Report no. 8
Local buckling of slender aluminium sections exposed to fire

Residual stresses in welded square hollow sections of alloy 5083-H111

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Summary

Residual stresses in a plate may influence the local buckling strength. It is well known that welding may cause significant residual stresses in aluminium (or steel). In order to be able to simulate compression tests on welded aluminium sections, it is necessary to know the values of the residual stresses in the sections.

X-ray measurements are carried out on a welded aluminium specimen in order to determine the residual stresses. The section was exposed to a heat treatment which was considered representative for fire exposure. The measurements were done before and after this heat treatment.

Before welding and before heat treatment, the residual stress at the surface of the plate was approximately 30 N/mm². These stresses are attributed to rolling.

After welding but before heat treatment, the maximum residual stress near the weld was determined at 80 N/mm² (average value over the thickness of the plate). Further away from the weld, the minimum residual stress was determined at -25 N/mm².

The specimen was subjected to a thermal treatment (heated to 260 °C in 38 min., then cooled down to room temperature in 3 minutes). The relaxation of residual stresses was simulated with the FEM.

The residual stresses after heating were reduced significantly after this heating process. The residual stresses at the end of the FEM simulation agreed reasonably with the measured residual stress.
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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.

Finite element models were developed to study local buckling of fire exposed aluminium alloys. In order to validate these finite element models, tests were carried out on specimens in compression at elevated temperature. A number of the specimens applied, were composed of plate material of alloy 5083-H111. Square hollow sections were obtained by folding and welding this plate material. It is expected that, especially due to welding, residual stresses are present in these sections.

Residual stresses may influence the local buckling behaviour of the sections. In order to use these sections for validation of finite element models, it is necessary to obtain information on the size and pattern of these residual stresses, in order to incorporate it into the finite element models.

This report gives the results of measurements to determine the residual stresses in the welded square hollow sections used in the validation tests. Measurements were carried out on the as received specimen and on the specimen after being subjected to a thermal treatment representative for fire exposure. The measurements are focussed on residual stresses introduced by welding.

The method applied to measure the residual stresses is based on the X-ray concept. The principles of this measuring method are elaborated in chapter 2. Chapter 3 gives the results of the measurements carried out. Chapter 4 gives the discussion of the test results and chapter 5 gives the results of finite element calculations. A small parameter study on the relaxation of residual stresses is given in chapter 6. Conclusions and recommendations are given in chapter 7.
2 Explanation of X-ray method for measurement of residual stresses

The X-ray method is used in this research to measure residual stresses. The principles of the method are elaborated in this chapter. The chapter is based on Van der Aa [1] and Cullity and Stock [2].

2.1 Diffraction basics

The atoms in a crystalline sample are arranged periodically on a lattice, with a distance $d_{hkl}$ between the lattice planes. In an X-ray set-up, a source transmits X-rays on the specimen with a specific wavelength $\lambda$. The incident X-rays are scattered by the lattice. Figure 2.1 indicates what might happen with the diffracted X-rays.

The diffracted X-rays are detected by a reflector. If the X-rays are constructive (in phase), a peak is detected by the reflector. The reflector does not detect a peak for destructive X-rays.

Whether the X-rays are constructive or destructive depends on the angle $\theta$ between the rays and the surface (Figure 2.2). The difference in path length between ray 1 and ray 2 is, in this figure, equal to $2d_{hkl} \sin \theta$. Only in case a natural number $n$ of wavelengths $\lambda$ exactly fits in this difference in path length, the diffracted X-rays are constructive. Otherwise, the diffracted X-rays are destructive. Hence, constructive X-rays occur when Bragg’s law is fulfilled:

$$n\lambda = 2d_{hkl} \sin \theta$$  \hspace{1cm} (2.1)

In which:

- $\theta$ = angle between the rays and the surface, also known as the diffraction angle
- $n$ = natural number

Bragg’s law allows to determine the distance $d_{hkl}$ by varying the angle $\theta$ and determining at what angles a peak exist in the diffraction pattern.

Figure 2.1 – Diffracted x-rays  a. Constructive rays  b. Example of destructive rays
Residual stresses in welded square hollow sections of alloy 5083-H111

2.2 Strain measurement in a stressed sample

Elastic strains are the result of changes in the interplanar spacing. If a sample is subjected to stresses, the interplanar spacing $d_n$ differs from the spacing $d_0$ of an unstressed specimen. The strain is calculated using equation 2.2.

$$
\varepsilon_{el} = \frac{d_n - d_0}{d_0}
$$

(2.2)

The lattice planes of the grains in a metal sample have various orientations in relation to the surface of the metal. Only the grains with lattice planes normal to the diffraction plane $N_p$ contribute to the detected reflection (Figure 2.3).

Figure 2.2 – Diffraction of X-rays on a set of lattice planes with interplanar spacing $d_{hkl}$ (after Van der Aa [1])

Figure 2.3 – Diffraction from a multi grained sample
Note that equation (2.2) gives the elastic strain, as elastic strain is responsible for a change in interplanar spacing. Plastic strain is the result of dislocation and atom movements, and is considered to not influence the interplanar spacing. Plastic strain is thus not detected with the X-ray method.

The interplanar spacing of a grain in a stressed sample depends on the size of the stress, the direction of the stress and the orientation of the grains. This allows for the detection of the strains.

Figure 2.4 gives an example. The sample is equal to that of Figure 2.3, but stressed. The interplanar spacing $d_n$ of grain 1, with an orientation parallel to the stress direction, decreases due to the stress, while the interplanar spacing of grain 2 increases due to the stress. Resultingly, in the stressed specimen, the diffraction angle $\theta_1$ of the constructive diffracted X-rays, with a normal to the diffraction plane $N_{p,1}$ coinciding with the normal to the sample surface $N_s$, differs from the diffraction angle $\theta_2$, measured at an angle $\psi$ between the normal to the diffraction plane $N_{p,2}$ and the normal to the sample surface $N_s$.

Figure 2.4 – Diffraction from a multi grained, stressed sample (grain distortion not displayed)

In case of an unstressed specimen, the measured constructive diffraction angle $\theta$ will be independent of the orientation $\psi$, while in case of a stressed specimen, the constructive diffraction angle $\theta$ is dependent of the orientation of $\psi$ (Figure 2.5). As the relations between $\theta$ and $d$ and between $d$ and $\varepsilon$ are known with equations 2.1 and 2.2, it is possible to determine the strain in the stressed specimen, depending on the variation of $\theta$ with $\psi$.

Figure 2.5 – Plane spacing diagram of variation of $d$ with $\psi$ (after Van der Aa [1])
2.3 Measurement of bi-axial stress state

In case of a bi-axial stress state, the strains in all directions can be derived from diffraction measurements in one plane, using the so-called \( \sin^2 \psi \) method. This method is explained below.

Consider a bi-axial stress state, as shown in Figure 2.6. The principal stresses are chosen such that \( \sigma_1 \) and \( \sigma_2 \) are parallel to the surface, while \( \sigma_3 = 0 \) is perpendicular to the surface. For elastic isotropic material the relation between the principal strains and stresses are:

\[
\varepsilon_1 = \frac{\sigma_1 - \nu \sigma_2}{E} \\
\varepsilon_2 = \frac{-\nu \sigma_1 + \sigma_2}{E} \\
\varepsilon_3 = \frac{-\nu (\sigma_1 + \sigma_2)}{E}
\]

(2.3)

Figure 2.6 – Definition of directions and angles (after Van der Aa [1])

Assume a stress vector \( \sigma_\phi \) that had an angle \( \phi \) with the principal stress vector \( \sigma \). Due to geometry:

\[
\sigma_\phi = \sigma_1 \cos^2 \phi + \sigma_2 \sin^2 \phi
\]

(2.4)

The strain in the direction characterized by the angle \( \phi \) and the diffraction angle \( \psi \) is:

\[
\varepsilon_{\phi,\psi} = \frac{d_{\phi,\psi} - d_0}{d_0} = -\frac{\nu}{E} (\sigma_1 + \sigma_2) + \frac{1+\nu}{E} \sigma_\phi \sin^2 \psi
\]

(2.5)

If the direction of \( \sigma_\phi \) is chosen along principal direction 1, equation 2.5 can be written as:

\[
\frac{d_{1,\psi} - d_0}{d_0} = -\frac{\nu}{E} (\sigma_1 + \sigma_2) + \frac{1+\nu}{E} \sigma_1 \sin^2 \psi
\]

(2.6)
Only the last part of the equation, and $d_{1\psi}$, depend on the angle $\psi$ (equation (2.7)). Thus, the slope of a plot of $d_{1\psi}$ as a function of $\sin^2 \psi$ gives the stress in principal direction 1, provided that $d_0$, $\nu$ and $E$ are known.

$$d_{1\psi} \sim d_0 \frac{1+\nu}{E} \sigma_1 \sin^2 \psi$$

Parameter $d_0$ can be measured at an unstressed specimen. If $\sigma_1$ is known, equation (2.6) can be used to determine $\sigma_2$.

An accurate determination of parameter $d_0$ is sometimes difficult. In such a case, using any of the measured values of $d_{1\psi}$ for $d_0$ still gives an accurate value for the stress in the measured direction ($\sigma_1$), since the variation in $d$ as a function of $\psi$ is very small (usually, $d_{1\psi}$ does not deviate more than 1% from $d_0$ for any value of $\psi$). However, in such a case the error introduced in the determination of $\sigma_2$ can be significant. Consequently, if $d_0$ is not accurately determined, the stress parallel to the measured plane defined by angle $\phi$ is still determined accurately, while the stress perpendicular to the measured plane is determined with less accuracy.

In the welded specimens, it is assumed that the principal directions are parallel and perpendicular to the weld direction.

The method is tested and used extensively by Van der Aa [1] in a research on residual stresses in welded steel and aluminium plates.
3 Tests

3.1 Set-up and specimens

The X-ray set-up is shown in Figure 3.1.

![Figure 3.1 – Set-up](image)

In order to determine $d_0$, two small samples were measured. The samples were flat plates with dimensions $35 \times 35 \times 1$ mm$^3$. The samples originated from the same rolled plate as from which the welded square hollow sections were made, however they were not welded.

The maximum depth of specimens in this set-up is 40 mm. The square hollow section to be measured has dimensions of the cross-section of $50 \times 50 \times 1$ mm$^3$. The section thus had to be cut in order to fit into the set-up (Figure 3.2). In paragraph 5.2, it is elaborated what the influence of cutting is on the residual stresses.

![Figure 3.2 – Cut specimen](image)
3.2 Example of elaboration of measurement

The elaboration of the measurement on one of the flat samples is given in this paragraph.

Figure 3.3 gives the diffraction intensity as a function of $2\theta$. Several peaks are detected, each peak related to a certain orientation of the diffraction pattern with the lattice planes. As an example, the diffraction peak at $2\theta \approx 93.6^\circ$ corresponds to an orientation in which a plane crosses a cube at two of the corner nodes and at 1/3 of the opposite plane, as indicated in Figure 3.4.

![Figure 3.3](image)

Figure 3.3 – diffraction intensity as a function of $2\theta$

![Figure 3.4](image)

Figure 3.4 – Orientation of diffraction plane for peak at $2\theta \approx 93.6^\circ$

The peak at $2\theta \approx 93.6^\circ$ is used in the evaluation of the measurements. The angle $2\theta$ at which this peak is detected will slightly shift with the angle $\psi$ between the normal to the diffraction plane and the normal to the surface, in case the specimen is stressed. Figure 3.5 gives an example of angle $2\theta$ at which the peak is measured for various angles $\psi$. 

![Figure 3.5](image)
Computer software is used to determine the position of $2\theta$ for each $\psi$, assuming a Gauss distribution of the reflection. Angle $\theta$ is used to determine lattice spacing $d$ with equation (1). For each measurement at angle $\psi$, the lattice spacing $d$ is plotted as a function of $\sin^2 \psi$ in Figure 3.6. Using the least square method, the red line gives the average relation between $d$ and $\sin^2 \psi$. This relation is used in equation (2.5) to determine the stress. Also the standard deviation can be determined.

**Figure 3.5 – Diffraction peaks 311 for various angles $\psi$**

**Figure 3.6 – lattice spacing $d$ as a function of $\sin^2 \psi$**
To determine the stress from the strain measurements, the modulus of elasticity and the coefficient of lateral contraction as measured in a tensile test at 20 °C are used (background report material properties [3]). The values applied on alloy 5083-H111 are: 

\[ E = 71000 \text{ N/mm}^2 \]
\[ \nu = 0.33 \]

The X-rays penetrate the specimen. The depth at which the X-rays are reflected varies (some X-rays even penetrate through the entire thickness and are not reflected). The average penetration depth is, according to the software accompanying the set-up, approximately 2 \( \mu \text{m} \). The specimen thickness is 1 mm. This means that the stresses are measured at the surface of the specimen.

### 3.3 Measurement results

This section gives the measurement results. A discussion of the results is given in chapter 4.

#### 3.3.1 Flat samples, before fire exposure

The stress in the two small samples, without welds, was determined parallel and perpendicular to the rolling direction at one position (in the middle of the plates). For one plate, the stresses were measured at both sides of the plate (up and down side). The stresses measured were not equal to zero. The measured values are indicated in Table 3.1.

<table>
<thead>
<tr>
<th>sample</th>
<th>position</th>
<th>stress [N/mm²]</th>
<th>standard dev. [N/mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>sample 1</td>
<td>parallel to rolling</td>
<td>-35</td>
<td>2.3</td>
</tr>
<tr>
<td>sample 2</td>
<td>parallel to rolling, side 1</td>
<td>-21.6</td>
<td>12.3</td>
</tr>
<tr>
<td>sample 2</td>
<td>parallel to rolling, side 2</td>
<td>-25</td>
<td>8.6</td>
</tr>
</tbody>
</table>

The average stress determined parallel to the rolling direction was -27.2 N/mm².

#### 3.3.2 Welded specimen, before fire exposure

The specimen was welded parallel to the rolling direction. Measurements were carried out at one cross-section in the middle of the specimen, along the dotted line in Figure 3.7. It was not possible to measure the bended edges (“side walls”) of the cut specimen.

Measurements were taken at various angles \( \psi \) in a plane perpendicular to the weld direction and in a plane parallel to the welding direction. For both measuring planes, the stresses perpendicular and parallel to the welding direction were determined, using the equations in paragraph 2.3.

To derive the stresses perpendicular to the welding direction, based on the parallel direction, the value of \( d_0 \) has to be known. This value was taken from the flat samples.

Figure 3.8 gives the stress in the direction parallel to the rolling direction (i.e. the longitudinal stress). Figure 3.9 gives the stress in the direction perpendicular to the rolling direction (i.e. the transverse stress). The standard deviation on each stress measurement is indicated in the figures.
Figure 3.7 – Measurement positions (along dotted line)

Figure 3.8 – Stress parallel to weld direction along measured line in the welded specimen before heat treatment
3.3.3 Specimens after fire exposure

The flat samples and welded specimen used for the measurements in paragraph 3.3.1 and 3.3.2 were exposed to a temperature course which was considered as representative for fire exposure of a protected aluminium member. The specimen was heated from room temperature to a temperature of 260 °C, with a constant heating rate of 6.3 °C/min (heating in 38 minutes). After this, the specimen was cooled down to room temperature by exposing it to ambient conditions (i.e. non active cooling).

After this heat treatment, X-ray measurements were carried out at the same positions as before the heat treatment. The flat samples were, after this heat treatment, almost free of stresses (average stress of -2 N/mm²). The stresses in the welded specimen parallel and perpendicular to the welding direction are given in Figure 3.10 and Figure 3.11, respectively.
Figure 3.10 – Stress parallel to weld direction along measured line in the welded specimen after heat treatment

Figure 3.11 – Stress perpendicular to weld direction along measured line in the welded specimen after heat treatment
4 Discussion of test results

4.1 Flat samples

The flat samples were not stress-free, although external loads were not applied on the specimens. It is possible that the residual stresses are caused by rolling. The penetration depth of the X-rays was 2 µm on average, while the specimen thickness was 1 mm. Figure 4.1 schematically shows the residual stress through thickness in a rolled plate. This pattern occurs both perpendicular as well as parallel to the rolling direction.

![Figure 4.1 – Schematic pattern of the residual stresses in a rolled plate (after Wolterink, [5])]'

The residual stress parallel to rolling was measured at approximately -25 to -30 N/mm² before heating and approximately equal for both sides of the plate. This thin plate is obtained after cold rolling. In a private discussion with Gitter (German expert in rolling of aluminium sheets and plates), it was concluded that these residual stresses can be well explained by the influence of rolling. As the plate is in equilibrium, the integral of the stress over the thickness has to be zero.

Due to relaxation, the residual stresses flow off during the heat treatment. The stresses after heating were almost zero.

4.2 Welded specimen, before heating

The welded specimen is composed of the same plate from which the flat samples were taken. This means that the residual stresses due to rolling, as measured in the flat samples, were also present in the material before welding. Due to the small plate thickness, the heat input during welding was relatively small and the period during which the specimen was subjected to high temperatures was short. It is therefore assumed that the residual stresses due to rolling, as measured in the flat samples, were also present after welding in the specimen. (In reality, the residual stress due to rolling close to the weld could have been reduced due to heat input by welding, but information on this is not available from the tests.)

The average value of the residual stress over the thickness of the plate is obtained by subtraction of the residual stress measured in the flat samples from the residual stress measured in the welded specimen. Figure 4.2 shows the resulting average residual stress parallel to the welding direction as a function of the distance from the weld.
Figure 4.2 – Average value over plate thickness of residual stress parallel to weld direction in the welded specimen before heat treatment

The residual stresses obtained in measurements parallel to the plotted stress direction (i.e. parallel to the weld) agree with the values obtained in measurements perpendicular to the welded direction. This indicates that the value for $d_0$ is determined correctly in the unstressed specimens.

The figure shows in general high tensile stresses near the weld and compression stresses in the rest of the plate. This is consistent with other researches on residual stresses in welded plates. There are, however, some differences:

- Near the corners of the plate (distances of $-22$ and $+22$ mm from weld centre), the stress derived from the perpendicular measurement is expected to be small, but the measurements give relatively high values. It is expected that this is due to the fact that the plates are bend in these corners. This causes residual stresses over the thickness of the plate near the corners of the plate. Besides, the fact that material is not flat gives problems to the measurement of angles $\theta$ and $\psi$.
- The maximum value of the residual stresses, near the weld, is usually approximately equal to the yield stress (e.g. Cañas et al [6]). In the current research, however, the maximum residual stress is approximately $65 - 70$ N/mm$^2$, while the 0.2% proof stress measured at 20 °C was equal to 150 N/mm$^2$.\(^1\)

A possible reason for this difference is that the width of the welded plate is limited. Due to this, the amount of material restraining the shrinkage of the material near the weld (with tensile residual stresses) is limited. As a result, the material near the weld is able to shrink more as in case of a wider welded plate, causing lower residual tensile stresses.

It is concluded that the differences with other researches can be explained.

A finite element simulation shows that the cut section is in equilibrium for a stress pattern near the weld according to Figure 4.2 (chapter 5).

---

\(^1\) Measured in a tensile test at 20 °C, on a specimen originating from the same plate as used for the welded specimens and flat samples (reference background report on material properties, [3])
4.3 Welded specimen, after heating

The residual stress in the flat samples after heating was almost equal to zero. This would mean that the residual stresses measured for the welded specimen after heat treatment do not have to be corrected for through thickness residual stresses due to rolling. The value for $d_0$ is determined from the heated flat samples.

If the residual stresses determined via measurement in transverse direction are compared with the residual stresses determined via measurement in longitudinal direction, it appears that the average level of the stresses of these two methods differs (Figure 3.10).

As explained in paragraph 2.3, the stresses determined parallel to the measuring plane (i.e. measurement in longitudinal direction) are relatively independent of the value for $d_0$, while the stresses determined perpendicular to the measuring plane (i.e. measurement in transverse direction) depend on the value for $d_0$. A possible explanation for the difference in average level of the stresses in the two directions is that the value for $d_0$ as based on the heated flat samples is not correct. In that case, the measurement in longitudinal direction is more reliable.

A different explanation for the difference is that the stress state is not bi-axial. However, considering the thin plate thickness of the specimen, the assumption of a bi-axial stress condition is plausible.

A second point of discussion of the measurements is that all stresses measured are negative. Equilibrium can then only be obtained if the stresses in the side plates of the sections, which are not measured, are positive. It is unlikely that relaxation due to the heat treatment causes such a residual stress pattern.

A sound explanation for this is not available. It could be that, due to the limited dimensions of the flat samples, residual stresses more easily flow off during the heat treatment, whereas in the real specimen, there is still a residual stress gradient through the plate thickness.

Especially the measurement of residual stresses after thermal treatment gives rise to discussion about the results. Besides, the stresses were only measured in one specimen in one plane perpendicular to the weld. The residual stress patterns may be inaccurate and not exactly representative for the entire section.

On the other hand, the measurements are only carried out to be able to simulate compression tests on these welded specimens. Although the residual stresses have some influence on the load bearing capacity of the compression tests, finite element simulations have shown that a considerable error in maximum and minimum values and the actual pattern results in only a marginal error on the calculation of the load bearing capacity (background report [4]).

Most important conclusion is that due to relaxation, the residual stresses in the specimens caused by welding reduce considerably when exposed to temperature courses as present in fire.
5 Finite element calculations on residual stresses

5.1 Description of FEM model

In paragraph 3.1, it is explained that the square hollow sections had to be cut in order to fit into the set-up. The influence of cutting on the residual stresses is determined with a finite element model in the program DIANA release 9.2. The description and results are given in this paragraph.

The total residual stress is composed of a contribution due to rolling and a contribution due to welding.

The residual stress due to rolling caused a stress of approximately $-30 \text{ N/mm}^2$ at the surface (paragraph 4.1). A parabolic stress pattern was assumed through thickness, in conformity with Wolterink [5]. In order to obtain equilibrium of stresses, the maximum residual stress in the middle of the plate is then approximately equal to $+15 \text{ N/mm}^2$.

![Schematic of residual stress pattern due to rolling](image)

The residual stress pattern due to welding is assumed according to the pattern in Figure 5.1, in conformity with e.g. [6]. The residual stress due to welding has to be in equilibrium. The values for the residual stress will be determined in paragraph 5.2.

![Schematic of residual stress pattern due to welding](image)

Figure 5.1 – Assumed pattern of residual stress in longitudinal direction along the cross-section

A finite element model was developed in which the residual stress patterns due to welding and due to rolling are applied. The model is composed of solid elements. Five elements through thickness were applied, so that an approximately parabolic residual stress pattern could be applied through thickness. The residual stresses due to rolling and due to welding are simply added to obtain the total residual stress applied in the model. As the residual stresses due to rolling and those due to welding are in
equilibrium, the summation is also in equilibrium. Table 5.1 and Figure 5.2 schematically show the residual stress in the model.

It is noted that the superposition of the residual stresses due to rolling and those due to welding may not be entirely correct. Heat input by welding causes recrystallisation at the weld and relaxation of residual stresses due to rolling close to the weld. However, due to the thin plate applied, it is expected that only the material very close to the weld is heated so severe that recrystallisation may have taken place, and the time the structure is exposed to elevated temperature by welding is so short that relaxation of residual stresses to a large extent is not plausible.

The residual stress at the surface of the plate should correspond to the measured values.

Table 5.1 – Model with residual stresses

<table>
<thead>
<tr>
<th>Residual stress due to rolling</th>
<th>Residual stress due to welding</th>
<th>Total residual stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plate width</td>
<td>+</td>
<td>Plate width</td>
</tr>
<tr>
<td>Plate thickness</td>
<td></td>
<td>= middle of the plate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>= where res. stress</td>
</tr>
<tr>
<td></td>
<td></td>
<td>due to rolling is</td>
</tr>
<tr>
<td></td>
<td></td>
<td>zero</td>
</tr>
<tr>
<td></td>
<td></td>
<td>= at plate surface</td>
</tr>
</tbody>
</table>

Figure 5.2 – Residual stress pattern in the front plate of the square hollow section
5.2 Influence of cutting

The finite element model consists of a model of the entire square hollow section. Subsequently, in a phased analysis, only the part of the model that remained after cutting was set as active, while the other part was set as inactive. The residual stresses changed from the model with the entire section to the model with only the cut part active.

- The residual stress due to rolling only changed at the cut edges. This is not important; the residual stresses are not measured at that position;
- The residual stresses due to welding changed in the entire section.

The residual stresses due to welding applied on the model of the entire section have to be such as to result in residual stresses in the cut section that correspond approximately to the measured residual stress pattern. This initial residual stress pattern was found by trial and error.

If the residual stresses due to welding in the entire section are according to Figure 5.3, the resulting residual stresses in the cut part are according to Figure 5.4. The total residual stress after cutting at the plate surface (i.e. the combined influence of rolling, welding and cutting) is then according to Figure 5.5. This figure shows that the total residual stress after cutting at the plate surface agrees with the measurements.

Note that the residual stress to be applied on the entire section in order to reduce to the measured stress depends on the assumed pattern of residual stresses (Figure 5.1). This pattern could not be checked.

However, the main conclusion drawn from the results is that the influence of cutting on the residual stresses is small. This conclusion holds also for slightly deviant initial residual stress patterns.

![Figure 5.3 –Residual stress pattern due to welding before cutting in the FEM model](image-url)
5.3 Simulation of residual stresses after heating

A material model for aluminium was developed, including the influence of creep, which is aimed to be used for fire design (background report on material properties, [3]). The material model was implemented in the finite element program DIANA release 9.2. Using this material model, the relaxation of residual stresses during the heat treatment was simulated. The remaining residual stresses are compared with the measured residual stresses after heating.
The finite element model of the cut section, including residual stresses according to Table 5.1, was subjected to the heating and cooling rates as applied in the test. The residual stresses at the end of the simulation, when the temperature is again equal to room temperature, are compared to measured data in Figure 5.6.

Considering the difficulty to measure these small residual stresses and the corresponding scatter in measurements, and considering the rough assumptions made in the input values of the residual stress patterns in the finite element model, it is concluded that the resulting residual stress at the end of the simulation agrees well with the test.

Figure 5.6 – Residual stress pattern after heating in the FEM model
6 Parameter study on relaxation of residual stresses at elevated temperature

With FEM models in which the constitutive model was applied, a small parameter study was carried out to relaxation of residual stresses.

The relaxation of the residual stress determined with a FEM model consisting of a single, completely restrained element, appears to be almost equal to the relaxation of the residual stress in the fem model of the entire, welded section in chapter 5. Therefore, the parameter study was carried out with a model consisting of a single, completely restrained element (Figure 6.1).

![Complete section](image)

![Single element](image)

Figure 6.1 – Parameter study based on a single element

Three stress levels were considered in the parameter study, equal to 143 N/mm² (equal to the 0.2 % proof stress of alloy 5083-H111 at room temperature), 82 N/mm² (equal to the maximum value of the residual stress in the square hollow section at room temperature, according to chapter 5) and 36 N/mm². These three simulations are carried out with a heating rate of 6 °C / min. Two additional simulations were carried out with different heating rates, being 3 °C / min and 12 °C / min, both with an initial stress of 82 N/mm², the cases are summarised in Table 6.1. Material properties of alloy 5083-H111 were considered.

<table>
<thead>
<tr>
<th>Stress Level (N/mm²)</th>
<th>12 °C / min</th>
<th>6 °C / min</th>
<th>3 °C / min</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>82</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>143</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 6.1 – Cases considered in the parameter study (combinations indicated with + are carried out)

The simulations indicate that the residual stresses reduce significantly during fire exposure, as indicated in Figure 6.2. As expected, high residual stresses result in a large relaxation. Figure 6.3 indicates that the heating rate has only a marginal influence on the relaxation of the residual stresses.
The relaxation of residual stresses at elevated temperature is partially caused by a reduction of the modulus of elasticity and partially caused by visco-elastic and/or visco-plastic material behaviour. To indicate which part of the relaxation is caused by the reduction of the modulus of elasticity, Figure 6.4 gives the relative value of the residual stress, i.e. the ratio between the residual stress at elevated temperature and the residual stress at room temperature, and the relative value of the modulus of elasticity. It is shown that the influence of visco-plastic behaviour on the relaxation of residual stresses is larger than the influence of the reduction of the modulus of elasticity at high temperatures (> 260 °C) and high residual stresses (> 80 N/mm²).

To obtain an indication of the importance of the residual stresses in fire, the residual stresses at elevated temperature have to be compared to the value of the 0.2 % proof stress at that temperature. Figure 6.5 gives the ratio between the residual stress and the 0.2 % proof stress at both at room temperature and at elevated temperature. It is shown that for high residual stresses at the start of the simulation, the ratio decreases as the temperature increases. For lower residual stresses, the ratio increases at moderately elevated temperatures and decreases at high elevated temperatures.
Figure 6.4 – Relative value of residual stress and relative value of the modulus of elasticity

Figure 6.5 – Ratio between residual stress and 0.2 % proof stress as a function of temperature
7 Conclusions and recommendations

X-ray measurements were carried out to determine the residual stresses due to welding and rolling in a square hollow section composed out of plate material of alloy 5083-H111. The residual stresses were measured both before and after exposure to a temperature course representative for fire exposure.

The following conclusions were drawn:
- The residual stress at the surface of the unwelded, rolled plate material with thickness of 1 mm was measured at approximately 30 N/mm². This residual stress is attributed to rolling;
- The residual stress in longitudinal direction close to the weld was a tensile stress while further away from the weld, a compression stress was determined. This pattern agrees with other researches on residual stresses in welded plates;
- The maximum residual tensile stress, before heating was approximately equal to 80 N/mm² (average value over thickness). The minimum residual compression stress was approximately equal to -25 N/mm². The value for the tensile stress is lower than found in other researches, where the maximum value is often close to the yield strength (125 N/mm² for the alloy considered). The low maximum stress could be caused by the fact that the welded plate has a relatively small width;
- Residual stresses relax significantly when an aluminium structure is exposed to fire;
- The residual stresses measured after the specimen was heated agreed reasonably with the residual stresses at the end of a FEM simulation of the heating process.
References


[3] Maljaars, J., Mechanical properties at elevated temperature, background report of PhD on Local buckling of slender aluminium sections exposed to fire

[4] Maljaars, J., FEM Simulations of tests on local buckling, background report of PhD on Local buckling of slender aluminium sections exposed to fire
