ELASTIC BUCKLING OF COLD FORMED STEEL BEAMS WITH UNSTIFFENED HOLES

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Elastic Buckling of Cold Formed Steel Beams with unstiffened Holes

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**Task list**

Elastic buckling of cold-formed C-section steel beams with perforations may be examined using finite element analysis and the simplified methods provided by the Direct Strength Method of the American Iron and Steel Institute.

The beams, which have to be analyzed, are based on experiments, in order to be able to compare the ABAQUS and simplified methods predictions to the experimental results. This comparison is not part of this task.

A shell finite element eigen-buckling analysis may be performed such that the influence of boundary conditions and the presence of holes on elastic buckling response are captured. Thus critical elastic buckling parameters may be determined and in addition, the influence of perforations can be delivered. To create the finite element models the program ABAQUS shall be used. The resulting elastic buckling parameters may be compared to recently derived design-motivated simplified methods employing the finite strip method.
Abstract

Critical elastic buckling analyses for cold-formed steel beams with unstiffened holes are performed in this assignment. The beam dimensions, boundary and loading conditions for the conducted simulations are based on experiments conducted by A. Schudlich [14]. Critical buckling moments for local, distortional and global buckling are calculated on the one hand by using the finite element method and on the other hand by employing the simplified methods for deriving critical elastic buckling parameters for cold-formed steel provided by the American Iron and Steel Institute’s Direct Strength Method (DSM) [1]. The results of both analyses have been compared in order to validate the DSM simplified methods. Also beams without holes are considered in this assignment as well as all beams with holes are also simulated without holes included. With comparing the results of members without holes to those members with holes, the influence of unstiffened holes can be obtained.
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1 Introduction

Cold-formed steel (CFS) structural components are occasionally produced with holes to induce building services into walls and ceilings of buildings. CFS members without holes can be designed with the DSM (refer to AISI-S100 [1] and B. W. Schafer [11]), which predicts ultimate strength by using the local, distortional, and global elastic buckling properties of a cross-section. The elastic buckling properties can be determined from an elastic buckling curve which is generated with the finite strip method (FSM). The finite strip method identifies, with high computational efficiency (compared to the FE method), the buckling modes which have to be determined for the design. One example of an elastic buckling curve for beams is shown in Figure 1.1. While the first minimum represent the local buckling mode, the second minimum reveals the distortional buckling mode. The global buckling mode is depending on the unbraced physical length of the member.

![Elastic buckling curve](image)

The FSM is only capable to analyze components with a constant cross-section along its length. Because of that, holes cannot be modeled utilizing the FSM. For an exact determination of the elastic buckling properties, finite element (FE) modeling is necessary.

FE modeling induces a number of problems. On the one hand it is computationally inefficient. On the other hand the results of FE modeling are very subjective, as the controlling buckling mode has to be determined by visual inspection. Overall it is a very time consuming process and therefore expensive.
As a convenient alternative to shell FE modeling, simplified design methods for CFS members with holes have been developed by C.D. Moen and B. Schafer [7] [10] and thus extended the DSM. With these simplified methods the elastic buckling properties can be determined with a small effort and thus CFS members with holes can be designed.

In this assignment, elastic buckling parameters have been determined using FE modeling [chapter 2], pure FSM analysis (for members without holes) [chapter 3] and the DSM simplified methods (for beams including holes) [chapter 3] for CFS beams in order to provide the derived elastic buckling parameters for the DSM equation development and to validate the simplified design methods for CFS beams with holes by comparing the detected elastic buckling properties with each other.

This assignment is part of a research project. As part of this project several physical experiments have been performed by Schudlich [14]. Some of the results of this report are used by Schudlich [14] in order to validate the DSM predictions by comparing them to experimental results obtained by Schudlich [14]. Therefore, the dimensions of the beams are based on the measurements of the experimentally tested beams. The dimensions are summarized in Appendix A.

### 1.1 Specimen notation and description

The beams are all of the same cross-section which has been chosen from a catalog of industry standard C-sections (Structural Stud Manufacturers Association (SSMA)). The beams were evaluated with their measured dimensions including holes in 12 of the 18 beams. Six specimens did not have perforations (NH: specimens without holes). Six beams were provided with holes which reduce the strong axis moment of inertia \( I \) of the cross section by 10 percent (H0.9: specimens with \( \frac{I_{\text{net}}}{I_g} = 0.9 \)) and another six specimens with holes which reduce \( I \) by 20 percent (H0.8: specimens with \( \frac{I_{\text{net}}}{I_g} = 0.8 \)). Additionally, the beams with holes are also analyzed without considering their holes in order to be able to estimate the direct influence of holes. The specimen naming convention used in the following is shown in Figure 1.2.

![Figure 1.2: Specimen naming convention](image)

Since the cross-section type, SSMA standard 800S250-68, is identical for all the beams, the cross-section type will be left out in the following. The depth \( H \) of this section is 203 mm (8 in.), while the width of
the flanges, $B_1$ and $B_2$, is 63 mm (2.5 in.). The lip lengths, $D_1$ and $D_2$, are 16 mm (0.625 in) and the thickness $t$ is 1.7 mm (0.068 in.). The inside corner radii ($RB_1$, $RT_1$, $RB_2$ and $RT_2$) are 2.7 mm (0.1069 in.), while the nominal angles $F_1$ and $F_2$ are 90° and $S_1$ and $S_2$ are °. The FE simulations were performed with measured dimension of each beam. The cross-section and hole-dimension notation are shown in Figures 1.3 and 1.4. The measured cross-section dimensions are provided in Appendix A in Table 5.1, while the measured hole dimensions and positions are summarized in Appendix A in Table 5.2. The depth of the hole is called $d_{\text{hole}}$. While the width of the strip above the hole is named $w_1$, the strip width beneath the hole is $w_2$ (Figure 1.3). The length of the hole is named $L_{\text{hole}}$, the hole spacing $S$ and the distances from the origin to the center of each hole are named $X_{\text{HoleA}}$, $X_{\text{HoleB}}$ and $X_{\text{HoleC}}$. Three rectangular holes are cut into 12 beams; the holes are centered in the web. One hole is centered in midspan; the centers of the other two holes are located 609 mm (24 in.) on each side from the midspan. The hole spacing $S$ (length between two holes) is 305 mm (12 in.). The hole length is nominally 152 mm (6 in.), while their depth ($d_{\text{hole}}$) is varying. They are either 137 mm (5.38 in.), which leads to $\frac{l_{\text{net}}}{l_{g}}=0.9$, or 172 mm (6.78 in.) due to $\frac{l_{\text{net}}}{l_{g}}=0.8$ is required.

![Figure 1.3: Cross-section and hole-dimension notation](image)

![Figure 1.4: Hole position notation](image)
1.2 Test setup

The specimens are tested in four-point bending, which creates a constant moment region between the load points. The shear force is zero in this area, which means that a pure moment is applied to the beams. In each test two C-sections are fastened together back to back by four HSS-sections (HSS 7x7x1/4) of 178 mm (7 in.) length; two of them at the supports, two at the load points. They are vertically attached to the webs of the CFS members with four bolts (Ø 13 mm/0.5 in.) (1.5,1.6). The load is applied through the two HSS-sections in the middle, which transport the load to the bolts and thus into the webs. They prevent the beams from web crippling at the load points, since they restrain the web and distribute the load.

In addition to that, the two beams are connected by metal sheet panels (shape, d= 0.45 mm(0.018 in.) ) at their top and at their bottom flanges with a self drilling screw on each member every 304 mm (12 in.). With the metal panels a closed cross-section is provided, which prevents the single C-channels from lateral-torsional buckling over the hole span. In the constant moment region the metal panels are left out in order to avoid influences on any failure mechanism. The whole test setup and important measurements are depicted in Figures 1.5 and 1.6).

![Figure 1.5: Test setup [14]](image)

![Figure 1.6: Cross-section at load point [14]](image)
2 Elastic Buckling of CFS beams examined with FEM

2.1 Introduction

Finite element (FE) eigen-buckling analysis is a common method for studying the elastic buckling properties of thin-walled structures. The accuracy of FE analysis is strongly influenced by the user, who has to decide about the FE type, meshing and density of the elements. In addition to that boundary conditions and constraints have to be considered thoroughly. The FE eigen-buckling simulation are realized with the finite element program ABAQUS [4]. For this kind of study, the accuracy of ABAQUS thin shell elements have been evaluated by Moen [7].

In order to provide elastic buckling parameters for the DSM equation development 15 simulations are performed. The results of the conducted simulations are used by Schudlich [14] to calculate the ultimate strength of beams with holes by using the DSM.

The simulations are also performed to validate the equations of the DSM simplified methods for members with holes by comparing the ABAQUS results for the elastic buckling parameters with those from the simplified methods. By providing critical elastic buckling moments for local \( (M_{crl}) \), distortional \( (M_{crd}) \) and global buckling \( (M_{cre}) \) modes the simplified methods make an efficient design of CFS members with holes possible.

The experiments contemplated in this report were accomplished by Schudlich [14]. Schudlich tested beams in four-point bending. The experimental setup is shown in 1.2.

2.2 Finite Element Modeling

2.2.1 Analysis based on existing tests

Eigen-buckling analyses are performed with ABAQUS [4] to determine the elastic buckling behavior of 18 beams. The beams are simulated with the measured dimensions based on Schudlich [14] in order to make a proper examination of the DSM simplified method possible which is conducted by Schudlich [14] by using the elastic buckling parameters derived in this assignment. In the existing experiments six beams were tested without holes, six with holes of \( \frac{I_{net}}{I_g} = 0.9 \) and six with holes of \( \frac{I_{net}}{I_g} = 0.8 \). In order to be able to make precise statements about the influence of holes, the perforated beams are also simulated.
without holes. The FE results for members with holes are only compared to the FE results of the same members simulated without considering their holes in order to avoid any irritations based on specific dimensions of the beams. Overall 30 different beams are analyzed in 15 simulations while modelling two specimens at a time trying to reflect the existing test procedure and boundary conditions.

### 2.2.2 Finite Element Type

S9R5 reduced integration nine-node thin shell elements are used in this study (Figure 2.1). This element is recommended for thin walled structures by ABAQUS among others (S4 and S4R). The S9R5 element has nine nodes. Therefore, on the one hand initially curved structures can be defined because S9R5 elements have a quadratic shape function and on the other hand the approximation of a half sine wave is possible in just one element. Figure 2.1 shows the difference between the shape functions of the different elements. The "5" indicates that this kind of element uses five instead of six degrees of freedom (three displacement components and two in-surface rotation components). The degree of freedom around the axis normal to the elements plane is removed from the element, which can make the element more economical. The modeling accuracy of the S9R5 element for stiffened and unstiffened elements is established by Moen [7].

![Figure 2.1: Finite Element Type](image)

### 2.2.3 Material Properties

Cold-formed steel material properties are assumed as $E = 203395 \text{N/mm}^2$ (29500ksi) and $\nu = 0.3$. In this case the yield stress of the material is not of interest, because all simulations consider only elastic material properties.
2.2.4 Boundary conditions

The experimental boundary conditions and constraints are considered in the ABAQUS model as shown in Figures 2.2 and 2.3. The HSS-tubes are not depicted in Figure 2.2 in order to avoid any confusion. To model the simple supports the specimens are vertically (in Y) and laterally (in Z) restrained at both ends. The simple supports are located under the bottom-flanges of the specimens and are distributed over three nodes in the longitudinal direction (in X); this does not represent the real conditions very well, but as these areas are far away from the constant moment region the influence is assumed to be very small. The restraint in the longitudinal direction of the beams is located in midspan as the warping displacement is zero at this point. There are additional restraints in Z-direction located at the middle of the top-flanges in the area of load application to prevent the model from lateral torsional buckling over the whole beam length.

![Figure 2.2: Boundary conditions](image)

Both the HSS-sections and the metal sheet panels are modeled as rigid body connections. This connection gives the liberty of rigid body movement but disallows a relative motion of the connected nodes. The assumed load, which the HSS-section and the metal panels have to carry, is much smaller than their capacity so that a rigid body connection represents the real conditions quite well. A picture of rigid body connections is given in Figure 2.3. A single reference node, which governs translational and rotational motion of the connected nodes, is required and shown in Figure 2.3. The metal panels are only considered where screwed into the flanges. The stub channels are assumed to be restraining the whole tangent area, because of their high stiffness. A disadvantage of using the rigid body restraint for the whole tangent area is possibly the fact, that the real connection is not carrying tension in areas without the bolts and washers. This might result an overestimation of capacity in some failure scenarios such as global buckling.
2.2.5 Load application

In the experiments, the loads are applied to the beams through vertically oriented stub tubes, which distribute the load and transport it to the webs of the specimens through bolts. Therefore, the load in the ABAQUS model is applied at the position of the bolts, which connect the HSS-sections with the specimens, by adding point loads to the web as depicted in Figure 2.4.
2.2.6 Modeling guidelines and input file creation

The following guidelines for modeling CFS-structures in ABAQUS, which were developed by Moen [7], are considered in the modeling process:

- A minimum of two S9R5 elements per half-wavelength shall be provided in stiffened elements in the direction normal to the applied load (e.g., flanges and web of a lipped C-section).

- The S9R5 element aspect ratio shall be less than or equal to 8:1 in unstiffened elements (e.g., flange lip in a C-section).

- The S9R5 element aspect ratio shall be between 0.5 and 2.0 when modeling holes with the discretization scheme described by Moen [7] (where the element sides are not perpendicular).

- Rounded corners shall be modeled with at least two S9R5 elements, and the element aspect ratio of these elements shall be less than or equal to 16:1.

Since many properties of the models are similar, it is recommended to use a routine to generate the input files for ABAQUS in order to increase the efficiency of FE modeling. Therefore, all ABAQUS models are created with a program using Matlab [5] program, based on an input file generator written by Moen [7]. Refer to Appendix B for a description of this program.

2.2.7 Finite Element Meshing

A typical FE mesh and the meshing of the holes is shown in Figure 2.5 and Figure 2.6. Along the cross-section the flanges are modeled with 6 elements per flange, the lips are created with 2 elements each, and the web is modeled with 8 elements. The rounded corners are meshed with only two elements, because S9R5 elements are able to display initially cambered geometry as depicted in Figure 2.7. Apart from that, Moen [7] has established that the number of S9R5 corner elements has a marginal influence on the critical elastic buckling behavior. The holes are created by removing the whole web over a certain length and refilling this area with a series of element lines around the opening. The number of element lines has to consider the hole depth in order to achieve a proper aspect ratio for the elements. Therefore, the H0.9 members have 4 element lines and H0.8 members have 2 element lines around the holes (Figures 2.5 and 2.6).
Figure 2.5: Meshing of beam and hole detail for H0.9

Figure 2.6: Meshing of beam and hole detail for H0.8

Figure 2.7: Mesh detail of rounded corner
2.3 Elastic buckling results

The ABAQUS results have been reviewed to determine local, distortional and global buckling modes. The modes are identified through mode-by-mode visual inspection. The difficulty in the process is the identification of pure local, distortional and global modes among many mixed buckling modes and only mathematically possible eigen-buckling modes.

Local buckling is known as plate buckling of slender elements in a cross-section. The half-wavelength is not more than the largest dimension of the member, which is under compression. Distortional buckling occurs in open cross-sections, where the compressed flanges buckle inward and outward along the length of the beam (refer to Moen [7]). Global buckling, or "Euler" buckling modes are flexural, torsional, torsional-flexural for columns and lateral-torsional for beams, which occur as the minimum mode at long half-wavelengths (refer to AISI (2009) [3]).

Pure distortional modes have been observed for all specimens in this study. However, some local modes are mixed with distortional buckling modes and global modes, which are all lateral-torsional for beams, are mixed with local buckling in every case.

Table 2.2 shows a summary of all ABAQUS results. $L_{cre}$ is not listed as it is equal to the unbraced length and always the same (1625 mm/64 in.). The coefficient of variation (COV) is calculated by $COV = \frac{\sigma}{\mu}$, where $\sigma$ is the standard deviation and $\mu$ is the mean. The COV is a unitless value of the dispersion of the results. It shows how much the results fluctuate around the mean. The means for the different kinds of specimens and critical buckling moments are also listed. The change of the critical elastic buckling moments of the members with holes compared to the same members calculated without considering their holes is also given relating to the NH specimens. While a positive percentage means an increase of $M_{cr}$ when holes are cut into the beams, a negative percentage means that the holes cause a decrease of the critical buckling moment of the members.

2.3.1 Local buckling

Local buckling sine half-waves are observed in the webs and in the top flanges of all specimens. They are caused by the compression component of the cross-section's stress distribution. Because of that the local buckling half-waves only develop in the upper half of the beams. A summary of all critical elastic local buckling moments ($M_{cr1}$) and their associated half-wavelengths ($L_{cr1}$) is given in Table 2.2. Figure 2.8 gives an overview of the different elastic local buckling modes.

All members without holes buckle in the same mode, mode LOC1 2.8. Both, web and top-flange buckle. Their half-wavelengths range between 102 mm (4 in.) and 114 mm (4.5 in.). The half-wavelengths are measured with the distance tool of ABAQUS by choosing two nodes by hand. The distance tool can only select nodes but not points in between two nodes. Because of that the accuracy of this measurement is limited to approximately 6 mm (0.25 in.). The COV for these beams is 1.5 percent.
The H0.9 members buckle in a different mode. The strip of web above the hole buckles in one half-wave (mode LOC2) in the strip, reminding of a plate which is simply supported on three sides, and one half-wave in the top flange. In addition to that a small distortional deflection is observed. It is a common occurrence that local modes mix with distortional modes if the critical distortional buckling moment is lower than $M_{crl}$. The half-wavelengths are 107 mm (4.2 in.). On average the critical local buckling moment ($M_{crl}$) for LOC2 is 8.3 percent higher than for the regular local mode LOC1, while the COV is 3 percent.

The lowest elastic local eigen-buckling mode of the H0.8 specimens is LOC1. These members buckle in the gross cross-section. The very thin strip above the hole has a higher axial stiffness than the buckled area in between the holes. The half-wavelengths range from 102 mm (4 in.) to 152 mm (6 in.). The average $M_{crl}$ of these beams is almost 27 percent higher than $M_{crl}$ for the identical specimens simulated without holes. The COV for H0.8 specimens is 1 percent.

The increase of $M_{crl}$ is based on the "wavelength stiffening" effect (refer to Moen and Schafer (2009)[9]). For a plate, which is simply supported on four sides, with wide holes ($\frac{h_{hole}}{h} > 0.66$) and a close hole spacing ($\frac{s}{l_{hole}} < 4$) (refer to Figure 1.4), an increase of the buckling stress $f_{cr}$ is observed (refer to Moen and Schafer (2009) [9]), because the fundamental half-wavelength of the plate is modified by the hole. S.P Timoshenko and J.M Gere [15] determined that a plate which buckles locally at a half-wavelength which is longer or shorter than its fundamental half-wavelength will have a higher critical stress. In this case ($\frac{h_{hole}}{h} > 0.66$) and ($\frac{s}{l_{hole}} < 4$) are observed for all specimens. The local buckling half-wavelengths ($L_{crl}$) of all specimens with holes have changed compared to the $L_{crl}$ for the same beams simulated without holes.

At this point, it is mentioned that an increase of $M_{crl}$ does not necessarily cause an increase of the ultimate strength of the member, as the holes might decrease capacities for other failure modes, e.g., distortional modes.
Figure 2.8: Local buckling modes LOC1 and LOC2 for NH-, H0.9- and H0.8 members
2.3.2 Distortional Buckling

Elastic distortional eigen-buckling is recognized as a design limit state for cold-formed steel columns and beams with open cross-sections, separate from that of global or local-global buckling interaction.[6], [12] In this case the top-flanges buckle distortationally, similar to a plate under compression, which is simply supported on three sides. Pure distortional buckling is observed for all specimens as the lowest eigen-buckling mode. Three or four distortional half waves are witnessed in between the two load points. The critical elastic distortional buckling moments \(M_{crd}\) and their associated half-wavelengths \(L_{crd}\) are listed in Table 2.2. Examples for all different distortional buckling modes are shown in Figure 2.9.

The specimens without holes buckle with three half waves and a distortional buckling half-wavelength between 457 mm (18 in.) and 508 mm (20 in.), except one, which buckles with four distortional half waves \(L_{crd}=419\) mm (16.5 in.)). The COV for the NH specimens is 4.6 percent.

\[M_{crd}\] of members with \(\frac{I_{net}}{I_g}=0.9\) is reduced by 22.7 percent. The half-wavelengths stay equal or become slightly longer; ranging between 508 mm (20 in.) and 546 mm (21.5 in.); they all buckle in three half-waves. The COV is 4.9 percent.

\[M_{crd}\] of members with \(\frac{I_{net}}{I_g}=0.8\) the decrease of \(M_{crd}\) is 26.5 percent. The half-wavelengths fluctuate between 508 mm (20 in.) and 533 mm (21 in.), as seen above for the H0.9 beams. They also buckle in three half-waves. The COV amounts to 3.8 percent.

The web provides bending stiffness to the flanges of open cross-sections and therefore rotationally restrains the flange. Because of that the magnitude of the critical elastic distortional buckling moment \(M_{crd}\) is controlled among other parameters by the properties of the web (refer to Moen and Schafer (2009) [8]). If holes, especially deep holes, are cut into the web of a C-section the stiffness provided by the web is reduced compared to a web without holes, thereby \(M_{crd}\) is reduced for a member with holes. The additional decrease of \(M_{crd}\) from H0.9 to H0.8 members is also caused by a variation of the compression lip length.

The coefficients of variation of \(M_{crd}\) are relatively high for all kinds of specimens. This is because every C-channel has a shorter (13 mm (0.52 in.) to 14.3 mm (0.56 in.)) and a longer (15 mm (0.59 in.) to 15.6 mm (0.61 in.)) lip. If the longer lip is the upper one and thus in compression, \(M_{crd}\) is relatively high. The lip lengths for all simulated NH beams and their resulting \(M_{crd}\) are summarized in Table 2.1. The light grey marked cells show the specimens, which have the shorter lip up and therefore a smaller \(M_{crd}\). It is observed that the most of the H0.8 specimens have the shorter lip in compression. However the obtained average decrease of \(M_{crd}\) for H0.8 and H0.9 specimens compared to NH specimens is not influenced by the orientation of the member since the members with holes are only compared to the same beams simulated without considering their holes, i.e. the orientation of the compared specimens is identical. Specimen 3.1-NH buckles in four half-waves, having the shortest lip in compression (Table 2.1).
Thus the fundamental distortional half-wavelength of this member is relatively small and buckling in four half-waves leads to an $L_{crd}$ which is closer to the fundamental half-wavelength. The lip provides stiffness to the flange. This observation suggests that the distortional buckling behavior of a beam is highly influenced by the lip length, even if it varies only a few millimeters. But it is also noticed that the lip length is not necessarily the controlling parameter for the magnitude of $M_{crd}$, as we can see that $M_{crd}$ of specimen 1.1-H0.9-NH is even smaller than $M_{crd}$ of specimen 3.1-NH, although the upper lip is slightly longer.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$M_{crd}$ [kNm]</th>
<th>Compression lip length [mm]</th>
<th>Tension lip length [mm]</th>
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<td>14.16</td>
<td>14.0</td>
<td>15.2</td>
</tr>
</tbody>
</table>

Table 2.1: Influence of lip length
Figure 2.9: Distortional buckling mode for NH-, H0.9- and H0.8 members
2.3.3 Global buckling

The elastic global buckling mode for beams is lateral-torsional buckling. A pure lateral-torsional buckling mode cross-section shape is shown in Figure 2.10. The whole cross section turns around the corner between bottom flange and web with a lateral torsional half-wavelength \( (L_{cre}) \) equal to the unbraced length.

![Figure 2.10: Cross-section of a pure lateral torsional buckling mode](image)

In the physically conducted experiments no lateral torsional buckling occurred as the unbraced length of the specimens is relatively short (1625 mm/64 in. between the load points) and therefore the specimens failed earlier because of other buckling modes in combination with yielding.

Global modes are found with the elastic analysis in ABAQUS. The modes are relatively high (between eigen-value 180 and 220) and therefore the critical global buckling moments \( (M_{cre}) \) are 35 to 100 percent higher than \( M_{crI} \) or \( M_{crD} \), depending on NH, H0.9 or H0.8. All \( M_{cre} \) values are listed in Table 2.2. Representative lateral-torsional buckling modes are seen for the three specimen types in Figure 2.11.

Lateral-torsional modes are seen for all specimens in combination with local buckling modes. There are no pure modes observed. Since the specimens are thin, the local buckling load is smaller than the global and thus the global modes are always mixed with local buckling modes. The lateral torsional half-wavelength is equal to the unbraced length of the specimens in the middle of the beam (1625 mm/64 in.).

The mean of \( M_{cre} \) for H0.9 is 4.1 percent smaller than the mean of \( M_{cre} \) for NH; the COV of \( M_{cre} \) for H0.9 is 1.5 percent. The mean of \( M_{cre} \) for H0.8 is 3.4 percent smaller than the mean of \( M_{cre} \) for NH while the COV for H0.8 is 0.4 percent. The COV for NH is 1.3 percent. The change of \( M_{cre} \) for H0.9 and H0.8 compared to NH is relatively small but as the COV for lateral torsional buckling in this case is also very small (less than 1.5 percent), it becomes evident that holes decrease the critical elastic lateral-torsional buckling moment of beams.
Figure 2.11: Global buckling mode for NH-, H0.9- and H0.8 members
<table>
<thead>
<tr>
<th>Specimen</th>
<th>local buckling</th>
<th>distortal buckling</th>
<th>global buckling</th>
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<td>(M_{cr}) [kNm]</td>
<td>(L_{crd}) [mm]</td>
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<td>3.2-H0.8-NH</td>
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<td>16.79</td>
<td>508</td>
</tr>
<tr>
<td>Change from NH → H0.9(^1)</td>
<td>8.3%</td>
<td>-22.7%</td>
<td>-4.1%</td>
</tr>
</tbody>
</table>

| Specimen     | 1.1-H0.9       | 107 | 16.84 Mean | 508 | 10.27 Mean | 28.17 Mean |
|              | 1.2-H0.9       | 107 | 18.29 [kNm] | 508 | 11.80 [kNm] | 28.17 [kNm] |
|              | 2.1-H0.9       | 107 | 18.41 18.00 | 533 | 11.88 11.53 | 29.13 28.77 |
|              | 2.2-H0.9       | 107 | 18.06      | 533 | 11.73      | 29.13      |
|              | 3.1-H0.9       | 107 | 18.06 COV[-] | 546 | 11.67 COV[-] | 29.02 COV[-] |
|              | 3.2-H0.9       | 107 | 18.34 0.030 | 533 | 11.81 0.049 | 29.02 0.015 |
| Change from NH → H0.8\(^1\) | 22.6\% | -26.5\% | -3.4\% |

1 Change from NH → H0.9 calculated by \(\frac{\text{Mean}(H0.9-NH)-\text{Mean}(H0.9)}{\text{Mean}(H0.9-NH)}\)

2 Change from NH → H0.8 calculated by \(\frac{\text{Mean}(H0.8-NH)-\text{Mean}(H0.8)}{\text{Mean}(H0.8-NH)}\)

Table 2.2: Elastic buckling properties derived from ABAQUS
3 Elastic buckling of CFS beams examined with simplified methods of DSM

3.1 Introduction

The goal of this study is on the one hand to provide elastic buckling parameters for the equation development of the Direct Strength Method (DSM) for cold formed steel structural members with holes. The results of this study (critical elastic buckling moments and half-wavelengths) are used by Schudlich [14] to calculate ultimate strength of beams with holes using the DSM, in order to compare the DSM results to experimental results obtained by Schudlich [14]. On the other hand the existing simplified methods to calculate elastic buckling properties for beams with holes are to be validated in this assignment. Therefore, in this chapter for all the specimens, which are simulated with the FE method, the elastic buckling moments and half-wavelengths are calculated by using the simplified methods. These methods include (depending on the property, which has to be derived) finite strip analyses and/or hand calculations by using certain equations provided.

3.2 Direct Strength Method

The Direct Strength method is a tool developed in order to make the design of CFS easier and more efficient. Since the DSM was extended by delivering a general design approach, the DSM is now capable to predict the strength of cold-formed steel flexural members with the ever expanding range of cross-section types, hole sizes, shapes and spacings common in industry.[10]

For structural members without holes the elastic buckling properties can be determined by running a finite strip analysis with a freely available software, such as CUFSM [13], which performs eigen-buckling analyses for a certain range of half-wavelengths. The result is an elastic buckling curve, which contains the necessary properties $M_{crl}$, $M_{crd}$, $M_{cre}$ as depicted in Figure 3.1. $M_{crl}$ ist the first minimum, $M_{crd}$ the second and $M_{cre}$ is dependend of the unbraced length (in this case 163 cm). By using the critical elastic buckling moments ultimate strength can then be predicted either with the design equations (refer to AISI (2007) [2]) provided by the DSM or approximatly with the DSM designcurves (Figure 3.2) for local and distortional buckling which display the design equations (Figure 3.2). The curves are drawn for a beam which is globally braced such as the examined beams ($M_{ne} = M_{y}$). The slenderness (local, distortional) is obtained from the elastic buckling properties of the member. The slenderness represents the unitless sensitivity to the associating buckling mode at failure, in which the sensitivity increases with an increase of slenderness.
The ultimate strength of a member is the minimum of the three nominal moment capacities for the three buckling modes.

![Elastic buckling curve derived with Matlab [5] and CUFSM [13]](image)

**Figure 3.1:** Elastic buckling curve derived with Matlab [5] and CUFSM [13]

![Local and distortional DSM design curves for a braced beam \( M_{nc} = M_{y} \) (refer to AISI [1])] (image)

**Figure 3.2:** Local and distortional DSM design curves for a braced beam \( M_{nc} = M_{y} \) (refer to AISI [1])

For CFS structural members with holes the DSM has recently been extended and is based on the maintenance of the assumption that elastic buckling properties can be used to predict strength. [10] This means for a beam the elastic buckling properties \( M_{cr1}, M_{crd} \) and \( M_{cre} \) including the influence of holes have to be detected. Therefore, simplified methods have been developed to avoid finite element modeling. The nominal capacities are calculated by using the DSM design equations for beams without holes, except that the elastic buckling moments include the influence of holes.
3.3 Finite Strip Method

The finite strip method (FSM) is a FE method variation. The methods are based on the same methodology and theory. The difference between FE method and FSM is the discretization. Instead of many elements the FSM is just using one single strip element in the longitudinal direction. The longitudinal direction is assumed to take the form of a half sine wave (refer to C. Yu [16]). The input files used for the finite strip analyses are created by using a Matlab [5] program considering the measured dimensions such as the program, which created the FE input files. All variations of the cross-section needed for the employment of the simplified methods are performed by hand on the existing gross cross-section in CUFSM.

3.4 Elastic buckling results

All elastic buckling results derived from the DSM simplified methods are listed in Table 3.1 . $L_{cre}$ is not listed as it is equal to the unbraced length and always the same (1625 mm/64 in.). The COVs are given for the different kinds of beams and buckling modes. The means for the different kinds of specimens and critical buckling moments are listed, too. Additionally, the influence of the holes can be seen in the change, which is calculated using the equation shown in Table 3.1.

3.4.1 Local buckling

For beams with holes local buckling occurs either in the web of the gross cross-section or in the strip above the hole which is under compression. The critical elastic local buckling moment of the beam ($M_{crl}$) is defined as the minimum of the critical local buckling moment of the gross cross-section ($M_{crl,nh}$) and the critical local buckling moment of the strip adjacent to the hole ($M_{crl,h}$):

$$M_{crl} = \min(M_{crl,nh}, M_{crl,h})$$  (3.1)

$M_{crl,nh}$ can be determined by performing a simple finite strip analysis with CUFSM, whereupon $M_{crl,nh}$ is the first minimum of the elastic buckling curve (Figure 3.1).[10]

For the determination of $M_{crl,h}$ a finite strip analysis also is conducted, but the cross-section has to be modified. Therefore, the cross-section is modeled in CUFSM with one element across the area of the hole with a thickness of zero. After that a unit-moment is applied to the cross-section and the associated stress distribution is generated. Now the element across the hole is deleted. The finite strip analysis can now be performed and the result is a local buckling curve for the net cross-section as shown in Figure 3.3, where $M_{crl,h}$ and the associated half-wavelength ($L_{crl,h}$) is at the minimum of the curve. [10]
The considered specimens without holes are calculated as described earlier by performing a finite strip analysis with CUFSM. To implement the measured dimensions of the beams in CUFSM, a program is written using Matlab. This program is a modified version of a Matlab CUFSM-file generator assembled by Moen (Moen 2007). $M_{crl}$ for the specimens without holes is on average 16.07 kNm. The coefficient of variation (COV) is 1.5 percent and the local buckling half-wavelengths are all 113 mm (4.4 in.). A summary of all $M_{crl}$ and their associating half-wavelengths is given in Table 3.1.

$M_{crl,h}$ for the H0.9 members is on average 16 percent higher than the mean of $M_{crl}$ for the specimens simulated without holes. $M_{crl,h}$ values for H0.9 have a COV of 1.6 percent and the half-wavelengths are 81 mm (3.2 in.).

The mean of $M_{crl,h}$ for the beams with $\frac{I_{net}}{I_g} = 0.8$ is 32 percent higher than the mean of $M_{crl}$ for the specimens without holes. COV for $M_{crl,h}$ of H0.8 beams is 1.1 percent. The half-wavelengths are all 64 mm (2.5 in.).

In this case, for all specimens (H0.9 and H0.8) the controlling $M_{crl}$ is equal to $M_{crl,nhr}$ since the critical local buckling moments for the beams without holes are overall lower. This prediction means that local buckling occurs in between the holes in the gross cross-section first. In Table 3.1 the listed $L_{crl}$ and $M_{crl}$ values are the $M_{crl,h}$ values although they are not controlling, in order to show the reader the influence of holes calculated by the simplified method for the specimens with holes.
3.4.2 Distortional buckling

The critical elastic distortional buckling moment \( (M_{crd}) \) for beams without holes is derived from a finite strip analysis by using CUFSM, while \( M_{crd} \) is the second occurring minimum of the elastic buckling curve as shown in Figure 3.1.

Because the finite strip method is not capable to consider cross-section variations, the calculation of beams with holes requires another procedure to consider the influence of holes. Therefore, a simplified method has been developed recently.[10]

At first the distortional buckling half-wavelength is determined for the gross cross-section of the beams by running a finite strip analysis with CUFSM. The reduced bending stiffness caused by the hole in the web is considered as a reduction of the entire web thickness of the beam. The following equation delivers the reduced web thickness:

\[
t_r = \left(1 - \frac{L_h}{L_{crd}}\right)^{\frac{1}{3}} t
\]  

(3.2)

where

- \( L_h \) = length of the hole
- \( L_{crd} \) = fundamental distortional half-wavelength of the gross cross-section
- \( t \) = measured web thickness

Next another finite strip simulation is performed where the thickness of the web is replaced by \( t_r \). \( M_{crd} \) is found at the distortional buckling half-wavelength of the gross cross-section as depicted in Figure 3.4. This means that the half-wavelength is considered to be equal to the one of the beam without holes, even if this half-wavelength is not at the minimum of the curve for the modified cross-section. The \( M_{crd} \) and \( L_{crd} \) values are listed in Table 3.1.

The simplified method for members with holes reduces \( M_{crd} \) by 15 percent on average. The COV for the members without holes is 4.5 percent, for the beams with holes the COV is 4.7 percent. In this case the H0.9 and H0.8 specimens are not contemplated separately, since the simplified method for distortional buckling does not consider the depth of holes. Therefore, the mean as well as the change (compared to the H0.8 and H0.9 members considered without holes) are calculated only once (not separately) for the beams with holes (Table 3.1).
3.4.3 Global buckling

$M_{cre}$ is evaluated for both the specimens with and without holes by using the associated simplified method. The DSM provides the following equation for the critical lateral-torsional buckling moment for a beam without holes:

$$M_{cre} = \frac{\pi}{kL} \sqrt{EI_z \left( GJ + EC_w \left( \frac{\pi}{kL} \right)^2 \right)}$$

(3.3)

where:

- $k$ = constant which represents warping restraint (from optimization)
- $L$ = unbraced length
- $E$ = elastic modulus
- $I_z$ = weak axis moment of inertia (e.g., from CUFSM)
- $G$ = shear modulus
- $J$ = St. Venant torsional constant (e.g., from CUFSM)
- $C_w$ = warping torsion constant (e.g., from CUFSM)

\[\text{Figure 3.4: Elastic buckling curve for gross cross-section and for net cross-section by running CUFSM [13] with a reduced web thickness}\]
The DSM has developed the "weighted average method" (refer to Moen and Schafer (2009) [8]) where $I_z$ and $J$ have to be replaced with $I_{z,\text{avg}}$ and $J_{\text{avg}}$ and $C_w$ has to be replaced with $C_{w,\text{net}}$. These modifications of Equation 3.3 consider the influence of holes and thus provide the following equation for the elastic global buckling moment for a beam with holes.

$$M_{\text{cre}} = \frac{\pi}{k L} \sqrt{EI_{z,\text{avg}} \left( G J_{\text{avg}} + E C_{w,\text{net}} \left( \frac{\pi}{k L} \right)^2 \right)}$$

(3.4)

$C_{w,\text{net}}$ is the warping torsion constant and determined with the property calculator of CUFSM. $I_{z,\text{avg}}$ is the weighted average of the weak axis moment of inertia calculated by the following equation:[8]

$$I_{z,\text{avg}} = \frac{I_{z,g} L_g + I_{z,\text{net}} L_{\text{net}}}{L}$$

(3.5)

where:

$I_{z,g}$ = weak axis moment of inertia $I_y$ of the gross cross-section (e.g., from CUFSM)
$L$ = total unbraced length
$L_g$ = total unbraced length, lengths of holes subtracted
$I_{z,\text{net}}$ = $I_z$ of net cross-section (e.g., from CUFSM)
$L_{\text{net}}$ = sum of hole lengths

$J_{\text{avg}}$ is the weighted average of the St.Venant torsional constant calculated by:

$$J_{\text{avg}} = \frac{J_g L_g + J_{\text{net}} L_{\text{net}}}{L}$$

(3.6)

where:

$J_g$ = St. Venant torsional constant $J$ of cross-section (e.g., from CUFSM)
$L_g$ = total unbraced length, lengths of holes subtracted
$J_{\text{net}}$ = $J$ of netto cross-section (e.g., from CUFSM)
$L_{\text{net}}$ = sum of hole lengths
The warping constant $k$ in Equation 3.3 is representing the warping restraint provided by the boundary conditions and constraints, at which $k=1$ means the specimen is warping free and $k=0.5$ means the specimen is warping fixed. It is assumed that the ABAQUS models are neither warping free nor warping fixed (0.5<$k<$1). To be able to compare the results from ABAQUS with the results of the simplified method for members with holes, $k$ is calculated by an optimization process while considering only the members without holes. Because of that the beams without holes cannot be considered in the comparison of the simplified methods with ABAQUS. But by performing an optimization process at least the simplified method for evaluating $M_{cre}$ for members with holes can be reviewed. The following equation is used for the determination of $k$:

$$minError(k) = \min\left(\sum (M_{cre,ABAQUS} - M_{cre,simplified-method}(k))^2\right)$$

(3.7)

The smallest Error is found for $k=0.80$. Therefore, $M_{cre}$ is calculated with $k=0.80$ for all the specimens. The calculated values are summarized in Table 3.1.

The COV for the $M_{cre}$ values of the beams without holes amounts to 1.1 percent. The global buckling half-wavelength is equal to the unbraced length between the load points 1626 mm (64 in.) for each specimen with or without holes.

The simplified method results in a decrease of 11 percent of the mean $M_{cre}$ values for H0.9 and a decrease by 21 percent for H0.8 compared to the mean $M_{cre}$ values for all specimens considered without holes. The COV for H0.9 is 0.4 percent for H0.8 1.3 percent.
<table>
<thead>
<tr>
<th>Specimen</th>
<th>$L_{crl}$ [mm]</th>
<th>$M_{crl}$ [kNm]</th>
<th>$L_{crd}$ [mm]</th>
<th>$M_{crd}$ [kNm]</th>
<th>$M_{cre}$ [kNm]</th>
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<th>$L_{crd}$ [mm]</th>
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<td>458</td>
<td>10.46</td>
<td>23.59 0.013</td>
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1 For local and global buckling: Change from NH $\rightarrow$ associated H0.8 or H0.9 members;
For distortional buckling Change: from NH $\rightarrow$ all members with holes;
Calculated by $\frac{\text{Mean(nohole)} - \text{Mean(hole)}}{\text{Mean(nohole)}}$

Table 3.1: Elastic buckling properties derived from the simplified methods
4 Comparison

One goal of this assignment is to validate the simplified methods for the determination of the elastic buckling properties of CFS beams. The elastic buckling properties are the critical elastic eigen-buckling moments and the half-wavelengths for local and distortional buckling. Therefore, the results of the elastic buckling analyses conducted with ABAQUS are compared with the results accomplished by using the simplified methods of the DSM.

4.1 Local buckling

The results for the controlling $M_{crl}$ and $L_{crl}$ values are compared in Table 4.1.

For the NH beams the simplified method employs a simple finite strip analysis. The $M_{crl}$ values for NH members, calculated by CUFSM, are on average 4 percent lower than the results of ABAQUS. The half-wavelengths differ on average by 8.7 percent, but due to the inaccuracy of the ABAQUS measurement the half-wavelength are not representative for small lengths and thus this comparison is not representative.

For specimens with holes the DSM simplified methods dictate to take the minimum of $M_{crl,h}$ and $M_{crl,nh}$ as $M_{crl}$ (Equation 3.1). This means in this case $M_{crl,nh}$ has to be chosen as $M_{crl}$ for each beam and with this the simplified method predicts the position for local buckling at the gross cross-section. However the ABAQUS simulation shows that the lowest local buckling mode occurs in the strip above the hole (Chapter 2.3.1). This wrong prognosis by the simplified method is based on the fact that the hole-spacing $S$ (Figure 1.4) is not considered in the simplified method. If the hole-spacing is small the fundamental half-wavelength may be influenced and thus increase the buckling load.[15] As the ABAQUS results show, for the H0.9 specimens this increase is big enough that the buckling of the strip above the hole becomes the lowest buckling mode and thus controlling.

The ABAQUS simulation demonstrates that the critical elastic moment for local buckling compared to NH specimens increases on average by 8.3 percent for H0.9 members and by 26.7 percent for H0.8, because the natural half-wavelength is influenced by the holes (Chapter 2.3.1). However the simplified method misses this increase by picking the minimal critical Moment (Equation 3.1) and underestimates the beam. On the other hand deciding for $M_{crl,h}$ instead of the smaller $M_{crl,nh}$ would be overestimating the beam, as the values of $M_{crl,h}$ from the simplified methods exceed most of the $M_{crl,h}$ values from the ABAQUS simulation by up to 7 percent. However, since the controlling $M_{crl}$ for the beams with holes is equal to $M_{crl,nh}$ the H0.9 specimens have a 11 percent smaller $M_{crl}$ than the ABAQUS simulation predicts. $M_{crl}$ of the H0.8 members are on average 24 percent smaller.

33
<table>
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<th>$L_{cr}$ in mm</th>
<th>$M_{cr}$ in kNm</th>
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**Specimens simulated without considering holes**

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<th>$M_{cr}$ in kNm</th>
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**Specimens simulated with holes included**

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<td>ABAQUS</td>
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<td>1.1-H0.8</td>
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$$\text{Average Difference} = \frac{\text{Mean(Simplified Method)} - \text{Mean(ABAQUS)}}{\text{Mean(ABAQUS)}}$$

**Table 4.1:** Local buckling comparison between CUFSM and ABAQUS results
4.2 Distortional buckling

The values derived from the simplified method are contrasted with the values ascertained with ABAQUS in Table 4.2.

The finite strip method delivers on average 12 percent lower values than the FE analysis for beams without holes. The half-wavelengths also differ from each other by 2 to 8 percent. The finite strip simulation calculates the fundamental wave-lengths of the members. The ABAQUS model considers the boundary conditions and therefore leads in this case to a longer half-wavelength. As the fundamental half-wavelength is modified by the boundary condition the critical elastic moment increases.[15] The effect can also be observed in the elastic buckling, which obviously delivers higher critical moments if the half-wavelength is varied.

The simplified method for distortional buckling does not consider the hole depth. Because of that all values for members with holes, derived from the simplified method, only vary because of their different dimensions. However the ABAQUS simulation determined a decrease of almost 4 percent of $M_{crd}$ from H0.9 to H0.8 specimens due to the increase of the hole depth. If the $M_{crd}$ values of the simplified method are now compared to the FE results, it is observed that for H0.9 members the values of the simplified method are on average 2.6 percent smaller than the ABAQUS results. Since the ABAQUS values for H0.8 members decrease comparing to the H0.9 specimens and the simplified method values do not, the FE results are on average 1.1 percent lower.
<table>
<thead>
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<td>480</td>
<td>508</td>
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<td>419</td>
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$$\text{Average Difference} = \frac{\text{Mean(Simplified Method)} - \text{Mean(ABAQUS)}}{\text{Mean(ABAQUS)}}$$

Table 4.2: Distortional buckling comparison between CUFSM/Simplified Method and ABAQUS results
4.3 Global buckling

Using the DSM simplified method the critical elastic lateral-torsional buckling moment for the beams without holes is calculated by using Equation 3.3. The factor $k$, which represents the warping restraint, is evaluated in an optimization process, based on the ABAQUS results for the simulated beams without holes. Thus the results for members without holes cannot be compared, because those of the simplified method are dependent on the ABAQUS values.

For the calculation of $M_{cre}$ for the beams with holes the simplified method for global buckling provides an equation (Equation 3.4) as announced in (Chapter 3.4.3). In this study the factor $k$ for the simplified method equation (Equation 3.4) is taken from the evaluation of the beams without holes. With this process the warping restraint, which is provided for the ABAQUS model, is included in the simplified method calculation. Therefore, the values derived from the simplified method are assumed to be comparable to the ABAQUS results.

A summary of the ABAQUS and simplified method results is provided in Table 4.3. The $M_{cre}$ values for H0.9 beams detected with the simplified method are on average 8.4 percent smaller than the ABAQUS results. $M_{cre}$ for the members with $\frac{I_{nc}}{I_g}=0.8$ is on average 17.8 percent below the ABAQUS $M_{cre}$ values. The enormous aberration for $M_{cre}$ is probably caused by the fact that the warping restrained provided by the boundary conditions in the ABAQUS model are not considered adequately in the equation. The fact that the values for warping free members with holes decrease is correct and confirmed by Moen and Schafer (2009) [8] by an FE analysis for a warping free beam with different hole sizes. In this study the $M_{cre}$ values for members with holes derived from ABAQUS merely decrease by up to 4 percent compared to those simulated without holes. A decrease by only 4 percent does not represent a reliable trend since the mode choice in ABAQUS is subjective, especially for a small number of simulations.
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</thead>
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<td></td>
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<tr>
<td>3.2-H0.9</td>
<td>26.24</td>
<td>29.02</td>
</tr>
</tbody>
</table>

| Specimens simulated with holes | 1.1-H0.8 | 23.62 | 28.56 | Average |
|                               | 1.2-H0.8 | 23.60 | 28.56 | Difference% |
|                               | 2.1-H0.8 | 23.37 | 28.71 | Difference% -17.8 |
|                               | 2.2-H0.8 | 23.86 | 28.71 |
|                               | 3.1-H0.8 | 22.91 | 28.44 |
|                               | 3.2-H0.8 | 23.59 | 28.44 |

Half-wavelength = 1626 mm (64 in.)  
Average Difference = $\frac{\text{Mean(Simplified Method)} - \text{Mean(ABAQUS)}}{\text{Mean(ABAQUS)}}$

**Table 4.3:** Global buckling comparison between CUFSM/Simplified Method and ABAQUS results
5 Conclusion

Elastic eigen-buckling parameters are provided for further research on the DSM for cold-formed steel structural members with holes. The critical elastic buckling moments which are delivered by this assignment can be used to calculate ultimate strength of the contemplated specimens as partly accomplished by Schudlich [14] in order to validate the existing DSM for beams with holes.

The simplified methods for the determination of critical elastic buckling properties are validated. The results derived from simplified methods are besides a sole exception \( M_{crd} \) for H0.8) conservative compared to the results which are derived from FE simulations. Some of the simplified methods deliver values which are very close to the ABAQUS results, however others are off by up to 24 percent \( M_{crl} \) for H0.8 beams). Therefore, it is mentioned that depending on the circumstances the simplified methods are viable tools in CFS design.

5.1 Local buckling

The local buckling results derived with the simplified methods as presented in Chapter 3.4.1 are all lower than the results of the FE analyses. For the H0.9 specimens they are on average 11 percent lower and thus very close by still being conservative.

The difference between the ABAQUS results for \( M_{cre} \) and those derived from the simplified method are on average 24 percent for a H0.8 beam, which is on the one hand very conservative but on the other hand leads to an uneconomical design, because the specimens are underestimated. Depending on the type of building the simplified method for local buckling may prove useful. If the beam, which has to be calculated, is a part which is built in large numbers it could be beneficial to perform a FE analysis in order to reach a better utilization factor for the beams and thus save resources by consuming less material.

The position of the local buckling half-waves is predicted incorrectly for all H0.9 beams (Chapter 4.1), because the hole-spacing is not considered by the simplified method. If it is necessary to know the exact position of occurring local buckling half-waves the prognosis of the simplified method is not reliable.

5.2 Distortional buckling

The simplified method for the evaluation of elastic buckling parameters for NH members dictates a finite strip analysis, which does not consider the influence of the boundary conditions on the half-wavelength.
Therefore, the simplified method is always conservative and may for some cases be uneconomical.

For the beams with holes the simplified method values are very close to those of the FE model, although the simplified method does not consider the hole-depth. For the H0.9 specimens the simplified method is conservative, but for the H0.8 members a reduction of $M_{crd}$ calculated with the simplified method is necessary, since the derived results are slightly higher than those of the FE model. The smaller the holes are the more conservative this method is, but if the hole-depth exceeds a certain value it is not viable. A factor which has to be added to the simplified method for beams with deep holes ($\frac{h}{I_g} > 0.8$), might be a simple solution.

It is also observed, that the lip-length of the upper lip (in compression) has a big influence on the critical distortional buckling moment (Chapter 2.3.2). Even a few millimeter can result in a change of the capacity by more than 10 percent.

### 5.3 Global buckling

Under the prevailing circumstances the ABAQUS results show that the holes have no important influence on the critical global buckling moment. However, the simplified method predicts a significant decrease of $M_{cre}$ (8 percent for H0.9 and 18 percent for H0.8). The simplified method is developed under the assumption of warping free members, and it is confirmed that the simplified method delivers very viable results for those beams (refer to Moen and Schafer (2009) [8]). The factor $k$ tries to include the warping restraint but the coherence between the influence of holes and the influence of the warping restraint is not represented correctly by the simplified method. The values derived from the simplified method are all conservative and in certain cases useful.
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I want to thank many people who supported me during the time this assignment developed. My girlfriend Anna helped me in many technical cases but also motivated me with her love, disciplin and optimism. We had a wonderful time in Blacksburg and in many other places in the USA with many unforgettable experiences.

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Finally I want to thank my Family, who funded me and provided me with strength and confidence to go abroad.
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[12] SCHÄFER, B. W. Tech note- g100-08: Design aids and examples for distortional buckling. Tech. rep., Cold-Formed Steel Engineering Institute, 2008.


Appendix A
| Specimen | $M_y$ [kNm] | $M_{y,net}$ [kNm] | $t$ [mm] | $H$ [mm] | $B_1$ [mm] | $B_2$ [mm] | $D_1$ [mm] | $D_2$ [mm] | $F_1$ [$^\circ$] | $F_2$ [$^\circ$] | $S_1$ [$^\circ$] | $S_2$ [$^\circ$] | $RB_1$ [mm] | $RB_2$ [mm] | $RT_1$ [mm] | $RT_2$ [mm] |
|----------|-------------|-----------------|--------|--------|-------|-------|-------|-------|--------|--------|--------|--------|--------|--------|--------|--------|--------| |
| 1.1-NH   | 13.77       | -               | 1.76   | 203.0  | 63.0  | 63.4  | 15.4  | 13.9  | 88.3   | 89.3   | 3.6    | 4.1    | 2.8    | 2.9    | 2.7    | 2.3    |
| 1.2-NH   | 13.32       | -               | 1.77   | 203.2  | 62.8  | 63.4  | 15.3  | 14.0  | 87.6   | 89.9   | 4.0    | 3.7    | 3.0    | 3.7    | 3.1    | 2.6    |
| 2.1-NH   | 13.45       | -               | 1.76   | 203.3  | 62.7  | 63.5  | 15.4  | 14.2  | 88.0   | 89.5   | 3.7    | 3.6    | 3.3    | 3.1    | 2.8    | 2.7    |
| 2.2-NH   | 13.74       | -               | 1.78   | 203.1  | 62.7  | 63.5  | 15.2  | 14.0  | 86.5   | 89.3   | 3.9    | 4.1    | 3.1    | 3.0    | 3.1    | 2.5    |
| 3.1-NH   | 13.44       | -               | 1.78   | 203.1  | 62.7  | 63.5  | 13.1  | 14.2  | 87.0   | 89.0   | 4.6    | 4.8    | 3.5    | 3.1    | 3.0    | 2.9    |
| 3.2-NH   | 13.70       | -               | 1.77   | 203.0  | 62.7  | 63.4  | 15.3  | 14.1  | 87.7   | 89.0   | 3.8    | 3.5    | 3.0    | 3.1    | 2.5    | 2.1    |
| 1.1-H0.9 | 13.24       | 11.98           | 1.76   | 203.0  | 63.7  | 62.6  | 13.7  | 15.6  | 89.6   | 87.6   | 2.9    | 3.5    | 3.4    | 3.6    | 3.4    | 3.2    |
| 1.2-H0.9 | 13.33       | 12.08           | 1.77   | 203.0  | 62.7  | 63.5  | 15.5  | 13.8  | 87.7   | 90.1   | 3.7    | 3.6    | 3.6    | 3.5    | 3.1    | 3.2    |
| 2.1-H0.9 | 13.44       | 12.26           | 1.76   | 203.1  | 62.7  | 63.6  | 15.4  | 13.9  | 87.2   | 89.9   | 4.0    | 4.2    | 3.4    | 2.9    | 3.4    | 2.6    |
| 2.2-H0.9 | 13.16       | 11.90           | 1.77   | 203.1  | 62.6  | 63.6  | 15.3  | 13.9  | 87.9   | 89.9   | 4.3    | 3.3    | 3.6    | 3.0    | 3.3    | 3.1    |
| 3.1-H0.9 | 13.39       | 12.32           | 1.77   | 203.0  | 62.8  | 63.4  | 15.5  | 13.8  | 86.7   | 89.1   | 4.1    | 3.7    | 3.2    | 3.3    | 2.6    | 3.1    |
| 3.2-H0.9 | 13.36       | 12.23           | 1.78   | 202.9  | 62.8  | 63.4  | 15.6  | 13.6  | 86.7   | 89.6   | 3.4    | 3.8    | 3.5    | 3.6    | 3.0    | 2.5    |
| 1.1-H0.8 | 13.33       | 10.67           | 1.76   | 203.0  | 62.7  | 63.4  | 15.0  | 13.7  | 88.2   | 89.8   | 3.5    | 2.8    | 2.6    | 3.3    | 2.1    | 2.1    |
| 1.2-H0.8 | 13.22       | 10.67           | 1.77   | 203.0  | 63.5  | 62.9  | 14.0  | 15.2  | 89.8   | 87.1   | 3.3    | 4.3    | 3.0    | 3.7    | 2.9    | 2.7    |
| 2.1-H0.8 | 13.18       | 10.66           | 1.77   | 203.1  | 62.8  | 63.6  | 15.1  | 14.0  | 87.3   | 89.3   | 3.3    | 3.5    | 4.1    | 3.6    | 3.4    | 3.1    |
| 2.2-H0.8 | 13.33       | 10.78           | 1.75   | 203.1  | 63.5  | 62.7  | 14.3  | 15.3  | 89.7   | 87.3   | 3.0    | 4.0    | 3.4    | 3.3    | 2.7    | 3.0    |
| 3.1-H0.8 | 13.64       | 11.03           | 1.76   | 202.9  | 63.4  | 62.7  | 13.7  | 15.4  | 88.9   | 87.7   | 3.3    | 3.4    | 4.0    | 3.9    | 3.1    | 3.4    |
| 3.2-H0.8 | 13.82       | 11.16           | 1.76   | 203.1  | 63.4  | 62.6  | 14.0  | 15.2  | 89.7   | 87.3   | 3.6    | 3.6    | 2.6    | 3.9    | 3.0    | 2.6    |

Table 5.1: Measured specimen cross-section dimensions [14]
<table>
<thead>
<tr>
<th>Specimen</th>
<th>X</th>
<th>Lhole</th>
<th>dhole</th>
<th>w1</th>
<th>w2</th>
<th>X</th>
<th>Lhole</th>
<th>dhole</th>
<th>w1</th>
<th>w2</th>
<th>X</th>
<th>Lhole</th>
<th>dhole</th>
<th>w1</th>
<th>w2</th>
</tr>
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<td>1980.3</td>
<td>152.3</td>
<td>136.6</td>
<td>32.5</td>
<td>33.3</td>
<td>2437.5</td>
<td>152.3</td>
<td>136.7</td>
<td>32.7</td>
<td>33.1</td>
<td>2894.7</td>
<td>152.3</td>
<td>136.7</td>
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<tr>
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<td>1980.3</td>
<td>152.3</td>
<td>136.7</td>
<td>33.5</td>
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<td>2894.7</td>
<td>152.3</td>
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<td>1980.3</td>
<td>152.3</td>
<td>136.7</td>
<td>33.0</td>
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<td>2437.5</td>
<td>152.3</td>
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<td>136.7</td>
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<tr>
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<td>152.1</td>
<td>172.1</td>
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<td>152.0</td>
<td>171.8</td>
<td>14.8</td>
<td>15.8</td>
</tr>
</tbody>
</table>

**Table 5.2:** Measured hole dimensions and positions [14]
Appendix B

clear all
close all

sourceloc=what.path
addpath([sourceloc 'jhab\functions\filewriting\'])
addpath([sourceloc 'jhab\functions\holes\'])
addpath([sourceloc 'jhab\functions\'])
addpath([sourceloc 'jhab\templates\'])
addpath([sourceloc ''])

jobname={'800S250-68-100-1';
'800S250-68-100-2';
'800S250-68-100-3';
'800S250-68-90-1';
'800S250-68-90-2';
'800S250-68-90-3';
'800S250-68-80-1';
'800S250-68-80-2';
'800S250-68-80-3'};

%CROSS-SECTION DIMENSIONS
%  Z
%
%  A
%  X
%  D2 / I  \
%  D1 % RT2/_S2___ S ___S1_/RT1
%  \ | / %
%  B2 \ | /  / B1
%  \ | / %
%  ___F2__/__________________/F1___ ABAQUS Y AXIS
%  RB2   H   RB1

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% Dimensions are out-to-out, angles are in degrees, t is base metal + coating thickness, tbare is base metal thickness

% dims=
[H B1 B2 D1 D2 F1 F2 S1 S2 RB1 RB2 RT1 RT2 t tbare]
sectdims1=
[7.991 2.479 2.498 0.606 0.547 88.3 89.3 -3.6 -4.1 0.18 0.18 0.18 0.16 0.07097 0.06924
  8.005 2.467 2.500 0.605 0.559 88.0 89.5 -3.7 -3.6 0.20 0.19 0.18 0.18 0.07170 0.06968
  7.996 2.470 2.501 0.515 0.557 87.0 89.0 -4.6 -4.8 0.21 0.19 0.19 0.18 0.07200 0.07007
  7.990 2.509 2.463 0.541 0.613 89.6 87.6 -2.9 -3.5 0.20 0.21 0.20 0.20 0.07177 0.06912
  7.995 2.469 2.503 0.607 0.546 87.2 89.9 -4.0 -4.2 0.20 0.18 0.20 0.17 0.07163 0.06967
  7.991 2.474 2.496 0.611 0.543 86.7 89.1 -4.1 -3.7 0.20 0.20 0.17 0.19 0.07147 0.06933
  7.990 2.467 2.498 0.590 0.540 88.2 89.8 -3.5 -2.8 0.17 0.20 0.15 0.15 0.07141 0.06932
  7.997 2.473 2.504 0.594 0.551 87.3 89.3 -3.3 -3.5 0.23 0.21 0.20 0.19 0.07180 0.06927
  7.989 2.496 2.468 0.541 0.606 88.9 87.7 -3.3 -3.4 0.23 0.22 0.19 0.20 0.07197 0.06988];

% dims=
[H2 B21 B22 D21 D22 F1 F2 S1 S2 RB1 RB2 RT1 RT2 t tbare]
sectdims2=
[8.002 2.472 2.495 0.603 0.551 87.6 89.9 -4.0 -3.7 0.19 0.22 0.19 0.17 0.07170 0.06968
  7.995 2.469 2.499 0.600 0.552 86.5 89.3 -3.9 -4.1 0.19 0.19 0.19 0.17 0.07157 0.06993
  7.994 2.469 2.497 0.601 0.555 87.7 89.0 -3.8 -3.5 0.19 0.19 0.17 0.15 0.07167 0.06983
  7.993 2.470 2.500 0.609 0.545 87.7 90.1 -3.7 -3.6 0.21 0.21 0.19 0.20 0.07197 0.06952
  7.997 2.464 2.503 0.602 0.548 87.9 89.9 -4.3 -3.3 0.21 0.19 0.20 0.19 0.07173 0.06899
  7.988 2.472 2.495 0.613 0.534 86.7 89.6 -3.4 -3.8 0.21 0.21 0.19 0.17 0.07130 0.06936
  7.993 2.502 2.475 0.551 0.598 89.8 87.1 -3.3 -4.3 0.19 0.21 0.18 0.18 0.07167 0.06955
  7.997 2.501 2.468 0.564 0.603 89.7 87.3 -3.0 -4.0 0.20 0.20 0.17 0.19 0.07187 0.06980
  7.995 2.498 2.464 0.552 0.599 89.7 87.3 -3.6 -3.6 0.17 0.22 0.19 0.17 0.07190 0.06991];

% [Channel 1  Channel 2]
holedims={
[0 0; 0 0; 0 0; 0 0; 0 0; 0 0; 0 0; 0 0; 0 0];
[0 0; 0 0; 0 0; 0 0; 0 0; 0 0; 0 0];
[0 0; 0 0; 0 0; 0 0; 0 0; 0 0];
[5.99 5.379; 5.99 5.380; 5.99 5.383; 5.99 5.380; 5.99 5.382; 5.99 5.385];
[5.99 5.380; 5.99 5.380; 5.99 5.380; 5.99 5.381; 5.99 5.380; 5.99 5.381];
[5.99 5.381; 5.99 5.381; 5.99 5.381; 5.99 5.379; 5.99 5.381; 5.99 5.382];
[5.987 6.774; 5.985 6.776; 5.986 6.770; 5.981 6.778; 5.982 6.777; 5.986 6.773];
[5.984 6.771; 5.986 6.781; 5.988 6.783; 5.981 6.778; 5.986 6.775; 5.984 6.764]};

% [Channel 1  Channel 2]
holespacing=[81 99 117 81 99 117
81 99 117 81 99 117
81 99 117 81 99 117]
%imperfection types, not used for elastic buckling analysis

for i=9

for j=1:length(imptypes)

%MEMBER LENGTH
L=16*12+6

%MESH ALONG LENGTH
nele=L;

%NUMBER OF SECTION POINTS THROUGH THE THICKNESS
sectionpoints=5

%CROSS-SECTION MESHING
%number of elements around the cross section
%[D1 RT1 B1 RB1 H RB2 B2 RT2 D2]
n=[4 4 12 4 16 4 12 4 4];

%CREATE node and elem CUFSM matrices
% [xy]=specgeom(dims);
% %define nodes, elements, and material properties in CUFSM
% CorZ=1;
% kipin=1;
% [prop,node,elem,lengths,springs,constraints]=
% templatecalccdm(CorZ,xy,dims,kipin,n);

dims1=sectdims1(i,:)
dims2=sectdims2(i,:)
%****CHANNEL 1****
%convert out to out dimensions to xy coordinates
[xy1]=specgeom(dims1);

%define nodes, elements, and material properties in CUFSM
CorZ=1;
kpin=1;
[prop1,node1,elem1,lengths1,springs1,constraints1]=
    templatecalccdm(CorZ,xy1,dims1,kpin,n);

%figure(1)
%plot(node1(:,2),node1(:,3),'.')
%stop

%*****CHANNEL 2*****
%convert out to out dimensions to xy coordinates
[xy2]=specgeom(dims2);
%define nodes, elements, and material properties in CUFSM
CorZ=1;
kpin=1;
[prop2,node2,elem2,lengths2,springs2,constraints2]=
    templatecalccdm(CorZ,xy2,dims2,kpin,n);
B1=max(node1(:,2))
B2=max(node2(:,2))
D=12-B1-B2-dims1(14)/2-dims2(14)/2

%flip channel 1 about vertical axis
node1(:,2)=-node1(:,2);
%shift channel 1
node1(:,2)=node1(:,2)-B1
%round nodes to avoid weird numbers way out in the decimal
node1(:,2:3)=round(node1(:,2:3)*10000)/10000;

%shift channel 2
node2(:,2)=node2(:,2)+D;
node2(:,2:3)=round(node2(:,2:3)*10000)/10000;

%*****ASSEMBLE CHANNELS*****
prop=[prop1 prop2];
node2(:,1)=node2(:,1)+length(node1(:,1));
node=[node1; node2];
elem2(:,1)=elem2(:,1)+length(node1(:,1))-1;
elem2(:,2:3)=elem2(:,2:3)+length(node1(:,1));

```
%find important node locations on cross section
BFlangeC1=n(1)+n(2)+1+n(3)/2
WebC1=n(1)+n(2)+n(3)+n(4)+1+n(5)/2
TFlangeC1=n(1)+n(2)+n(3)+n(4)+n(5)+n(6)+1+n(7)/2
```

```
nodesC1=sum(n)+1
BFlangeC2=nodesC1+BFlangeC1
WebC2=nodesC1+WebC1
TFlangeC2=nodesC1+TFlangeC1
```

```
nnodes=length(node(:,1));\%Number of FSM cross-section nodes
\%Determine FE number of nodes and increment
nL=2*nele+1; \%Number of FE nodes along the length
\%Determine the node numbering increment along the length
if nnodes<100
    FEsection_increment=100; \%so along the length the numbering goes up by 100's
else
    FEsection_increment=nnodes+1;
end
```

```
\%ADD ADDITIONAL NODES
nodeadd=[]
```

```
\%MATERIAL PROPERTIES
\%steel
matprops(1).name='MAT100';
matprops(1).elastic=[29500 0.3];
matprops(1).plastic=[];
```

```
\%IMPERFECTIONS
\%*****IMPERFECTIONS*****
\%type=0 no imperfections
\%type=1 use mode shapes from ABAQUS results file
%type=2  input from file
%type 3  impose CUFSM shapes as imperfections

%imperfections.member  =1 column
%imperfections.member  =2 beam

imperfections.type=0;
imperfections.filename=[];
imperfections.step=[];
imperfections.mode=[]
imperfections.member=[]
imperfection.magnitude=[]
imperfections.plumb=[]
imperfections.wavelength=[]

%DEFINE HOLES
%Add holes to your member.
%hole.type=1  circular
%hole.type=2  rectangular
%hole.type=3  slotted w\radial ends
%hole.dimension=['width or length (ABAQUS x direction)' 'height or diameter']
%hole.location=['CUFSM cross section node (must be odd!)'
%   'longitudinal location' 'shift hole in direction of height']
%hole.thickness = thickness of finite elements making up hole,
%   usually the same as the rest of the member

hole.type=[2 2 2 2 2 2];
%define dimensions for slotted hole
hole.dimension=holedims{i};
%define location of hole in cross-section
    hole.location=[WebC1 holespacing(i,1) 0;WebC1 holespacing(i,2) 0;
           WebC1 holespacing(i,3) 0;WebC2 holespacing(i,4) 0;
           WebC2 holespacing(i,5) 0;WebC2 holespacing(i,6) 0]
hole.thickness = [sectdims1(i,15); sectdims1(i,15); sectdims1(i,15);
                   sectdims2(i,15); sectdims2(i,15); sectdims2(i,15)]
hole.material=[100*ones(length(hole.type),1)];
hole.groups=[100000+[1:length(hole.type)]];
hole.fill=[zeros(length(hole.type),1)];
if holedims{i}(1,1)==0
    hole=[]
end

%hole=[]

%MEMBER END LOADINGS
%Loading notation is similar to CUFSM. Apply P for compression, M for
%moment, or a combination of both. Compression at both ends of column are
%shown here. Loads are applied as consistent nodal loads in ABAQUS.

end1load.P=0;
end1load.Mxx=0;
end1load.Mzz=0;
end1load.M11=0;
end1load.M22=0;

end2load.P=0;
end2load.Mxx=0;
end2load.Mzz=0;
end2load.M11=0;
end2load.M22=0;

%CALCULATE CONSISTENT NODAL LOADS ON MEMBER ENDS*****
unsymm=0
[end1cload, end2cload, A, Ixx]=consist_endloads(node,elem,end1load,end2load,

%ABAQUS NODE SETS
%Define these node sets to apply boundary conditions in ABAQUS
%nodesetinfo={'nodeset name' [xlim1 xlim2 xint] [ylim1 ylim2 yint]
%
%where nodes are grouped based on xlim1<=x<=xlim2 and ylim1<=y<=ylim2 and
%
%Instead of ranges, assign xint,yint,zint to something other than zero to
%group nodes at specific x,y,and z distance intervals
%The exclude command can be used to exclude previously defined node sets from
%the current node set.
%exclude = θ  all nodes in range are included in nodeset
%exclude = m  excludes nodeset m from current nodeset
% nodesetinfo={'REFXZERO' [0 0 0] [xcg xcg 0] [zcg zcg 0] 0;
% 'REFXL' [L 0] [xcg xcg 0] [zcg zcg 0] 0;
% 'ENDXZERO' [0 0 0] [-1000 1000 0] [-1000 1000 0] 1;
% 'ENDXL' [L 0] [-1000 1000 0] [-1000 1000 0] 2;
% 'SCREWSTOP' [8 100 8] [max(node(:,3) max(node(:,3) 0) [max(node(:,3)

%Webheight hweb1 & hweb2 needed for loadpoint location
hweb1=(abs(xy1(5,3))+abs(xy1(6,3)))/2;
hweb2=(abs(xy2(5,3))+abs(xy2(6,3)))/2;

nodesetinfo={'ENDXZERO' [2.5 3.5 0] [-1000 -3.96 0] [-1000 1000 0] 0;
'ENDXL' [L-3.5 L-2.5 0] [-1000 -3.96 0] [-1000 1000 0] 0;
'C1BRACE' [67 131 64] [node(TFlangeC1,3) node(TFlangeC1,3) 0]
[node(TFlangeC1,2) node(TFlangeC1,2) 0] 0;
'C2BRACE' [67 131 64] [node(TFlangeC2,3) node(TFlangeC2,3) 0]
[node(TFlangeC2,2) node(TFlangeC2,2) 0] 0;
'RBRES' [99 99 0] [node(TFlangeC1,3) node(TFlangeC1,3) 0]
[node(TFlangeC1,2) node(TFlangeC1,2) 0] 0;
'LeftLoadPointC2' [L/2-32-1.5 L/2-32+1.5 3]
[node(WebC2,3)+hweb2/2 node(WebC2,3)+hweb2/2 0]
[node(WebC2,2) node(WebC2,2) 0] 0;
'LeftLoadPointC2' [L/2-32-1.5 L/2-32+1.5 3]
[node(WebC2,3)-hweb2/2 node(WebC2,3)-hweb2/2 0]
[node(WebC2,2) node(WebC2,2) 0] 0;
'LeftLoadPointC1' [L/2-32-1.5 L/2-32+1.5 3]
[node(WebC1,3)+hweb1/2 node(WebC1,3)+hweb1/2 0]
[node(WebC1,2) node(WebC1,2) 0] 0;
'LeftLoadPointC1' [L/2-32-1.5 L/2-32+1.5 3]
[node(WebC1,3)-hweb1/2 node(WebC1,3)-hweb1/2 0]
[node(WebC1,2) node(WebC1,2) 0] 0;
'RightLoadPointC2' [L/2+32-1.5 L/2+32+1.5 3]
[node(WebC2,3)+hweb2/2 node(WebC2,3)+hweb2/2 0]
[node(WebC2,2) node(WebC2,2) 0] 0;
'RightLoadPointC2' [L/2+32-1.5 L/2+32+1.5 3]
[node(WebC2,3)-hweb2/2 node(WebC2,3)-hweb2/2 0]
[node(WebC2,2) node(WebC2,2) 0] 0;
'RightLoadPointC1' [L/2+32-1.5 L/2+32+1.5 3]
numloadpts=length(find(node1(:,3)>=node(TFlangeC2,3)-1.0 & node1(:,3)<=
node(TFlangeC2,3)+1.0))*4;

%generate node sets to model angle bracing across top and bottom of channels
x=[3:12:63 135:12:L-3];
nodesetcouple=size((nodesetinfo),1);
nodesetlength=size((nodesetinfo),1);

for k=1:length(x)

%Bottom Tie
nodesetinfo(nnodesetlength+1,1:5)={['BottomTie' num2str(x(k))] [x(k) x(k) 0]
[0]));

%Bottom Tie Reference Node
nodesetinfo(nnodesetlength+2,1:5)={['BottomTieREF' num2str(x(k))] [x(k) x(k) 0]
[nodesetlength=size((nodesetinfo),1);

end

x=[3:12:63 135:12:L-3];
%Top Tie
nodesetlength=size((nodesetinfo),1);

for k=1:length(x)
%Top Tie
nodesetinfo(nodesetlength+1,1:5)={'TopTie' num2str(x(k)) [x(k) x(k) 0] [min([node(TFlangeC1,3) node(TFlangeC2,3)]) max([node(TFlangeC1,3) node(TFlangeC2,3)]) 0] [node(TFlangeC1,2) node(TFlangeC2,2) node(TFlangeC2,2)-node(TFlangeC1,2)] 0};

%Top Tie Reference Node
nodesetinfo(nodesetlength+2,1:5)={'TopTieREF' num2str(x(k)) [x(k) x(k) 0] [min([node(TFlangeC1,3) node(TFlangeC2,3)]) max([node(TFlangeC1,3) node(TFlangeC2,3)]) 0] [node(TFlangeC1,2) node(TFlangeC1,2) 0] 0};

nodesetlength=size((nodesetinfo),1);
end

%x=[12:12:60 132:12:L-12];
x=[0:6 64:1:70 128:1:134 192:198];

%Tube section restrain
nodesetlength=size((nodesetinfo),1);

for k=1:length(x)
%Tube section restrain
    nodesetinfo(nodesetlength+1,1:5)={'TubeRestr' num2str(x(k)) [x(k) x(k) 0] [node(WebC1,3)-3 node(WebC2,3)+3 0] [node(WebC1,2) node(WebC2,2) node(WebC2,2)-node(WebC1,2)] 0};
%Tube section restrain Reference Node
    nodesetinfo(nodesetlength+2,1:5)={'TubeRestrREF' num2str(x(k)) [x(k) x(k) 0] [node(WebC1,3) node(WebC1,3) 0] [node(WebC1,2) node(WebC1,2) 0] 0};

    nodesetlength=size((nodesetinfo),1);
end

%nodesetinfo={'nodeset name' [xlim1 xlim2 xint] [ylim1 ylim2 yint] [%zlim1 zlim2 zint] exclude}

%DEFINE SPRINGS
springs=[]

%DEFINE CONTACT SURFACES, NODE SURFACES, KINEMATIC CONSTRAINTS,....
surface.type={}
surface.type=[]
surface.local=[]
surface.coord=[]

%set up warping fixed boundary conditions
surface.coupling={};
surface.interaction=[]
surface.contact=[]
surface.areadist=[]

%DEFINE ANALYSIS STEP
step(1).stepinfo={"STEP 1, 'perturbation' []};
step(1).solutiontype='Buckle, EIGENSOLVER=LANCZOS';
step(1).solutionsteps={'250, , ,'};
%step(1).solutionsteps={};
step(1).solutioncontrols={};
step(1).boundarycon={'ENDXZERO' 2 3;
'ENDXL' 2 3;
'C1BRACE' 3 3;
'C2BRACE' 3 3;
'RBRES' 1 1}
%step(1).coupling=[]

%write coupling to model individual aluminium angles connecting top and
%bottom of channels
count=1;
for q=nodesetcouple+1:2:length(nodesetinfo)
  step(1).coupling(count)={['*Rigid Body,', 'Ref Node=', char(nodesetinfo(q+1,1)),
    ',Tie nset=', char(nodesetinfo(q,1))]};
  count=count+1;
end

step(1).loads={'*Cload' 'LeftLoadPointC2' 2 -0.5/4;
'*Cload' 'LeftLoadPointC1' 2 -0.5/4;
'*Cload' 'RightLoadPointC2' 2 -0.5/4;
'*Cload' 'RightLoadPointC1' 2 -0.5/4}

step(1).outrequest={'*Output, field, variable=PRESELECT'};

%WRITE ABAQUS INP FILE
%this is the important function, you can use this in for loops to
%generate parameter studies
jhabnl(L, node, elem, nele, end1load, end2load, hole, nodesetinfo, surface,
    nodeadd, step, jobname{i},matprops,imperfections,springs,sectionpoints)
end

end

% walltime(:,1)=ones(length(jobname),1)*0 %hours
% walltime(:,2)=ones(length(jobname),1)*10 %min
% cpus=ones(length(jobname),1)*1
% %create files to run ABAQUS files on Inferno2
% infernoscript(jobname,walltime,cpus)
% submitscript('nikhila', jobname)