Report no. 6
Local buckling of slender aluminium sections exposed to fire

FEM simulations of tests on local buckling

Date June 2007
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Number of pages 84
Number of Annexes 4
Sponsor NIMR
Project name PhD Local buckling of slender aluminium sections exposed to fire
Summary

In order to be used for the development of a design model for local buckling of fire exposed aluminium sections, FE models are developed and validated with tests in this report.

The validation is based on three types of tests:

- Compression tests on thin walled square hollow sections (SHS) and angles at room temperature;
- Steady-state compression tests on thin walled SHS and angles at elevated temperature, which are carried out in the same way as at room temperature, i.e. the specimen is brought to a constant, elevated temperature and subsequently loaded with a certain strain rate until collapse occurs;
- Transient-state compression tests on thin walled SHS and angles, in which the load on the specimen remains constant and the temperature increases with an approximately constant heating rate, until collapse occurs.

The average value of the ratios between the ultimate buckling resistance of the model and of the steady-state test (at room and elevated temperature) is 1.03 and 1.12 for square hollow sections (SHS) and angles, respectively. The standard deviation of these ratios is 0.08 and 0.12 for SHS and angles, respectively. (Total amount of tests: 19 and 9 for SHS and angles, respectively.)

The average value and the standard deviation of the differences in critical temperature between simulations and transient state tests was 1 °C and 6 °C, respectively, for critical temperatures ranging from 235 to 340 °C (total amount of tests was 28).

Some parameters used in the simulations are uncertain. The influence of these parameters on the ultimate buckling resistance or critical temperature was determined with FE models. The differences found in critical temperature and ultimate resistance between tests and simulations can be explained with the assumed uncertainties in input parameters of the FE models.

Based on this, the FE models are considered as validated for local buckling of slender aluminium sections at elevated temperature and during fire conditions.
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1 Introduction

This report is a background document to a PhD research on local buckling of slender aluminium sections exposed to fire.
Aim is to develop a response model for local buckling of aluminium sections when exposed to fire. This response model will be based on a parameter study with FE models.
For this purpose, finite element models (FE models) are developed. These models are validated with the tests on local buckling carried out at elevated temperature (see report no. 5).
Three types of tests and simulations were carried out:
- Tests / simulations at room temperature;
- Steady-state tests / simulations at elevated temperature, which are carried out in the same way as at room temperature, i.e. the specimen is brought to a constant, elevated temperature and subsequently loaded with a certain strain rate until collapse occurs;
- Transient-state tests / simulations, in which the load on the specimen remains constant and the temperature increases with an approximately constant heating rate, until collapse occurs.

This report gives the description of the FE models as well as the results of the validation.

Chapter 2 describes the models. FE simulations of the steady state tests and transient state tests are given in chapters 3 and 4, respectively. In order to explain the differences between models and tests, some sensitivity studies are carried out in chapter 5. Conclusions are given in chapter 6.
2 Description of the FEM models

2.1 Geometry, types and number of elements

The tested specimens are square hollow sections (SHS) and angles width a nominal length $L = 300$ mm and a plate width $w = 50$ mm (see Figure 2.1).

For each specimen, the actual wall thickness and width of all four plates of which the section is composed and the specimen length were measured. The dimensions are given in the report with the compression tests results [11]. The thickness of each plate of which the specimens were composed differed slightly along the width and the length of the plate. In the FEM model, a uniform thickness was applied for each wall. This thickness was the average value of the measurements for each plate.

The elements applied were four-sided shell elements (CQ40S) with eight nodes (including intermediate nodes at each element side) and a $2 \times 2$ integration scheme. Through thickness, 7 integration points were applied.

The nodal degrees of freedom are three translations and two rotations (the rotation about the axis perpendicular to the shell is not incorporated in the element description). Using these elements, it is assumed that normals remain straight, but not necessarily normal to the reference surface. The normal stress component is forced to zero. The in-plane lamina strains $\varepsilon_{xx}$, $\varepsilon_{xy}$ and $\gamma_{xy}$ vary linearly in the thickness direction. The transverse shear strains $\gamma_{xy}$ and $\gamma_{yz}$ are forced to be constant in the thickness direction. The elements are therefore applicable in case of thin structures only (thickness $<<$ width).

To determine the amount of elements necessary to accurately describe the buckling loads, the specimens were modelled with various element sizes and various thicknesses of the plates. The elastic critical buckling load and the ultimate resistance were determined with each model. It appeared that it was sufficient to apply 8 elements in
width direction in case of the square hollow sections. In this way, each half-sinus of a buckle is described by the deformation of 8 elements. A model with 16 elements in width direction resulted in a critical buckling load that was less than 1% lower than that of a model with 8 elements. Also the difference in ultimate resistance for these models was less than 1%. In a similar way, it was determined that the 10 elements in width direction are necessary to model an angle.

In length direction, the dimension of the elements was such that the position of the nodes corresponded with the position of the imperfection measurements. This means that 54 elements are applied in length direction. The elements are approximately square.

To check the model with shell elements, an alternative model was developed consisting of solid elements. The elements applied were brick elements with six surfaces (CHX60) with twenty nodes (including intermediate nodes at each element side) and a 3 x 3 x 3 integration scheme. This model is described in Annex C.

The nodal degrees of freedom are three translations.

### 2.2 Boundary conditions

To explain the boundary conditions of the individual plates of which the section is composed, the conventions according to Figure 2.2 are used.

![Figure 2.2 – Conventions](image)

All boundaries (edges) were restrained against out of plane translations (in direction of the z-axis). It was further assumed that the plates could not slide along the supports, thus also the translations in x-direction were restrained.

The rotations perpendicular to the boundaries and in plane of the plate were also restrained; i.e. the rotations about the y-axis were restrained for both edges. Restraining these rotations prevents the boundaries to wave out-of-plane (Figure 2.3), so that they remain straight. This increases the elastic critical buckling load with 0.2% for slender plates ($\lambda_{p,rel} = 2.5$) to 2% for stocky plates ($\lambda_{p,rel} = 0.67$).

![Figure 2.3 – Waving edge, in case rotations of boundaries are not restrained (top view of plate)](image)
The nodes on edge 1 are restrained against translations in direction of the y-axis. The load is applied in one node on edge 2. All other nodes on edge 2 are tied with this node for translations in direction of the y-axis, so that during loading, edge 2 remains parallel to the original (undeformed) situation.

2.3 Material model

The material model is based on uniaxial tensile tests, described in the background report on material properties [12]. Different types of material models are applied for steady state and for transient state conditions.

Steady state tensile tests are carried out to determine the strength at elevated temperature, to be used for simulation of the steady state compression tests. The modulus of elasticity was not determined accurately in the tensile tests. Instead, the modulus of elasticity was based on bending tests and the tensile tests data given in Kaufman [4]. The construction of the stress-strain relationships based on these tensile tests is given in Annex D.

The test temperature of the steady state compression tests was not always exactly equal to the test temperature of the steady state tensile tests. In these cases, linear interpolation was used to determine the modulus of elasticity at the test temperature. Linear interpolation was also used to determine the stress at fixed values for plastic strain to construct the stress-strain relationship at the test temperature, see Annex D.

The strain rate in the compression tests was not always equal to the strain rate in the tensile tests. In these cases, the stress-strain relationships based on the tensile tests and used in the simulations differ from the actual stress-strain relationships belonging to the compression tests.

In order to determine the material properties for a transient state condition, creep tensile tests are carried out, which were used to determine the parameters in the Dorn-Harmathy creep model. The material model developed was validated with transient state tensile tests. This material model is implemented in DIANA via a user supplied subroutine (USS) as described in background report [13].

2.4 Temperature

The temperature was measured at 5 spots along the length of each specimen. In most tests, the temperature along the specimen was approximately uniform. In these cases, the temperature was modelled uniform.

In some tests on square hollow sections of alloy 6060-T66, however, a temperature gradient was measured along the specimen length. For each of these tests, a quadratic function was constructed in such a way that it approached the measured temperature as a function of the specimen height. An example is given in Figure 2.4. This temperature was subsequently applied in the finite element model. It is indicated in the discussion of the tests in which models this non uniform temperature was applied.
Figure 2.4 – Measured temperature and temperature applied in the FEM model for test 6-0.8 mm

The temperature was applied to assign the temperature dependent material properties to the integration points of each element.

While heated, the specimens are subjected to thermal expansion. This expansion is possibly restrained at the supports in the transient state tests, so that the cross-section at the supports is forced to remain undeformed. This may affect the resistance of the transient state compression tests. The influence of restrained thermal expansion at the supports is given in chapter 5. The results in this report are based on simulations in which thermal expansion was not modelled.

2.5 Initial geometric imperfections

For each plate of each specimen, the out of straightness of the plate between the supports was measured. These initial imperfections are given in the report with the compression tests results [11]. These imperfections are modelled accordingly. In length direction, the positions of the nodes corresponded with the positions of the imperfection measurements. In width direction, the positions of the nodes did not correspond with the positions of the imperfection measurements. The imperfection modelled in each node was determined by linear interpolation of the imperfection measurements in width direction.

This imperfection shape is difficult to reproduce for other researchers. Therefore, additional models are made of all specimens in which initial imperfections were applied by scaling the first Euler buckling mode with certain amplitude. The initial shape, with exaggerated imperfections, is then according to Figure 2.5. The amplitude applied was equal to the average value of the maximum imperfections of the four plates. In this way, the amplitude of the imperfections in the FEM model corresponds with the amplitude of the measured imperfections, while the shape of the initial imperfections is different.
2.6 Rounded corners in the sections of alloy 5083-H111

The sections of alloy 5083-H111 are composed of folded plates. Consequently, the corners between the walls of the sections are rounded, with a radius of approximately 4 to 4.5 mm. These rounded corners are modelled with 4 to 6 elements, respectively. The difference in ultimate resistance with a model with two times as much elements for the corners was less than 0.5%.

The root radii were difficult to measure. The possible measurement error in radii is estimated at 0.5 mm. However, a simulation including roots resulted in an almost equal ultimate resistance as a simulation with roots equal to 5 mm (chapter 5). Based on this, it is concluded that the possible measurement error does not affect the ultimate resistance.
2.7 Welds in the square hollow sections of alloy 5083-H111

Two types of modifications on the models of SHS of alloy 5083-H111 are applied in order to account for the influence of the weld.

The weld itself is thicker than the rest of the plate (approximately 1.5 and 1 mm, respectively). The weld is modelled by applying the measured weld thickness and the weld width (approximately 6 mm) into the model. The stress-strain relationships of the parent material were assumed for this weld. The possible error introduced by this assumption is investigated in chapter 5.

Welding introduces residual stresses into the section. DIANA provides the possibility to apply residual stresses into the model. A residual stress pattern according to Figure 2.7 was applied at room temperature. The values agree with the measurements on residual stresses as described in report [14]. For the tests at elevated temperatures, the relaxation of these residual stresses was simulated with the Dorn Harmathy material model in finite element models as described in report [12].

In case of the steady state tests, relaxation of the residual stresses during heating has to be simulated using the Dorn Harmathy material model, while the actual test has to be simulated with material properties according to the steady state tensile tests. Relaxation of the residual stresses during heating of the steady state tests was therefore simulated in a separate finite element model, with the Dorn Harmathy material model and without external load. The resulting residual stresses were implemented in the model of the steady-state test itself, with material properties according to the steady-state tensile tests and the strain rate as measured.
In case of the transient state tests, it is not necessary to apply two separate calculations. Relaxation of the residual stresses occurs during heating of the loaded specimen.

In DIANA, the residual stress of each node of each element has to be assigned. A Fortran program has been written to determine the position of each node and to assign the corresponding residual stress. The resulting residual stress is given in Figure 2.7.

![Figure 2.7](image)

Figure 2.7 – Residual stress applied in the model at room temperature

To model the weld and residual stresses, the element division is modified, as shown in Figure 2.8.

![Figure 2.8](image)

Figure 2.8 – Modified geometry in the model of the SHS of alloy 5083-H111 to account for the weld thickness and for residual stresses

The residual stresses due to extrusion are usually very small (Frey and Mazzolani [3]). Residual stresses in the extruded sections are not measured in this study and also not modelled.
2.8 Modelling of non-parallel loaded edges

The edges of the specimens are in some cases not exactly parallel. Also the plates of the supports are possibly not exactly parallel. As a consequence, at some specimens a gap between one of the edges and its supports exists at the beginning of loading.

The specimens were placed on the lower support of the test set-up. Subsequently the displacement of the actuator was controlled such that the upper support came down until it made contact with the specimen. In case the supports or specimen ends are not parallel, a situation results where the lower end of the specimen has full contact with the lower support, while a gap between the upper specimen end and its support, as shown in Figure 2.9.

![Figure 2.9 – Geometry in case supports or specimen ends are not parallel](image)

The contact between the specimen and the support is modelled with interface elements, which have a high stiffness for compression and a negligibly low stiffness for tension and shear. The upper nodes of the interface elements are tied to one another in such a way that these nodes describe one plane. This plane represents the support plate of the test set-up. Interface elements are applied both at the upper support and at the lower support. Figure 2.10 shows the subsequent steps in the analysis.

- The specimen and it's supports are modelled straight, with interface elements between the model of the specimen and the supports;
- In the first analysis step, the support is rotated and translated upwards. The translation is such, that all interface elements are just loaded in tension. As the stiffness for tension is negligible, the specimen is unstressed. This condition corresponds to the actual situation of the specimen just before starting the test;
- In subsequent analysis steps, the support is incrementally translated downwards. The specimen is then loaded in compression.

The bottom support remains straight during the analysis.
Figure 2.10 – Interface elements at upper support - stresses and deformation prior to loading
3 Comparison of FE models with steady-state tests

This chapter gives the results of the simulations with FE models of steady state tests. Paragraph 3.1 gives the types of simulations carried out. Paragraph 3.2 gives a selection of the results of tests and simulations (all results are given in Annex A). Paragraph 3.3 gives an evaluation of the results.

3.1 Types of simulations

In case of many tests (especially the sections of alloy 6060-T66), there was no gap visible between the supports and the specimen from the beginning of loading. Still, it is well-possible that there was a small gap, caused by non-parallel loaded edges or supports. In the model ‘FEM-actual’, a gap of 0,2 mm was modelled, corresponding to an angle between the support and the loaded edge of 0,23 degrees. This corresponds to a gap that is just not visible in the set-up.

In general, three types of finite element analyses were carried out:

- Simulations with geometrical imperfections of the specimen walls in the shape of the first Euler buckling mode, and with parallel supports and specimen ends, are referred to as ‘FEM mode’ and indicated with a dashed curve in the graphs in this document;
- Simulations with geometrical imperfections of the specimen walls as measured, and with parallel supports and specimen ends, are referred to as ‘FEM measured’ and indicated with a solid curve in the graphs in this document;
- Simulations with geometrical imperfections of the specimen walls as measured, and with a gap between the upper end of the specimen and its support, are referred to as ‘FEM gap measured’ and indicated with a dash-dotted curve.

Table 3.1 gives an overview of all steady-state tests that are simulated.

Table 3.1 – Test programme of steady state compression tests

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>Test temperatures [°C]</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHS 6060-T66 b/t = 25</td>
<td>20 (3x), 179, 265, 290</td>
<td></td>
</tr>
<tr>
<td>SHS 6060-T66 b/t = 44</td>
<td>20, 179, 268, 287, 290</td>
<td></td>
</tr>
<tr>
<td>SHS 6060-T66 b/t = 60</td>
<td>20 (2x)</td>
<td></td>
</tr>
<tr>
<td>angle 6060-T66 b/t = 25</td>
<td>20, 181, 267, 299</td>
<td>At el. temp. only transient state</td>
</tr>
<tr>
<td>SHS 5083-H111 b/t = 50</td>
<td>20, 178, 267, 323, 345</td>
<td>Imperf. not accurately measured</td>
</tr>
<tr>
<td>angle 5083-H111 b/t = 50</td>
<td>20, 167, 270, 325, 339</td>
<td>Welded specimens</td>
</tr>
</tbody>
</table>

In all cases, the measured geometry and temperature were applied in the models according to the measurements. In case of the welded specimens of alloy 5083-H111, also residual stresses were applied.

3.2 Selection of results

This paragraph gives a selection of the results of the steady-state compression tests and the FE simulations of these tests. Each graph gives the stress-strain relationship in light grey, the results of the compression test in dark grey and the results of the FE analyses in black. The results of the simulation of all steady-state tests are given in Annex A.
For the square hollow sections of alloy 6060-T66, distinction is made between thick walled specimens (b/t = 25), which are in class 3 or higher both at room and at elevated temperature, and thin walled specimens (b/t = 44 or 60), which are in class 4 both at room and at elevated temperature.

Cross-section class 3 means that the ultimate resistance is equal to or larger than the plastic capacity, which is defined as the gross area of the cross-section multiplied with the 0,2 % proof stress. The deformation capacity, however, is limited due to local buckling. Class 4 means that the ultimate resistance is affected by local buckling.

The average stress in the section is plotted as a function of the axial strain for test and simulations in Figure 3.1 for a thick walled SHS and in Figure 3.2 for a thin walled SHS.

Figure 3.1 – Result of test SHS T3-2mm at 265 °C (alloy 6060-T66)

Figure 3.2 – Results of SHS T7-1mm at 290 °C (alloy 6060-T66)

Figure 3.3 gives the average stress in the section as a function of the axial strain for a test on an angle of alloy 6060-T66 with b/t = 25 mm
For the welded square hollow sections of alloy 5083-H111, results are given for models with residual stresses. Table 3.2 gives the magnitude of the maximum residual stress after heating and before the actual test is carried out, according to the FE simulations of the relaxation of residual stresses. At room temperature and at 180 °C, the maximum value of the residual stresses is significant. Only in these cases, a model without residual stresses resulted in a slightly higher resistance than a model with residual stresses. The difference in resistance was approximately equal to 4%.

Table 3.2 Maximum values of the residual stresses after heating and before the test is carried out according to the FEM model

<table>
<thead>
<tr>
<th>Specimen no.</th>
<th>Test temperature</th>
<th>Max. residual stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>shs-O6</td>
<td>20 °C</td>
<td>80 N/mm²</td>
</tr>
<tr>
<td>shs-O9</td>
<td>180 °C</td>
<td>56 N/mm²</td>
</tr>
<tr>
<td>shs-O4</td>
<td>270 °C</td>
<td>14 N/mm²</td>
</tr>
<tr>
<td>shs-O3</td>
<td>323 °C</td>
<td>4 N/mm²</td>
</tr>
<tr>
<td>shs-O5</td>
<td>345 °C</td>
<td>3 N/mm²</td>
</tr>
</tbody>
</table>

Figure 3.4 gives the average stress in the section as a function of the axial strain of a welded SHS of alloy 5083-H111, with b/t = 50.
Figure 3.4 – Results of shs O9 at 178 °C (alloy 5083-H111)

Figure 3.5 gives the average stress in the section as a function of the axial strain of an angle of alloy 5083-H111 with b/t = 50. For this type of specimen, the imperfections were not measured. Instead, the imperfections applied have the shape of the first Euler buckling mode with a maximum imperfection equal to the average value of the maximum imperfections measured for all angles of alloy 6060-T66 (0.15 mm).

Figure 3.5 – Result of angle O3 at 20 °C (alloy 5083-H111)

3.3 Evaluation of the results

Figure 3.6 up to Figure 3.9 give the ratio between the ultimate resistance determined with FEM and the ultimate resistance of the tests as a function of the test temperature, with measured imperfections. Figure 3.6 gives the results for alloy 6060-T66, simulated without a gap and Figure 3.7 gives the results with gap. Figure 3.8 and Figure 3.9 give the results for alloy 5083-H111. For the specimens for which the imperfection pattern was measured (SHS with b/t= 25 and 44 and angles of alloy 6060-T66 and SHS of alloy 5083-H111), the results of models with measured imperfections is displayed. For the
other specimens (SHS with b/t = 60 of alloy 6060-T66 and angles of alloy 5083-H111), the models with mode imperfections are displayed.

The figures show that the ultimate resistance determined with the FEM of the square hollow sections agrees better with the tests than that of the angles. Especially in case of high temperatures, the agreement between models and tests on angles is worse than in other cases. The average value and standard deviation of the ratios are given in table Table 3.3 for angles and for square hollow sections separately. The table shows that the average value is closer to unity and the standard deviation is smallest in case a gap between the specimens and the supports is modelled. The resulting ultimate resistance of a simulation with mode imperfection is in many cases significantly different from the ultimate resistance of a simulation with measured imperfections, even though the maximum value of the imperfections are equal. The difference in resistance is in most cases 4 to 10 %, but for test shs O9 the difference was 18 % (Figure 3.4).

The figures in 3.2 and Annex A indicate that the initial stiffness of the simulations agrees slightly better with that of the tests if a gap between specimens and supports is modelled. At higher temperatures, however, the agreement in stiffness is not good, with sometimes even a factor 2 between the stiffness of the simulation and that of the test. This is attributed to the fact that the displacements could not be determined accurately with the set-up used, due to the fact that the noise generated by thermal expansion of the specimen and the measuring devices, and heating of the LVDTs is significant at higher temperatures.

![Figure 3.6](image_url)  
**Figure 3.6** – Ultimate strength of the FEM model compared with ultimate strength of the test as a function of the test temperature for steady state tests of alloy 6060-T66, with measured imperfections
Figure 3.7 – Ultimate strength of the FEM model compared with ultimate strength of the test as a function of the test temperature for steady state tests of alloy 6060-T66, with measured imperfections and gap.

Figure 3.8 – Ultimate strength of the FEM model compared with ultimate strength of the test as a function of the test temperature for steady state tests of alloy 5083-H111, with measured imperfections.
Table 3.3 – Average value and standard deviation of ratio $F_{u,FEM} / F_{u,test}$

<table>
<thead>
<tr>
<th>Specimen and model type</th>
<th>average of $F_{u,FEM} / F_{u,test}$</th>
<th>stand. dev. of $F_{u,FEM} / F_{u,test}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHS, without gap</td>
<td>1.05</td>
<td>0.09</td>
</tr>
<tr>
<td>SHS, with gap</td>
<td>1.00</td>
<td>0.07</td>
</tr>
<tr>
<td>angle, without gap</td>
<td>1.15</td>
<td>0.14</td>
</tr>
<tr>
<td>angle, with gap</td>
<td>1.09</td>
<td>0.10</td>
</tr>
</tbody>
</table>

In recognising the fact that the ratio between the ultimate resistance between the models and the tests of angles at relatively high temperatures is worse than for other cases, it should be considered that the absolute value of the strength at these high temperatures is only a fraction of the strength at room temperature. Consequently, the reduction in strength as a function of the temperature, which is the governing parameter if the fire resistance has to be computed, is simulated with reasonable accuracy, as shown in figures Figure 3.10 and Figure 3.11.
The deformed shape and the size of the deformations of the model at the end of the simulations agreed reasonable with that of the specimens at the end of the tests in Figure 3.1 up to Figure 3.5. In many other cases, the size of the deformations of the specimens and models was different, but the deformed shape agreed reasonable. The fact that the size of the deformations was different is attributed to the difficulty in measuring the axial deformation in the test. The axial deformation at which the deformed shapes of the FEM model are compared with the tests may therefore be slightly wrong. It is noted that a small change in axial deformation is attended by a large change in out-of-plane deformation.

A sensitivity study is given in chapter 5 in order to explain the differences found in ultimate buckling resistance between the tests and the models.
4 Comparison of FE models with transient state tests

The results of the transient state tests and simulations are given in this chapter. Paragraph 4.1 gives a description of the type of simulations carried out. Paragraph 0 gives a selection of the results of the tests and the simulations (a comparison between all tests carried out is given in Annex B). The results are evaluated in paragraph 4.3.

4.1 Types of simulations

In the simulations of the steady-state tests, a possible small gap between the specimen and its supports turned out to be of significant importance for the ultimate buckling resistance. Before carrying out the transient state tests, the set-up was modified in order to minimise the gap (background report [11]). Most tests are therefore simulated without a gap. Only for specimens where the upper and lower edges were not parallel, so that a gap was visible in the test, a simulation with a gap was carried out. This considers the welded square hollow sections of alloy 5083-H111.

In case of the transient state tests on SHS of alloy 6060-T66 with b/t = 25 and b/t = 60, there was a significant temperature gradient measured along the length of the specimen. For these sections, the measured temperature gradient is also modelled. The figures give the maximum measured temperature and the temperature of the simulation at the same position along the specimen. All other tests were simulated with a uniform temperature.

In case of the welded specimens of alloy 5083-H111, simulations were carried out with measured residual stresses and without residual stresses. The resulting critical temperatures of these simulations were almost equal (difference in critical temperature was approximately 1 °C). Displayed are the results without residual stresses.

In background report [12], it was noted that the parameters of the Dorn Harmathy material model were determined for two batches of specimens of alloy 6060-T66, giving two different sets of material parameters (called mat 2005 and mat 2006). The tests are simulated with both sets of material parameters. Only in case of the specimens with the highest stress levels, i.e. the thick walled SHS of alloy 6060-T66 (b/t =25) and tests T6-1 and TA-10, there was a significant difference in critical temperature between the simulations with the two sets of material parameters. Only for these tests, the results of both simulations are given. For the other specimens of alloy 6060-T66, only the results of the simulations with mat 2005 are displayed.

Loads, heating rates, geometry are applied as measured.

Table 4.1 gives an overview of all transient state tests carried out. The table gives the stress levels applied in the tests and, between brackets, the heating rates of the individual tests carried out. If more than one heating rate is mentioned, more than one test is carried out with the same stress levels and with the indicated heating rates. The tests are carried out with a load equal to a certain percentage of the ultimate resistance of the tests at room temperature. This percentage is indicated in the columns of the table.
Table 4.1 – Test programme of transient state compression tests

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Stress level [N/mm²] (heating rates [ºC/min])</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30 % 45 % 60-65 %</td>
<td></td>
</tr>
<tr>
<td>SHS 6060-T66</td>
<td></td>
<td></td>
</tr>
<tr>
<td>b/t = 25</td>
<td>93 (7,8; 7,9; 2,2; 2,2)</td>
<td>Non-uniform temperature, imperf. not accurately meas.</td>
</tr>
<tr>
<td>SHS 6060-T66</td>
<td>37 (8,6)</td>
<td></td>
</tr>
<tr>
<td>b/t = 44</td>
<td>57 (8,1; 7,8; 7,4; 2,9)</td>
<td></td>
</tr>
<tr>
<td>SHS 6060-T66</td>
<td>39 (9,7; 9,8; 2,4; 2,4)</td>
<td>Non-uniform temperature, imperf. not accurately meas.</td>
</tr>
<tr>
<td>b/t = 60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>angle 6060-T66</td>
<td>29 (7,8)</td>
<td></td>
</tr>
<tr>
<td>b/t = 25</td>
<td>43 (6,7; 6,7; 2,9)</td>
<td>59 (6,5)</td>
</tr>
<tr>
<td>SHS 5083-H111</td>
<td>30 (7,4)</td>
<td></td>
</tr>
<tr>
<td>b/t = 50</td>
<td>45 (7,0; 6,7; 2,4; 2,4)</td>
<td>60 (6,6)</td>
</tr>
<tr>
<td>angle 5083-H111</td>
<td>15 (8,7)</td>
<td></td>
</tr>
<tr>
<td>b/t = 50</td>
<td>23 (9,6; 2,1)</td>
<td>30 (6,5)</td>
</tr>
</tbody>
</table>

1) Applied load is indicated percentage of the ultimate resistance of the test(s) at room temperature.

4.2 Selection of results

This paragraph gives a selection of the results of the transient state compression tests and the FE simulations of these tests. The figures show the axial mechanical strain as a function of the temperature. Each figure gives the stress-strain relationship in light grey, the results of the compression test in dark grey and the results of the FE analyses in black. The mechanical strain of the test was determined by subtraction of the thermal strain measured in a dummy specimen from the total measured strain. The simulations were carried out without thermal expansion. The results of the simulation of all transient state tests are given in Annex B.

The load applied in the test and in the simulation is a certain percentage of the ultimate buckling resistance at room temperature. This percentage is mentioned in the subscript of the figures.

The imperfections of the thick walled SHS of alloy 606-T66 (b/t) were only roughly measured, resulting in an indication of the maximum value of the imperfection, but no information on the shape of the imperfection. The simulations are carried out with imperfections shaped according to the first Euler buckling mode, with a maximum imperfection equal to the maximum measured imperfection (FEM mode). Figure 4.1 gives a result of a simulation on this type of specimens.
Figure 4.1 – Result of test 3-20 with a load of 35.8 kN (45%) and a heating rate of 7.8 °C / min (approximately 30 minutes)

The geometrical imperfections of the walls of the SHS with b/t = 44 of alloy 6060-T66 were measured accurately before the test was carried out. Simulations are made with these measured imperfections (FEM measured) and with imperfections shaped according to the first Euler buckling mode and a maximum imperfection equal to the maximum measured imperfection value (FEM mode). Loads, heating rates and geometry were applied as measured. An example of the simulation is given in Figure 4.2.

Figure 4.2 – Result of test T12-1 with a load of 12.07 kN (45 %), a heating rate of 7.4 °C / min (appr 30 minutes) and a critical temperature of 300 °C

The geometrical imperfections of the thin-walled SHS of alloy 6060-T66 with b/t = 60 were only roughly measured, resulting in an indication of the maximum value of the imperfection, but no information on the shape of the imperfection. The simulations are carried out with imperfections shaped according to the first Euler buckling mode, with a maximum imperfection equal to the maximum measured imperfection (FEM mode).

An example of the results of one simulation is given in Figure 4.3.
The geometrical imperfections of the walls of the angles of alloy 6060-T66 with b/t = 44 were measured accurately before the test was carried out. Simulations are made with these measured imperfections (FEM measured) and with imperfections shaped according to the first Euler buckling mode and a maximum imperfection equal to the maximum measured imperfection value (FEM mode). An example of the result of a simulation is given in Figure 4.4.

The edges of the welded SHS of alloy 5083-H111 were not parallel in all cases, resulting in a gap between the specimen and its supports. The size of the gap was difficult to measure. Simulations are therefore carried out with a gap of 0.5 mm and without a gap.

The geometrical imperfections of the walls of the specimens were measured accurately before the test was carried out. Simulations are made with these measured imperfections (FEM measured and FEM gap measured). For the specimen without a gap, simulations were also made with imperfections shaped according to the first Euler buckling mode and a maximum imperfection equal to the maximum measured imperfection value.
(FEM mode). Loads, heating rates and geometry were applied as measured. An example of the results is given in Figure 4.5.

Figure 4.5 – Result of test O8 with a load of 11.84 kN (60 %), a heating rate of 6.6 °C / min (appr 30 minutes) and a critical temperature of 237 °C.

The imperfections of the angles of alloy 5083-H111 with b/t = 50 specimens could not be measured (see background report [11]). Simulations are therefore carried out with mode imperfections, with a maximum value of the imperfections equal to 0.15 mm, which is the average value of the maximum imperfections of all angles of alloy 6060-T66 (with b/t = 25). An example of the results of a simulation is given in Figure 4.6.

Figure 4.6 – Result of test OA9 with a load of 2.26 kN (45 %), a heating rate of 2.10 °C / min (approximately 110 minutes) and a critical temperature of 257 °C.

4.3 Evaluation of the results

The critical temperature is defined as the asymptote of the temperature – axial strain diagrams of the previous paragraphs. The resulting critical temperatures of the tests and the simulations are summarised in Table 4.2. The last column of the table gives the difference in critical temperature between the simulation and the test.

For the thick walled SHS of alloy 6060-T66 (b/t = 25), this difference is determined using the average critical temperature of the simulations with material parameter set 05.
and material parameter set 06. (For the other specimens, there was almost no difference in critical temperature between these two simulations).

For the welded SHS of alloy 5083-H111, the difference in critical temperature was determined using the average critical temperature of the simulations with and without a gap. (For the other specimens, no gap was visible in the tests).

The difference in critical temperature between the tests and the models is largest for the welded SHS of alloy 5083-H111. These specimens had the largest imperfections of all tests carried out. It must be noted that divergence occurred at relatively small axial strains in case of the specimens with a gap.

The figures of the individual tests on welded SHS of alloy 5083-H111 show that the difference between mode imperfections and measured geometrical imperfections is largest for this type of specimens. Considering the fact that the exact imperfection pattern is difficult to measure, this might be an important reason for the large differences. Other possible reasons are uncertainty in the material properties and thickness of the weld and uncertainty in residual stresses.

A sensitivity study into the influence of input variables of the model on the critical temperature is given in chapter 5.
Table 4.2 – Critical temperatures of transient state compression tests and simulations of these tests

<table>
<thead>
<tr>
<th>specimen type no.</th>
<th>heating rate [°C/min]</th>
<th>load [kN]</th>
<th>crit. temp. test [°C]</th>
<th>crit. temp. simulation standard mat 06 &amp; gap [°C]</th>
<th>difference test &amp; FEM [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHS 3-2.0</td>
<td>7.75</td>
<td>35.77</td>
<td>276</td>
<td>271</td>
<td>-1.5</td>
</tr>
<tr>
<td>b/t = 25</td>
<td>7.88</td>
<td>35.77</td>
<td>289</td>
<td>279</td>
<td>-6.5</td>
</tr>
<tr>
<td>6060-T66 5-2.0</td>
<td>2.24</td>
<td>35.77</td>
<td>264</td>
<td>258</td>
<td>-2</td>
</tr>
<tr>
<td>6-2.0</td>
<td>2.18</td>
<td>35.77</td>
<td>263</td>
<td>259</td>
<td>-0.5</td>
</tr>
<tr>
<td>SHS T3-1</td>
<td>8.61</td>
<td>8.02</td>
<td>341</td>
<td>333</td>
<td>-7</td>
</tr>
<tr>
<td>b/t = 44</td>
<td>T8-1</td>
<td>7.81</td>
<td>308</td>
<td>307</td>
<td>-1</td>
</tr>
<tr>
<td>6060-T66 T11-1</td>
<td>8.13</td>
<td>12.07</td>
<td>313</td>
<td>302</td>
<td>-10.5</td>
</tr>
<tr>
<td>T12-1</td>
<td>7.43</td>
<td>12.07</td>
<td>300</td>
<td>295</td>
<td>-3.5</td>
</tr>
<tr>
<td>T10-1</td>
<td>2.91</td>
<td>12.08</td>
<td>298</td>
<td>286</td>
<td>-8.5</td>
</tr>
<tr>
<td>T6-1</td>
<td>6.62</td>
<td>17.43</td>
<td>239</td>
<td>230</td>
<td>-1.5</td>
</tr>
<tr>
<td>SHS 3-0.8</td>
<td>9.79</td>
<td>5.4</td>
<td>306</td>
<td>312</td>
<td>6</td>
</tr>
<tr>
<td>b/t = 60</td>
<td>4-0.8</td>
<td>9.69</td>
<td>305</td>
<td>312</td>
<td>7.5</td>
</tr>
<tr>
<td>6060-T66 5-0.8</td>
<td>2.36</td>
<td>5.4</td>
<td>292</td>
<td>296</td>
<td>4.5</td>
</tr>
<tr>
<td>6-0.8</td>
<td>2.43</td>
<td>5.4</td>
<td>297</td>
<td>300</td>
<td>3.5</td>
</tr>
<tr>
<td>angle TA12</td>
<td>7.75</td>
<td>5.96</td>
<td>335</td>
<td>341</td>
<td>4</td>
</tr>
<tr>
<td>b/t = 25</td>
<td>TA1</td>
<td>6.67</td>
<td>291</td>
<td>289</td>
<td>-2</td>
</tr>
<tr>
<td>6060-T66 TA2</td>
<td>6.67</td>
<td>9.04</td>
<td>289</td>
<td>295</td>
<td>4.5</td>
</tr>
<tr>
<td>TA13</td>
<td>2.9</td>
<td>9.06</td>
<td>282</td>
<td>282</td>
<td>0</td>
</tr>
<tr>
<td>TA10</td>
<td>6.51</td>
<td>11.94</td>
<td>256</td>
<td>243</td>
<td>-4.5</td>
</tr>
<tr>
<td>SHS O7</td>
<td>7.43</td>
<td>5.96</td>
<td>300</td>
<td>295</td>
<td>-5</td>
</tr>
<tr>
<td>b/t = 50</td>
<td>O2</td>
<td>6.66</td>
<td>257</td>
<td>231</td>
<td>-</td>
</tr>
<tr>
<td>5083-H111 O12</td>
<td>7.03</td>
<td>8.86</td>
<td>266</td>
<td>277</td>
<td>7.5</td>
</tr>
<tr>
<td>O10</td>
<td>2.42</td>
<td>8.89</td>
<td>255</td>
<td>250</td>
<td>-6</td>
</tr>
<tr>
<td>O11</td>
<td>2.42</td>
<td>8.85</td>
<td>255</td>
<td>273</td>
<td>7</td>
</tr>
<tr>
<td>O8</td>
<td>6.6</td>
<td>11.84</td>
<td>237</td>
<td>245</td>
<td>8</td>
</tr>
<tr>
<td>angle OA11</td>
<td>8.7</td>
<td>1.52</td>
<td>315</td>
<td>310</td>
<td>-5</td>
</tr>
<tr>
<td>b/t = 50</td>
<td>OA8</td>
<td>9.63</td>
<td>281</td>
<td>282</td>
<td>1</td>
</tr>
<tr>
<td>5083-H111 OA9</td>
<td>2.1</td>
<td>2.26</td>
<td>257</td>
<td>266</td>
<td>9</td>
</tr>
<tr>
<td>OA10</td>
<td>6.51</td>
<td>3.04</td>
<td>241</td>
<td>251</td>
<td>10</td>
</tr>
</tbody>
</table>

Figure 4.7 gives a comparison between the critical temperature of the FEM models and of the tests. Each dot represents the critical temperature of the test and of the simulation of one test.
The light grey lines in the graph indicate +5%, 0% and -5% deviation between models and tests. All simulation results are within the limits set by these lines. The average difference in critical temperature between the models and the tests is 1 °C, the standard deviation is 6 °C.

The plots of the axial deformation as a function of the temperature in paragraph 0 show that the agreement between the displacements of models and tests is not always good. Especially in case of angles of alloy 6060-T66, the deformation of the simulation is often lower than that of the tests and in case of SHS with b/t = 44 of alloy 6060-T66, the deformation of the simulation is often higher than that of the tests. Reasons are:

- The deformations could not be determined accurately in the tests, due to the fact that thermal expansion of the specimen and the LVDTs causes deformations that are several orders of magnitude larger than the deformation caused by mechanical strain;
- Finite element simulations showed that a small gap between the supports and the specimen of e.g. 0.1 mm, results in an almost equal critical temperature but larger displacements compared to a simulation without a gap;
- Finite element simulations showed that a slightly non-uniform temperature along the length of the specimen results in an almost equal critical temperature but smaller displacements compared to a simulation with a uniform temperature.

If the deformed shapes of the specimens at the end of the tests are compared with that of the models at the end of the simulations, it appears that the agreement is worse as in case of the steady state tests. This is attributed to the fact that the simulation had to be ended, due to divergence, at axial displacements which are smaller than that of the tests. Figure 4.8 gives an example. The deformations of the model are scaled with a factor 30.
Figure 4.8 – Deformed specimen and model of test SHS T8-1 mm (alloy 6060-T66) (Deformation of model scaled with factor 30)
5 Sensitivity studies

The test set-up is not as ideal as applied in the simulations. Also, some parameters were difficult to measure in the tests. Almost all input parameters for the FE models are random variables (stochastic variables). This may explain some of the differences found between the tests and the simulations. This chapter gives the result of sensitivity studies on the parameters that were difficult to measure in the tests.

5.1 Selection of parameters that may influence the test results

A selection is made of possible measurement errors in the tests which may have influenced the test results. The errors can be divided into errors concerning the geometry of the specimens and the test set-up and errors concerning the material properties of the specimens.

The following possible geometric errors are identified:

1. The loaded edges of the specimens and the supports of the test set-up were not exactly parallel, especially in case of the steady-state tests (Figure 5.1 a). The gap in between was however difficult to measure, and therefore uncertain;
2. The thickness of each wall of each specimen was measured at six locations near the loaded edges. These six measurements were slightly different (maximum 1.5 %). The average thickness was modelled in the FE simulations. The wall thickness can be accurately measured, however the influence of an error on the ultimate resistance is relatively large.
3. The geometrical imperfections (non-straightness) of each wall of each specimen were measured. Especially the angle between the walls and the loaded edges was difficult to measure, and therefore uncertain;
4. The thickness of the welds in the square hollow sections of alloy 5083-H111 was not uniform along the length, and difficult to measure. These welds are thicker than the rest of the plates and may act as stiffeners. Such stiffeners may have an important influence on the ultimate buckling resistance;
5. The radii of the rounded corners, apparent in the folded sections of alloy 5083-H111 (both angles and square hollow sections), were difficult to measure. These radii may have an important influence on the buckling behaviour;
6. Possibly, due to imperfections in the test set-up, the load on the specimens was not introduced perpendicular to the supports, but at a certain angle (Figure 5.1 b).
7. In the simulations in chapters 4 and 5, it is assumed that there is full contact between the specimens and its supports, and that the loaded edges are clamped. In case of angles, it is possible that the axial tensile stress developing near the unloaded plate end became so large that the adhesive between the specimen and the supports can no longer maintain contact between the specimen and supports. It is then possible that the plate edges are no longer entirely restrained against rotation (Figure 5.2). Also in case of a gap between the supports and a specimen, the loaded edges of the specimen are free to rotate.
Figure 5.1 – Imperfections of the test set-up (imperfections are exaggerated)

a. Non-parallel supports and loaded edges of the specimen
b. Non-vertical load introduction

Figure 5.2 – Support conditions of the loaded edges of a specimen

The following possible material errors are recognized:

8. The stress-strain relationships assumed for the steady-state compression tests originated from the steady-state tensile tests. Due to differences in the test temperature, thermal exposure period and strain rate between the tensile tests and the compression tests, the stress-strain relationships assumed for the steady-state compression tests may not agree exactly with the real tests.

9. There was some scatter in the strain rates in the creep tensile tests carried out (background report [12]). The parameters of the Dorn Harmathy material model, used in the simulations of the transient state tests, are based on curve fitting of these creep tests with the least square method. Differences exist.

10. The modulus of elasticity was measured in bending tests. At high temperatures, the results were different from the data on similar alloys as given by Kaufman.

11. Welding may introduce large residual stresses in the square hollow sections of alloy 5083-H111. These stresses are measured with X-ray diffraction, elaborated in background report [14]. Measurements on residual stresses are always difficult and the results are uncertain;

12. The material properties of the weld itself were not determined in this research. Instead, the same properties are applied as for parent metal. The ultimate tensile strength of the weld metal is, according to EN 1999-1-1, approximately equal to that of the parent metal at room temperature (275 N/mm² and 240 N/mm², respectively). Information is not available on the strength of the weld metal at elevated temperature.
5.2 Influence of uncertain geometrical parameters on the ultimate resistance or critical temperature

The influence of the uncertain parameters on the ultimate resistance in case of steady state tests or on the critical temperature in case of transient state tests is determined with FEM. Results are given in the following paragraphs.

5.2.1 Gap between specimen and supports

The influence of non-parallel supports, causing a gap between the specimen and its supports in the set-up, is already given in the results of the simulations of the tests in chapters 3 and 4. It was shown that this error may have a significant influence on the ultimate resistance. The average values of the ratios between the ultimate resistance of a simulation with gap of 0.2 mm and a simulation without a gap \( \frac{F_{u,\text{gap}}}{F_u} \) for the steady state tests is given in Table 5.1. In case of the thick walled SHS of alloy 6060-T66 (b/t = 25), a gap of 0.2 mm influenced the deformation capacity, but not the ultimate resistance.

Table 5.1 – Influence of a gap on the ultimate resistance of simulations of steady-state tests

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>SHS t = 1 mm alloy 6060</th>
<th>angle alloy 6060</th>
<th>SHS alloy 5083</th>
<th>angle alloy 5083</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F_{u,\text{gap}} / F_u )</td>
<td>0.95</td>
<td>0.98</td>
<td>0.91</td>
<td>0.93</td>
</tr>
</tbody>
</table>

The influence of a gap of 0.5 mm on transient state tests on welded SHS of alloy 5083-H111 is 6 °C on average. For the other transient state tests, there was no or only a very small gap.

5.2.2 Wall thickness

The wall thickness was measured several times at the same or nearly the same spot. The difference of these measurements was 0.01 mm maximum. This is equal to 0.5 % (if t = 2 mm) or 1 % (if t = 1 mm) of the gross area of the cross section. The influence on the ultimate buckling resistance of a steady state situation was estimated using the design model of Winter [9]. Results are shown in Table 5.2.

Table 5.2 – Influence of a difference in wall thickness of 0.01 mm on the ultimate resistance of simulations of steady-state tests

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>SHS 2 mm alloy 6060</th>
<th>SHS 1 mm alloy 6060</th>
<th>angle 2 mm alloy 6060</th>
<th>SHS 1 mm alloy 5083</th>
<th>angle 1 mm alloy 5083</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F_{u,t+0.01\text{mm}} / F_u )</td>
<td>1.01</td>
<td>1.02</td>
<td>1.01</td>
<td>1.02</td>
<td>1.02</td>
</tr>
</tbody>
</table>

The influence on the ultimate resistance of this possible error in the thickness is negligible. The influence will also be negligible on the critical temperature of the steady state tests.
5.2.3 Geometrical imperfections

Distinction is made between the influence of the shape of the imperfections and maximum value of the imperfections on the ultimate buckling resistance and critical temperature.

An impression of the influence of the shape of the imperfections is obtained by comparing the ultimate resistance (critical temperature) of simulations with measured imperfections and simulations with mode imperfections in chapters 3 and 4.

The error in the measurement on the imperfection may be quite large, especially in case of the welded square hollow sections. Simulations have been carried out with mode imperfections, in which the maximum imperfection was twice as large as the measured maximum imperfection. This is an upper limit: it should be noted that the imperfection measurements were more accurate.

The results of the simulations are summarized in Table 5.3 for steady state tests and in Table 5.4 for transient state tests. The first row gives the influence of the shape of the imperfection, by comparing the results of the measured imperfections with those of the mode imperfections. The second row gives the influence of the size of the imperfection, by comparing the mode imperfection with the mode imperfections with double size.

The influence on the shape and the size of the imperfections on the ultimate resistance and critical temperatures of angles is negligible. This is also shown in the force-displacement plot of Figure 5.3: the steady state simulations with different imperfection sizes give equal values of the ultimate resistance.

In case of the thick walled SHS of alloy 6060-T66 (b/t = 25), the ultimate resistance and critical temperature are not influenced by shape and size of the imperfections, but the deformation capacity does depend on the imperfections (Figure 5.4).

Both the shape and size of the imperfections have a significant influence on the resistance and on thin walled SHS is significant (Figure 5.5). The influence is especially large on the SHS of alloy 5083, but this is attributed to the fact that the initial imperfections of these sections are so large.

Table 5.3 – Influence of geometrical imperfections on the ultimate resistance of simulations of steady-state tests (first row: influence of shape, second row: influence of size)

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>SHS 2 mm alloy 6060</th>
<th>SHS 1 mm alloy 6060</th>
<th>angle alloy 6060</th>
<th>SHS alloy 5083</th>
<th>angle alloy 5083</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{u,\text{mode}} / F_{u,\text{measured}}$</td>
<td>0.99</td>
<td>0.94</td>
<td>1.00</td>
<td>0.87</td>
<td>1)</td>
</tr>
<tr>
<td>$F_{u,\text{mode,Ax2}} / F_{u,\text{mode}}$</td>
<td>0.99</td>
<td>0.96</td>
<td>0.99</td>
<td>0.85</td>
<td>1.00</td>
</tr>
</tbody>
</table>

1) Imperfections were not measured
Table 5.4 – Influence of geometrical imperfections on the critical temperature of simulations of transient state tests (first row: influence of shape, second row: influence of size)

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>SHS 2 mm alloy 6060</th>
<th>SHS 1 mm alloy 6060</th>
<th>angle 6060</th>
<th>SHS alloy 5083</th>
<th>angle 5083</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\theta_{cr,mode} - \theta_{cr,measured})</td>
<td>20 ºC</td>
<td>10 ºC</td>
<td>3 ºC</td>
<td>28 ºC</td>
<td>1)</td>
</tr>
<tr>
<td>(\theta_{cr,mode,Ax2} - \theta_{cr,mode})</td>
<td>2)</td>
<td>6 ºC</td>
<td>1 ºC</td>
<td>15 ºC</td>
<td>0 ºC</td>
</tr>
</tbody>
</table>

1) Imperfections were not measured
2) Imperfections were only roughly measured

Figure 5.3 – Influence of imperfections on ultimate resistance of angles 5083-H111

Figure 5.4 – Influence of imperfections on ultimate resistance of SHS b/t=25, 6060-T66
5.2.4 Weld thickness

The square hollow sections of alloy 5083-H111 were manufactured by welding two folded u-sections. The weld is thicker than the rest of the plates, and may act as a stiffener. The width and thickness of the weld was difficult to measure and not uniform along the length. The variation in weld thickness is estimated as 0.2 mm. With an average width of 6 mm, this results in a variation of the area of the gross cross-section of only 1%. The weld may, however, act as a stiffener of the plate, so that a variation in weld thickness may have an important influence on the ultimate resistance.

In order to determine the influence of the thicker weld on local buckling, two analyses were carried out of the square hollow section as tested at room temperature. In the first analysis, the weld thickness was modelled equal to the plate thickness of 1.0 mm. In the second analysis, the thickness of the weld was modelled as 1.5 mm and a width of 6 mm. Figure 5.6 gives the force as a function of the axial displacement.
The ultimate buckling resistance of the section with a weld thickness of 1.5 mm is 6%. 3% is caused by the larger area of the cross-section. The contribution of the stiffening in on this higher ultimate buckling resistance is thus 3%.

For the estimated variation in weld thickness of 0.2 mm, the influence on the ultimate buckling resistance of steady state tests is approximately equal to 2%. The influence on the ultimate resistance of this possible error in the thickness is thus very small. The influence will also be negligible on the critical temperature of the steady state tests.

5.2.5 Radii of rounded corners

The SHS and angles of alloy 5083-H111 are manufactured by folding plate material. The corners of these sections are therefore rounded. The radius of the root is approximately 4.5 mm, and the ratio between root radius and wall width is approximately $r/b = 0.09$.

Models are made of the square hollow section and angles tested at room temperature, with straight corners between the plates and with rounded corners with $r/b = 0.1$. Results are given in Figure 5.7 and Figure 5.8 for the SHS and angle, respectively.

![Figure 5.7 – Influence of rounded corners on ultimate resistance of a SHS, 5083-H111](image)

![Figure 5.8 – Influence of rounded corners ultimate resistance of an angle, 5083-H111](image)
The ultimate buckling resistance of the SHS with a corner radius of 5 mm is 2%. In case of an angle, this difference is approximately 4%. This difference is mainly due to a difference in area of the sections. The influence of these radii on local buckling is small.

In case of the SHS, the length of the buckles changes as radii are introduced. With radii, the buckle dimension in axial direction of the specimen increases.

The results agree with a study on the influence of radii by Shigematsu et al [8]. In both researches, it appears that rounded corners with the dimensions as applied may have a small influence on the ultimate local buckling resistance, but that less buckles along the length develop as in case of a section without corner radii.

The error in the measurement of the corner radii is estimated at 0.5 mm. The influence of this error on the ultimate buckling resistance is negligible.

5.2.6 Non-vertical load introduction

It was noted that the axle of the actuator was not exactly vertical. Also the specimen was not exactly vertical, i.e. the supports of the specimens are not horizontal. An attempt to measure the angle between the axle and the specimen showed that the difference in angle between the axle and the specimen is less than 1 degree, however the measurement was difficult and possibly not reliable.

In order to determine the influence of a possible non-vertical load introduction, finite element analyses were made of a square hollow section of alloy 6060 T66, and angle of alloy 6060-T66 and an angle of alloy 5083-H111, all with material properties at 270 ºC. The load was applied under an angle of 2.9 degrees, so that the horizontal component is 5% of the vertical component of the load (Figure 5.9).

![Figure 5.9 – Schematised model of a non-parallel load introduction](image_url)

The results are compared with models with straight load introduction for SHS of alloy 6060-T66, angles of alloy 6060-T66 and angles of alloy 5083-H111 in Figure 5.10, Figure 5.11 and Figure 5.12. For angles, it appears to matter whether the load introduction has the same or opposite direction as the initial geometrical imperfection of the specimen. Both cases are presented.
Figure 5.10 – Influence of non-vertical load on ultimate resistance of a SHS, 6060-T66

Figure 5.11 – Influence of non-vertical load on ultimate resistance of an angle, 6060-T66

Figure 5.12 – Influence of non-vertical load on ultimate resistance of an angle, alloy 5083-H111
The load introduced under an angle of 3 degrees has no or a negligible influence on the ultimate resistance.

Only in case of the very slender angle of alloy 5083-H111, the shape of the load-displacement plot differs from that of a straight load introduction, but only if the horizontal component of the load direction is in opposite direction as the initial geometrical imperfection of the specimen.

5.2.7 Contact between specimens and support

Due to a possible gap between the specimen and its supports, or due to extreme out of plane deformations of angles, there may be only partial contact between a specimen and its supports, causing that the specimen edge is not fully clamped (Figure 5.2). This may affect the ultimate buckling resistance and critical temperature of especially angles.

Angles were simulated with clamped and with free edges. In case of simulations with free edges, contact elements were modelled which are able to carry compression forces but not tensile forces. The edges of the modelled specimen are not constrained against rotation along the entire length (i.e. also at the positions where there is still full contact between the specimen and its supports. This gives a lower limit of the actual strength.

Figure 5.13 and Figure 5.14 give the results of steady-state simulations with clamped edges and with free edges. The influence on the ultimate buckling resistance of steady state simulations of angles and on the critical temperature of transient state simulations of angles are summarised in Table 5.5.

The simulations of steady-state tests on angles in chapters 3 and 4, with clamped edges, gave in general a larger ultimate resistance than the test itself. Different boundary conditions may be an explanation for this difference.

Table 5.5 – Influence of support conditions of angles on the ultimate resistance of simulations of steady-state tests

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>angle 6060-T66</th>
<th>angle 5083-H111</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{u,free} / F_{u,clamped}$ steady state</td>
<td>0.91</td>
<td>0.95</td>
</tr>
<tr>
<td>$\theta_{c,free} - \theta_{c,clamped}$ transient state</td>
<td>-9 °C</td>
<td>-2 °C</td>
</tr>
</tbody>
</table>
5.3 Influence of uncertain physical parameters on the ultimate resistance or critical temperature

5.3.1 Strain rate

Especially at elevated temperature, the strain rate influences the material strength (background report [12]). The stress-strain relationships resulting from the steady state tensile tests were used in the simulation of the steady-state compression tests, but the strain rate was not always equal. Besides, the method to determine the displacements was not reliable, so that the measured strain rate in both the compression and the tensile tests is uncertain. In a sensitivity study on the influence of the strain rate on compression tests, the following steps are made:
- The error in strain rate between tensile and compression tests was estimated;
- The influence of this error in strain rate on the stress-strain relation was determined;
- Simulations of steady-state compression tests were made with these different strain rates.

An impression of the measuring error in the strain rate is obtained by comparing the initial stiffness measured for the tensile tests with the (accurate) measurements on the bending tests (background report [12] and Figure 5.15). The difference in stiffness determined with these two measurements was on average 17 % and the coefficient of variation (= standard deviation divided by average) was approximately 0.25. The difference in strain rate measured for the compression test and the tensile test at the same temperature was on average approximately 35 %, with a coefficient of variation of 0.25.

The influence on the ultimate resistance is evaluated for a difference in strain rate of 50 %.

The steady state tensile tests, carried out with various values of the strain rates, were simulated with the Dorn-Harmathy constitutive model in background report [12]. The simulations gave approximately equal values for the ultimate tensile strength. This indicates that the influence on the strength of a variation in strain rate may be obtained by simulating tensile tests with different strain rates (at an equal temperature). This was done with a FE model consisting of one truss element.

The results of simulations of compression tests with the different strength curves resulting from the different strain rates is given in Figure 5.16 for SHS of alloy 5083-H111 and in Figure 5.17 for angles of alloy 6060-T66.

The influence of the strain rate on the strength, and hence on the ultimate resistance of compressed sections, increases with increasing temperature. Figure 5.18 and Figure 5.19 show the influence of the error in strain rate on the resistance as a function of the temperature for sections of alloys 5083-H111 and 6060-T66, respectively.

The influence on the ultimate resistance of a difference in strain rate of 50 % is on average 3 % at 180 °C, 10 % at 280 °C and 20 % at 325 °C.

The difference in the relative ultimate resistance between the steady state tests and the simulations in chapters 3 and 4 increased in general for increasing temperature. The variation in strain rate may be an explanation for this difference.

Figure 5.15 – Initial stiffness determined in tensile tests (cross dots) and bending tests (square dots) a. Alloy 5083, b. Alloy 6060
Figure 5.16 – Influence of strain rate on ultimate resistance of a SHS, 5083-H111

Figure 5.17 – Influence of strain rate on ultimate resistance of an angle, 6060-T66

Figure 5.18 – Influence of strain rate on ultimate resistance as a function of temperature for steady-state simulations of sections of alloy 5083-H111
5.3.2 Parameters of the Dorn Harmathy model

The parameters in the Dorn Harmathy model are based on the results of creep tests. The parameters are determined with the least square method. The standard deviation between measured values and the model parameters A (linearly related to the Zener Holloman parameter, describing the influence of stress on the secondary creep strain rate) and D (linearly related to the primary creep strain) are given in Table 5.6, (under condition that all other parameters keep their original value).

### Table 5.6 – Values determined with least square and standard deviations for parameters of Dorn-Harmathy model

<table>
<thead>
<tr>
<th>Alloy</th>
<th>A</th>
<th>stdev A</th>
<th>D</th>
<th>stdev D</th>
</tr>
</thead>
<tbody>
<tr>
<td>6060-T66 (mat 06)</td>
<td>2.00E+14</td>
<td>4.90E+13</td>
<td>2.00E-18</td>
<td>8.17E-19</td>
</tr>
<tr>
<td>5083-H111</td>
<td>6.70E+10</td>
<td>1.50E+10</td>
<td>3.94E-10</td>
<td>2.48E-10</td>
</tr>
</tbody>
</table>

Simulations of transient state tests were carried out with the model parameters A and D, with (A + stdev) and (D + stdev) and with (A – stdev) and (D – stdev). The average value of the difference in critical temperature for simulations with these three sets of material parameters are summarised in Table 5.7. Despite the fact that the standard deviations of the parameters are large, the influence on the critical temperature is small. The influence of the variation in parameter D is larger than that of parameter A. The influence of the variation in parameters is larger for higher load levels.

### Table 5.7 – Influence of variation in the parameters of the Dorn Harmathy model on the critical temperature

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>SHS 2 mm alloy 6060</th>
<th>SHS 1 mm alloy 6060</th>
<th>angle alloy 6060</th>
<th>SHS alloy 5083</th>
<th>angle alloy 5083</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δθ_{cr,par A and D}</td>
<td>2 °C</td>
<td>5 °C</td>
<td>5 °C</td>
<td>4 °C</td>
<td>6 °C</td>
</tr>
</tbody>
</table>
5.3.3 Modulus of elasticity

The modulus of elasticity of alloys 6060-T66 and 5083-H111 was determined in bending tests. The values agreed reasonable with data in Kaufman on similar alloys, but especially at high temperatures of alloy 5083 there was a difference.

In the simulations in chapters 3 and 4, the average values of the modulus of elasticity determined with the bending tests and with Kaufman are applied. Figure 5.20 gives the force-displacement plot of angles of alloy 5083-H111, simulated with the modulus of elasticity resulting from the bending tests and the value according to Kaufman. The results are summarised in Table 5.8 for the simulations of steady state tests (first row) and transient state tests (second row).

![Figure 5.20 – Influence of modulus of elasticity on ultimate resistance of an angle, 5083-H111](image)

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>angle 5083</th>
<th>angle SHS 5083</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{u,\text{Kaufman}}/F_{u,\text{bending}}$ steady state</td>
<td>0.98</td>
<td>0.98</td>
</tr>
<tr>
<td>$\theta_{cr,\text{Kaufman}} - \theta_{cr,\text{bending}}$ transient state</td>
<td>-1.1 °C</td>
<td>-1.5 °C</td>
</tr>
</tbody>
</table>

5.3.4 Residual stresses

Residual stresses are very low in case of extruded sections (Mazzolani [5], although numbers are not given). The residual stresses of the extruded sections are not measured. The residual stresses in the welded SHS of alloy 5083-H111 are measured (background report [14]). Measurements on residual stresses are always difficult and there is a relatively large scatter in the results.
The maximum residual stresses close to the weld at room temperature are determined at 80 N/mm², while the 0.2 % proof stress is equal to approximately 150 N/mm².

The pattern of the residual stresses agrees with that given in Cañas et al [1] and Robertson [7], but the size of the maximum residual stresses is, according to these references, close to the 0.2 % proof stress. Simulations are made of tests at room temperature with maximum residual stresses equal to the 0.2 % proof stress, 0.5 times the 0.2 % proof stress and without residual stresses (Figure 5.21). The results of the simulations are given in Figure 5.22. It is shown that residual stresses have an important influence on the buckling resistance.

At elevated temperature, the value of the residual stress reduces due to the fact that the modulus of elasticity decreases and due to creep (relaxation). FE simulations were carried out to determine the residual stresses at elevated temperature, with initial residual stresses of 80 N/mm² at room temperature. Subsequently, simulations were carried out of SHS of alloy 5083 without residual stresses, and with the initial residual stresses of 80 N/mm² at room temperature.
In case of steady state tests, the influence of these residual stresses on the ultimate resistance is 9 % at room temperature, 4 % at 180 °C and (less than) 1 % at temperatures of 270 °C and higher.

In case of transient state tests, the influence of these residual stresses on the critical temperature is approximately 1 °C.

5.3.5 Material properties of the weld

It is known that the heat input by welding may influence the temper of the material near the weld (heat affected zone). In case of the non-heat treated alloy 5083 in soft temper (H111) the parent material is already (almost) annealed and the temper and strength of heat affected zone is (almost) equal to that of the parent material.

The stress-strain relationship of the weld metal itself was not measured. According to EN 1999-1-1, the representative value of the ultimate tensile strength at room temperature of the weld metal is approximately equal to that of the parent metal (240 and 270 N/mm², respectively). Therefore, in the simulations, the stress-strain relationship of the weld metal was taken equal to that of the stress-strain relationship of the parent metal. Also at elevated temperature, the strength of the weld metal was taken equal to that of the parent material. However, information is not available on the strength of the weld metal at elevated temperature, and this may differ from that of the parent material.

Steady state simulations are made of SHS of alloy 5083-H111 with strength of the weld metal equal to 0.7, 1.0 and 1.3 times the strength of the parent metal. Results are given in Figure 5.23.

Figure 5.23 – Influence of the strength of the weld metal on the ultimate buckling resistance of SHS, 5083-H111

The strength of the weld metal has only a marginal influence on the ultimate buckling resistance of the sections (1 or 2 %).

5.4 Evaluation of the results

A sensitivity study was carried out into the influence on the ultimate buckling resistance or critical temperature for a number of input parameters. Obviously, the variation in
ultimate resistance depends to a large extent on the variation assumed for the input parameters, such as the possible error in the measurement of the imperfections. These variations of the input parameters are sometimes difficult to estimate. Nevertheless, an impression is obtained of the important parameters for local buckling at elevated temperature.

The most important parameters and the influence of their variation on the ultimate buckling resistance or critical temperature are summarised in Table 5.9, roughly in sequence of important to less important.

Table 5.9 – Influence of variation of important parameters on local buckling

<table>
<thead>
<tr>
<th>Input parameter</th>
<th>Values input par.</th>
<th>Influence steady state</th>
<th>Influence transient state</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>angle</td>
<td>SHS</td>
<td>angle</td>
</tr>
<tr>
<td>Geom. imperfection</td>
<td>mode vs meas values x 2</td>
<td>0 %</td>
<td>6 - 13 %</td>
<td>2 ºC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0 %</td>
<td>4 - 15 %</td>
<td>1 ºC</td>
</tr>
<tr>
<td>Strain rate</td>
<td>1.5 x measured</td>
<td>0 - 20 %</td>
<td>0 - 20 %</td>
<td>6 ºC</td>
</tr>
<tr>
<td>Gap supp. &amp; spec.</td>
<td>0 - 0.2 mm</td>
<td>5 %</td>
<td>7 %</td>
<td>6 ºC</td>
</tr>
<tr>
<td></td>
<td>0 - 0.5 mm</td>
<td></td>
<td></td>
<td>0 ºC</td>
</tr>
<tr>
<td>Hinged or clamped supp</td>
<td></td>
<td>7 %</td>
<td>0 %</td>
<td>6 ºC</td>
</tr>
<tr>
<td>Dorn Harm. const. model</td>
<td>av ± st.dev. par. A and D</td>
<td></td>
<td></td>
<td>5 ºC</td>
</tr>
<tr>
<td>Residual stresses</td>
<td></td>
<td>1-9 %</td>
<td>1 ºC</td>
<td></td>
</tr>
</tbody>
</table>

1) For the influence of the shape of the imperfection, mode imperfections are compared with measured imperfections. For the influence of the size of imperfections, the sizes of the imperfections are multiplied with 0.5 and with 2. The results are given separately in the table;
2) For the SHS, two values are given. The first value is related to SHS of alloy 6060-T66. The second value is related to SHS of alloy 5083-H111, which has much larger geometrical imperfections;
3) The influence of the strain rate on the buckling resistance of steady state tests increases with increasing temperature. The influence is 3 % at 180 ºC, 10 % at 270 ºC and 20 % at 325 ºC. The influence is assumed to be 0 ºC at room temperature;
4) For the steady state tests, a gap was not visible between the supports and the specimens, but it could have occurred. Results are given for a gap between the supports and the specimen of 0,2 %;
5) For the transient state tests, a gap was either not present or very small, apart from the tests on SHS of alloy 5083-H111. The difference in temperature of 20 ºC is the result of these sections (SHS, alloy 5083-H111) for a gap of approximately 0.5 mm;
6) The influence of the support conditions of the angles of alloy 6060-T66, with b/t = 25 is larger than that of angles of alloy 5083-H111, with b/t = 50. Average values are given;
7) The residual stresses are only evaluated for the welded sections of alloy 5083-H111. The values and thus the influence of these residual stresses reduce at increasing temperature. At room temperature, the influence on the ultimate buckling resistance is 9 % and at 170 ºC or higher, the influence is only 1 %. The
residual stresses are small in case of extruded sections. These residual stresses were not evaluated.

Other parameters have a smaller impact on the simulation results, either because the influence on local buckling is small, or because the input value of the parameters is more certain. The following parameters have an influence of maximum 3% on the ultimate buckling resistance of steady state simulations or 3 °C on the critical temperature of transient state tests:
- The wall thickness of the specimen (for the studied range: 2% change in ultimate resistance for 1% change in wall thickness);
- The thickness of the weld;
- The radii of the rounded corners of the sections of alloy 5083-H111;
- A possible non-straight load introduction;
- The modulus of elasticity (for the studied range: 3% change in ultimate resistance for 15% change in modulus of elasticity);
- The material properties of the weld.

The influence on the ultimate buckling resistance of more of these possible errors acting simultaneously on a specimen was not determined.

It should be noted that the results of the sensitivity study are strictly valid for the tested specimens carried out. Real columns often have larger dimensions. The influence of a weld in the middle of a wall of a column, for example, is expected to have an even smaller influence in columns with larger dimensions than stated in this sensitivity study. However, if the weld is situated at the intersection of two walls of the column, the influence may be larger.

The differences found between the steady state and transient state tests and the simulations of these tests, in chapters 3 and 4, are of the same order of magnitude as the variation in result of the simulations due to the variation of uncertain input parameters. Hence the differences between tests and simulations are explainable.
6 Conclusions and recommendations

Steady state compression tests on mainly thin walled sections (subjected to local buckling) at room and at elevated temperature are simulated with FE models. The average value of the ratios between the ultimate buckling resistance of the model and of the test is 1.03 and 1.12 for square hollow sections (SHS) and angles, respectively. The standard deviation of these ratios is 0.08 and 0.12 for SHS and angles, respectively. From this, it is concluded that, using the developed FE models, it is possible to determine the ultimate resistance of sections subjected to local buckling at elevated temperature with reasonable accuracy.

Transient state compression tests on mainly thin walled sections are simulated with FE models. The average value and the standard deviation of the difference in critical temperature between simulations and tests was 0 °C and 6 °C, respectively. From this, it is concluded that, using the developed FE models with the Dorn-Harmathy material model, it is possible to accurately determine the critical temperature of fire exposed sections subjected to local buckling.

A proper evaluation of the differences in deformations is difficult, because the method used to measure the deformations at elevated temperature turned out to be inaccurate.

Some parameters used in the simulations are uncertain. The influence of these parameters on the ultimate buckling resistance or critical temperature was determined with FE models. Important parameters are the shape and size of the imperfections, a possible gap between the supports and the specimen, the restraint against rotation of the loaded edges of a specimen (in case of angles), the strain rate (in case of steady state conditions), the parameters of the Dorn Harmathy material model (in case of transient state conditions), and residual stresses (in case of a welded section at room temperature). The differences found in critical temperature and ultimate resistance between tests and simulations can be explained with the assumed uncertainties in input parameters of the FE models.
7 References


[7] Robertson, I., Strength loss in welded aluminium structures, University of Cambridge, 1985


A Simulation of steady state tests

This Annex gives the results of the simulations of all the steady-state compression tests carried out.

A.1 Square hollow sections of alloy 6060-T66 with b/t = 25

![Graph](image1)

Figure 7.1 – Results of SHS T4-2 at 20 ºC

![Graph](image2)

Figure 7.2 – Results of SHS 1-2,0 at 20 ºC
Figure 7.3 – Results of SHS 2-2.0 at 20 °C

Figure 7.4 – Result of SHS T5-2mm at 179 °C
Figure 7.5 – Result of test SHS T3-2mm at 265 °C

Figure 7.6 – Results of SHS T2-2mm at 290 °C

A.2 Square hollow sections of alloy 6060-T66 with b/t = 44 and b/t = 60
Figure 7.7 – Results of SHS T9-1 at 20 ºC

Figure 7.8 – Results of SHS 1-0,8 at 20 ºC
Figure 7.9 – Results of SHS 2-0.8 at 20 ºC

Figure 7.10 – Results of SHS T4-1mm at 179 ºC
Figure 7.11 – Results of SHS T2-1mm at 268 ºC

Figure 7.12 – Results of SHS T7-1mm at 290 ºC
A.3 Angle of alloy 6060-T66 with b/t = 25
Figure 7.15 – Results of angle T11 at 181 °C

Figure 7.16 – Results of angle T4 at 267 °C
A.4 Square hollow section of alloy 5083-H111 with b/t = 50

Figure 7.18 – Result of SHS O6 at 20 ºC
Figure 7.19 – Results of SHS O9 at 178 °C

Figure 7.20 – Results of SHS O4 at 267 °C
Figure 7.21 – Results of SHS O3 at 323 °C

Figure 7.22 – Results of SHS O5 at 345 °C (stress-strain relationship uncertain)
A.5 Angle of alloy 5083-H111 with b/t = 50

Figure 7.23 – Result of angle O3 at 20 °C

Figure 7.24 – Results of angle O4 at 167 °C
Figure 7.25 – Results of angle O5 at 270 °C

Figure 7.26 – Results of angle O6 at 325 °C
Figure 7.27 – Results of angle O7 at 339 °C (stress-strain relationship uncertain)
B Simulation of transient state tests

B.1 Results on specimens of type SHS – b/t = 25 – alloy 6060-T66

The imperfections were only roughly measured, resulting in an indication of the maximum value of the imperfection, but no information on the shape of the imperfection. The simulations are carried out with imperfections shaped according to the first Euler buckling mode, with a maximum imperfection equal to the maximum measured imperfection (FEM mode).

Figure 7.28 – Result of test 3-20 with a load of 35,8 kN (45%) and a heating rate of 7,8 ºC / min (approximately 30 minutes)

Figure 7.29 – Result of test 4-20 with a load of 35,8 kN (45%) and a heating rate of 7,9 ºC / min (approximately 30 minutes)
Figure 7.30 – Result of test 5-20 with a load of 35.8 kN (45%) and a heating rate of 2.2 ºC / min (approximately 120 minutes)

Figure 7.31 – Result of test 6-20 with a load of 35.8 kN (45%) and a heating rate of 2.2 ºC / min (approximately 120 minutes)

B.2 Results on specimens of type SHS – b/t = 44 – alloy 6060-T66

For the tests on SHS of alloy 6060-T66 with b/t = 44, the result of the simulation with material parameters 2005 was almost equal to that of the simulation with material parameters 2006. In the figures, results are given of the tests with material 2006.

The geometrical imperfections of the walls of the specimens were measured accurately before the test was carried out. Simulations are made with these measured imperfections (FEM measured) and with imperfections shaped according to the first Euler buckling mode and a maximum imperfection equal to the maximum measured imperfection value (FEM mode). Loads, heating rates and geometry were applied as measured.
Figure 7.32 – Result of test T3-1 with a load of 8.02 kN (30 %), a heating rate of 8.6 °C / min (approximately 30 minutes) and a critical temperature of 340 °C

Figure 7.33 – Result of test T8-1 with a load of 12.08 kN (45 %), a heating rate of 7.8 °C / min (approximately 30 minutes) and a critical temperature of 308 °C

Figure 7.34 – Result of test T11-1 with a load of 12.07 kN (45 %), a heating rate of 8.1 °C / min (approximately 30 minutes) and a critical temperature of 308 °C
Figure 7.35 – Result of test T12-1 with a load of 12.07 kN (45 %), a heating rate of 7.4 °C / min (approximately 30 minutes) and a critical temperature of 300 °C

Figure 7.36 – Result of test T10-1 with a load of 12.08 kN (45 %), a heating rate of 2.9 °C / min (approximately 100 minutes) and a critical temperature of 298 °C

Figure 7.37 – Result of test T6-1 with a load of 17.43 kN (65 %), a heating rate of 6.6 °C / min (approximately 30 minutes) and a critical temperature of 239 °C
B.3 Results on specimens of type SHS – b/t = 60 – alloy 6060-T66

For the tests on SHS of alloy 6060-T66 with b/t = 60, the result of the simulation with material parameters 2005 was again almost equal to that of the simulation with material parameters 2006. In the figures, results are given of the tests with material 2006.

The imperfections were only roughly measured, resulting in an indication of the maximum value of the imperfection, but no information on the shape of the imperfection. The simulations are carried out with imperfections shaped according to the first Euler buckling mode, with a maximum imperfection equal to the maximum measured imperfection (FEM mode). Loads, heating rates and geometry were applied as measured.

![Graph](image1)

Figure 7.38 – Result of test 3-08 with a load of 5.4 kN (45%), a heating rate of 9.8 °C / min (approximately 30 minutes) and a critical temperature of 306 °C

![Graph](image2)

Figure 7.39 – Result of test 4-08 with a load of 5.4 kN (45%), a heating rate of 9.7 °C / min (approximately 30 minutes) and a critical temperature of 305 °C
Results on specimens of type angle – b/t = 25 – alloy 6060-T66

For the tests on angles of alloy 6060-T66 with b/t = 44, the result of the simulation with material parameters 2005 was again almost equal to that of the simulation with material parameters 2006. In the figures, results are given of the tests with material 2006.

The geometrical imperfections of the walls of the specimens were measured accurately before the test was carried out. Simulations are made with these measured imperfections (FEM measured) and with imperfections shaped according to the first Euler buckling mode and a maximum imperfection equal to the maximum measured imperfection value (FEM mode). Loads, heating rates and geometry were applied as measured.
Figure 7.42 – Result of test TA12 with a load of 5.96 kN (30 %), a heating rate of 7.8 °C / min (approximately 30 minutes) and a critical temperature of 336 °C

Figure 7.43 – Result of test TA1 with a load of 9.04 kN (45 %), a heating rate of 6.7 °C / min (approximately 30 minutes) and a critical temperature of 290 °C

Figure 7.44 – Result of test TA2 with a load of 9.04 kN (45 %), a heating rate of 6.67 °C / min (approximately 30 minutes) and a critical temperature of 289 °C
Figure 7.45 – Result of test TA13 with a load of 9.06 kN (45 %), a heating rate of 2.9 ºC / min (approximately 100 minutes) and a critical temperature of 282 ºC

Figure 7.46 – Result of test TA10 with a load of 11.94 kN (60 %), a heating rate of 6.5 ºC / min (approximately 30 minutes) and a critical temperature of 254 ºC

B.5 Results on specimens of type SHS – b/t = 50 – alloy 5083-H111

The edges of the welded SHS of alloy 5083-H111 were not parallel in all cases, resulting in a gap between the specimen and its supports. The size of the gap was difficult to measure. Simulations are therefore carried out with a gap of 0.5 mm and without a gap.

The geometrical imperfections of the walls of the specimens were measured accurately before the test was carried out. Simulations are made with these measured imperfections (FEM measured and FEM gap measured). For the specimen without a gap, simulations were also made with imperfections shaped according to the first Euler buckling mode and a maximum imperfection equal to the maximum measured imperfection value (FEM mode). Loads, heating rates and geometry were applied as measured.
Figure 7.47 – Result of test O7 with a load of 5.96 kN (30 %), a heating rate of 7.4 °C / min (approximately 30 minutes) and a critical temperature of 300 °C

Figure 7.48 – Result of test O12 with a load of 8.86 kN (45 %), a heating rate of 7.0 °C / min (approximately 30 minutes) and a critical temperature of 249 °C

Figure 7.49 – Result of test O10 with a load of 8.89 kN (45 %), a heating rate of 2.4 °C / min (approximately 100 minutes) and a critical temperature of 255 °C
Figure 7.50 – Result of test O11 with a load of 8.85 kN (45 %), a heating rate of 2.4 °C / min (approximately 100 minutes) and a critical temperature of 255 °C

Figure 7.51 – Result of test O8 with a load of 11.84 kN (60 %), a heating rate of 6.6 °C / min (approximately 30 minutes) and a critical temperature of 237 °C

B.6 Results on specimens of type angle – b/t = 50 – alloy 5083-H111

The imperfections of these specimens could not be measured (see background report [11]). Simulations are therefore carried out with mode imperfections, with a maximum value of the imperfections equal to the average value of the maximum imperfections of the other angle test series, i.e. angles of alloy 6060-T66 with a wall thickness of 2 mm.
Figure 7.52 – Result of test OA11 with a load of 1.52 kN (30 %), a heating rate of 8.7 °C / min (approximately 30 minutes) and a critical temperature of 315 °C

Figure 7.53 – Result of test OA8 with a load of 2.25 kN (45 %), a heating rate of 9.63 °C / min (approximately 30 minutes) and a critical temperature of 281 °C
Figure 7.54 – Result of test OA9 with a load of 2.26 kN (45 %), a heating rate of 2.10 °C / min (approximately 110 minutes) and a critical temperature of 257 °C.

Figure 7.55 – Result of test OA10 with a load of 3.04 kN (60 %), a heating rate of 6.5 °C / min (approximately 30 minutes) and a critical temperature of 241 °C.
C Model with solid elements

Models were made of a SHS in DIANA vs 9.1. The models consist of solid elements with 20 nodes (element type CHX60) and a 2 x 2 x 2 integration scheme.

Contrary to shell elements, the integration points of solid elements are not at the surface of the element. This has some influence in case the elements are loaded in bending (Figure C 1):

- If an element is loaded in bending, the stress in the ultimate fibre may be larger than the yield stress in the solid element. This causes that the buckling resistance is overestimated with solid elements.
- The stress division in a solid element in bending, with two integration points, is elastic, while in a shell element with several integration points through thickness, a plastic stress division can be obtained. This causes that the buckling resistance is underestimated with solid elements.

In order to obtain a proper modelling with solid elements, several elements may be required through thickness.

A model was made of a SHS with plate width \( b = 50 \) mm and wall thickness \( t = 1 \) mm \( (A = 196 \text{ mm}^2, \frac{b}{t} = 50) \).

The (elastic critical buckling load and) ultimate resistance of a model with two solid elements through thickness was only \((3.5 \% \) and\) 1.9 \% lower than that of a model with one element through thickness. It is concluded that a model with two solid elements through thickness is accurate enough.

The ultimate resistance and the load-displacement trajectory of a model consisting of two elements through thickness agrees well with that of a model consisting of shell elements (with 7 integration points through thickness), see Figure C 2.
Figure C 2 – Load-displacement trajectories of models of a SHS with b/t = 50 (models consisting of solid elements and models consisting of shell elements)
D Construction of stress-strain relationships for steady state compression tests

The stress-strain relationships are based on tensile tests and bending tests as described in the background report on mechanical properties [12]. The modulus of elasticity resulting from the bending tests was similar to the values based on tensile tests in Kaufman. Only in case of alloy 5083-H111 at temperatures above 300 °C, there was a significant difference in the modulus of elasticity between the two methods (approximately 10 %). In the construction of the stress-strain relationships, the average value of the modulus of elasticity resulting from the bending tests and from Kaufman was taken. The modulus of elasticity used is given with black dots in Figure D 5 and Figure D 6 for alloys 6060-T66 and 5083-H111, respectively. For intermediate temperatures, linear interpolation was applied, according to the black curve.

![Figure D 1 – Modulus of elasticity of alloy 6060-T66 (source: background report on mechanical properties [12])]()

![Figure D 2 – Modulus of elasticity of alloy 5083-H111 (source: background report on mechanical properties [12])]()
The strain gage measurements in the tensile tests carried out in the current research (report [12]) were not accurate enough to be used for the modulus of elasticity. However, since the strain gage measurement is still more reliable than the LVDT measurement, the strain gage measurement is used to determine plastic strains.

In the determination of the plastic strains, it is assumed that the elastic strains are measured incorrectly, but that plastic strains are measured correctly with the strain gages. There are various ways to interpret the data for the construction of the stress-strain relationship. Three possibilities are elaborated for the tensile test with the largest difference between strain gage measurement in the tensile test and modulus of elasticity in bending tests / Kaufman’s tests, Figure D 3:

1. When assuming that the strain gage measurement is incorrect only for small strains in the elastic range, while it is correct at larger strains, the stress-strain relationship with asterisks in Figure D 4 results (option 1). In this case, the proportional limit is equal to the crossing between E-modulus curve and the tensile test. This possibility only gives a result when the initial stiffness in the tensile test is larger than the modulus of elasticity according to bending tests and Kaufman’s tests;

2. When assuming that there is a fixed factor between the measured strains and the actual strains, the stress-strain relationship with open squares in Figure D 4 results (option 2). The measured strains are multiplied with a factor equal to the ratio of the E-modulus according to bending tests and Kaufman’s tests, and the initial stiffness measured in the tensile test (i.e. the ‘wrong’ E-modulus);

3. An intermediate curve results when assuming that the plastic strains are measured correctly, while the elastic strains are determined by dividing the stress by the E-modulus according to bending tests and Kaufman’s test. This option is indicated with closed circles in Figure D 4 (option 3).

Although in option 3 it is physically difficult to imagine how the strain gage produces these results, this option is used to construct the stress-strain relationships, because it gives intermediate values for the stress-strain relationships between the two extremes given by option 1 and 2. It is noted that the stress-strain relationships according to the three options are almost equal for most tensile tests carried out.

Figure D 3 – Tensile test and E-mod according to bending tests and Kaufman for 6060-T66 at 293 °C
At each temperature at which a tensile test is carried out, the stresses are determined at selected values of plastic strains. The resulting stress versus plastic strain diagrams are given in Figure D 5 and Figure D 6 for alloys 6060-T66 and 5083-H111, respectively.

For intermediate temperatures, linear interpolation between stresses at each of the fixed plastic strains was applied. Interpolation between plastic strains at several stress levels would possibly result in a different stress-strain relationship. However, due to the limited number of tensile tests carried out, there is not enough data to apply this method.
Figure D 6 – Stress versus plastic strain at various temperatures for alloy 5083-H111 (source: background report on mechanical properties [12])