness. The imperfections used are $l/200$ for all three different imposed imperfections, see heading 3.3. The used lace step is 0.75.

The results show that the utilization ratio between $N_{ABQ}$ and $N_{b,Rd}$ is equal to one or below for local slenderness 10. The lowest utilization ratio occurs with local slenderness 10 and flexural slenderness 0.9. For local slenderness 10 only flexural buckling failures occur.

For local slenderness 15 there are three different buckling modes, Localized failure, flexural failure and flexural-torsional failure.

For local slenderness 20 all buckling modes are due to localized failures.

For local slenderness 25 localized buckling is the dominated failure mode, with the exception for one case of torsional buckling failure when the flexural slenderness is equal to 0.9. The highest utilization ratio is for local slenderness 25 when the column has a flexural slenderness of 0.4.

Figure 26 shows the results for laced columns with regard to local- and flexural slenderness. The imperfections used are $l/400$ for all three imposed imperfections, see heading 3.3. The used lace step is 0.75.
The results show that the utilization ratio between $N_{\text{ABQ}}$ and $N_{\text{b,Rd}}$ slightly above one for local slenderness 10. The lowest utilization ratio occurs for local slenderness 10 with flexural slenderness 0.9. For local slenderness 10 only flexural buckling failures occur.

For local slenderness 15 there are two different buckling modes, localized failure flexural-torsional failure.

For local slenderness 20 all buckling modes are due to localized failures.

For local slenderness 25 localized buckling is the dominant failure mode, this occurs when the flexural slenderness is in the interval of 0.4-0.7. Torsional buckling occurs for flexural slenderness 0.8 and 0.9. The highest utilization ratio is for local slenderness 25 when the column has a flexural slenderness of 0.4.
5 Analysis

In this chapter the results are analyzed. Unlaced columns are compared to laced columns with regard to local slenderness, flexural slenderness, lacing density and the imposed imperfections.

5.1 IMP: 200 – Unlaced VS Laced

An unlaced column in class-section class 10, with any analyzed flexural slenderness, buckles in a flexural buckling mode. The same buckling mode occurs for the laced columns, independently of the lace step. Lacing gives no effect on the buckling modes for local slenderness 10. See Table 10. In the tables the different buckling modes are presented as:

- Torsional buckling – TB
- Flexural buckling – FB
- Flexural-torsional buckling – FTB
- Localized buckling – LB

<table>
<thead>
<tr>
<th>CS-class</th>
<th>$\lambda_{flex}$</th>
<th>Unlaced</th>
<th>Laced: Step 1.25</th>
<th>Laced: Step 1.0</th>
<th>Laced: Step 0.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.4</td>
<td>FB</td>
<td>FB</td>
<td>FB</td>
<td>FB</td>
</tr>
<tr>
<td>10</td>
<td>0.5</td>
<td>FB</td>
<td>FB</td>
<td>FB</td>
<td>FB</td>
</tr>
<tr>
<td>10</td>
<td>0.6</td>
<td>FB</td>
<td>FB</td>
<td>FB</td>
<td>FB</td>
</tr>
<tr>
<td>10</td>
<td>0.7</td>
<td>FB</td>
<td>FB</td>
<td>FB</td>
<td>FB</td>
</tr>
<tr>
<td>10</td>
<td>0.8</td>
<td>FB</td>
<td>FB</td>
<td>FB</td>
<td>FB</td>
</tr>
<tr>
<td>10</td>
<td>0.9</td>
<td>FB</td>
<td>FB</td>
<td>FB</td>
<td>FB</td>
</tr>
</tbody>
</table>

The unlaced column buckles in a torsional mode for any analyzed local slenderness 15. The result show that for the same column with lacing, the buckling mode transition from torsional- to localized- and flexural-torsional buckling. See Table 11.

<table>
<thead>
<tr>
<th>CS-class</th>
<th>$\lambda_{flex}$</th>
<th>Unlaced</th>
<th>Laced: Step 1.25</th>
<th>Laced: Step 1.0</th>
<th>Laced: Step 0.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>0.4</td>
<td>TB</td>
<td>TB</td>
<td>TB</td>
<td>LB</td>
</tr>
<tr>
<td>15</td>
<td>0.5</td>
<td>TB</td>
<td>TB</td>
<td>LB</td>
<td>LB</td>
</tr>
<tr>
<td>15</td>
<td>0.6</td>
<td>TB</td>
<td>LB</td>
<td>LB</td>
<td>FTB</td>
</tr>
<tr>
<td>15</td>
<td>0.7</td>
<td>TB</td>
<td>LB</td>
<td>FTB</td>
<td>LB</td>
</tr>
<tr>
<td>15</td>
<td>0.8</td>
<td>TB</td>
<td>FB</td>
<td>LB</td>
<td>FTB</td>
</tr>
<tr>
<td>15</td>
<td>0.9</td>
<td>TB</td>
<td>FB</td>
<td>LB</td>
<td>FB</td>
</tr>
</tbody>
</table>

For local slenderness 20 the unlaced column buckles torsionally for any analyzed flexural slenderness. Compared to local slenderness 15, there is a more clear transition from torsional- to localized buckling modes. See Table 12.
Table 12: Buckling modes in IMP: 200 Unlaced VS Laced for local slenderness 20

<table>
<thead>
<tr>
<th>CS-class</th>
<th>(\lambda_{flex})</th>
<th>Unlaced</th>
<th>Laced: Step 1.25</th>
<th>Laced: Step 1.0</th>
<th>Laced: Step 0.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.4</td>
<td>TB</td>
<td>TB</td>
<td>LB</td>
<td>LB</td>
</tr>
<tr>
<td>20</td>
<td>0.5</td>
<td>TB</td>
<td>TB</td>
<td>LB</td>
<td>LB</td>
</tr>
<tr>
<td>20</td>
<td>0.6</td>
<td>TB</td>
<td>TB</td>
<td>LB</td>
<td>LB</td>
</tr>
<tr>
<td>20</td>
<td>0.7</td>
<td>TB</td>
<td>TB</td>
<td>LB</td>
<td>LB</td>
</tr>
<tr>
<td>20</td>
<td>0.8</td>
<td>TB</td>
<td>TB</td>
<td>LB</td>
<td>LB</td>
</tr>
<tr>
<td>20</td>
<td>0.9</td>
<td>TB</td>
<td>LB</td>
<td>LB</td>
<td>LB</td>
</tr>
</tbody>
</table>

The same pattern can be seen for local slenderness 25 as for 15 and 20. The lacing makes the buckles mode transition from torsional- to localized buckling. The transition is not that clear as for class 20.

Table 13: Buckling modes in IMP: 200 Unlaced VS Laced for local slenderness 25

<table>
<thead>
<tr>
<th>CS-class</th>
<th>(\lambda_{flex})</th>
<th>Unlaced</th>
<th>Laced: Step 1.25</th>
<th>Laced: Step 1.0</th>
<th>Laced: Step 0.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>0.4</td>
<td>TB</td>
<td>TB</td>
<td>TB</td>
<td>LB</td>
</tr>
<tr>
<td>25</td>
<td>0.5</td>
<td>TB</td>
<td>TB</td>
<td>TB</td>
<td>LB</td>
</tr>
<tr>
<td>25</td>
<td>0.6</td>
<td>TB</td>
<td>TB</td>
<td>TB</td>
<td>LB</td>
</tr>
<tr>
<td>25</td>
<td>0.7</td>
<td>TB</td>
<td>TB</td>
<td>TB</td>
<td>LB</td>
</tr>
<tr>
<td>25</td>
<td>0.8</td>
<td>TB</td>
<td>LB</td>
<td>LB</td>
<td>LB</td>
</tr>
<tr>
<td>25</td>
<td>0.9</td>
<td>TB</td>
<td>LB</td>
<td>LB</td>
<td>TB</td>
</tr>
</tbody>
</table>

Figure 27 a) – c) shows the difference between the two Abaqus calculated buckling resistances for unlaced and laced columns. The graphs show that the laced columns have a higher buckling resistance than the unlaced columns, with the exception for lower local slenderness. This might be due to the lower local slenderness buckle due to flexural buckling or that the torsional buckling has a similar buckling strength to the localized buckling for these columns.

The result shows that largest difference in utilization ratio is for flexural slenderness 0.5 – 0.7 and increased local slenderness.
5.2 IMP: 400 – Unlaced VS Laced

An unlaced column in class-section class 10, with any analyzed flexural slenderness, buckles in a flexural buckling mode. The same buckling mode occurs for the laced columns, independently of the lace step. Lacing gives no effect on the buckling modes for local slenderness 10. See Table 14.

Table 14: Buckling modes in IMP: 200 Unlaced VS Laced for local slenderness 10

<table>
<thead>
<tr>
<th>CS-class</th>
<th>$\lambda_{\text{flex}}$</th>
<th>Unlaced</th>
<th>Laced: Step 1.25</th>
<th>Laced: Step 1.0</th>
<th>Laced: Step 0.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.4</td>
<td>FB</td>
<td>FB</td>
<td>FB</td>
<td>FB</td>
</tr>
<tr>
<td>10</td>
<td>0.5</td>
<td>FB</td>
<td>FB</td>
<td>FB</td>
<td>FB</td>
</tr>
<tr>
<td>10</td>
<td>0.6</td>
<td>FB</td>
<td>FB</td>
<td>FB</td>
<td>FB</td>
</tr>
<tr>
<td>10</td>
<td>0.7</td>
<td>FB</td>
<td>FB</td>
<td>FB</td>
<td>FB</td>
</tr>
<tr>
<td>10</td>
<td>0.8</td>
<td>FB</td>
<td>FB</td>
<td>FB</td>
<td>FB</td>
</tr>
<tr>
<td>10</td>
<td>0.9</td>
<td>FB</td>
<td>FB</td>
<td>FB</td>
<td>FB</td>
</tr>
</tbody>
</table>
The unlaced column buckles torsionally for flexural slenderness 0.4 – 0.6 and in a flexural-torsional mode for flexural slenderness 0.7 – 0.9. The result shows that for the same column with lacing, the bucking mode transition to a dominating localized buckling mode. This pattern is most distinct for lace step 1.0 and flexural slenderness 0.5 – 0.6. See Table 15.

*Table 15: Buckling modes in IMP: 400 Unlaced VS Laced for local slenderness 15*

<table>
<thead>
<tr>
<th>CS-class</th>
<th>$\lambda_{flex}$</th>
<th>Unlaced</th>
<th>Laced: Step 1.25</th>
<th>Laced: Step 1.0</th>
<th>Laced: Step 0.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>0.4</td>
<td>TB</td>
<td>TB</td>
<td>LB</td>
<td>LB</td>
</tr>
<tr>
<td>15</td>
<td>0.5</td>
<td>TB</td>
<td>LB</td>
<td>LB</td>
<td>LB</td>
</tr>
<tr>
<td>15</td>
<td>0.6</td>
<td>TB</td>
<td>LB</td>
<td>LB</td>
<td>LB</td>
</tr>
<tr>
<td>15</td>
<td>0.7</td>
<td>FTB</td>
<td>LB</td>
<td>LB</td>
<td>FTB</td>
</tr>
<tr>
<td>15</td>
<td>0.8</td>
<td>FTB</td>
<td>LB</td>
<td>LB</td>
<td>FTB</td>
</tr>
</tbody>
</table>

For local slenderness 20 the unlaced column buckles torsionally for any analyzed flexural slenderness. Compared to local slenderness 15, there is clear transition from torsional- to localized buckling modes, see Table 16.

*Table 16: Buckling modes in IMP: 400 Unlaced VS Laced for local slenderness 20*

<table>
<thead>
<tr>
<th>CS-class</th>
<th>$\lambda_{flex}$</th>
<th>Unlaced</th>
<th>Laced: Step 1.25</th>
<th>Laced: Step 1.0</th>
<th>Laced: Step 0.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.4</td>
<td>TB</td>
<td>LB</td>
<td>LB</td>
<td>LB</td>
</tr>
<tr>
<td>20</td>
<td>0.5</td>
<td>TB</td>
<td>LB</td>
<td>LB</td>
<td>LB</td>
</tr>
<tr>
<td>20</td>
<td>0.6</td>
<td>TB</td>
<td>LB</td>
<td>LB</td>
<td>LB</td>
</tr>
<tr>
<td>20</td>
<td>0.7</td>
<td>TB</td>
<td>LB</td>
<td>LB</td>
<td>LB</td>
</tr>
<tr>
<td>20</td>
<td>0.8</td>
<td>TB</td>
<td>LB</td>
<td>LB</td>
<td>LB</td>
</tr>
<tr>
<td>20</td>
<td>0.9</td>
<td>TB</td>
<td>LB</td>
<td>LB</td>
<td>LB</td>
</tr>
</tbody>
</table>

The same pattern can be seen for local slenderness 25 as for 15 and 20. The lacing makes the buckles mode transition from torsional- to localized buckling. The transition is not that clear as for class 20.

*Table 17: Buckling modes in IMP: 400 Unlaced VS Laced for local slenderness 25*

<table>
<thead>
<tr>
<th>CS-class</th>
<th>$\lambda_{flex}$</th>
<th>Unlaced</th>
<th>Laced: Step 1.25</th>
<th>Laced: Step 1.0</th>
<th>Laced: Step 0.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>0.4</td>
<td>TB</td>
<td>LB</td>
<td>LB</td>
<td>LB</td>
</tr>
<tr>
<td>25</td>
<td>0.5</td>
<td>TB</td>
<td>LB</td>
<td>TB</td>
<td>LB</td>
</tr>
<tr>
<td>25</td>
<td>0.6</td>
<td>TB</td>
<td>TB</td>
<td>TB</td>
<td>LB</td>
</tr>
<tr>
<td>25</td>
<td>0.7</td>
<td>TB</td>
<td>TB</td>
<td>LB</td>
<td>LB</td>
</tr>
<tr>
<td>25</td>
<td>0.8</td>
<td>TB</td>
<td>TB</td>
<td>LB</td>
<td>TB</td>
</tr>
<tr>
<td>25</td>
<td>0.9</td>
<td>TB</td>
<td>TB</td>
<td>LB</td>
<td>LB</td>
</tr>
</tbody>
</table>
Figure 28 a) – c) shows the difference between the two Abaqus calculated buckling resistances for unlaced and laced columns. The graphs show that the laced columns have a higher buckling resistance than the unlaced columns, with the exception for the lower local slenderness. This might be due to the lower local slenderness buckle due to flexural buckling or that the torsional buckling has a similar buckling strength to the localized buckling for these columns.

The result shows that largest difference in utilization ratio is for flexural slenderness 0.5 – 0.7 and increased local slenderness.

*Figure 28: The differences in utilization ratio for IMP: 400*
5.3 Columns: IMP: 400 VSIMP: 200

As can be seen in Figure 29 the utilization ratio is higher for all columns with lower imposed imperfections. The smallest difference in the results is obtained when the two unlaced columns are compared.

![Figure 29: The differences in utilization ratio. Comparing IMP: 400 to IMP: 200](image)

5.4 Summary of analysis

5.4.1 Lacing suitability with regard to local- and flexural slenderness

In the local slenderness interval between 10 and 15 the results for laced and unlaced columns are almost the same. The lacing is most efficient for columns in cross-section class 4, this means a local slenderness above 15.

With regard to flexural slenderness the lacing have a positive contribution on any analyzed cross-section in class 4. The largest contributions of the lacing is found in the flexural slenderness interval between 0.5 – 0.8.

These results hold true for both analyzed imperfections. The difference between them being the Abaqus calculated buckling resistance being higher for 1/400.
5.4.2 The Eurocode buckling resistance compared to the finite element method

*IMP: 200*

The Abaqus values for columns with flexural slenderness above 0.6 in cross-section class 3 yields results below the Eurocode buckling resistance. All other analyzed values are above the Eurocode calculated resistance, this is true for both unlaced and laced columns. The lacing gives the largest contribution for columns in cross-section class 4.

*IMP: 400*

The results are very similar to when 1/200 imperfections are used with exception of all columns getting a higher result than the Eurocode buckling resistance.

5.4.3 Buckling modes with regard to laced and unlaced columns

The results show that lacing is not efficient below cross-section class 3 according to transition of buckling modes. All analyzed specimen with local slenderness 10 buckles flexurally, with or without lacing. For the other cross-section classes there is a clear pattern of buckle transition from torsional buckling to localized buckling. This pattern gets clearer with increased lacing and local slenderness.
6 Conclusions

The lacing has been proven to have a positive effect on columns in cross-section class 4, where the lacing is most efficient. The effect of adding laces to the columns are none in cross-section class 3 when buckling resistance is considered. The resistance gain in cross-section class 4 fluctuates between

- 5-10% for columns with local slenderness 20
- 30-50% for columns with local slenderness 25

The effect of the lacing is barely increased by the density of the laces;

- 0-1 % for columns with local slenderness 20
- 1-6 % for columns with local slenderness 25

From the results it can be concluded that lacing is only suitable for columns in cross-section class 4. The three densities of lacing that were used in this study yielded similar results when buckling resistance is considered.

The lacing has altered the buckling modes at a large extent for the columns in cross-section class 4 from a torsional buckling mode to localized buckling. Columns with local slenderness 15 also have altered buckling modes when the lacing is introduced. The buckling mode alters from torsional buckling to flexural-torsional- or localized buckling.

Some of the Abaqus generated columns have buckling resistance below the Eurocode values when an imperfection l/200 is applied. When the imperfections are halved to l/400 the results are above unlaced columns calculated with Eurocode.
7 Discussion

The lacing was proven to have a positive effect on the buckling resistance which was assumed. It would be interesting to experiment with different types of lacing to see how they would affect the buckling resistance. The lacing used in this thesis have yielded some interesting results and improved the rigidity of the columns but there is no way to know if it is efficient compared to other types of lacing by the data presented in this thesis. Since economical aspects have not been considered, it’s not possible to determine the practical use these columns.

The buckling modes were determined by visually looking at the buckling procedure of all columns in Abaqus. There is no inherent function to determine this in Abaqus. An alternative would be to make a software to determine the buckling modes, but due to limited time that was not possible.

It would seem reasonable that the lacing is an efficient way to prevent torsional buckling of angle members due to them being susceptible to torsional buckling. Further on it’s also logical that the torsional buckling mode is altered to localized buckling for many specimen.
8 Further studies

- As mentioned in the discussion chapter it would be interesting to see the result from different types of lacing see Figure 30

![Figure 30: An example of lacing (Bernuzzi et al., 2014)](image)

- Other load cases could be analysed
- A program to determine the buckling modes can also be developed
9 References


from part import *
from material import *
from section import *
import abq_toolset as xtr
from assembly import *
from step import *
from interaction import *
from load import *
from mesh import *
from optimization import *
from job import *
from sketch import *
from visualization import *
from connectorBehavior import *
import sys
import os
from shutil import copyfile
import odbAccess

# Cross section b / (epsilon * t) according to EC3-1-1 table 5.1 sheet 3 for angles
p_class = 15.

# Total width of the leg (from the intersection of the midlines to the edge)
l_leg = 100.

# flexural slenderness
lambda_flex = 0.4

# Lacing density. Lacing dist over leg width ratio
lace_over_leg = 1.1

# Imperfection amplitude for local, flexural and torsional modes
loc_imp = 200.
flex_imp = 200.
tor_imp = 200.

# Yield stress
fy_steel = 690.

try:
    l_leg = float(sys.argv[-4])
except:
    pass

try:
    p_class = float(sys.argv[-3])
except:
    pass

try:
    lambda_flex = float(sys.argv[-2])/100
except:
    pass

try:
lace_over_leg = float(sys.argv[-1]) / 10
except:
pass

# MATERIAL
# Modulus of elasticity, poisson's ratio, yield stress and epsilon
# (Yield stress used for design calculations, not for material properties
# of the model)
v_poi = 0.3
E_steel = 210000.
G_steel = E_steel / (2*(1+v_poi))
epsilon = sqrt(235 / fy_steel)

# BASIC GEOMETRY
# Shell thickness
t_shell = l_leg / (p_class * epsilon)

# The straight part of the leg (l_strght) and the corner bending radius
# The bending radius is defined as a ratio to the shell thickness
r_over_t = 1.
r_bend = r_over_t * t_shell
l_strght = l_leg - r_bend

# Create a string which will be used as an identifier for the current
# model. Used for directory and filename.
IDstring = str(int(l_leg))+'-\nstr(int(p_class))+'-\nstr(int(lambda_flex *100))+'-\nstr(int(lace_over_leg *10))

# Make a new subdirectory for the current session
os.mkdir(IDstring)

# Copy necessary files to the new directory
copyfile('abq_toolset.py', './'+IDstring+'/abq_toolset.py')
copyfile('laced_angle.py', './'+IDstring+'/laced_angle.py')
copyfile('GN_Riks_killer.f', './'+IDstring+'/GN_Riks_killer.f')

# Change the working directory
os.chdir('./'+IDstring)

# CROSS SECTION PROPERTIES
# CORNER
# Outer radius
r_max = r_bend + (t_shell / 2)

# Inner radius
r_min = r_bend - (t_shell / 2)

# AREA
# Area of leg in Y-axis
A1 = l_strght * t_shell

# Area of leg in X-axis
A2 = A1

# Area of large quarter circle
# Area of small quarter circle
A3 = r_max **2 * pi / 4

# Area of large quarter circle
A4 = r_min **2 * pi / 4

# Total area
A_tot = A1 + A2 + A3 - A4

# CENTRE OF GRAVITY
# Leg in Y-axis
yg1 = r_bend + l_strght / 2

# Leg in x-axis
yg2 = t_shell / 2

# Large quarter circle
yg3 = r_bend * (1 - 4 / (3 * pi))

# Small quarter circle
yg4 = t_shell + (r_bend - t_shell) * (1 - 4 / (3 * pi))

# Center of gravity from Origo
ytp = (A1 * yg1 + A2 * yg2 + A3 * yg3 - A4 * yg4) / A_tot

# MOMENT OF INERTIA
# Moment of intertia part 1 (leg in Y-axis)
Iz1 = t_shell * l_strght **(3/12) + l_strght * t_shell * (yg1 - ytp)**2

# Moment of intertia part 2 (leg in X-axis)
Iz2 = l_strght * t_shell **(3/12) + l_strght * t_shell * (yg2 - ytp)**2

# Moment of intertia part 3 (large quarter circle)
Iz3 = r_bend **4 * (pi / 16 - 4 / (9 * pi)) + pi * r_bend **2 / 4 * (yg3 - ytp)**2

# Moment of intertia part 3 (small quarter circle)
Iz4 = (r_bend - t_shell)**4 * (pi / 16 - 4 / (9 * pi)) + pi *(r_bend - t_shell)**2 / 4 * (yg4 - ytp)**2

# Moments of intertia
I_z = Iz1 + Iz2 + Iz3 - Iz4
I_y = I_z

# Product of intertia

# Principal moments and X-Y direction about centroid
I1 = I_z + abs(Iyz)
I2 = I_z - abs(Iyz)

# Polar radius of gyration
i_pol = sqrt((I1 + I2) / A_tot)
i_zero = sqrt(i_pol **2 + ytp **2)

# Bending stiffness E*I
E_I1 = E_steel * I1
E_I2 = E_steel * I2

# COLUMN LENGTH
l_tot = lambda_flex * pi * sqrt(E_I2 / (A_tot * fy_steel))

# LACING
# Approximate longitudinal spacing of lacing attachment points
l_lace_approx = lace_over_leg * l_leg

# Calculate the number of laces that best fit to the requested ratio
n_laces = int(ceil(l_tot / l_lace_approx))

# Final lacing spacing
l_lace = l_tot / n_laces

# The following calculations conclude to the cross-sectional area of the lacing rods.
# It is calculated for a tubular section of slenderness = 1 and d/t = 70

# distance of two opposite points on the legs' edges
l_hypot = sqrt(2) * l_leg

# Rod length
l_wire = sqrt(l_lace ** 2 + l_hypot ** 2)

# Rod slenderness
lambda_wire = 1.

# Rod class
wire_classification = 70.

# the following two constants (constant a and b) are used to assist the calculations
constant_a = (lambda_wire * pi / l_wire)**2 * E_steel / fy_steel
constant_b = 2 / (70 * epsilon ** 2)

# Outer radius of the tube
r_wire = sqrt(4*(1-(1-constant_b)**2)/(constant_a*(1-(1-constant_b)**4)))

# Area.
# For the case of no lacing, uncomment the second line to decrease the lacing cs are
A_wire = pi * r_wire ** 2 * (1-(1-constant_b)**2)
A_wire = 1.e-8

# DESIGN RESISTANCE
# The following calculations take are for the design resistance of the compression element
# according to EC1-1-1 and EC3-1-5 and include overall and local buckling resistance.
# The calculations regard to a plain L-profile neglecting the lacing.

# Classification and Aeff
# Aeff is calculated assuming uniform compression on the sectors.
psi = 1.
kapa_sigma = 0.57 - 0.21 * psi + 0.07 * psi ** 2
p_class = l_leg / (t_shell * epsilon)
lambda_p = p_class / (28.4 * sqrt(kapa_sigma))
if lambda_p > 0.748 and int(p_class) > 15:
rho = (lambda_p - 0.188) / lambda_p ** 2
else:
rho = 1.

# Effective cross-section
A_eff = 2 * A1 * rho + A3 - A4
# Overall buckling. Calculation of Ncr.
# All three modes (bending over the principal axes and torsional) are taken
into account.
# Formulas from Trahair.
I_torsion = 2*(t_shell **3* l_leg /3)
I_warp = 0.

# Independent critical loads for flexural and torsional modes
N_cr_max = (pi **2* E_steel * I1)/(l_tot **2)
N_cr_min = (pi **2* E_steel * I2)/(l_tot **2)
N_cr_tor = (1/ i_zero **2)* (G_steel * I_torsion + (pi **2* E_steel * I_warp / l_tot **2))

# Coefficients of the 3rd order equation for the critical loads
# The equation is in the form aaaa * N ^ 3 - bbbb * N ^ 2 + cccc * N - dddd
aaaa = i_zero **2 - ytp **2 - ytp **2
bbbb = ((N_cr_max + N_cr_min + N_cr_tor) * i_zero **2) - (N_cr_min * ytp **2) - (N_cr_max * ytp **2)
cccc = i_zero **2 * (N_cr_min * N_cr_max) + (N_cr_min * N_cr_tor) + (N_cr_tor * N_cr_max)
dddd = i_zero **2 * N_cr_min * N_cr_max * N_cr_tor

DD = (4*(-bbbb **2+3* aaaa * cccc)**3+ (2* bbbh **3-9* aaaa * bbbh * cccc +27* aaaa **2* dddd)**2)
if (DD <0):
    DD = -1.* DD
cf =1j
else:
cf =1

# Critical load
# The following N_cr formulas are the roots of the 3rd order equation of
# the global critical load
N_cr_1 = bbbh/(3.*aaaa)-(2**((1./3)*(-bbbb**2+3*aaaa*cccc))/
\(3.*aaaa*(2*bbbh**3-9*aaaa*bbbh*cccc +27*aaaa**2*dddd) +
\((cf*sqrt(DD)))**(1./3)+(2*bbbh**3-9*aaaa*bbbh*cccc +27*aaaa**2*dddd) +
\((cf*sqrt(DD)))**(1./3)/3**2**(1./3)*aaaa)
N_cr_2 = bbbh/(3.*aaaa)+(1/(0+1j)*sqrt(3))*(-bbbb**2+3*aaaa*cccc))/
\(3.*2**(2./3)*aaaa*(2*bbbh**3-9*aaaa*bbbh*cccc +27*aaaa**2*dddd) +
\((cf*sqrt(DD)))**(1./3)-(1/(0+1j)*sqrt(3))*
\(2*bbbh**3-9*aaaa*bbbh*cccc +27*aaaa**2*dddd) +
\((cf*sqrt(DD)))**(1./3)/6**2**(1./3)*aaaa)
N_cr_3 = bbbh/(3.*aaaa)+(1/(0+1j)*sqrt(3))*(-bbbb**2+3*aaaa*cccc))/
\(3.*2**(2./3)*aaaa*(2*bbbh**3-9*aaaa*bbbh*cccc +27*aaaa**2*dddd) +
\((cf*sqrt(DD)))**(1./3)-(1/(0+1j)*sqrt(3))*
\(2*bbbh**3-9*aaaa*bbbh*cccc +27*aaaa**2*ddddd +
\((cf*sqrt(DD)))**(1./3)/6**2**(1./3)*aaaa)

# Lowest root is the critical load
N_cr = min(abs(N_cr_1), abs(N_cr_2), abs(N_cr_3), N_cr_min, N_cr_tor)
# Design plastic resistance
N_pl_rd = fy_steel * A_eff

# Member slenderness
lambda_flex_tor = sqrt(N_pl_rd / N_cr)

# Reduction factor chi
a_imp_fact = 0.34
phi_capital = (1 + a_imp_fact * (lambda_flex_tor - 0.2) + lambda_flex_tor ** 2) / 2
chi_glob = 1 / (phi_capital + sqrt(phi_capital ** 2 - lambda_flex_tor ** 2))

# Buckling resistance
N_b_rd = chi_glob * N_pl_rd

# WRITE OUT FILE
# model information are written in a text file
out_file = open('./model_info-' + IDstring + '.dat', 'w')
out_file.write('\-GEOMETRIC CHARACTERISTICS\n')
out_file.write('Total leg width:..................................................... ' + str(l_leg) + '[mm]\n')
out_file.write('Bending radius (midline):............................................ ' + str(r_bend) + '[mm]\n')
out_file.write('Length of the leg\'s flat part:....................................... ' + str(l_strght) + ' [mm]\n')
out_file.write('Total column length:................................................... ' + str(l_tot / 1000) + ' [m]\n')
out_file.write('Profile thickness:................................................... ' + str(t_shell) + '[mm]\n')
out_file.write('Number of lacing bars:............................................. ' + str(int(n_laces)) + '\n')
out_file.write('Lacing length over leg width:........................................ ' + str(lace_over_leg) + '\n')
out_file.write('Yield strength:.......................................................... ' + str(fy_steel) + ' [MPa]\n')
out_file.write('Gross cross-sectional area:................................................. ' + str(A_tot) + ' [mm^2]\n')
out_file.write('Cross-sectional area of lacing rods, A_rod:.......................... ' + str(A_wire) + ' [mm^2]\n')
out_file.write('Moment of inertia around the axes parallel to the legs, I_y, I_z:........ ' + str(I_y) + ' [mm^4]\n')
out_file.write('Max principal moment of inertia, I_1:................................. ' + str(I1) + ' [mm^4]\n')
out_file.write('Min principal moment of inertia, I_2:................................. ' + str(I2) + ' [mm^4]\n')
out_file.write('Cross-section classification, c/(epsilon*t):......................... ' + str(p_class) + '\n')
out_file.write('Plate slenderness, lambda_p:......................................... ' + str(lambda_p) + '\n')
out_file.write('Effective area reduction factor, rho:................................ ' + str(rho) + '\n')
out_file.write('Effective cross-sectional area:........................................ ' + str(A_eff) + ' [mm^2]\n')
out_file.write('Max flexural critical load, N_cr_max:................................ ' + str(N_cr_max / 1000) + '[kN]\n')
out_file.write('Min flexural critical load, N_cr_min:............ '+'str(N_cr_min/1000)+' [kN]\n')
out_file.write('Torsional critical load, N_cr_tor:............. '+'str(N_cr_tor/1000)+' [kN]\n')
out_file.write('Combined torsional-flexural critical load, N_cr:............. '+'str(N_cr/1000)+' [kN]\n')
out_file.write('Flexural slenderness, lambda_flex:............... '+'str(lambda_flex)+'\n')
out_file.write('Flexural-torsional slenderness, lambda_flex_tor:......... '+'str(lambda_flex_tor)+'\n')
out_file.write('Flexural-torsional buckling reduction factor, chi:............. '+'str(chi_glob)+'\n')
out_file.write('Plastic resistance, N_pl_rd:........................... '+'str(N_pl_rd/1000)+' [kN]\n')
out_file.write('Buckling resistance, N_b_rd:............................ '+'str(N_b_rd/1000)+' [kN]\n')

out_file.write('MODEL IMPERFECTIONS'+'\n')
out_file.write('Flexural buckling bow imperfections:.................... l/+'+str(flex_imp)+'\n')
out_file.write('Torsional buckling imperfections:..................... l/+'+str(tor_imp)+'\n')
out_file.write('Plate imperfections:...................................... b/+'+str(loc_imp)+'\n')

### MODEL ###
#Create a model
mdb.models.changeKey(
    fromName='Model-1',
    toName='BracedLBeam',
)

beamModel = mdb.models['BracedLBeam']

#Sketch: Create the cross-section: L-section
p11 = (0, l_leg)
p12 = (0, 0)
p21 = (l_leg, 0)
p22 = (0, 0)
np1 = (0, l_leg)
np2 = (l_leg, 0)

cs_sketch = beamModel.ConstrainedSketch(
    name='__profile__',
    sheetSize= l_leg + r_bend
)

cs_sketch.Line(
    p11,
    p12
)

cs_sketch.VerticalConstraint(
    addUndoState=True,
    entity= cs_sketch.geometry[2]
)

cs_sketch.Line(}
#Sketch: Create angle to the L-section

cs_sketch.HorizontalConstraint(
    addUndoState=False,
    entity= cs_sketch.geometry[3]
)

cs_sketch.PerpendicularConstraint(
    addUndoState=False,
    entity1= cs_sketch.geometry[2],
    entity2= cs_sketch.geometry[3]
)

cs_sketch.FilletByRadius(
    curve1= cs_sketch.geometry[2],
    curve2= cs_sketch.geometry[3],
    nearPoint1= np1,
    nearPoint2= np2,
    radius= r_bend)

#Creating the beam: Extrudes the cross-section

column_prt = beamModel.Part(
    dimensionality= THREE_D,
    name= 'Part',
    type= DEFORMABLE_BODY
)

column_prt.BaseShellExtrude(
    depth= l_tot,
    sketch = cs_sketch
)

#Creating datumplanes

#Creating datumplane every l_lace in the range 0 < ext

for datumplanes in range(1, n_laces):
    column_prt.DatumPlaneByPrincipalPlane(
        offset= datumplanes * l_lace,
        principalPlane= XYPLANE
    )

## Creating a partition on every datumplane

for datum_partition in column_prt.datums.items():
    column_prt.PartitionFaceByDatumPlane(
        datumPlane= datum_partition[1],
        faces= column_prt.faces[:]
    )

# Creating the zigzag bracing for the column_prt

for wir1 in range(0, n_laces, 2):
    column_prt.WirePolyLine(
        points=((0., l_leg, wir1 * l_lace),(l_leg, 0., wir1 * l_lace+l_lace)),
        meshable= ON)

for wir2 in range(1, n_laces, 2):
column_prt.WirePolyLine(points =((l_leg,0., wir2 * l_lace),(0.,l_leg ,wir2 * l_lace+l_lace)), meshable = ON)

#Defining material: Steel
beamModel.Material(name = 'steel')
beamModel.materials['steel'].Elastic(table =((E_steel, v_poi),))
beamModel.materials['steel'].Plastic(
    table=
    (fy_steel,0.0),
    (fy_steel *1.2,0.2)
)

#Creating section: Shell
beamModel.HomogeneousShellSection(
    idealization= NO_IDEALIZATION,
    integrationRule= SIMPSON,
    material= 'steel',
    name= 'shell',
    numIntPts=5,
    poissonDefinition= DEFAULT,
    preIntegrate= OFF,
    temperature= GRADIENT,
    thickness= t_shell,
    thicknessField= '',
    thicknessModulus= None,
    thicknessType= UNIFORM,
    useDensity= OFF
)

#Creating section: Beam
beamModel.TrussSection(area = A_wire,
    material= 'steel',
    name= 'bracing'
)

# Create set with all faces
all_faces = column_prt.Set(
    faces= column_prt.faces[:],
    name= 'All_Faces'
)

#Assign section: To the shell
column_prt.SectionAssignment(
    offset=0.0,
    offsetField='' ,
    offsetType= MIDDLE_SURFACE,
    region= all_faces,
    sectionName= 'shell',
    thicknessAssignment= FROM_SECTION
)

# Create a set for the wires
edge_list = []
for z_lace in range(1,2*n_laces,2):
    point_coord =((l_leg*0.5, l_leg*0.5, l_lace * z_lace /2),)
    edge_list.append(column_prt.edges.findAt(point_coord))

# The findAt function does not seem to work. The required arguments are 2.
The `find_points` has 11 arguments.
```
all_wires = column_prt.Set(
edges= edge_list,
    name='all_wires'
)
```

# Assign section: To the bracing
```
column_prt.SectionAssignment(
    offset=0.0,
    offsetField='',
    offsetType= MIDDLE_SURFACE,
    region= all_wires,
    sectionName='bracing',
    thicknessAssignment= FROM_SECTION
)
```

# Creating material orientation: The the shell
```
column_prt.MaterialOrientation(
    additionalRotationType= ROTATION_NONE,
    axis= AXIS_2,
    fieldName='',
    localCsSys=None,
    orientationType= GLOBAL,
    region= all_faces
)
```

# Assign truss element type for the lacing wires
```
column_prt.setElementType(
    elemTypes=(ElemType(
        elemCode= T3D2,
        elemLibrary= STANDARD
    ),),
    regions= all_wires
)
```

# Creating the assembly
```
beamModel.rootAssembly.DatumCsSysByDefault(CARTESIAN)
beamAssembly= beamModel.rootAssembly
AssemblyInstance = beamAssembly.Instance(
    dependent= OFF,
    name='Column Instance',
    part= column_prt
)
```

# Step: Creating the riks step
```
beamModel_STATIC_RIKS = beamModel.StaticRiksStep(
    initialArcInc=0.1,
    name='RIKS',
    nlgeom= ON,
    previous='Initial',
    maxNumInc=25
)
```

# Creating RP: reference points
```
cog1 = column_prt.getMassProperties()
#cog1['areaCentroid']
lst= list(cog1['areaCentroid'])
lst[2]=0
cog1 = tuple(lst)
```
cog2 = column_prt.getMassProperties()
# cog2['areaCentroid']
lst = list(cog2['areaCentroid'])
lst[2] = l_tot
cog2 = tuple(lst)

beamAssembly.ReferencePoint(point = cog1)
beamAssembly.ReferencePoint(point = cog2)

# Creating a Set for the selection at RP - 1, the one at the bottom of the column
beamAssembly.Set(
name = 'RP-1',
referencePoints = beamAssembly.referencePoints[4],)

# Creating a Set for selecting the edges at the base of the column
beamAssembly.Set(
edges = AssemblyInstance.edges.getByBoundingBox(0, 0, 0, l_leg+1, l_leg+1, 0),
name = 'Base_edge',)

# Coupling: The RPs to the ends
beamModel.Coupling(
controlPoint = beamAssembly.sets['RP-1'],
couplingType = KINEMATIC,
influenceRadius = WHOLE_SURFACE,
localCsys = None,
name = 'Constraint-1',
surface = beamAssembly.sets['Base_edge'],
   u1 = ON,
   u2 = ON,
   u3 = ON,
   ur1 = ON,
   ur2 = ON,
   ur3 = ON)

# Creating a Set at RP - 2, the one at the top of the column
beamAssembly.Set(
name = 'RP-2',
referencePoints = beamAssembly.referencePoints[5],)

# Creating a Set for selecting the edges at the head of the column
beamAssembly.Set(
edges = AssemblyInstance.edges.getByBoundingBox(0, 0, l_tot, l_leg+1, l_leg+1, l_tot),
name = 'Top_edge',)

# Coupling: The RPs to the ends
beamModel.Coupling(
controlPoint = beamAssembly.sets['RP-2'],
couplingType = KINEMATIC,
influenceRadius = WHOLE_SURFACE,
localCsys = None,
name = 'Constraint-2',
surface = beamAssembly.sets['Top_edge'],
   u1 = ON,
   u2 = ON,
u3 = ON,
ur1 = ON,
ur2 = ON,
ur3 = ON
)

# Boundary condition: Bottom : boundary condition set on the RPs
beamModel.DisplacementBC(
amplitude= UNSET,
buckleCase= PERTURBATION_AND_BUCKLING,
createStepName= 'RIKS',
distributionType= UNIFORM,
fieldName= '',
fixed= OFF,
localCsys= None,
name= 'BC-1',
region= beamAssembly.sets['RP-1'],
  u1 = 0.0,
  u2 = 0.0,
  u3 = 0.0,
  ur1 = UNSET,
  ur2 = UNSET,
  ur3 = 0.0
)

# Boundary condition: Top : boundary condition set on the RPs
beamModel.DisplacementBC(
amplitude= UNSET,
buckleCase= PERTURBATION_AND_BUCKLING,
createStepName= 'RIKS',
distributionType= UNIFORM,
fieldName= '',
fixed= OFF,
localCsys= None,
name= 'BC-2',
region= beamAssembly.sets['RP-2'],
  u1 = 0.0,
  u2 = 0.0,
  u3 = UNSET,
  ur1 = UNSET,
  ur2 = UNSET,
  ur3 = UNSET
)

# Mesh: Changed type to structured mesh
beamAssembly.setMeshControls(
  regions= AssemblyInstance.faces[:],
technique= STRUCTURED
)

# seed the lacing wires so that they are a single element per brace
beamAssembly.seedEdgeByNumber(
  constraint= FINER,
  edges= AssemblyInstance.sets['all_wires'].edges[:],
  number=1
)

# Seed the shell
beamAssembly.seedPartInstance(
  deviationFactor=0.1,
  minSizeFactor=0.1,
regions={(AssemblyInstance,),
size= l_leg /10
)

# Mesh: Generating the mesh
beamAssembly.generateMesh(
regions={(AssemblyInstance,)
)

## LOCAL AND GLOBAL BUCKLING IMPERFECTIONS
loc_imperfection_amp = l_lace /loc_imp
dat=lam /dat
flex_imperfection_amp = l_tot /flex_imp
tor_imperfection_amp = l_tot /tor_imp

beamAssembly.makeIndependent(
instances=(
    AssemblyInstance,
  )
)

for j in range(len(AssemblyInstance.nodes[0].coordinates):
x_i= AssemblyInstance.nodes[j].coordinates[0]
y_i= AssemblyInstance.nodes[j].coordinates[1]
z_i= AssemblyInstance.nodes[j].coordinates[2]
glob_bow =-flex_imperfection_amp *sin(pi * z_i / l_tot)* sin(pi /4)
theta_tor = tor_imperfection_amp /((l_leg + r_bend)*sin(pi * z_i / l_tot)
dx_torsion = (x_i *cos(theta_tor) - y_i * sin(theta_tor) - x_i)
dy_torsion = (x_i *sin(theta_tor) + y_i * cos(theta_tor) - y_i)
if x_i==0:
    beamAssembly.editNode(
        nodes= AssemblyInstance.nodes[j],
        offset1 = glob_bow + dx_torsion + loc_imperfection_amp *sin(pi * z_i /(2* l_lace))*(y_i - r_bend)/(l_leg - r_bend)),
        offset2 = glob_bow + dy_torsion
    )
elif y_i==0:
    beamAssembly.editNode(
        nodes= AssemblyInstance.nodes[j],
        offset1 = glob_bow + dx_torsion,
        offset2 = glob_bow + dy_torsion + loc_imperfection_amp *cos(pi /1. + pi *(z_i /(2* l_lace)))*(z_i - r_bend)/(l_leg - r_bend)
    )
else:
    beamAssembly.editNode(
        nodes= AssemblyInstance.nodes[j],
        offset1 = glob_bow + dx_torsion,
        offset2 = glob_bow + dy_torsion
    )

# Add concentrated force
beamModel.ConcentratedForce(
    cfs=-N_b_rd,
createStepName='RIKS',
distributionType= UNIFORM,
field='',
localCsys=None,
name='compression',
region= beamAssembly.sets['RP-2']
)
# Field and History output requests

```python
beamModel.historyOutputRequests.changeKey(
    fromName='H-Output-1',
    toName='load'
)
```

```python
beamModel.historyOutputRequests['load'].setValues(
    rebar=EXCLUDE,
    region=beamAssembly.sets['RP-1'],
    sectionPoints=DEFAULT, variables=('RF3',)
)
```

```python
beamModel.HistoryOutputRequest(
    createStepName='RIKS',
    name='disp',
    rebar=EXCLUDE,
    region=beamAssembly.sets['RP-2'],
    sectionPoints=DEFAULT, variables=('U3',)
)
```

```python
beamModel.fieldOutputRequests.changeKey(
    fromName='F-Output-1',
    toName='fields'
)
```

```python
beamModel.fieldOutputRequests['fields'].setValues(
    variables=('S','Mises','E','PEEQ','U')
)
```

# Creating the riks analysis

```python
# Job: Creating the job
riks_job = mdb.Job(
    atTime=None,
    contactPrint=OFF,
    description=''

echoPrint=OFF,
explicitPrecision=SINGLE,
getMemoryFromAnalysis=True,
historyPrint=OFF,
memory=90,
memoryUnits=PERCENTAGE,
model='BracedLBeam',
modelPrint=OFF,
multiprocessingMode=DEFAULT,
name='riks-job-' + IDstring,
nodalOutputPrecision=SINGLE,
umCpus=4,
umDomains=4,
umGPUs=0,
queue=None,
scratch=''

type=ANALYSIS,
userSubroutine='',
waitHours=0,
waitMinutes=0
)
```

#Job: Submiting the job

```python
riks_job.submit(consistencyChecking = OFF)
```
# Wait for completion
riks_job.waitForCompletion()

# Collect the max results and write rhem in the output file
odb_name = 'riks-job-+IDstring'
myOdb = odbAccess.openOdb(path=odb_name+'.odb')
RIKSstep = myOdb.steps['RIKS']

tp1key = RIKSstep.historyRegions.keys()[-1]
ho1key = RIKSstep.historyRegions[tp1key].historyOutputs.keys()[0]

tp2key = RIKSstep.historyRegions.keys()[0]
ho2key = RIKSstep.historyRegions[tp2key].historyOutputs.keys()[0]
asskey = RIKSstep.historyRegions.keys()[0]
hoass = RIKSstep.historyRegions[asskey].historyOutputs.keys()[0]

t_load = RIKSstep.historyRegions[tp1key].historyOutputs[ho1key].data

t_disp = RIKSstep.historyRegions[tp2key].historyOutputs[ho2key].data

t_lpf_hist = RIKSstep.historyRegions[asskey].historyOutputs[hoass].data

maxpos = t_load.index(max(t_load, key=lambda x: x[1]))
t_load = t_load[maxpos][1]
t_disp = t_disp[maxpos][1]
t_lpf = t_lpf_hist[maxpos][1]

odbAccess.closeOdb(myOdb)

# Write the results in the file
out_file.write('
-RESULTS
')
out_file.write('Maximum LPF:..........................................................
+str(lpf)+
Max load:............................................................
+str(load/1000)+ [kN]
Displacement at maximum load:........................................
+str(disp)+ [mm]

# Close the output file
out_file.close()

# Save the cae model
mdb.saveAs(pathName = os.getcwd()+'/'+IDstring+'.cae')

# Return to parent directory
os.chdir('..')

# Write a file where all the results of a batch run are to be gathered
batch_out_file =open('./batch.dat','a')
batch_out_file.write("%7.1f %7.1f %3s %4.2f %5.2f %7.3E %6.3f %7.3E %7.3E %7.3E\t %7.3E %7.3E %7.3E\n(l_leg, t_shell, int(p_class), lambda_flex, lace_over_leg, l_tot, lpf, load, N_cr_max, N_cr_min, N_cr_tor, N_cr)+\n")
batch_out_file.close()
Annex B

Annex B1

IMP:200. Unlaced columns

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<th>p_class</th>
<th>λ</th>
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<th>LPF</th>
<th>Load</th>
<th>N_cr_max</th>
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