



Department of Structural Engineering
Faculty of Civil Engineering
Budapest University of Technology and Economics

Welding simulation and measurement of normal and high strength steel box sections

**A diplomawork submitted to the
Department of Structural Engineering of
Budapest University of Technology and Economics
for the degree of Master of Science - Specialization in Structures**

Diplomawork
(MSc-SP-T-023-22/23/1)

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Budapest
2022



DIPLOMAMUNKA FELADAT

Név:	Horváth András	Neptun kód:	CT1C30
Képzés:	Szerkezet-építőmérnök mesterszak (MSc)	Szemeszter:	2022/23/1
Specializáció:	Tartószerkezetek specializáció	Nyilvánt.sz.:	MSc-SP-T-023-22/23/1
Cím:	Welding simulation and measurement of normal and high strength steel box sections		

A feladat leírása:

The subject of the thesis is the welding simulation of box section steel beams. Effects of manufacturing of normal and high strength steel box sections are to be analysed using both measurements and numerical models. The aim is to determine shape and size of fusion zones and residual stresses due to welding. Differences between normal and high strength steels are need to be highlighted.

Tasks to be carried out:

1. Summary (30-40 rows, Times New Roman, 12 pt font size, including name of the candidate, title and registry number of the diploma, name of supervisors).
2. Literature review on (i) welding processes, (ii) measurement techniques and (iii) welding simulations.
3. Development of advanced numerical model for simulating thermal and mechanical behaviour during welding in order to predict temperature, displacement and stress fields due to manufacturing.
4. Validation of the developed numerical model based on measurements.
5. Numerical parametric study focusing on the determination of typical residual stress distributions in normal and high strength steel box sections.
6. Conclusions about measurements and numerical results.

A diploma diary has to be made during the diploma semester, which has to be attached to the thesis at the end of semester. The level and specifications of the tasks and additional data for the design of the structure are to be registered in the diary by the consultants.

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A feladat kiadásának időpontja: 2022.09.05

A feladat beadásának határideje: 2022.12.09

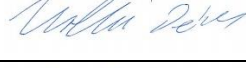
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Consultation diary

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Title of the diploma work: **Welding simulation and measurement of normal and high strength steel box sections**

#	Date	Topic of consultation	Signature of consultant
1	09/09/2020	Outline of the literature review, welding processes	
2	12/09/2022	Literature review of residual stress measurement techniques, effects of welding processes	
3	20/09/2022	Overview of the measurement programme	
4	28/09/2022	Processing the results of strain measurement methods	
5	03/10/2022	Geometrical parameters, dimensions of the welding pool	
6	11/10/2022	Consultation about deformed shape measurement	
7	17/10/2022	Overview of the structure of the welding simulation model, possibility of incorporating welding parameters into the model	
8	24/10/2022	Results of thermal analysis, material certifications	
9	02/11/2022	Result of mechanical analysis	
10	08/11/2022	Mesh convergence study, validation of the numerical model	
11	14/11/2022	Elements of the parametric study, symmetrical model	
12	21/11/2022	Result of thermal and mechanical analysis of parametrical study	
13	29/11/2022	Residual stress models	
14	07/12/2022	References and appendices	

The diploma work is ready to submission:

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Abstract

Nowadays, in structural engineering, there is a strong demand to speed up and ensure the right quality of the manufacturing processes. It is important to highlight that each step of the manufacturing process generates residual stresses in the workpiece, and this has an impact on the geometric imperfections that ultimately affect the lifetime and load bearing capacity of the product. In manufacturing of steel structures welding has become the leading joining process. Importance of welding has increased, because of the varied structural designs and the diversity of the used material characteristics. As the welding processes have developed, it has also become more and more relevant in on-site constructions, while it has been widely used in workshops for a long time.

It is very important to mention, welding inevitably induces residual stresses and deformations, which must be taken into consideration in the design, fabrication, and construction. Previous research emphasized the influence of residual stresses and geometric imperfections regarding the load bearing capacity of structural elements. To address these effects, standards give only approximations. In addition, application of simplified residual stress models is limited to typical cross-sectional layouts, steel grades and geometrical dimensions, while manufacturing specialities are not taken into consideration directly. These approximations and models can be improved by both experiments and numerical simulations.

According to the above-mentioned purposes, experimental investigation was made about residual stresses and distortions of nine welded specimens with box sections. Results of the experimental program were used to validate a welding simulation model, which was the basis of a parametric study. The parametric study focused on the influence of steel grade on residual stresses and the behaviour of welded hybrid box sections.

Összefoglaló

A szerkezetépítésben, napjainkban nagy igény mutatkozik a gyártási folyamatok felgyorsítására a megfelelő minőség megőrzése mellett. Mivel a gyártás folyamata maradó feszültséget és deformációkat okoz a munkadarabban, így végső soron a termék élettartamát és ellenállását is befolyásolja. Az acélszerkezetek gyártásában és kivitelezésben a hegesztés a világ vezető kötési eljárása, mely komoly hatást gyakorol a késztermékre. A hegesztés jelentősége a változatos szerkezeti kialakítások és a felhasznált anyagjellemzők sokfélesége miatt egyre növekszik. Az eljárások fejlődésével a hegesztés a helyszíni munkákban is kiemelten fontos szerepet nyert, míg a gyártásban már régóta, széles körben alkalmazzák.

Nagyon fontos megemlíteni, hogy a hegesztés elkerülhetetlenül maradó feszültségeket és deformációkat okoz a munkadarabban, amelyeket a tervezés, a gyártás és a kivitelezés során kezelni kell venni. A korábbi kutatások bebizonyították, hogy ezek a hatások kiemelten fontosak a szerkezeti elemek teherbírásának szempontjából. Ezen deformációk és maradó feszültségek kezelésére a szabványok csak közelítéseket adnak. Továbbá az egyszerűsített maradó feszültség modellek csupán tipikus keresztmetszeti kialakításokra, szilárdsági osztályokra és geometriai méretekre korlátozódnak, a gyártási sajátosságokat közvetlenül nem veszik figyelembe. Ezek a közelítések és sajátfeszültség modellek kísérleti úton és numerikus szimulációkkal pontosíthatók lennének.

A fent említett céloknak megfelelően kísérleti vizsgálatokat végeztünk kilenc darab hegesztett zárt szelvény próbatesten, mely mérések fókuszában a maradó alakváltozások és maradó feszültség mérési eljárások álltak. A kísérleti eredményeket, azok önálló értékelése mellett, egy hegesztésszimulációs modell validálására is felhasználtuk, amely modell segítségével paraméteres vizsgálatot végeztünk. A paraméteres vizsgálat célja a szilárdsági jellemzők maradó feszültségekre gyakorolt hatásának, illetve a hegesztett hibrid zárt szelvények sajátfeszültség eloszlásának vizsgálata volt.

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1 Introduction

Currently, there is a strong demand to speed up and ensure the right quality of the manufacturing processes in structural engineering. In the theme of the manufacturing, we should mention the plate cutting with knife, plasma cutting, flame cutting, rolling, bending, and welding, which are the most used manufacturing processes. Each of these processes generate residual stresses in the workpiece and it has an impact on geometric imperfections, which ultimately affect the quality of the weldment.

Nowadays, welding became the world leading joining process in manufacturing, because of the varied structural designs and the diversity of the used material characteristics. We can find diverse welding solutions to join different steel materials, in different positions, under different environmental conditions. As the welding processes have developed, it has also become more and more relevant in on-site constructions, while it has been widely used in workshops for a long time. This study generally focuses on arc welding, but it also mentions other welding processes. The arc welding technology is based on a welding arc, which is an electrical discharge between two electrodes. It ensures the right temperature to melt the base material and filler material, so there is no need for pressure during the welding process. Arc welding is a rather complex process, proof of this is that to understand this process it also requires special knowledge including thermal and fluid flow, electromagnetic, metallurgical, and mechanical phenomena.

Welding inevitably induces residual stresses and deformations, which must be taken into consideration in the design, fabrication, and construction. However, there is the possibility to use in-process control like local and global weld sequencing, variation of welding variables, control of welding consumables, precambering, prebending, transient thermal tensioning, heat sink welding and fixture design, etc. The other option to deal with residual stresses and distortions is the post-weld corrective methods, such as press straightening, flame straightening, post-weld heat treatment, laser shock peening, shot peening, hammer peening and high frequency mechanical impact treatment, etc. However, these techniques could be expensive, laborious, and time-consuming. In order to minimize the extent of corrective methods, virtual manufacturing (i.e., manufacturing simulations) could be used for optimization and development purposes as an economical solution, while the realistic structural behaviour could be analysed as well. The aforementioned control and corrective methods can be modelled, while the number of experiments and tests on actual prototypes could be reduced.

Previous research emphasized the influence of residual stresses and geometric imperfections regarding the load bearing capacity of structural elements. Standards give solely approximations on using (i) equivalent geometric imperfections or (ii) residual stress model with geometrical imperfections based on manufacturing tolerances, while the structural behaviour can be significantly different. On the other hand, application of simplified residual stress models is limited to typical cross-sectional layouts, steel grades and geometrical dimensions, while manufacturing specialities are not taken into consideration directly. These approximations and models can be improved by both experiments and numerical simulations. As a final aim, results of validated numerical models can be also used in the design of structures instead of applying standardised models. Reliability of welded structures in the civil engineering practice can be improved the used as more realistic structural behaviour and resistance can be determined using virtual tests. The current research investigates and evaluates the advantages of virtual manufacturing of welded box sections using normal and high strength steels.

2 Literature review

A comprehensive literature review is carried out related to welded box sections focusing on (i) typical section shapes and manufacturing techniques, (ii) common welding processes used in the manufacturing, (iii) residual stress measurement techniques found in the international literature, (iv) proposed residual stress models for engineering applications in the design of normal and high strength steel welded box sections and (v) previous results of welding simulations.

2.1 Box section shapes and manufacturing techniques

Welded box sections are widely used in engineering practice and in the realisation of structures. There are many possibilities for manufacturing welded box section, in addition to the variety of cross-sectional designs, this area features a wide range of weld types. This chapter intends to present some manufacturing techniques for different cross-sections. The thesis classifies cross-sections into four categories based on the design of constituent plates and profiles.

The first category consists of sections with only flat plates, some of whose designs are shown in **Fig. 1**. For cross-section 1, joints can be made typically with (i) single-V butt welds with broad root face, (ii) single V-butt weld or (iii) single-bevel butt weld, where the edge preparation of plates is different. Weld and joint types are denoted according to EN ISO 2553 [1]. Except for the weld seams, cross-section is doubly symmetrical. Cross-section 2 consists of flange plates overhanging the webs. This is a doubly symmetrical cross-section, but it may be important to note that these cross-sections can be made with different flange widths as single symmetrical cross-sections. At each corner point, fillet welds are used. Cross section 3 is made with corner joints and fillet welds. The cross-section is doubly symmetrical.

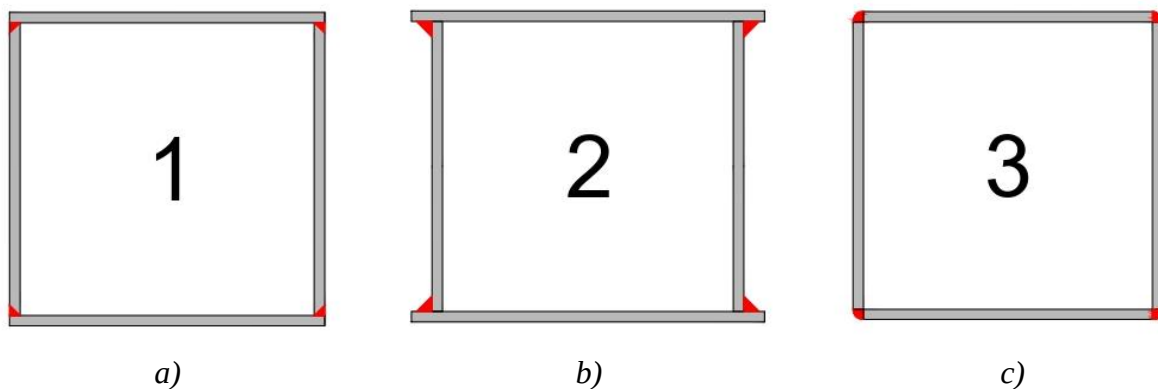


Fig. 1 - Cross-sections of box sections using flat plates

The second category of sections with only cold-formed plates includes two types of designs shown in **Fig. 2**. Cross-section 4 is made with two C sections and longitudinal (i) single-V butt welds with broad root face, (ii) or single V-butt welds, depending on the plate thickness. Cross-section 5 is manufactured using four L sections, which can also be joined with the aforementioned weld types. Considering the position of the welds, cross-section 5 is doubly symmetrical, while cross-section 4 is monosymmetrical.

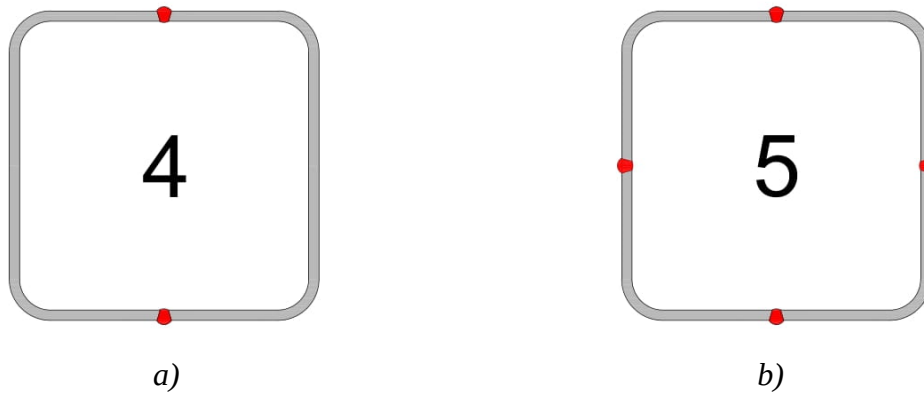


Fig. 2 - Cross-sections of box sections using cold-formed profiles

The third category includes box sections combining flat and cold-formed plates, summarized in **Fig. 3**. The difference between cross-sections 6 and 7 is due to flange plate width and the resulting weld type (butt welds and fillet welds, respectively). Welded box section with cross-section 8 is made with fillet welds and corner joints.

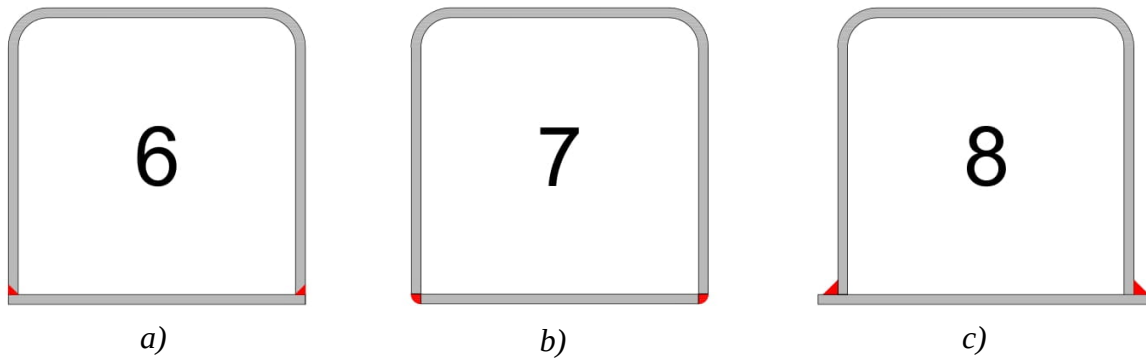


Fig. 3 - Cross-sections of box sections using flat and cold-formed plates

The last category, shown in **Fig. 4**, consists of cross-sections using only hot rolled sections. The singly symmetrical cross-section 9 is made by joining e.g., IPE, HEA or HEB sections. The assembled cross-section can be made with (i) single-V butt welds with broad root face, (ii) or single V-butt welds, depending on the thickness of constituent plates. Each of the listed weld types requires different edge preparation. Cross-section 10 is formed by welding two rolled U profiles. The resulting singly symmetrical cross-section is welded by (i) single-V butt welds with broad root face, (ii) or single V-butt welds. Cross-sections 11, 12 and 13 are all made using rolled angle sections. Cross-section 11 is made with single-V butt welds with broad root face in this design, cross-section 12 is made with fillet welds and corner joint. Cross-section 13 may have (i) single-V butt welds with broad root face, (ii) or single V-butt welds in the cross-section with different edge preparation, depending on the plate thickness. The introduced weld types may require permanent or temporary backing plates.

For each cross-sectional design, a distinction is made between continuous and intermittent welds, and tack welded cross-sections, while the effect of heavy and light welds must be mentioned also in the case of box sections. In general, light welds are single pass welds with plate thickness less than 5 mm, while heavy welds are multi-pass welds if plate thickness is greater or equal to 16 mm. The different weld types are shown in **Fig. 5**.

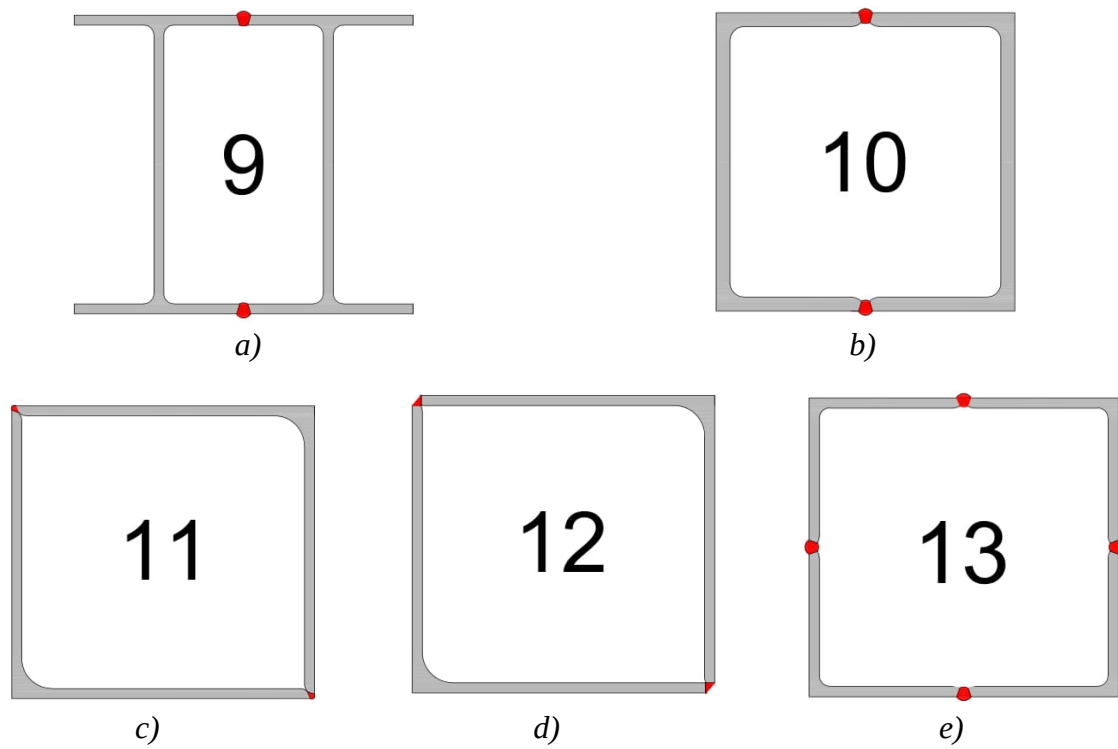


Fig. 4 - Cross-sections of box sections using hot rolled shapes

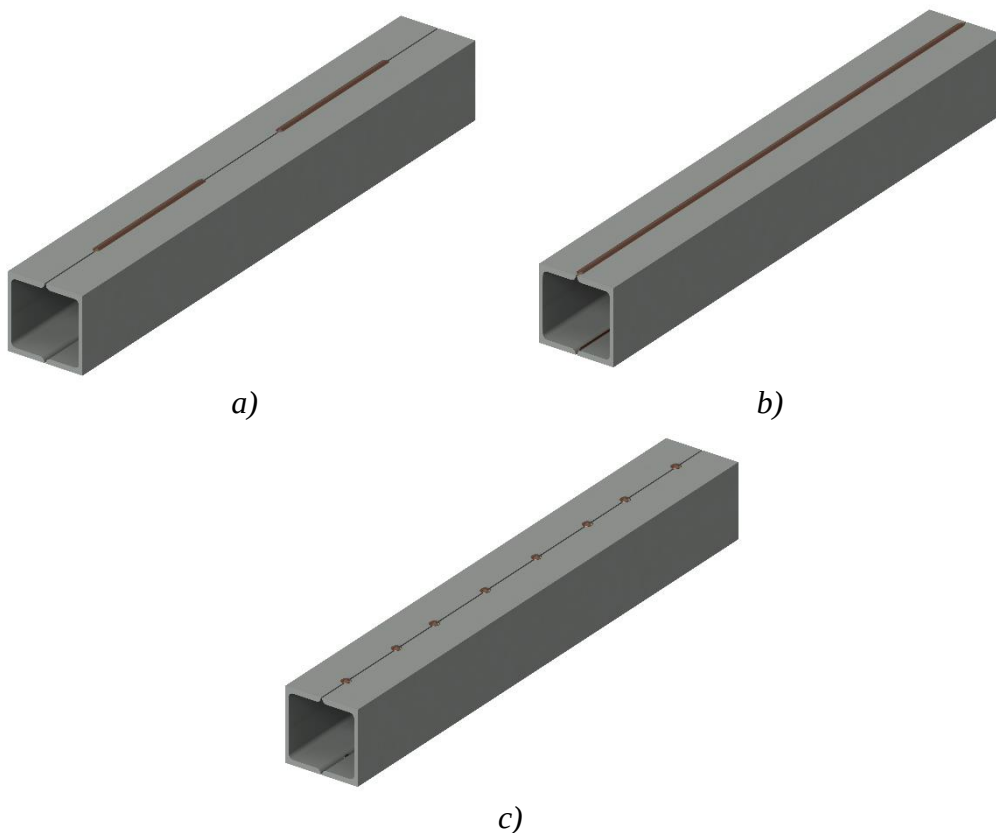


Fig. 5 - Different welding types: box section with a) intermittent, b) continuous, and c) tack welds

2.2 Welding processes

During the manufacturing process, residual stresses and deformations are inevitably generated in steel structures. The residual stress intensity appreciably depends on the manufacturing process and the geometry of the specimen. Cutting, different processing techniques and cold-forming result in completely different residual stress distributions and deformations in steel structures. Development of welding technologies and material quality has turned welding into the leading manufacturing process in creating joints. In addition, it is important to mention that different welding processes need different heat input resulting in distinct cooling parameters, which have a large impact on residual stresses. The most important welding processes used for manufacturing welded box sections are:

- manual metal arc (MMA) welding,
- tungsten inert gas (TIG) welding,
- metal inert gas and active gas (MIG/MAG) welding,
- submerged arc welding (SAW),
- electron beam welding,
- laser beam welding,
- and plasma arc welding.

Metal inert gas and active gas welding is presented in detail since (i) it is among the most commonly used welding processes in the industry and (ii) it is used in the production of workpieces presented in this study. The welding technology is based on a welding arc, which provides the temperature that melts the material. The welding arc is an electrical discharge between two electrodes. The welding current is conducted from the electrode to the workpiece through a heated and ionised gas, which is called plasma. At the end of the 19th century, it became possible to combine and store gases safely; in addition, sufficient electrical current could then be generated for arc welding. This has led to the rapid development of welding technology, including arc welding. A large number of subtypes and variants appeared and are still used in the construction industry today. Gas-shielded metal arc welding, its schematic drawings is shown in **Fig. 6**, includes two main types of processes. Shielding gas of metal inert gas (MIG) and metal active gas (MAG) welding are inert gases (e.g., argon) and active gases (e.g., carbon dioxide). The principle of MIG/MAG welding is the following:

- The welding arc is struck between the workpiece and the base material, the wire electrode is continually fed forward into the arc.
- The arc has electrical energy is passed to the wire through the contact tube in the welding torch.
- The gas nozzle, that surrounds the contact tube, supplies shielding gas, which protects the arc and the weld pool during welding.

The main advantages of MIG/MAG welding are the low heat input, which is particularly useful when welding thin plates. The technique has better productivity in welding thicker plates than many other techniques. In addition, it is applicable with all commonly used structural materials such as mild, low-alloy and stainless steel. The primary disadvantage of the MIG/MAG process is the complex welding equipment, which results in a less portable setup. In addition, MIG/MAG welding also has a limited application outdoors, similar to TIG, but this problem is manageable if we use flux-cored wire for welding. Gas-shielded metal arc welding during manufacturing is shown in **Fig. 7**.

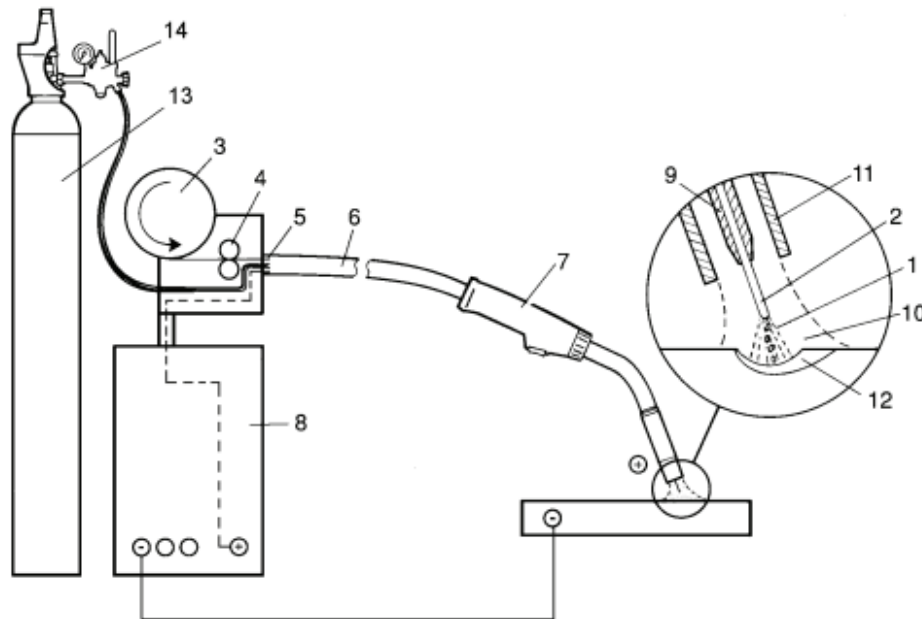


Fig. 6 - Schematic drawing of MIG/MAG welding process [2]



Fig. 7 - MIG/MAG welding during manufacturing [3]

MIG/MAG welding can be used with many types of wires. The wire is normally solid but can also be tubular, flux or metal powder filled cored wire. The two main MIG/MAG welding processes with cored wires are the MCAW (Metal-cored arc welding) and the FCAW (flux-cored arc welding). The metal powder-filled cored wires contain a powder that consists mainly of iron and alloying elements. Adding metal powder produces a slag-free cored wire, which induces higher productivity. The flux cored wires have two basic types, either a rutile or basic filling. This wire produces slag which supports the weld metal and causes a so-called fast freezing weld. As a summary, flux cored wire allows special welding positions with high efficiency. This welding technique requires shielding gas; however, it has a special version called self-shielded flux cored wire which does not need additional shielded gas and it is mainly used for site welding. The main welding parameters for MIG/MAG welding are the following: voltage, wire diameter, wire feed speed and current, contact-tip-to-work distance, travel speed, shielding gas, gas flow rate, and relative position of the welding torch and the joint.

Other types of welding processes are shown in **Fig. 11**, including three arc welding processes and a laser welding process. During manual metal arc welding electrode rods are used consisting of a wire core with an external coating. During the welding process the striking an arc between the electrode and the workpiece, the heat of the arc melts the electrode coating and the wire core. The melted electrode coating forms protective slag on the weld. After welding the slag on top of the joint needs to be removed. The outer coating may contain a mixture of materials such as chemicals, minerals and iron powder that impart different properties to the weld. The schematic drawing of the MMA welding process is shown in **Fig. 8**. Manual metal arc welding can also be used outdoors, so it is particularly suitable for jobs such as on-site installation of structures. The main disadvantages are that the arc time factor is relatively low, because of the time required for chipping away slag and changing the electrodes. **Fig. 11a** shows the MMA welding process during manufacturing.

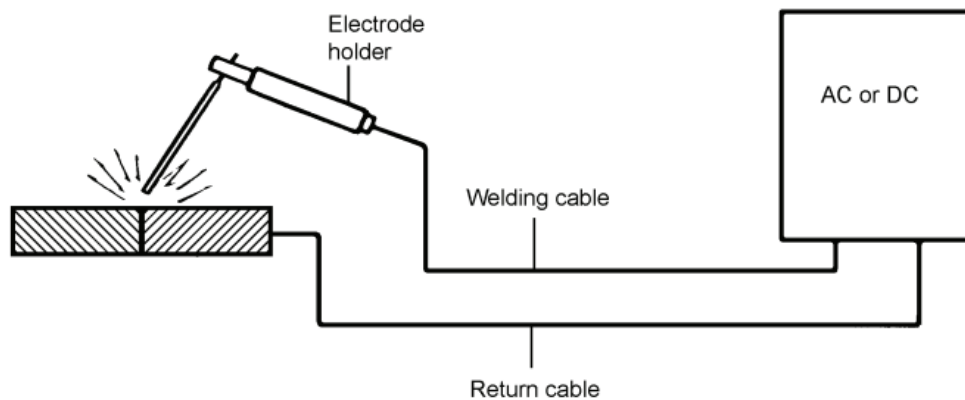


Fig. 8 - Schematic drawing of manual metal arc welding process [2]

Tungsten inert gas (TIG) welding uses the heat generated by an electric arc struck between a non-consumable tungsten electrode and the base material to produce the weld pool. **Fig. 9** shows the schematic drawing of the welding process. The weld pool and the electrode are protected by an inert gas, during the welding process. In general, argon is used as shielding gas for TIG welding, which is used for low-alloyed and stainless steels. If it is necessary to increase the heat input, helium or hydrogen can be added to the shielding gas. When we should make quality welds with TIG, it is also very common to use a root gas in order to protect the root side of the weld against oxidation. It can be used with filler material or without it in case of autogenous welding, which is fed by hand or automatically. **Fig. 11b** shows TIG welding process during manufacturing. The main advantage of the TIG process is the stable arc. In addition, we can control the welding process very well. TIG welding is best suited to thin materials, and one of the most important applications are welding of stainless steel and aluminium. A limitation of the TIG method compared to gas welding is that the welding equipment is more complex and less portable. The method has also limited application outdoors, as the shielding gas must be protected from draughts, welding tent must be applied.

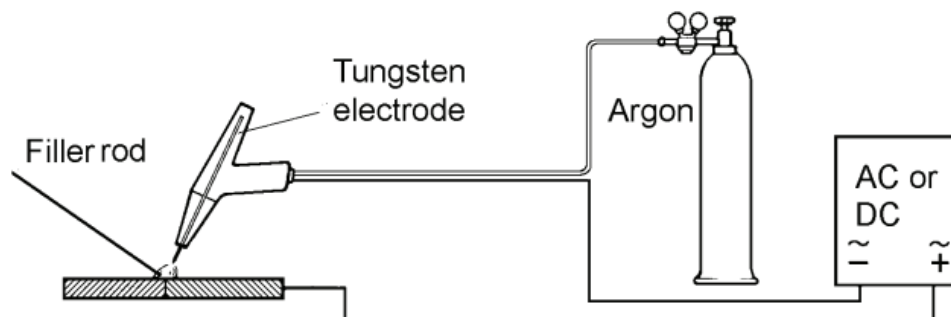


Fig. 9 - Schematic drawing of tungsten inert gas welding [2]

Submerged arc welding, which schematic drawing is shown in **Fig. 10**, is a highly productive welding process used primarily for welding large thicknesses of plate. The basis of the procedure is that the arc or arcs are struck and burn beneath a layer of flux, which is supplied to the welding head. The flux closest to the arc melts and forms slag on the surface of the weld; thus, protecting the molten metal from reacting with gas in the air. The SAW has high weld quality with effective welding time. It can also be claimed that the technique provides deep penetration, which allows the quantity of filler material to be reduced. As it was stated before, the technique is mainly used for welding thick materials. The disadvantages of the welding technique is that there is still the need to handle the flux. In addition, the welding process partially limits the possible welding positions, which means that the method is mainly used for butt welds and fillet welds in the horizontal position. The welding parameters of SAW are the following: welding speed, polarity, arc voltage, arc current, the size and shape of the welding wire, the filler wire angle, the number of welding wires, contact-tip-to-work distance, the use of additional filler wire or additive metal powder, the type of flux. **Fig. 11c** shows SAW welding process during manufacturing.

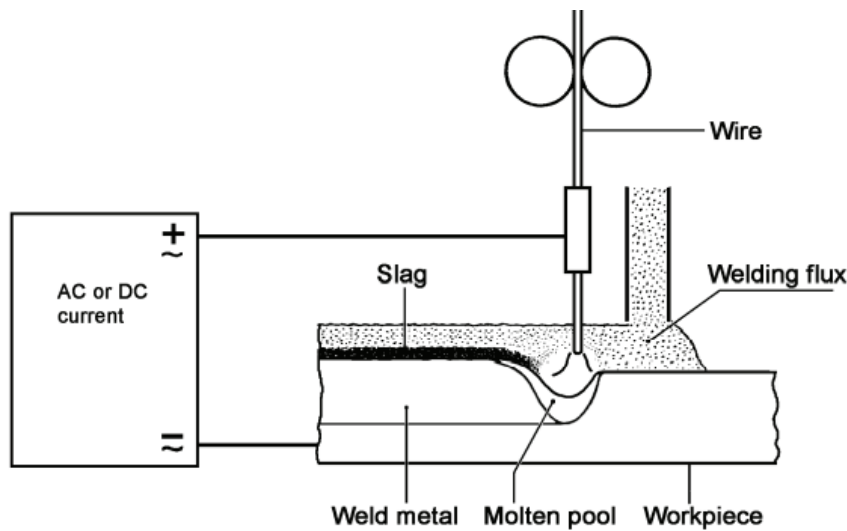


Fig. 10 - Schematic drawing of SAW [2]

There are some less commonly used welding techniques, one of the less commonly used technique is laser welding. **Fig. 11d** shows the process of laser welding in fabrication. During the welding process, laser beam is focused a point only a few tenths of a mm in diameter. As soon as the beam has moved on, the metal solidifies quickly because of the small heat affected zone. Shielding gas could be used to protect the welding pool and the welding machine lens from spatter and vapour. In addition, fillers can also be used in laser hybrid welding.

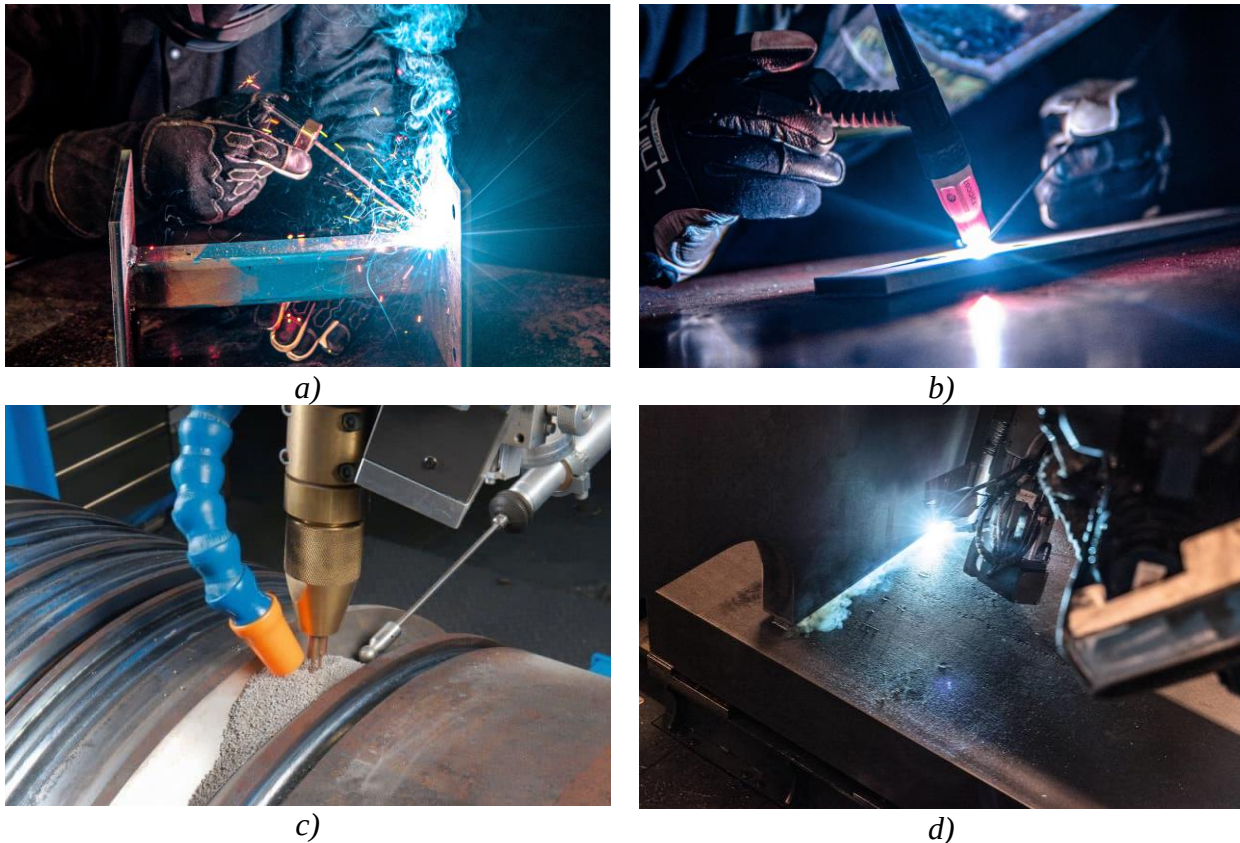


Fig. 11 – Other types of welding processes: a) MMA welding, b) TIG welding, c) SAW welding and d) laser welding [4–7]

2.3 Residual stress measurement methods

Numerous previous research projects highlighted how important it is to learn more about the induced residual stresses and geometrical imperfections due to manufacturing since large deformations and residual stresses can reduce the resistance of steel structures. Measurement of residual stresses, e.g., in welded box section in this research, have a dual role. Residual stress measurement is an important tool for developing idealized residual stress models, while it can especially have an important part in validating numerical models. The literature classifies residual stress measurement techniques into three groups: destructive, semi-destructive or non-destructive. The destructive and semi-destructive techniques are also called mechanical method, which rely on the measurement of deformations due to the release of residual stresses upon removal of material from the specimen. The most widely used destructive or semi-destructive techniques are sectioning, contour, and hole-drilling method. Non-destructive methods include X-ray or neutron diffraction, ultrasonic methods, and magnetic methods.

2.3.1 Destructive methods (mechanical methods)

Destructive methods or so-called stress-relaxing methods presents that the measurement method is based on the stress-relaxation produced in the material; thus, the technique is based on measuring the deformation caused by relaxation. By analysing the consecutive states of equilibrium, residual stress present in the part before the destructive process can be determined. During the past few decades, many different destructive methods have been developed for measuring residual stresses in different situations. Nowadays, these techniques are the most commonly used ones since they are easy to use, and they have lower price compared to e.g., diffraction techniques. In addition, in comparison to non-destructive methods, destructive and

semi-destructive residual stress measurement techniques generally require fewer specific calibrations. The most used mechanical methods are as follows:

- hole-drilling method,
- ring core method,
- deep hole method,
- sectioning technique,
- contour method,
- layer removal method,
- splitting method,
- and slitting method.

The **hole-drilling method** is one of the most common used semi-destructive techniques, because it is relatively simple and quick. It has the advantages of good accuracy and reliability, while it is a standardized test procedure, and has convenient practical implementation. The caused damage on the specimen is localized to a small, drilled hole, and is often tolerable or easily repairable. The hole drilling method is shown in **Fig. 12**. The measurement procedure involves four steps:

- A special strain gage rosette is installed on the test specimen where we want to determine residual stresses.
- The gauge grids are wired and connected to strain indicator.
- A precision milling guide is attached to the test part, after that a small, shallow hole is drilled through the geometric centre of the rosette.
- Readings are made of the relaxed strains.
- From the strains measured, the residual stresses are calculated using appropriate calibration constants derived for the particular type of strain gauge rosette used as well as the most suitable analysis procedure for the type of stresses expected.

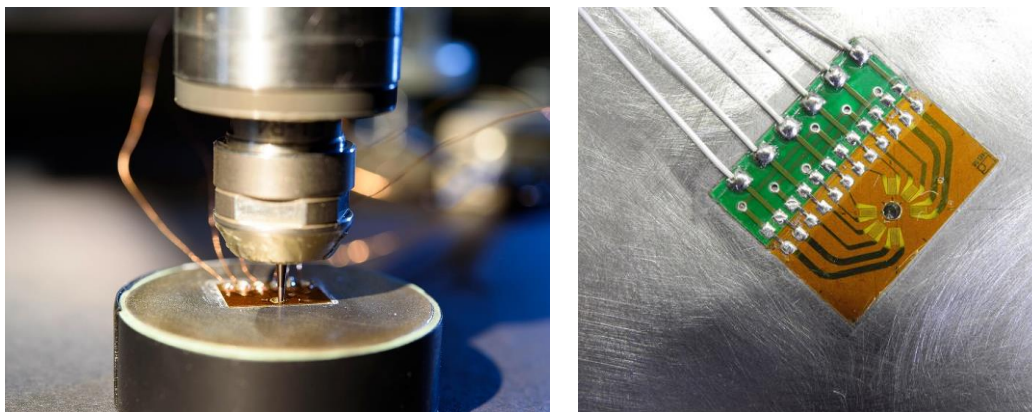


Fig. 12 - Hole-drilling measurement method setup [8]

When using the hole-drilling method there are some expectations regarding the investigated material. Firstly, the materials should be isotropic, and the elastic parameters must be known. Secondly, the analysed materials should be machinable. Drilling of the hole needs to be done with significant care to avoid potential errors. There are three main error sources: introduction of machining stresses, non-cylindrical hole shape, and eccentricity of the hole. The two more effective hole drilling methods are the high-speed (HS) hole-drilling and the electrical discharge machining (EDM) process. Both techniques have advantages, but generally it can be concluded that HS technique is the commonly used one, EDM hole-drilling provides an alternative method. Many researchers have used this method to investigate the residual stress in welded components and many studies discuss the possibilities of refining the procedure. For example. Lee et al. [9] stated that the accuracy of the residual stress measurements obtained using the hole-drilling

technique could be improved by calibrating the measurement results using the hole-drilling induced stress. The application of this calibration scheme requires a special machining operation or calibration with the properties of the base material.

There are some further variants of the hole-drilling method, e.g., the **ring core method** or the **deep hole method**. Latter is which is shown in **Fig. 13**, which combines elements of both the hole-drilling and ring core methods. In the deep hole method, a hole is first drilled through the thickness of the component, and then the diameter of the hole is measured accurately. After that, a core of material around the hole is trepanned out, and relaxation of residual stresses in the holed core takes place. The diameter of the hole is remeasured, which can be used to calculate residual stress state of the specimen. Because of its effectiveness and relative accuracy, the deep-hole method has become a standard technique for the measurement of residual stresses in isotropic materials. The method is particularly useful to thick components, because the method enables the measurement of deep interior stress.



Fig. 13 - Deep hole method [10]

Sectioning technique is a destructive method that relies on the measurement of deformation due to the release of residual stresses upon removal of material from the specimen. The strains are generally measured using electrical or mechanical strain gauges. Nowadays, the method has been used extensively to analyse residual stress in structural carbon steel. The residual stress measurement procedure is as follows:

- Gauge holes are drilled before cutting, and then the distance of the drilled holes is measured for mechanical strain gauges.
- The two ends are cut off by waterjet cutting machine and removed from the original specimens.
- The tested sections are cut into plates through wire EDM. Furthermore, the individual plate is cut into many thick strips, and finally the thick strips are layered into the experimental strips by using wire EDM.
- After the complete cutting procedure, all deformations of the material strips are recorded, allowing the residual stress to be calculated in the specimen.

The whole process is shown in **Fig. 14**. After cutting, some strips may have significant curve deformation. The curve deformation may be caused by the inhomogeneous shrinkage of internal and external fibres during residual stress release. In addition, two further errors must be taken into account in the measurement, these are the error from the difference between the residual stress on the surface and the residual stress in the middle layer, and the error from disaccord between the axe of the drilled-hole and the cone-head of length measuring instrument. There are many techniques in the literature for solving these problems due to measurement inaccuracies.

Yang et al. [11] found that circular curve correction method is one of the most efficient methods to correct strip curve deformation. The researchers also proposed another efficient method named by straightening measurement to consider the effect of strip curve deformation. In the case of welded beams, previous research has shown that test segments must be far enough away from the ends to rule out end-to-end interference. The literature recommends a distance of 1.5 to 2.0 times the side dimension. In addition, a reference bar made by the same material with the experimental specimens was used to be able to consider the temperature variation during the experimental process.

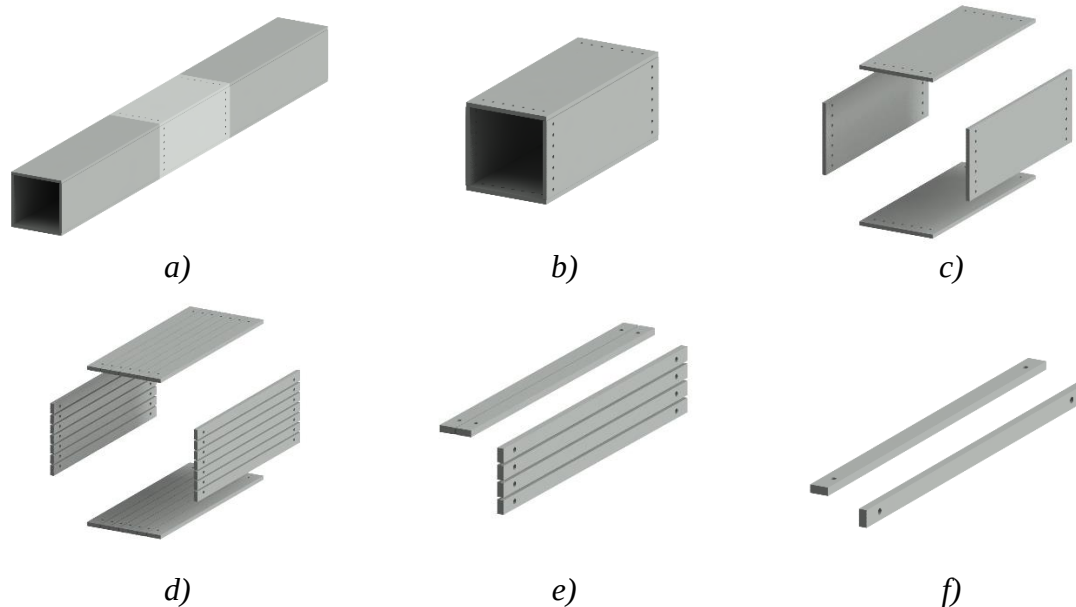


Fig. 14 - Process of sectioning method: a) drill gauge holes, b) cut off the two ends, c) cut the section into plates, d) cut plates into thick strips, e) and f) separate thick strips into experimental strips based on [12]

The **contour method** is a destructive measurement method that enables two-dimensional residual stress map to be evaluated on a plane of interest. Application of the contour method includes four steps: specimen cutting, contour measurement, data reduction and stress analysis. The steps are described in detail below, and some of the steps are shown in **Fig. 15**.

- **Weld cutting:** This is the most critical step in the contour method, because the quality of the cutting surface largely determines the efficiency of the measurement. Wire electric discharge machining is one of the most suitable methods of cutting for the contour method, as it uses electrical discharge instead of hard cutting tools.
- **Contour measurement:** After the weld cut, the resulting surface is measured. A co-ordinate measuring machine (CMM) has been proved to be sufficiently accurate for measurement the surface profile. This technique is designed to measure complex shapes with high precision.
- **Data reduction:** Any error in the measured data could generate high stress points. Smoothing of the measurements to minimize the errors in the data is, therefore, crucial to achieve accurate stress evaluation.
- **Stress analysis and result:** The smoothed data is to be input to a finite element model, with opposite sign, as displacement boundary conditions, so with this procedure the residual stress can be calculated.

To sum up, the contour method promises to give us useful complementary information to existing methods, being the first destructive method to provide high-resolution maps of the stress normal to the cut surface.

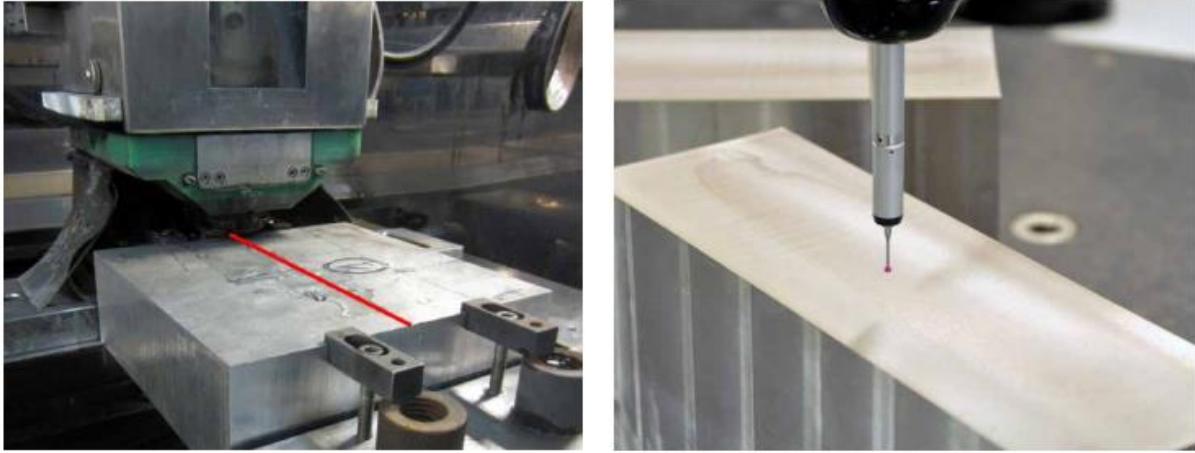


Fig. 15 - Contour method for residual stress measurement [13]

Other destructive methods can be also distinguished which are summarized in **Fig. 16**. The **layer removal method** is a technologically demanding technique in which the deformation caused by the successive removal of layers of material is observed. Indeed, the method involves measuring deformations on one of the surfaces, with strain gauges, as layers of material are removed from the opposite surface. The method is suited to flat plate and cylindrical specimens where the residual stress is known to vary with depth of the material, but to be uniform parallel to the level. Some researchers have applied this method using electrochemical machining (ECM) for measurement of the residual stress, because it has high removal rates, and applicability of ECM is independent of the hardness and toughness of the material. On the other hand, the **splitting method** uses a deep cut in the specimen and the opening of the adjacent material indicates the approximate size of the residual stress present. This method is widely used as a quick comparative test for quality control during steel material production. The **slitting method** has many similarities with the hole-drilling method, but using a long slit rather than a hole, as shown in the figure below. Strain gauges are attached on the plate and the relieved strains are measured as the slit is incrementally increased in depth. After cutting a long gap, the residual stress can be calculated from the measured strains, using finite element analysis. Calibration constants can be incorporated into numerical analysis. Overall, the slitting method has the advantage over the hole-drilling method that it can evaluate the stress profile over the entire specimen depth. However, the slitting method provides only the residual stress normal to the cut surface.

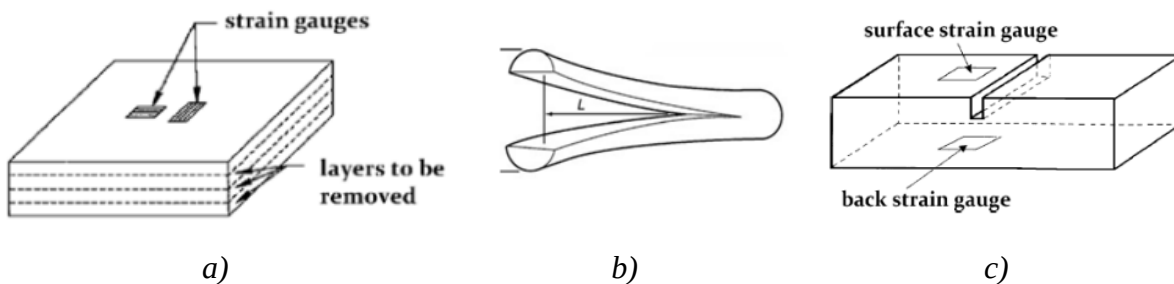


Fig. 16 – Other less used techniques: a) layer removal, b) slitting and c) splitting [14]

2.3.2 Non-destructive techniques

Non-destructive methods are very useful for production quality control and for measurement of valuable specimens or on-site measurements, where applicable, where destructive techniques are not possible. However, these methods commonly require detailed calibrations. The following are the most common non-destructive methods:

- X-ray diffraction method,
- neutron diffraction method,
- Barkhausen magnetic noise method,
- ultrasonic method.

The **X-ray diffraction method** is shown in **Fig. 17a**, which is one of the most commonly used non-destructive techniques. Metals are made up of atoms in a regular three-dimensional arrangement that forms a crystal, so most metals of practical importance have a crystalline structure. When such a metal is placed under stress, elastic strains are produced in the crystal lattice. In other words, by knowing the elastic constants of the material, residual stress can be calculated. The prerequisite for the testability is about the internal structure since it has to be relatively fine-grained crystalline. Some previous research have concluded that there are two basic problems to be addressed when testing welded joints with X-ray diffraction. First of all, the geometry has to be such that an X-ray can both hit measurement area and still be diffracted to the detector without hitting any obstacles. To solve this problem, portable diffractometers could be used nowadays. In addition, these portable diffractometers could be combined with some form of layer removal technique so that a stress profile can be generated, but then the method becomes destructive. Secondly, the measurement sometimes takes a long time. The speed of measurement depends on a number of factors, so with careful selection of the X-ray source and test set-up the speed of measurement can be reduced.

Neutron diffractions method is very similar to the X-ray method. Neutron diffraction method is also based on elastic deformations within the polycrystalline material. The main advantage of the neutron diffraction methods in comparison with the X-ray technique is its larger penetration depth. The neutron is able to penetrate a few centimetres into the inside of a material, thus it can be applied to evaluate an internal the measurement of residual stress up to 25 mm in steel. The other important advantage of the technique is that the neutron diffraction method can provide complete three-dimensional maps of the residual stress in material with an appropriate measurement set-up. These advantages have led to the spread of neutron diffraction over the past decade, but the method also has serious disadvantages. Compared to other diffraction technique such as X-ray diffraction, the relative cost of application of neutron diffraction method is much higher, mainly because of the equipment cost. It is not suitable for routine process. The newly constructed diffractometers, e.g., ENGIN-X, was designed with the single aim of making engineering strain measurements, unlike the neutron diffractometers from the past. With the increasing number and performance of dedicated neutron strain measurement instruments around the world, neutron diffraction is becoming an increasingly important factor in the engineering measurement of deformations. The ENGIN-X is shown in **Fig. 17b**.

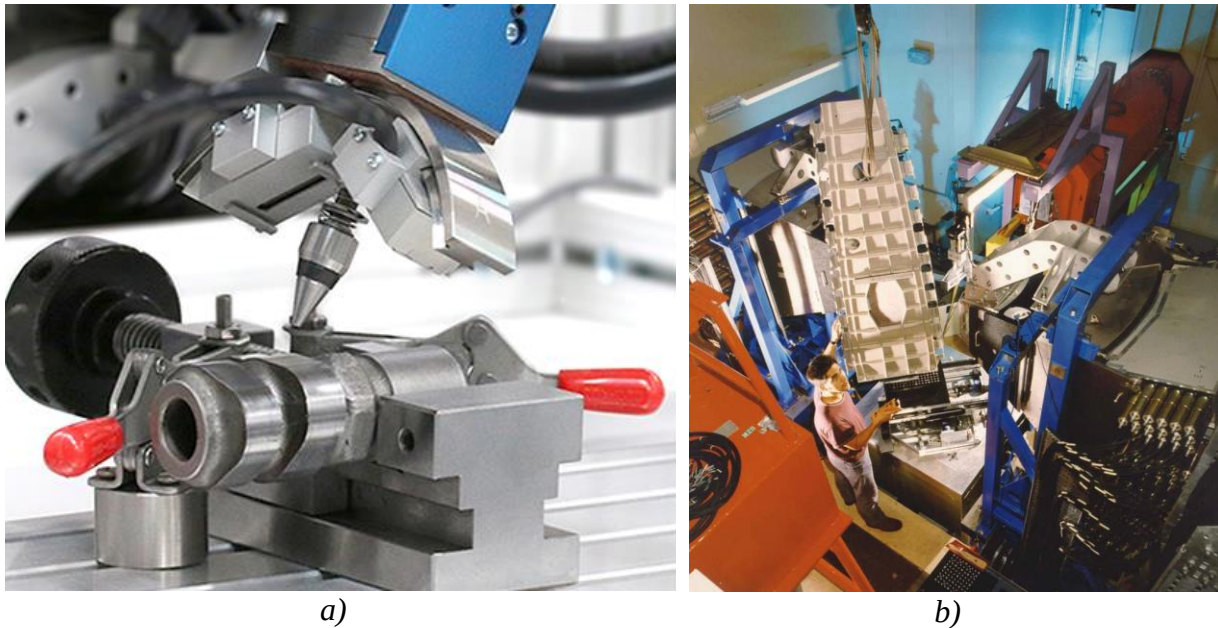


Fig. 17 – a) X-ray diffraction method [15] and b) ENGIN-X neutron diffractometer [16]

There are some other methods for residual stress measurements, which are based on measurements of electromagnetic, optical, and other physical phenomena. The most commonly used technique is the **Barkhausen magnetic noise method**, or ultrasonic method. The Barkhausen magnetic noise (BMN) method is suitable for measuring surface residual stress, and it is also suitable for measuring other microstructural parameters. In most metals used in civil engineering practice, compressive stress will decrease the intensity of the Barkhausen noise while tensile stress increases it. This fact can be exploited so that by measuring the intensity of the Barkhausen noise the amount of residual stress can be determined. The measurement technique is shown in **Fig. 18a**. Some scientific articles can be found on the literature, which are focused on BMN method. Stewart et al. [17] have made measurements on a welded steel plate with BMN method. Studies have shown that, away from the weld the results are consistent with the expected compressive stress. Previous studies have also shown that it is almost impossible to use the BMN to assess residual stress in weldments containing heat-affected zones, because of the rapid microstructural changes. Juan et al. [18] provided a solution to partially address the handicap. In their study, they developed a modified magnetic Barkhausen magnetic noise method to determine the residual stress distribution in the thermal zone by taking calibration samples from four different regions, so that the analysis reflects the microstructural changes in the thermal zone. The measurement depth depends mainly on the magnetic properties of the material; therefore, measurement depth can be much bigger than that of X-ray diffraction for certain materials. To sum up, MBN can show subsurface residual stress, while it works as a non-destructive method.

Ultrasonic method, which is also called refracted longitudinal wave technique, can be used for residual stress measurements on thick samples. Ultrasonic method is based on the acoustic-elasticity effect, which means that, the velocity of elastic wave propagation in solids depends on the mechanical stress. The residual stress measurement technique is shown in **Fig. 18b**. Different configurations of ultrasonic equipment can be used for residual stress measurements, but the simple setup includes two important devices. Waves are launched by a transmitting transducer and are detected by a receiving transducer. The technique in which the same transducer is used for excitation and receiving of ultrasonic waves is often called the pulse-echo method. In ultrasonic method the depth of the examined layer is related to the ultrasonic wavelength, so the measured depth can be much greater than measured depth for X-ray method. Other advantages of the ultrasonic technique are the facts that instrumentation is convenient to use, quick to step up,

portable and one of the most important advantages is that it is free of radiation hazards. The main disadvantages are that wave velocities depend on microstructural inhomogeneities and there are difficulties in separating the effects of multi-axial stresses.



Fig. 18 – a) Barkhausen magnetic noise [15] and b) ultrasonic [19] measurement methods

2.4 Residual stress models in the literature

It is an important task to determine residual deformations and residual stress due to welding since it can have influence on the quality of the manufacturing process as well as on the resistance of steel members. That is why determination of residual deformations and residual stress are highly recommended for manufacturers as well as for designers. Results of previous laboratory tests showed that the shape and the residual stress intensity significantly depend on the manufacturing process and the geometry of the specimen. That is the main reason why practical design needs different types of residual stress models for different section types, and for material qualities. Hereunder, residual stress models for normal strength (NSS) and high strength steel (HSS) box sections are summarized. It must be emphasized, that no proposed residual stress models are available for hybrid sections, which combine NSS and HSS structural steels.

2.4.1 Residual stress models for NSS sections

We can find a variety of previous studies dealing with the residual stress distribution of welded box section members made from NSS, and there are some developed models as well, such as the models of ECCS, Chinese standard, or the Swedish code. Mentioning these models is important because some of these models are the basics of the HSS models. Typical residual stress patterns are given in ECCS (European Convention for Constructional Steelwork) these patterns are applied in structural design of welded sections of S235 to S355 steels. The ECCS residual models [20] were derived experimentally and theoretically, the models are shown in **Fig. 19**. As it is shown the models have different h/t ratios. The model determined the tensile stress as a fixed value, i.e., the steel yield strength, and the h/t rates and the heavy or light weld are also taken into account. As it is mentioned before, the ECCS model is not suitable for designing HSS sections, because of a significant increase in the yield strength.

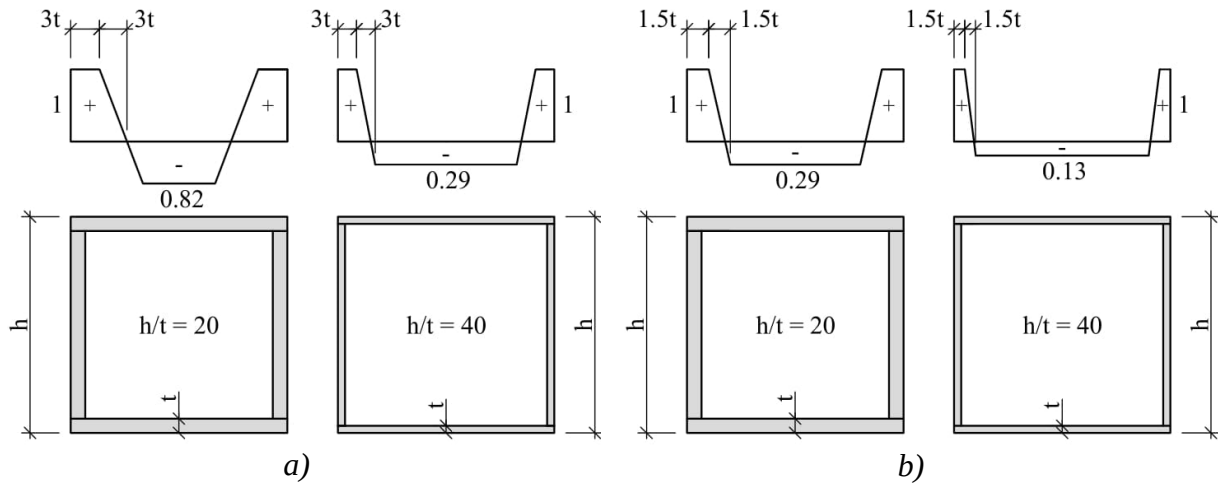


Fig. 19 - ECCS residual stress models for heavy welds (a) and light welds (b) based on [21]

The Chinese standard [22] gives similar model like ECCS, but with rounded shape and constant values as maximum and minimum residual stress independent from the b/t ratio. All the presented models give the tensile as well as the compressive residual stress in linear function of the yield strength and the given constants are independent from the exact material grades. Models of the Chinese and Swedish standards are shown in **Fig. 20**.

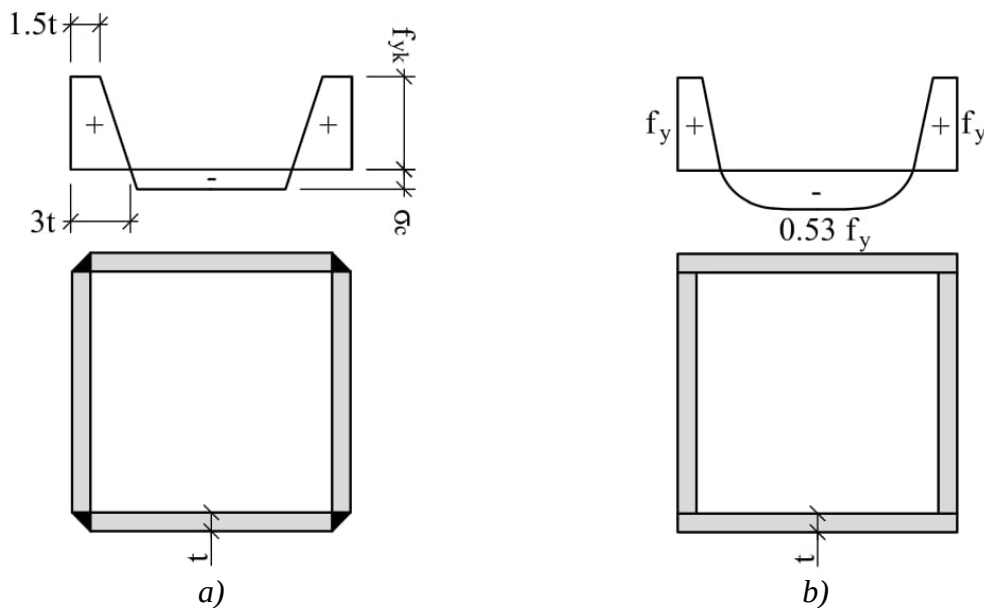


Fig. 20 - Swedish (a) and Swedish Chinese (b) residual stress models for box sections based on [23]

2.4.2 Residual stress models for HSS sections

There are a relatively large number of studies with NSS sections, but a much smaller number of previous studies dealing with HSS rectangular box sections are available. However, due to the increasing importance of HSS material, there is a growing need for such studies and models.

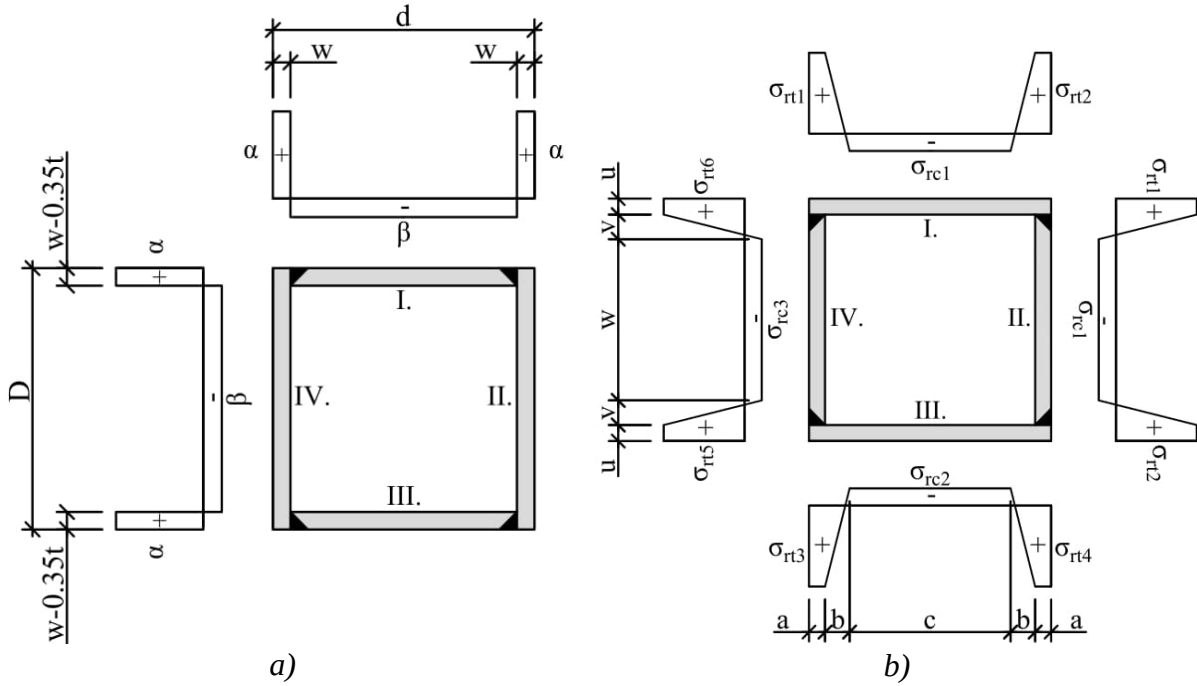


Fig. 21 - a) Proposed residual stress model by Wang et al. [24], b) proposed residual stress model by Ban et al. [12]

In 2012, Wang et al. [24] published a study that focused on the magnitude and distribution of residual stress in HSS box sections. The specimens of this paper were fabricated from Q460 steel plates. The thickness of the plates were 11 mm and the b/t ratio of the specifications varied between 7.7 and 17.3. Based on the experimental results a simplified residual stress distribution was suggested. The proposed model is shown in **Fig. 21a**, where w is the width of tensile residual stress in plates I and III, $\alpha = \sigma_{rt}/R_{p0.2}$ and $\beta = \sigma_{rc}/R_{p0.2}$ are tensile and compressive residual stress ratios, where $R_{p0.2}$ is the 0.2% proof stress, which was adopted as yield strength of steel plates. Tensile and compressive stress ratios varied between 0.555-0.787 and 0.142-0.255 in the experiments. Width w can be calculated by applying equilibrium condition.

In 2013, Ban et al. [12] also investigated residual stresses of welded HSS box sections fabricated from S460 HSS plates. Plate thickness was 10 mm, 12 mm and 14 mm which were connected with butt welds. The investigation pointed out that the stress distribution shape of the HSS box sections was similar to that of NSS box sections. The proposed model, which is based on the test results, is shown on **Fig. 21b**. The magnitudes of the model are labelled as follows. Constant tensile stress in flanges is denoted with $\sigma_{frt} = \sigma_{rt1-4}$, constant tensile stress in webs is $\sigma_{wrt} = \sigma_{rt5-8}$, while constant compressive stress in both flanges and webs is labelled with $\sigma_{rc} = \sigma_{rc1-4}$. The multiple stepped functions of the distribution shape in flanges $\sigma_{fr}(x)$ and webs $\sigma_{wr}(y)$ are described in **Eqs. (1-2)**:

$$\sigma_{fr}(x) = \sigma_{fr}(B-x) = \begin{cases} \sigma_{frt}, & 0 \leq x < a \\ \sigma_{frt} + \frac{\sigma_{rc} - \sigma_{frt}}{b}(x-a), & a < x < a+b \\ \sigma_{rc}, & a+b \leq x \leq B/2 \end{cases} \quad (1)$$

$$\sigma_{wr}(y) = \sigma_{wr}(h_0-y) = \begin{cases} \sigma_{wrt}, & 0 \leq y < u \\ \sigma_{wrt} + \frac{\sigma_{rc} - \sigma_{wrt}}{v}(y-u), & u < y < u+v \\ \sigma_{rc}, & u+v \leq y \leq h_0/2 \end{cases} \quad (2)$$

where the residual stress extension lengths (a , b , u and v) are illustrated in **Fig. 21b**, B is the flange width and h_0 is the web height a , x is the coordinate along flange width B and y is the coordinate along web height h_0 . In addition, a simplified empirical equation was suggested to calculate compressive residual stress, as shown in **Eq. (3)** for engineering application. The maximum (f_y) and a minimum value ($0.1f_y$) of the compressive stress is determined as limits. In addition to this formula, Ban et al. also published a more mathematically sophisticated formula, it shows in **Eq. (4)**.

$$\sigma_{rc} = -10-1500 \frac{1}{t/h_0} - 550 \frac{1}{t} \quad (3)$$

$$\sigma_{rc} = 900-1100 \frac{h_0}{t} - 550t^{-0.4} \quad (4)$$

In 2015, Li et al. [25] published a paper about residual stresses in Q690 HSS welded box sections. First conclusion of the experiment was that the width of the tensile zone is almost unaltered. The second main conclusion was that the residual compressive stress ratio decreases with the increase of plate slenderness ratio. In the model, which is shown in **Fig. 22a**, the relative tensile residual stress and compressive residual stress can be calculated using $\alpha = f_{rc}/f_y$ and $\beta = f_{rt}/f_y$, similarly to the approach proposed by Wang et al. [24], where f_{rc} and f_{rt} are the tensile and compressive residual stresses, respectively, and f_y is the mean value of the yield strength.

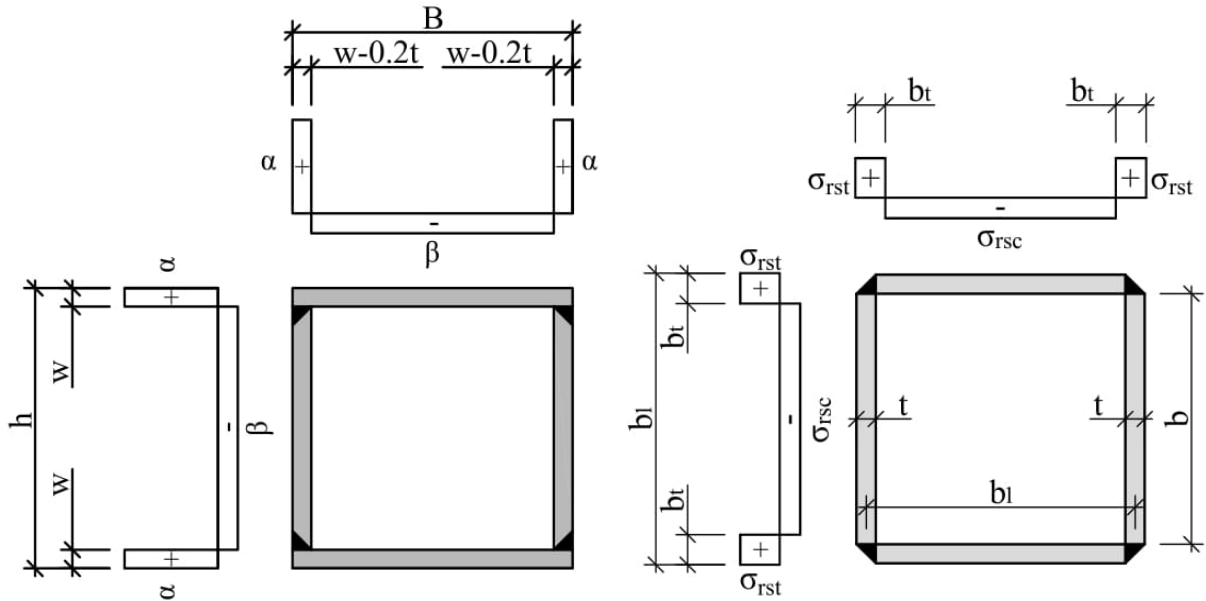


Fig. 22 - a) Proposed residual stress model by Li et al. [25] and b) Ban et al. [26]

Khan et al. [26] published their paper in 2013 about residual stresses of box sections with S690 steel material. Six sections were tested in the experiment program: four sections were fabricated with light weld, and two sections were fabricated with heavy weld. The investigation used non-destructive neutron diffraction technique. The proposed simplified residual stress distribution, which estimates the residual stress distribution conservatively is shown in **Fig. 22b**. The tensile stress distribution width b_t can be determined by stress equilibrium as shown in **Eq. (5)**, where b_l is the width of a plate from the weld centre, and t is the thickness of the plate as shown in **Fig. 22b**.

$$b_t = \frac{b_l \sigma_{rsc}}{2(\sigma_{rst} + \sigma_{rsc})} \quad (5)$$

$$\sigma_{rsc} = f_y \cdot 3.6607 \left(\frac{b_1}{t} \right)^{-0.924} \quad (6)$$

Kövesdi and Somodi [23] published a paper in 2018, which focuses on measuring the residual stresses, and determining the dependency of the extreme values (maximum tensile and compressive residual stresses) and the residual stress pattern on the steel grade and on the b/t ratio. Furthermore, based on the test results and the previous measurements a trapezoidal shape residual stress model was developed (**Fig. 23**). According to the study the tension zone of the residual stress model can be assumed to be equal by the yield strength, for all the steel grades. According to the tested specimens the compressive residual stress can be considered as a constant value in the compression zone. The measurements showed that the average compressive residual stress is independent from the steel grade, but it is not independent from b/t ratio and the plate thickness. Based on this information, the values of the compressive stress can be determined by **Eqs. (7-10)**. **Eqs. (7-8)** approximate the measured average of residual stresses, while **Eqs. (9-10)** approximate the 5% upper quantile value of the measured residual stresses.

$$t \leq 5 \text{ mm: } \sigma_{rc} = 70 - 21t + t^2 - [2900 - 3600 \cdot (t - 5)] \cdot [b/t]^{-1} \quad (7)$$

$$t \geq 5 \text{ mm: } \sigma_{rc} = 70 - 21t + t^2 - [2900 - 290 \cdot (t - 5)] \cdot [b/t]^{-1} \quad (8)$$

$$t \leq 5 \text{ mm: } \sigma_{rc,95\%} = 41 - 21t + t^2 - [2900 - 3600 \cdot (t - 5)] \cdot [b/t]^{-1} \quad (9)$$

$$t \geq 5 \text{ mm: } \sigma_{rc,95\%} = 41 - 21t + t^2 - [2900 - 290 \cdot (t - 5)] \cdot [b/t]^{-1} \quad (10)$$

The study also gave instructions for the shape of the tension zone and width of the compression zone (L_c). They found that the stress-shape of the tension zone and the width of the compression zone depends on the steel grade. The length of the constant part of the tension zone $a = 2t$, if the section made by S355-S460, and $a = 0.75t$ if it is made using S700. Furthermore, the study stated that the compression zone width depends on the steel grade, b/t ratio and the thickness of the plate, and it can be determined by equilibrium equations using **Eq. (11)**. The width c of the triangle part of the residual stress model can be calculated based on the geometrical equation given by **Eq. (12)**. The application range of the proposed model is plate thickness between 4-12 mm, and b/t ratios between 9.7 and 62.5. In addition, the developed values are relevant for welded box sections, where the welds are placed in the four corner zones.

$$L_c = \frac{\sigma_{rt} (b - t + 2a)}{2 \cdot |\sigma_{rt}| + \sigma_{rt}} \quad (11)$$

$$c = \frac{b - t - 2a - L_c}{2} \quad (12)$$

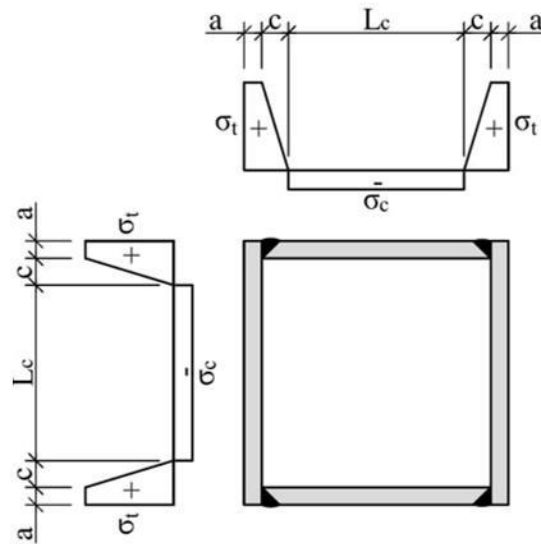


Fig. 23 - Proposed residual stress model by Kövesdi and Somodi [23]

2.5 Numerical simulations of welding-induced residual stresses

Beside residual stress measurements, numerical models could be used for investigating residual stresses due to manufacturing. Numerical simulations are essential since they allow a wide range of design parameters and material types to be investigated. In this chapter, manufacturing simulations focusing on the residual stresses in welded box sections are introduced.

Kollár et al. [27] published a paper in 2016, which investigation presented a numerical model for the effect of the welding procedure in ANSYS 14.5. The paper introduced several numerical results of butt-welded plates and box sections. The presented research program includes an uncoupled thermomechanical analysis focusing on the main structural effects of arc welding. This modelling technique means that temperature fields are determined first during welding using thermal analysis, while in the mechanical analysis temperature fields are applied as nodal loads. The problem is solved step by step while the heat source is moving during the welding process. In the analyses, 20-node three-dimensional solid elements were applied. It is especially important to have a dense solid mesh in the heat affected zone thus it is possible to follow the residual stress and microstructural changes. Far from the welding path it is enough to use a coarser mesh. The solid model is meshed with appropriate thermal elements in the thermal analysis; then, they were transferred to equivalent structural elements at the beginning of the mechanical analysis. The applied heat source model is one of the most demanding tasks in the uncoupled analysis. The investigation used Goldak's double ellipsoidal heat source model, as recommended in literature for arc welding simulation. In this method the front and rear ellipsoid could be calibrated and fitted separately, so the heat source can be applied even to simulate deep penetration welding. Convective heat transfer coefficient of $25 \text{ W}/(\text{m}^2 \cdot \text{K})$ was used, while the emissivity ε was 0.8. The applied thermal and mechanical material properties were based on the EN 1993-1-2 [28] for structural steel S355, which code is basically recommended for structural fire design, but has been proved to be appropriate for welding simulations of structural steels as well. The paper also draws attention to setting mechanical boundary conditions, because the clamping conditions have an important influence on the evolution of deformations and stresses. The optimization of the stress-deformation relation is one of the most important tasks, while rigid body motion must be avoided in the static analysis. Elements with low stiffness can cause convergence problems in the numerical model; therefore, these elements were 'killed' during the analysis if their

temperature was above 1200 °C, which was taken as zero strength temperature. ‘Killing’ means that the element stiffness is reduced radically, and their strains and stresses are zeroed out. If the element cooled below the zero-strength temperature, it was activated again. This special modelling technique is the so called ‘birth and death’ method.

In 2016, Somodi et al. [29] published a study in the topic of residual stresses induced in welded box sections. Parallel to the laboratory tests, the effect of the welding process was subjected to a certain numerical welding simulation technique. In the study, the numerical model was used to investigate the effect of different geometrical parameters and steel grades on the residual stress pattern over a large parameter range, beyond the experimental specimens. In the numerical research program, uncoupled thermomechanical analyses were carried out to simulate MAG welding of test specimens. In addition, the simulation combined four-node shell elements and eight-node solid elements to reduce computational time. The heat effected zone and the surrounding region of the weld beads were modelled using solid elements, because of the high thermal gradients. A dense mesh was used near the butt welds at the corners, and the zones with shell elements had coarser mesh. The numerical model is shown in **Fig. 24a**. The presented paper used the same thermal boundary conditions, and temperature-dependant material models as [27]. The paper used one weld pass for thin plates ($t \leq 8$ mm), otherwise two weld passes were modelled. The verification of the thermomechanical model was completed by comparing the numerical and experimental residual stress of a tested specimen made of S460 steel grade. **Fig. 24b** shows the comparison of the measured (using sectioning technique) and computed residual stresses for one quarter of the specimen. The researchers found that experimental and numerical results were in good agreement.

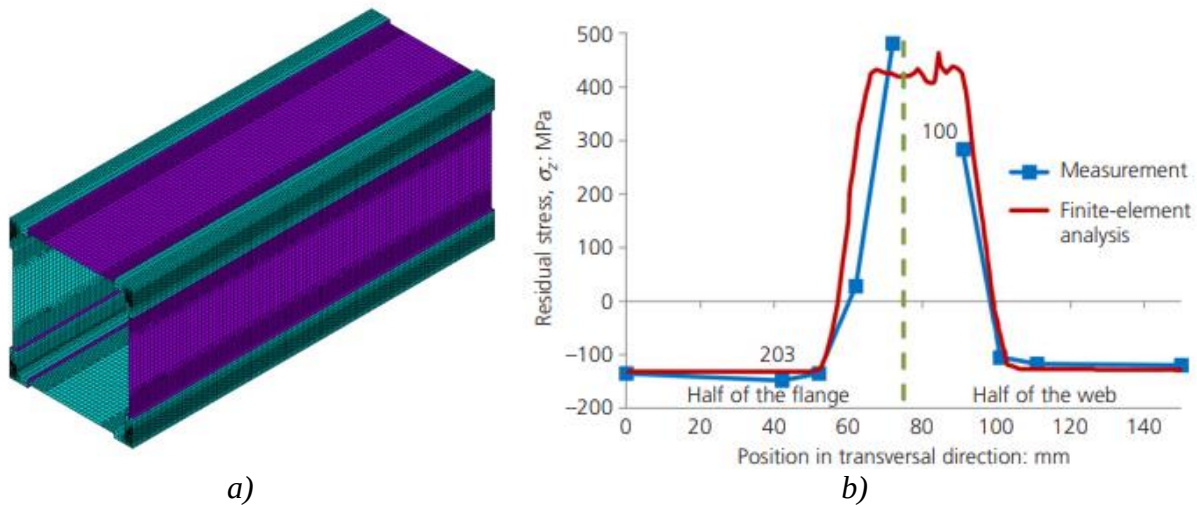


Fig. 24 - a) Numerical model of the box section analysed and b) comparison between finite element results and test results by Somodi et al. [29]

In 2022, Xiao et al. [21] presented three different finite element models with different geometrical and manufacturing parameters. An important point of the study is the presentation of the numerical modelling of transverse bending in manufacturing of cold-formed profiles to be welded (e.g., **Fig. 25a** with similar layout). This process was simulated with a two-dimensional model assuming plane strain, with CPE4R elements in ABAQUS. The steel plate was modelled as a deformable body, while the punch and the two supports were modelled as rigid bodies. The surface properties were set to enable friction between the punch and the plate. In the modelling process the supports were fixed, while the punch travelled vertically. The geometry of the punch and the vertical distance were compensated with the plate spring back angle. **Fig. 25** shows the results of the numerical analysis with different plate thickness. In order to incorporate this

residual stress pattern into the three-dimensional finite element models, residual stress results were implemented in the three-dimensional thermomechanical models through a block data transfer as initial stress.

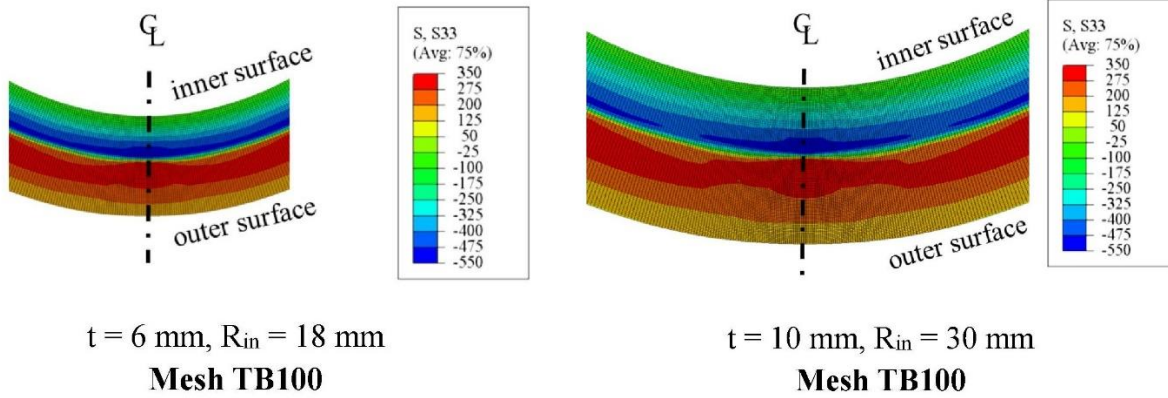


Fig. 25 - Longitudinal residual stresses due to transverse bending of the cold-formed profile to be welded [21]

The second step of modelling was the simulation of longitudinal continuous welding which included the uncoupled three-dimensional thermomechanical analysis. The researchers applied the double ellipsoidal heat source model. In addition, the paper used the EN 1993-1-2 [28] for thermal and mechanical properties of materials, which provides a set of reduction factors for temperature-dependent thermomechanical properties for S235 to S460 steels. The researchers also used the EN 1993-1-2 recommendations for S960 steel. The specified parameters are the thermal conductivity, specific heat capacity, thermal expansion coefficient as well as yield strength and Young's modulus. **Fig. 26** illustrates the finite element model with the boundary conditions for the mechanical analyses. The boundary conditions were defined so that the element can expand longitudinally during the welding process. All the investigated sections were welded with multi-pass welding, because of the reduction of the heat input energy during welding. **Fig. 27** illustrates the modelling processes of the multi-pass welded sections. The paper mentions that this is not practical to specify that the volumes deposited in various welding passes are the same.

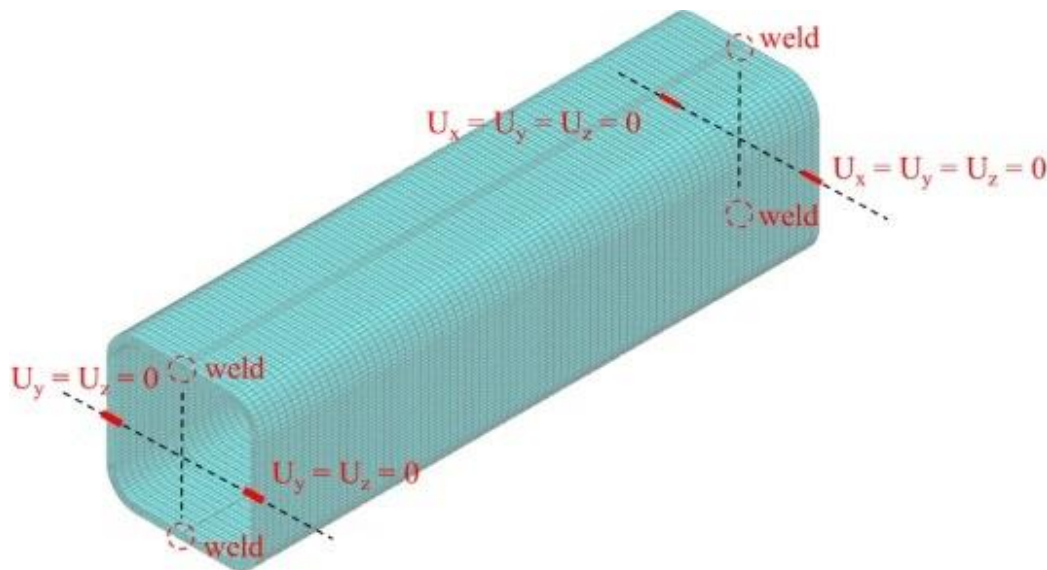


Fig. 26 - Numerical models of the box sections with the applied mechanical boundary conditions [21]

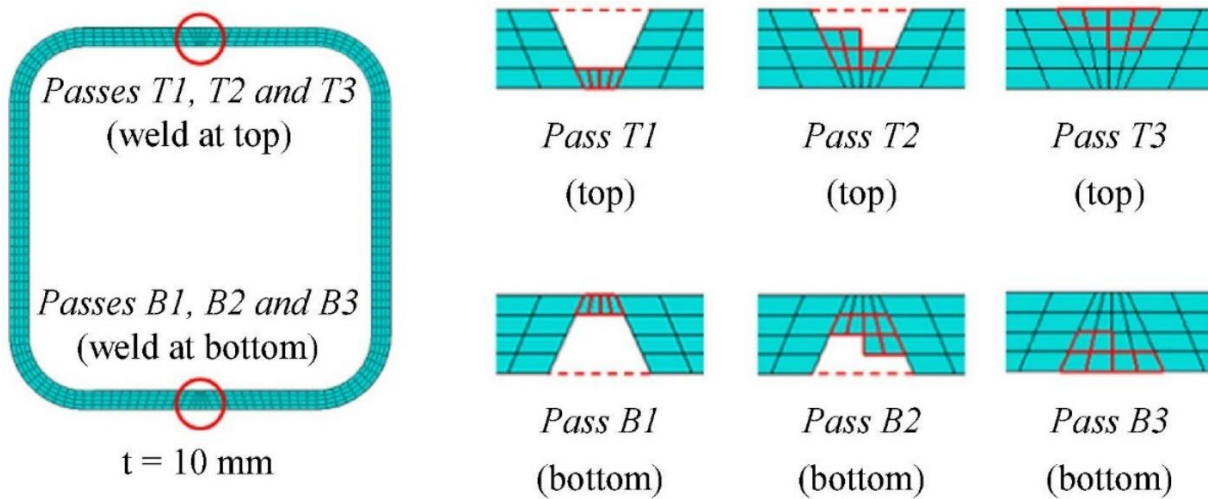


Fig. 27 - Multi-pass welding during modelling [21]

Experimental investigations were carried out as well aiming to validate the numerical model. It was found that the proposed models and the experimental temperature curves had a good agreement, so the proposed models are able to predict the transient temperatures of the welded box sections. Temperature history of a tested specimen and the finite element model (FEM) are shown in **Fig. 28**.

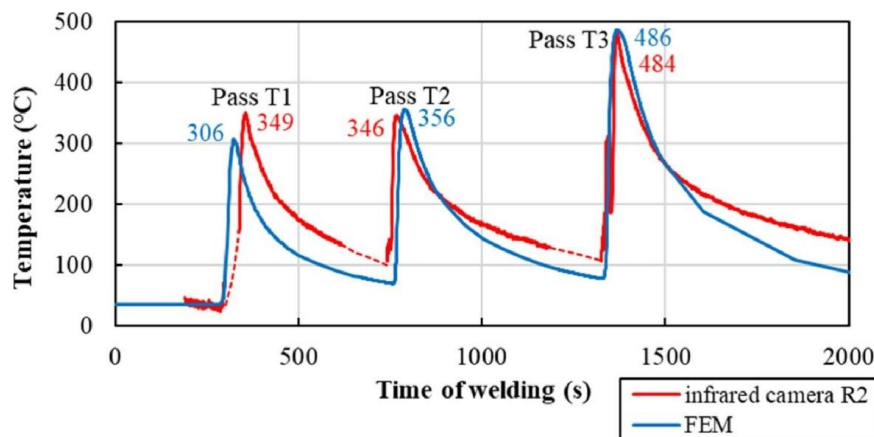


Fig. 28 - Results of the thermal analysis [21]

The experimental results have shown that there is a good agreement between the predicted and the measured residual stresses at both the outer and the inner surfaces of the sections. The comparison results are shown in **Fig. 29**. **Fig. 30** illustrates cross-sectional view of longitudinal stresses, induced by transverse bending and longitudinal welding, in the developed numerical model after an exact calibration.

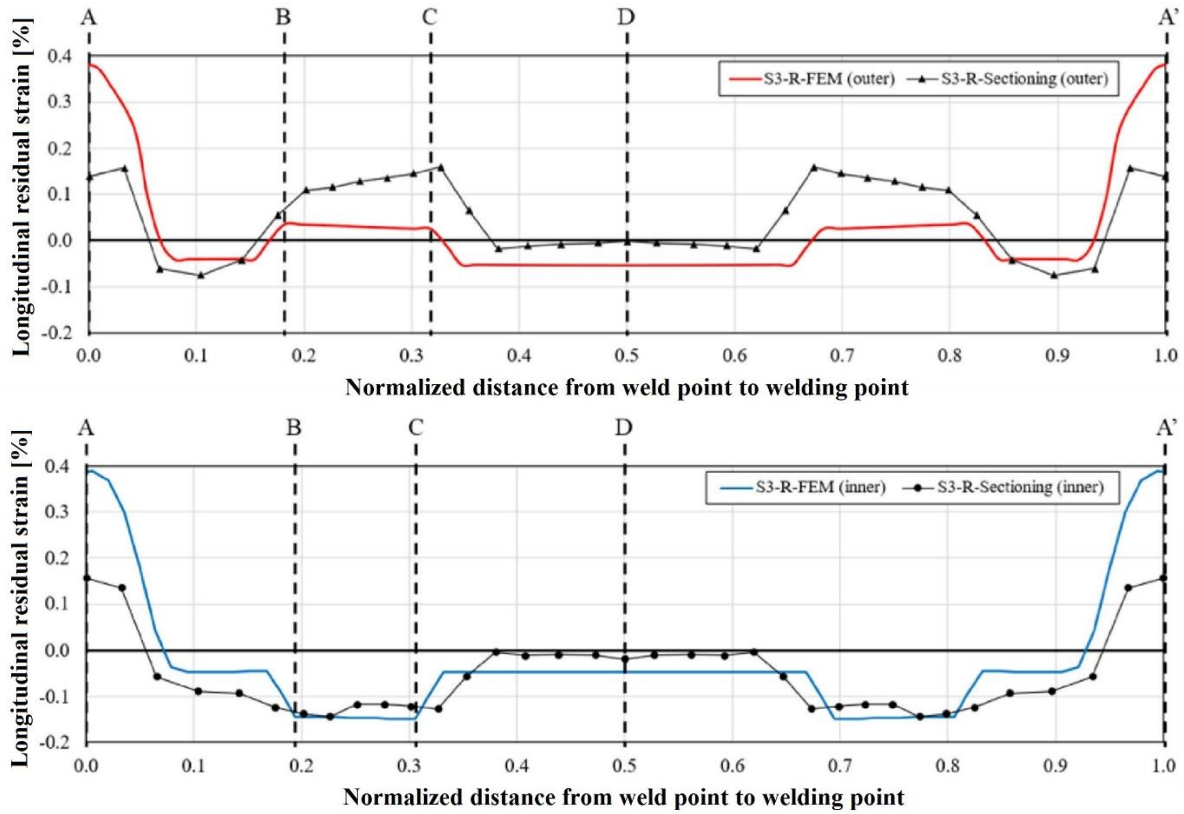


Fig. 29 - Experimental and numerical (FEM) residual stresses based on [21]

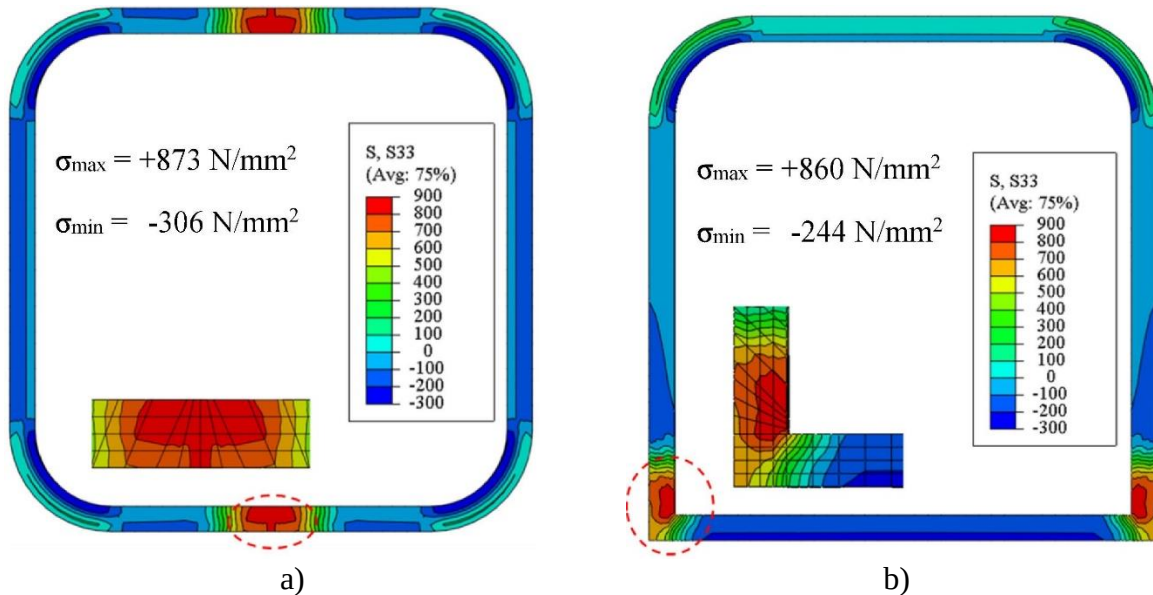


Fig. 30 - Plots of the FEM-based longitudinal residual stresses in two types of welded box sections: a) using two C profiles and b) a U-profile with a flat plate [21]

Jiang et al. [30] presented a study which focused on the behaviour of welded high strength steel box columns under compression. Therefore, a numerical model was developed in ABAQUS (Fig. 30). The aim of the developed three-dimensional fully coupled welding simulation was to define the generated residual stress distributions by the welding process. In addition to the objectives already mentioned, the researchers discussed the effects of different welding processes and heat treatment methods on the welded box sections. The presented study modelled two

different welding methods – flux-cored arc welding (FCAW) and submerged arc welding (SAW). In addition, the paper also discussed some different heat treatment conditions in numerical modelling. These heat treatment conditions are the as-welded condition (AW), HAZ preheating (PH) and post-weld heat treatment (PWHT). The study used 3D coupled linear brick element (C3D8T) for the heat transfer analysis and for the stress analysis. This element consists of a brick with eight nodes and four degrees of freedom (DOF) per each node (three translational and one temperature DOFs). In order to control the computational time, multi-pass welding was lumped into two blocks during modelling. Nonlinear material properties and large deformations were considered in the analysis based on previous studies [31]–[33]. The presented paper used a simplified thermal interaction, which means that all the inner and outer surfaces will have thermal convection and radiation for heat dissipation. The used convection coefficient h was 25 W/(m²·K) and the emissivity ε was 0.2. The chosen heat source model was the double ellipsoidal heat source model introduced by Goldak and Akhlaghi [34]. The presented numerical simulation took post-weld heating (PWHT) into account as mentioned before, which process is mainly applied to reduce the magnitude of manufacturing-induced residual stresses. To simulate the effect of PWHT, the researchers used a viscoplastic analysis step after the end of the thermomechanical analysis. During the analysis, the power law creep model was used in ABAQUS, which can be described by **Eq. (13)**.

$$\dot{\varepsilon}^{cr} = \frac{A \cdot q^n [(m + 1) \cdot \varepsilon^{cr}]^m}{(m + 1)} \quad (13)$$

where ε^{cr} and $\dot{\varepsilon}^{cr}$ are the uniaxial equivalent creep strain and the uniaxial equivalent creep strain rate, respectively, q is the uniaxial equivalent deviatoric stress and A , n and m are parameters that depend on the material type.

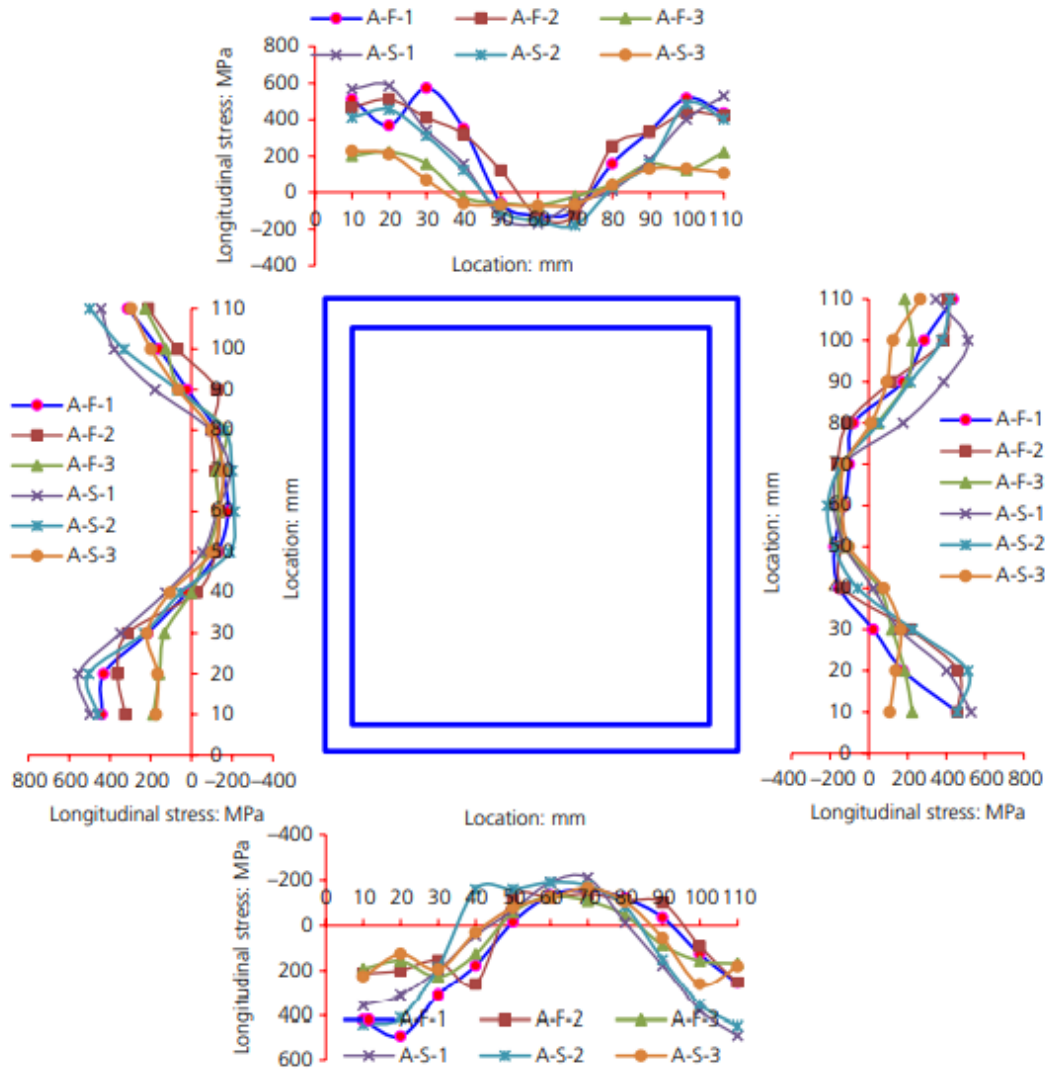


Fig. 31 – Computed longitudinal residual stress distribution from simulation [30]

The residual stress profiles from the numerical models are shown in **Fig. 31**, which reveals that, all the modelled box sections longitudinal stress distributions were similar. Based on the residual stress distributions, the researchers found that high tensile stress was generated near the corners, while significant compressive stress occurred in the middle of the plates. No obvious difference was found between the residual stress distribution patterns from modelling FCAW and SAW welding processes. This is explained by the fact that, the similar heat input per unit length used during the fabrication process was similar for the two welding processes. Regarding heat treatment processes, the study found that preheating has a very low effect on the residual stress distribution. However, PWHT can effectively reduce the amount of the tensile stress near the corners of the box sections.

3 Measurements

The current research work includes experimental testing of specimens with box sections. In this chapter, the tested structural configurations, welding variables used in the fabrication of the specimens and the measured dimensions of specimens are presented. Furthermore, dimensions of weld pools, methods and results of residual stress measurements are also discussed. In addition, mechanical properties and chemical composition of the base materials are presented.

3.1 Tested geometries

The study investigates nine welded box **sections**. The sketch of a specimen is shown in **Fig. 32** with the geometrical dimensions. The geometric and material properties of the tested specimens are summarized in **Table 1**. As shown in the table, three plate thicknesses (6 mm, 8 mm, 10 mm) and two steel grades (S355, S700) are used in the tested specimens. It should be noted that while the material grades of the flange and the weld are the same for four specimens, they are different for three cross sections.

Table 1 - Geometrical parameters and steel grades of specimens

Specimens	Geometrical parameters			Steel grade	
	a [mm]	t [mm]	L [mm]	Flange	Web
RS6-355	220	6	800	S355	S355
RS6-700	220	6	800	S700	S700
RS6-H0	220	6	800	S700	S355
RS8-700A	200	8	700	S700	S700
RS8-700B	200	8	700	S700	S700
RS8-H0	200	8	700	S700	S355
RS4-700A	200	4	700	S700	S700
RS4-700B	200	4	700	S700	S700
RS4-H0	200	4	700	S355	S700

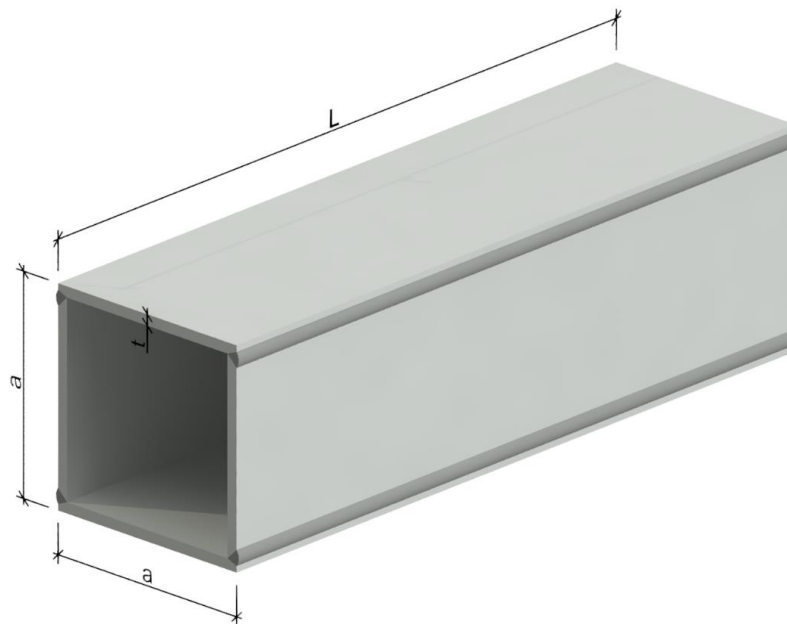


Fig. 32 - Sketch of the modelled specimen

The code names of the specimens are interpreted as follows. In all cases, the number following the letter RS is the size of the plate thickness of the box sections in millimetres (4, 6, or 8). The last part of the names carries information about the steel grades. The designation identifiers 355 and 700 indicate steel grades S355 and S700 respectively. If there is a difference between the applied materials of the flange and web, the designation is indicated by the symbol H0 for hybrid sections. The joint of the plates in the box section was made with single-bevel butt welds. The number of weld passes varies for different plate thicknesses. This means that for cross-sections with 4 mm and 6 mm plates, only one layer per seam was used, and for cross-sections with 8 mm plates, two layers per seam were used, as it is shown in **Fig. 33**.

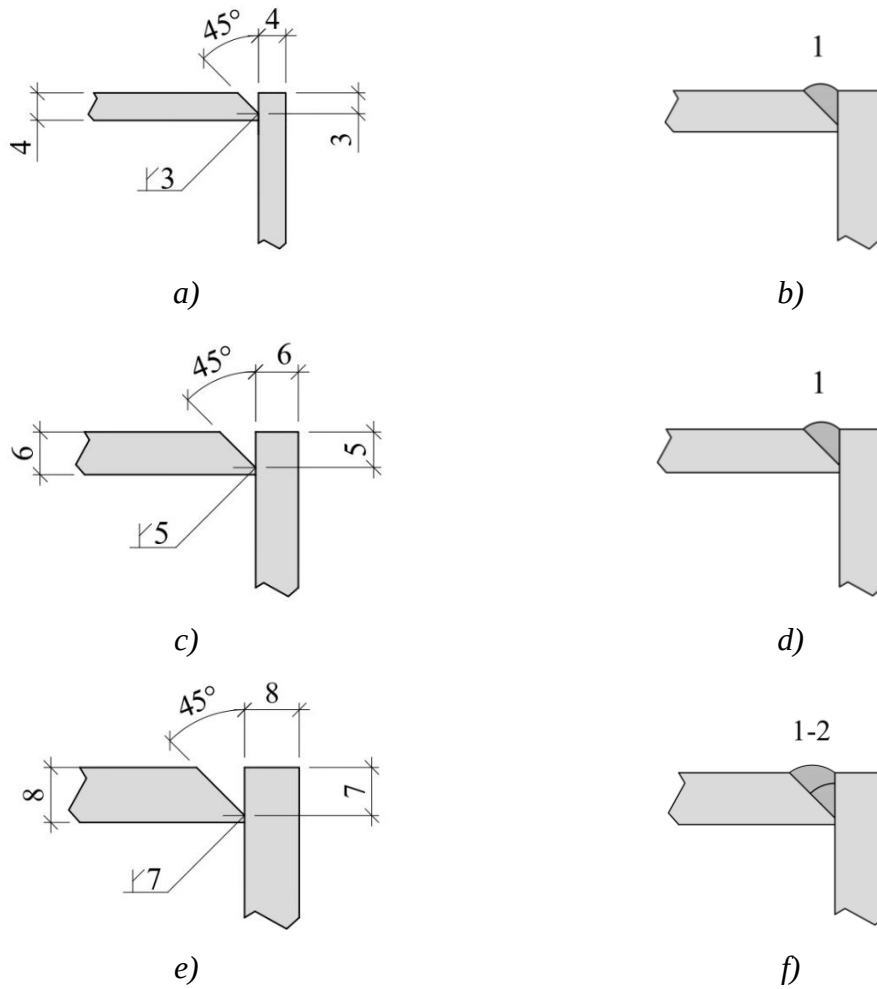


Fig. 33 - Sketch of the modelled specimen

As mentioned above, plate thickness of test specimens varies, so the plates are made with different edge preparation and weld sizes summarized in **Fig. 33** above. Parts a) and b) of the figure show edge preparation for RS4-700A and RS4-700B, RS4-H0 specimens, c) and d) parts of the figure show for RS6-355 and RS6-700, RS6-H0 and parts e) and f) of the figure are for RS8-700A, RS8-700B, RS8-H0.

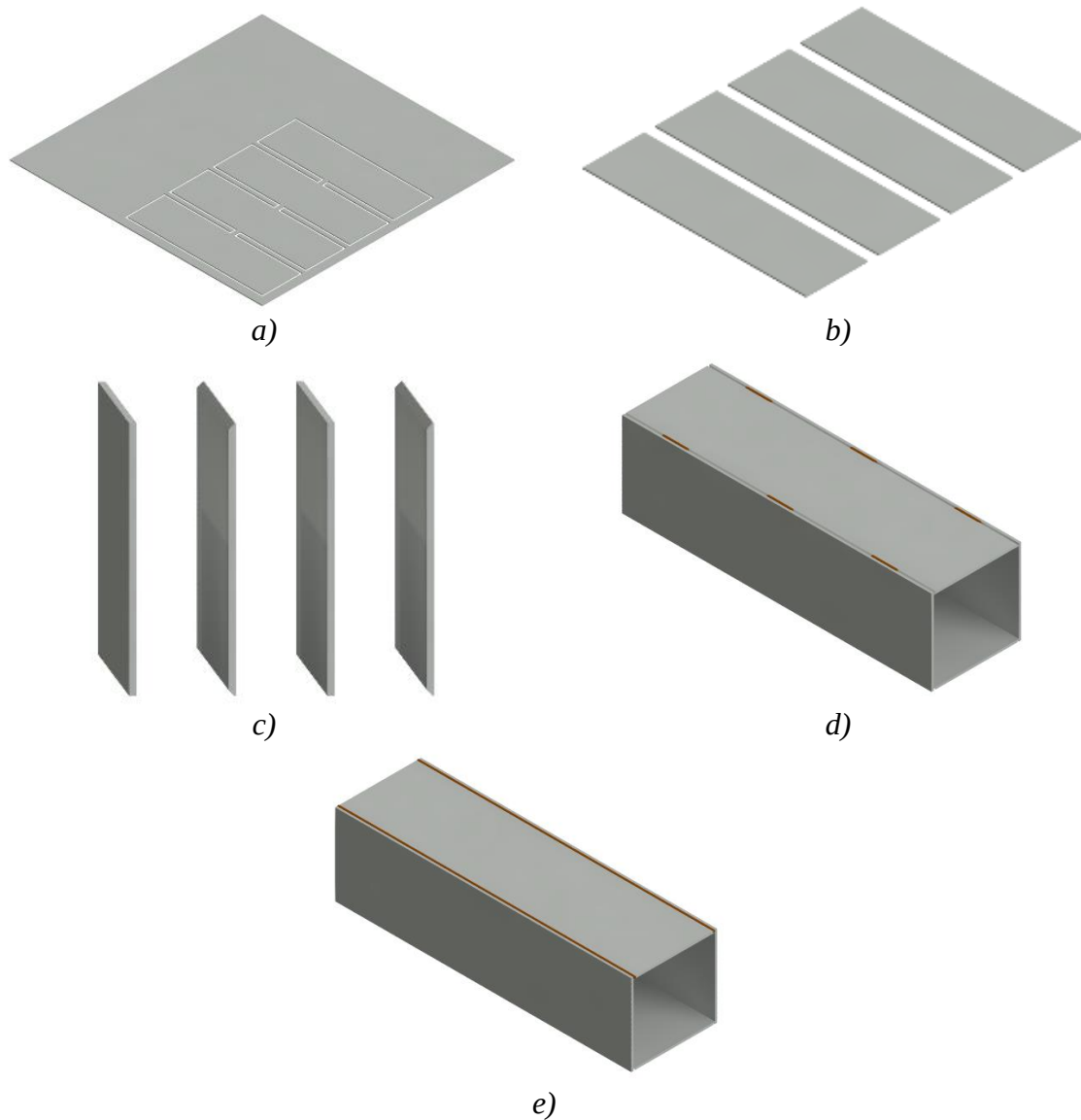


Fig. 34 - Manufacturing process: a) plasma cutting of constituent plates, b) separation of constituent plates, c) edge preparation, d) tack welding, and e) welding of the box section

The entire manufacturing process starts with the plasma cutting of the constituent plates, with the web plates and flange plates of the same plate thickness being joined by bridges during plasma cutting. The bonding of the individual plates is necessary to minimize the number of starting required for plasma cutting and to avoid the already cut elements from warping during cutting. This process is followed by the separation of the individual plates with the cutting up of the bridges. After edge preparation of the plates as specified in the WPS, the box sections can be assembled using tack welding. After that, welding of the box section begins. The sketch of the full process is shown in **Fig. 34**.

3.2 Welding variables

During manufacturing of specimens, it is essential to keep a record of the welding procedure and the welding variables used, as each of these variables has a significant influence on the heat input during production and thus on the residual stresses induced in the specimen. The applied welding process was MAG welding, which is one of the two main types of gas-shielded metal arc welding processes. During MAG welding, typically a mixture of inert gases (e.g., argon) and active gases (e.g., carbon dioxide) were used to protect the molten welding pool. A Fronius Trans

SynSteel 5000 welding power source was used for welding specimens. Wire and shielding gas were the same for all test specimens. The type of the shielding gas during manufacturing was M21 (82% Argon + 18% CO₂) mixed gas. The used solid wire was Mn3Ni1Mo (EN ISO 16834) WDI MoNi SG, with a diameter of 1.2 millimetres. Inspection certificate of the welding consumable, with a guaranteed minimum proof strength of 690 MPa, is presented in **Appendix A**. Certificates of the base materials are also presented in **Appendix A**. During the manufacturing process, no preheating was applied to the specimens, which is not justified due to the size of the specimen thicknesses. Ambient temperature was between 24.1 – 29.6 °C during manufacturing. Welding sequence of the weld passes was recorded, plotted and summarized in **Fig. 35**.

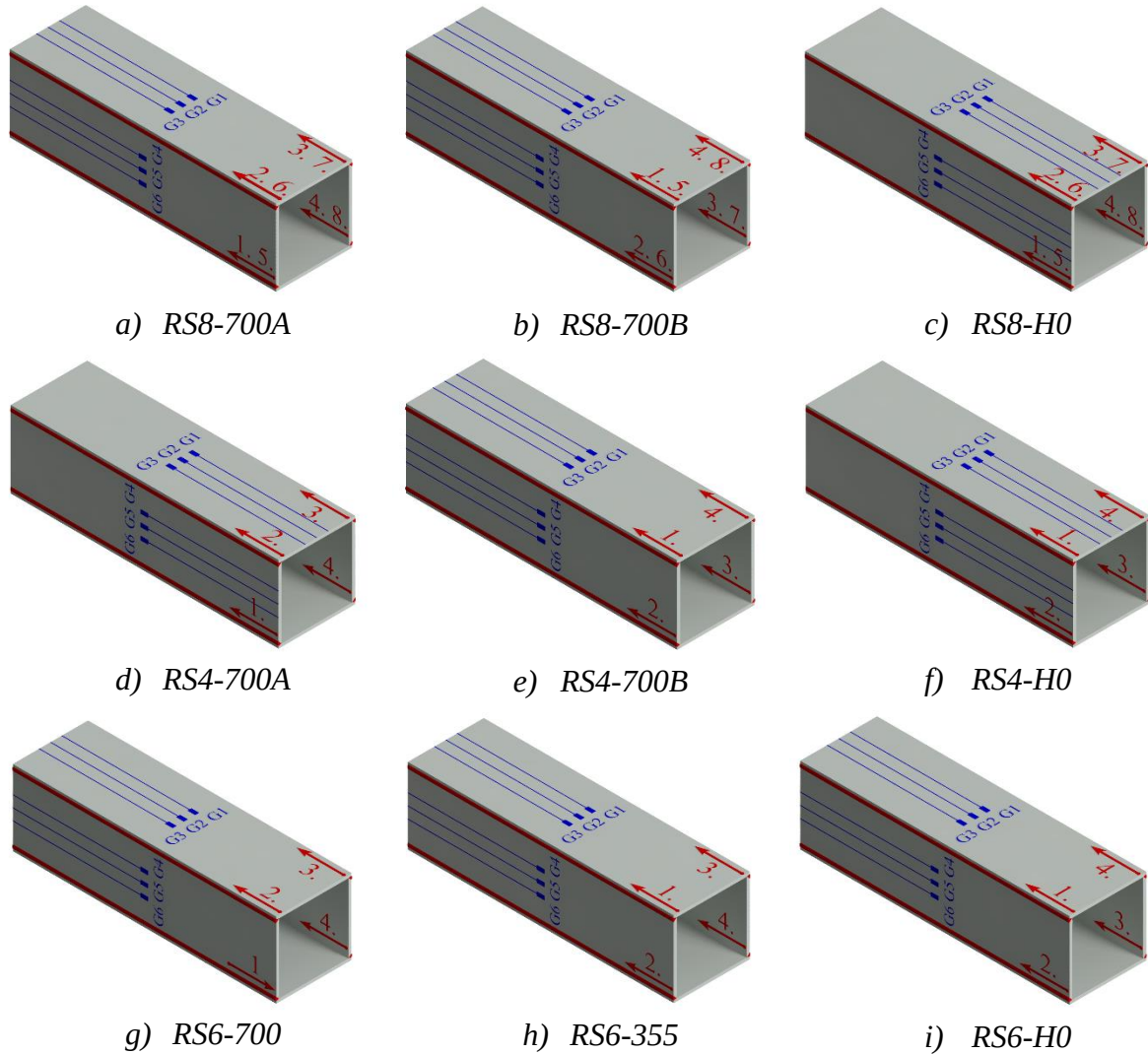


Fig. 35 - The welding sequence of the specimens in accordance with strain gauge positions

Table 2 summarize the welding parameters of the test specimens. The table includes the specimen name, the welding pass number #, the welding current I , the voltage U , the travel speed v , the total heat input $q = UI/v$ and welding time t . All specimens are manufactured with the same number of weld passes, except for the RS8 specimens. Test specimens containing 8 mm thick plates were made with one root and one cover weld, with eight weld passes in total. The joint of the plates in the box section was made with single-bevel butt weld in accordance with the welding procedure specifications (WPS), which can be found in **Appendix B**.

Table 2 - Welding parameters of the test specimens

Specimen	#	I [A]	U [V]	v [mm/s]	q [kJ/mm]
RS4-700A	1	220	19.5	7.45	0.58
	2	205	19	7.78	0.5
	3	192.5	18.5	7.78	0.46
	4	200	18.5	8.14	0.45
RS4-700B	1	200	20.25	9.59	0.42
	2	225	21.25	10.77	0.44
	3	215	20.75	10.14	0.44
	4	215	20.25	10	0.44
RS4-H0	1	215	20.75	10.61	0.42
	2	215	20.75	12.28	0.36
	3	215	20.75	10.61	0.42
	4	207.5	20.25	9.86	0.43
RS6-355	1	215	20.5	6.25	0.71
	2	210	20.25	6.2	0.69
	3	222.5	19.25	6.61	0.65
	4	225	20.75	6.72	0.69
RS6-700	1	215	19.5	5.59	0.75
	2	215	20	6.5	0.66
	3	215	19.75	6.11	0.7
	4	225	20	6.4	0.7
RS6-H0	1	222.5	23.25	7.77	0.67
	2	215	22.75	7.55	0.65
	3	225	22.75	7.69	0.67
	4	222.5	22.75	7.41	0.68
RS8-700A	1	197.5	18.5	9.33	0.39
	2	197.5	18.5	9.59	0.38
	3	187.5	18.75	10.94	0.32
	4	195	18.5	8.54	0.42
	5	225	20.5	7	0.66
	6	230	20.5	7.22	0.65
	7	235	21.75	7.87	0.65
	8	235	22.5	8.24	0.64
RS8-700B	1	200	20.25	12.73	0.32
	2	202.5	20.25	11.86	0.35
	3	205	20.25	9.86	0.42
	4	195	20.25	11.29	0.35
	5	222.5	24.25	8.14	0.66
	6	227.5	24.25	7.69	0.72
	7	217.5	24.25	8.43	0.63
	8	225	24.75	7.22	0.77
RS8-H0	1	215	21.75	12.96	0.36
	2	205	20.75	11.11	0.38
	3	205	20.25	11.48	0.36
	4	205	20.25	10.61	0.39
	5	205	23.75	7.53	0.65
	6	220	24.25	7.61	0.7
	7	220	24.75	8.05	0.68
	8	232.5	24.25	8.14	0.69

3.3 Dimensions of specimens

Although the nominal values of the geometric data of the manufactured specimens have been presented in the previous chapter of this paper, the numerical model uses the real geometric values of the specimens. In order to input these values, it is necessary to register the geometric data of the box sections, such as the gauge length (L), the plate iron thicknesses (t_1 , t_2) and the flange widths (a_1) and web height (a_2). The lengths of the specimens and the widths of the plates were measured with a tape measure, the plate thicknesses were measured with a digital caliper. **Table 3-5** summarize the measured geometrical data.

Table 3 – Dimensions of RS4 specimens

Specimen	L [mm]	L_{av} [mm]	t_1 [mm]	$t_{1,av}$ [mm]	t_2 [mm]	$t_{2,av}$ [mm]	a_1 [mm]	a_2 [mm]
RS4-700A	698	698.75	4.24	4.17	4.19	4.11	199	200
	699		4.12		4.10			
	698		4.13		4.10			
	700		4.17		4.06			
RS4-700B	700	699.50	4.11	4.10	4.10	4.10	200	200
	699		4.10		4.13			
	699		4.09		4.11			
	700		4.08		4.06			
RS4-H0	698	698.50	4.16	4.11	4.14	4.16	198	199
	699		4.14		4.19			
	699		4.11		4.15			
	698		4.01		4.16			

Table 4 - Dimensions of RS6 specimens

Specimen	L [mm]	L_{av} [mm]	t_1 [mm]	$t_{1,av}$ [mm]	t_2 [mm]	$t_{2,av}$ [mm]	a_1 [mm]	a_2 [mm]
RS6-355	799	799.00	6.19	6.20	6.21	6.19	219	220
	799		6.22		6.21			
	799		6.15		6.17			
	799		6.23		6.17			
RS6-700	799	798.50	6.13	6.10	6.17	6.17	220	219
	798		6.05		6.11			
	799		6.11		6.19			
	798		6.11		6.21			
RS6-H0	799	798.50	6.13	6.21	6.08	6.15	218	219
	798		6.24		6.22			
	798		6.22		6.06			
	799		6.25		6.24			

Table 5 - Dimensions of RS8 specimens

Specimen	L [mm]	L_{av} [mm]	t_1 [mm]	$t_{1,av}$ [mm]	t_2 [mm]	$t_{2,av}$ [mm]	a_1 [mm]	a_2 [mm]
RS8-700A	698	697.75	8.06	8.07	7.96	7.97	200	199
	698		8.11		7.97			
	697		8.05		7.97			
	698		8.06		7.99			
RS8-700B	698	698.50	8.03	7.98	7.93	8.00	198	199
	699		7.97		8.04			
	698		7.93		8.00			
	699		7.99		8.03			
RS8-H0	699	698.50	8.10	7.94	8.01	7.94	200	199
	698		7.85		7.82			
	699		7.95		8.02			
	698		7.87		7.90			

3.4 Dimensions of weld pools

The size of the weld pool is an important factor for the simulation of welding. The heat source model used in the modelling can be calibrated by knowing these parameters. To evaluate these data, detailed documentation was made by measuring the weld seams of the completed specimens and by inspecting the macro samples taken from the specimens. First, photographic documentation of the weld seam was made, and then semi-ellipsoids were fitted to the weld pool using AutoCAD software. The size of the weld pool for a given weld was calculated as the average of at least three semi-ellipsoids per weld. The fitting of the semi-ellipsoids is shown in **Fig. 36a**. To define the size of the weld pool, the three geometric dimensions shown in **Fig. 36b** are required. Since the dimension of the semi-ellipsoid in front of the source cannot be measured, the assumption of Goldak et al. [35] is followed for c_r and c_f using **Eq. (14)**. **Fig. 37-39** shows the weld pools of the specimens, while **Table 6-8** summarize the weld pool parameters for each weld.

$$c_r = 4c_f \quad (14)$$

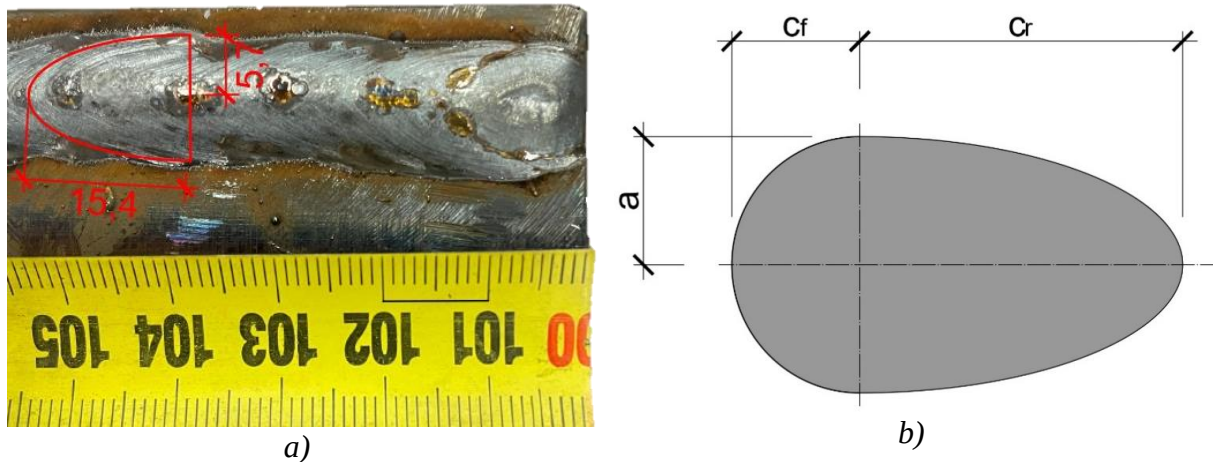


Fig. 36 - a) Measuring the size of weld pools and b) geometrical parameters of the weld pool



a) Weld pools of RS4-700A specimen



b) Weld pools of RS4-700B specimen

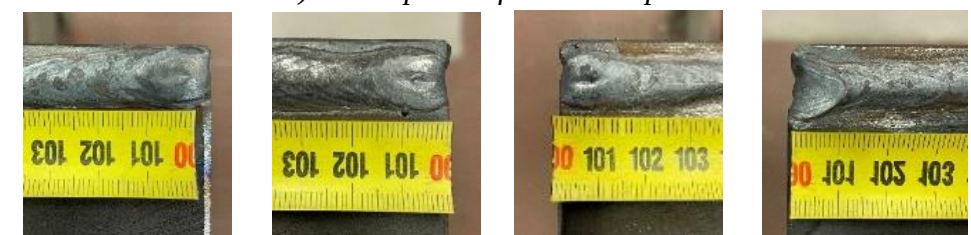


c) Weld pools of RS4-H0 specimen

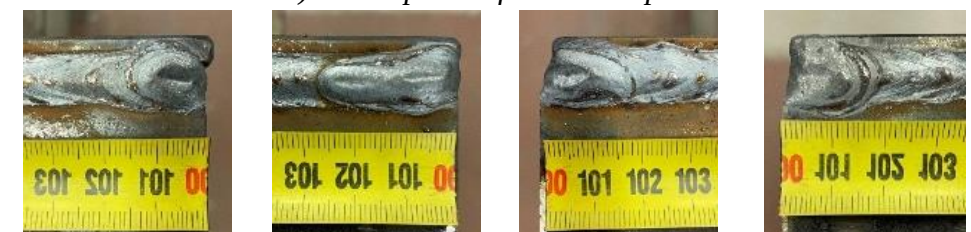
Fig. 37 - Weld pools of RS4 specimens: a) RS4-700A, b) RS4-700B, c) RS4-H0



a) Weld pools of RS6-355 specimen



b) Weld pools of RS6-700 specimen



c) Weld pools of RS6-H0 specimen

Fig. 38 - Weld pools of RS6 specimens: a) RS6-355, b) RS6-700, c) RS6-H0

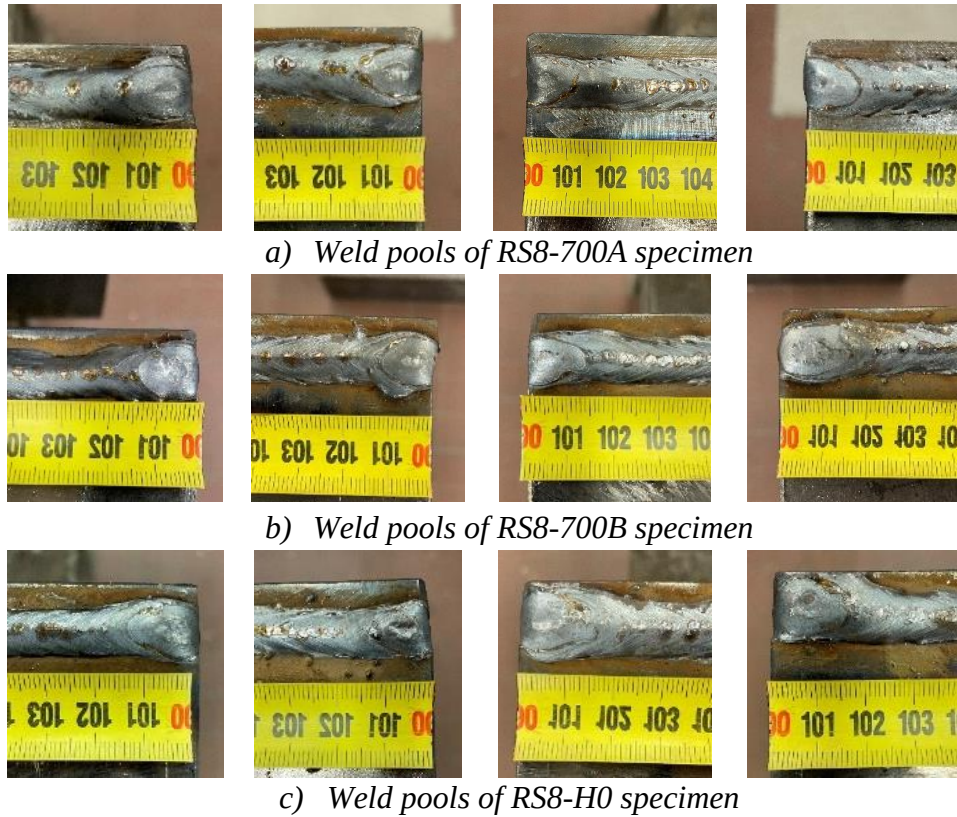


Fig. 39 - Weld pools of RS8 specimen: a) RS8-700A, b) RS8-700B, c) RS8-H0

By recording the welding parameters and the geometric dimensions of the weld pool, the relationship between these parameters can be investigated. Diagrams in **Fig. 40** show the relationship between total heat input, width a and the semi-axis length c_r of the rear semi-ellipsoid of the weld pools. The plotted points show that an increase in heat input causes an unambiguous increase in the width of the weld pool, while there is a larger scatter for semi-axis length c_r . However, a slight increase can be found as well; although, the slope of the trend line laid on the points is smaller than for the a - q chart.

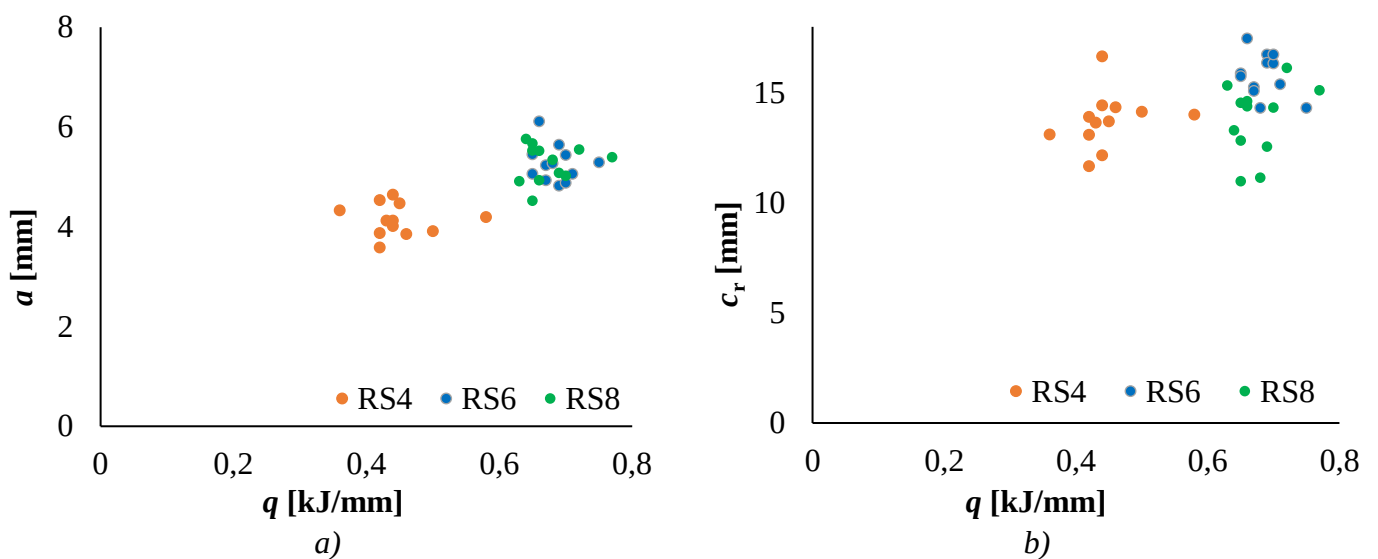


Fig. 40 - Relationship between total heat input and a) weld pool width and b) semi-axis length of rear ellipsoid

Table 6 - Dimensions of weld pools - RS4 specimens

Specimen	#	a_{mean} [mm]	$Cf.\text{mean}$ [mm]	$Cr.\text{mean}$ [mm]
RS4-700A	1	4.19	3.5	14.01
	2	3.91	3.54	14.14
	3	3.85	3.59	14.35
	4	4.47	3.43	13.7
RS4-700B	1	4.53	3.27	13.09
	2	4.64	3.61	14.43
	3	4.12	3.04	12.16
	4	4.01	4.17	16.66
RS4-H0	1	3.87	3.48	13.91
	2	4.33	3.28	13.11
	3	3.58	2.92	11.67
	4	4.12	3.41	13.65

Table 7 - Dimensions of weld pools - RS6 specimens

Specimen	#	a_{mean} [mm]	$Cf.\text{mean}$ [mm]	$Cr.\text{mean}$ [mm]
RS6-355	1	5.06	3.85	15.39
	2	5.64	4.19	16.75
	3	5.45	3.97	15.88
	4	4.82	4.09	16.37
RS6-700	1	5.29	3.58	14.31
	2	6.11	4.37	17.47
	3	5.44	4.09	16.34
	4	4.88	4.19	16.75
RS6-H0	1	4.93	3.82	15.26
	2	5.06	3.94	15.76
	3	5.23	3.77	15.09
	4	5.27	3.58	14.32

Table 8 - Dimensions of weld pools - RS8 specimens

Specimen	#	a_{mean} [mm]	$Cf.\text{mean}$ [mm]	$Cr.\text{mean}$ [mm]
RS8-700A	5	5.52	3.65	14.62
	6	5.67	3.64	14.55
	7	5.53	3.21	12.83
	8	5.76	3.32	13.3
RS8-700B	5	4.93	3.6	14.38
	6	5.55	4.03	16.13
	7	4.91	3.83	15.33
	8	5.39	3.78	15.11
RS8-H0	5	4.52	2.75	10.99
	6	5.02	3.58	14.33
	7	5.34	2.78	11.14
	8	5.08	3.14	12.56

3.5 BAM strain-measuring extensometer

The BAM strain-measuring extensometer is a mechanical device for measuring static deformation. Its primary use is to check static deformations and verify stress analysis calculations, and to monitor crack and cavity width changes. Its use is widespread in underground mining to check deformations of mine pillars. The device consists of the meter housing, the associated trigger and dial gauge, and two measuring legs. The extensometer has two measuring legs, one of which is fixed and the second one is adjustable. The adjustable leg is connected to the dial gauge of the instrument. During the measurement, the adjustable and fixed legs of the extensometer are attached to small steel bearing balls hammered or glued into the material of the body to be measured. The elongation or compression of the measured object during the measurement is due to the difference in the instrument dial before and after the deformation of the measuring section. An important advantage of this measurement method over strain gauges is that the measuring instrument is not permanently exposed to the effects to which the measured object is. Another advantage is that the bearing ball marks, which give the measuring distance, are very stable under harsh environmental conditions. Furthermore, temperature effects and wear of the instrument can be compensated by comparative measurements on the device's control sections. [36]

The longitudinal deformations of specimens in the present experimental program were measured in the midsection of the test samples using a 40 mm base length. A sketch of the measuring points on each specimen is summarized in **Fig. 41**. Several measurements were taken before and after welding to determine the distance between the measuring points. The minimum, maximum, and average values of the extensometer measurements were collected when processing the measurement results. For the post-weld condition, the measured values were corrected by the values measured on the BAM extensometer reference during welding. Using the pre-weld measurement data and the post-weld data corrected by the etalon, the length variation of the measurement section can be calculated. The elongations calculated in this way were projected back to a reference temperature of 20°C using the linear expansion coefficient. The outlined calculation steps were used to determine the minimum strains, the maximum strains and the average strains of the elongation data, and then plotted in a common coordinate system.

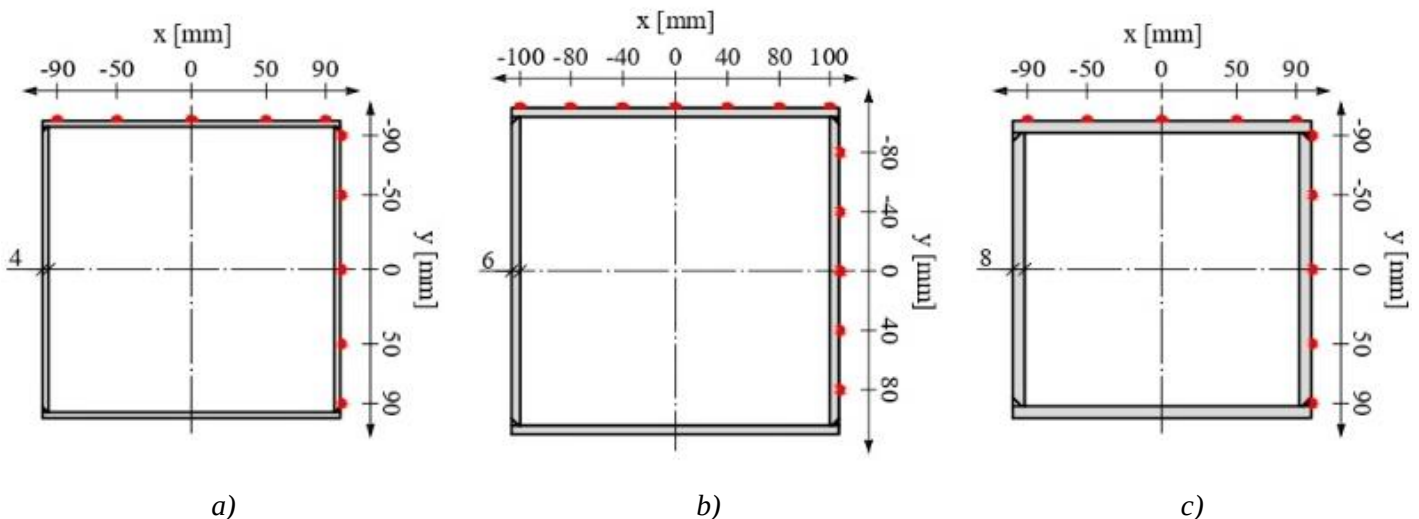


Fig. 41 - Sketch of BAM strain-measuring extensometer's measuring points: a) RS4 specimens
b) RS6 specimens c) RS8 specimens

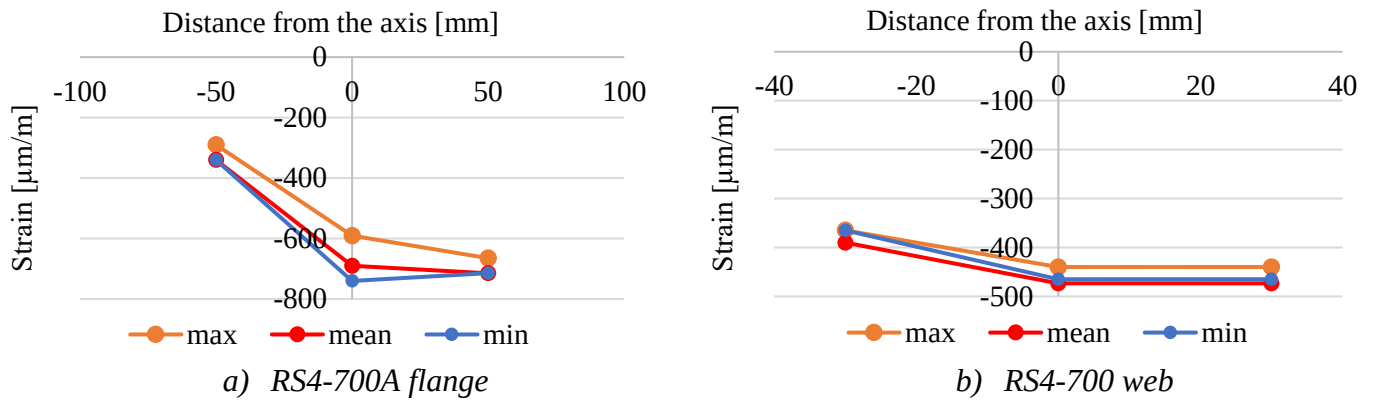


Fig. 42 - Axial strains $[\mu\text{m/m}]$ with BAM strain-measuring extensometer

During the processing of the results, it was concluded not to use the measurement points that were close to HAZ zone, due to the unreliability of these results. **Fig. 42** summarize the measured and corrected strains for RS4-700A specimen, whose are sufficiently far from the HAZ zone. The plots of the measurement results for all the specimens are shown in **Appendix C**. It can be concluded based on the measurement procedure that it is recommended to use pre-drilling when placing the measurement points in case of high strength material. Furthermore, it is not recommended to use the measurement procedure close to the weld seam.

3.6 Strain gauge-based measurements during welding

Measurement with strain gauges can provide essential data on the amount of deformation and residual stresses that occur during welding. During the measurement, the strain gauges bonded to the closure sections deform together with the material of the test specimen, whereby their electrical resistance changes in proportion to the deformation. From the change in electrical resistance, the degree of deformation can be calculated. In all cases, the measurement points were placed in the midsection of the test samples. It is very important that strain gauges should be placed at an appropriate distance from the high temperature zone of the weld to ensure its integrity. Locations of the measuring points are summarized in **Fig. 43** and are determined using FEM-based precalculations based on the data given in the WPS sheets. As can be seen, the number of strain gauges installed on the specimens is the same in all cases, six to six pieces area installed per specimen on the outer surfaces and two strain gauges are used on the inner surfaces. In case of the welded specimens due to the symmetry, measurements are carried out only on two sides of the specimens.

The first step in the installation of strain gauges is to create a clean surface at the location of the strain gauges using a metal grinding disc. After grinding, a surface cleaning agent was used. In the second step, the strain gauge stamp is glued to the test piece and the electrical wires are soldered to it. In the experimental set-up, the strain gauges are connected to the HBM MGCplus data aquisition system via an HBM Canhead amplifier system. During the measurement, the strains are continuously displayed on a laptop in HBM CatmanEasy software. During the measurements, 72 Kyowa strain gauges (KFGS-3-350-C1-11) with 350Ω resistance were used in total.

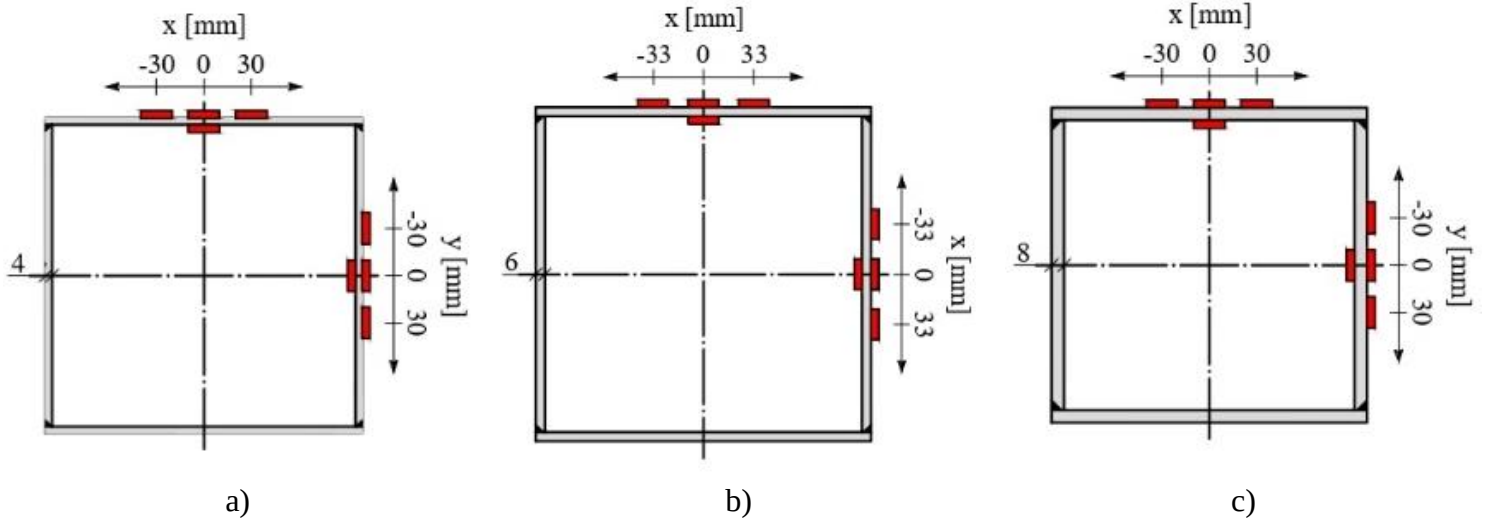


Fig. 43 - Sketch for the positions of strain gauges: a) RS4 specimens, b) RS6 specimens, and c) RS8 specimens

When processing the measurement results of the strain gauges, the measured final strain values were collected for each strain gauge. During the welding process, the temperature of the specimens at the end of the measurement was recorded so that the results could be extrapolated to a reference temperature of 20°C using the coefficient of thermal expansion. Finally, strains of the flange and the web are plotted in a common coordinate system, just as the values of the internal and external gauges. The results of the strain gauge-based measurement are summarized in **Fig. 44** and **Fig. 45**, with the first and the third quartile, for different b/t parameters and steel grades, respectively, while results in detail are presented in **Appendix D**. It can be concluded that absolute value of compressive residual strains (and thus stresses) in the flange decrease in by increasing the b/t ratio, while steel grade has minor importance which is in agreement with the model proposed by Kövesdi and Somodi [23]. It is clearly shown that strains are smaller in the webs than in the flanges due to the position of single-bevel butt welds.

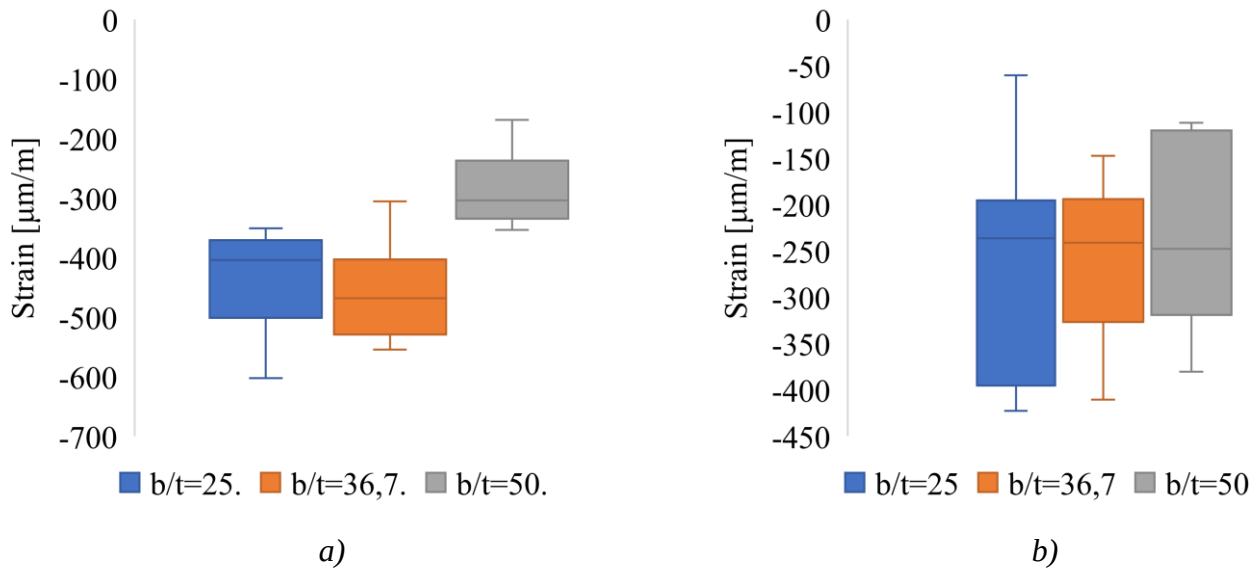


Fig. 44 - Measured residual strain ranges of different b/t parameters on a) flange, and on b) web

3 Measurements

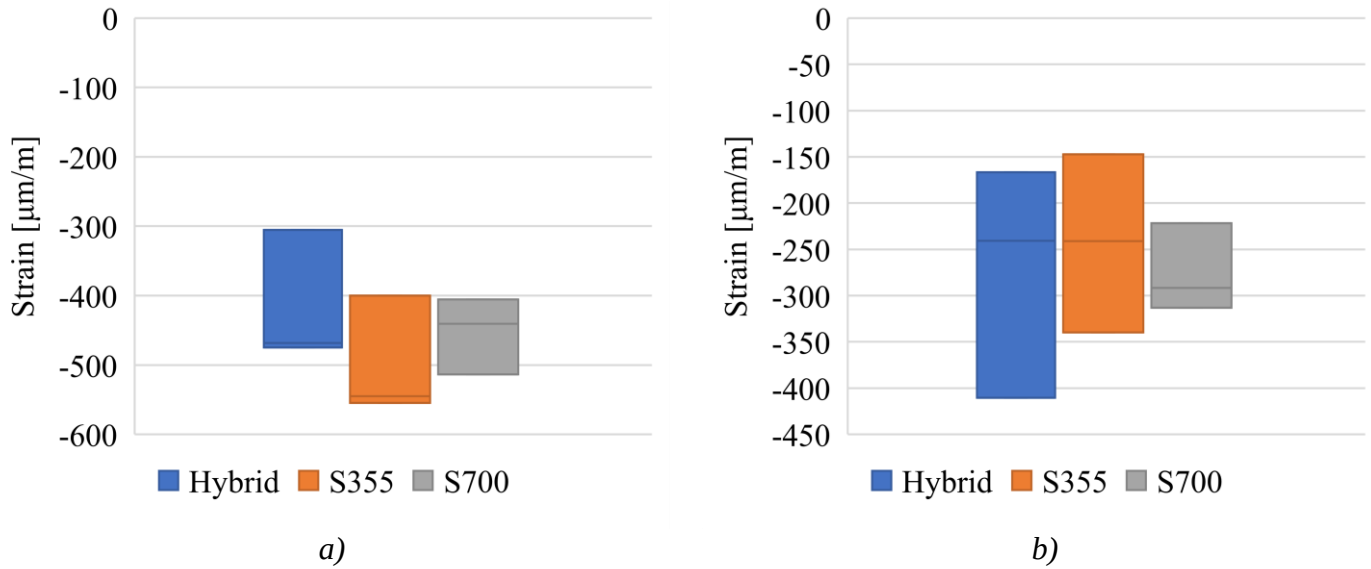


Fig. 45 - Measured residual strain ranges of different steel grades on a) flange, and on b) web

As already mentioned, we placed external and internal strain gauges in the plate axis, on both the flange and the web, the results of these measurements are summarized in **Fig. 46**. The data from the internal and external strain gauges can be used to infer the stress distribution of the plate along the thickness and the magnitude of bending in the plate. As summarized in **Fig. 47**, it can be concluded that as plate thickness increases, the strain measured on the external strain gauges deviates at an increasing rate from the value measured on the internal gauge. Data not available for some specimens due to failure of the strain gauge stamp, these specimens data's are missing from the diagrams.

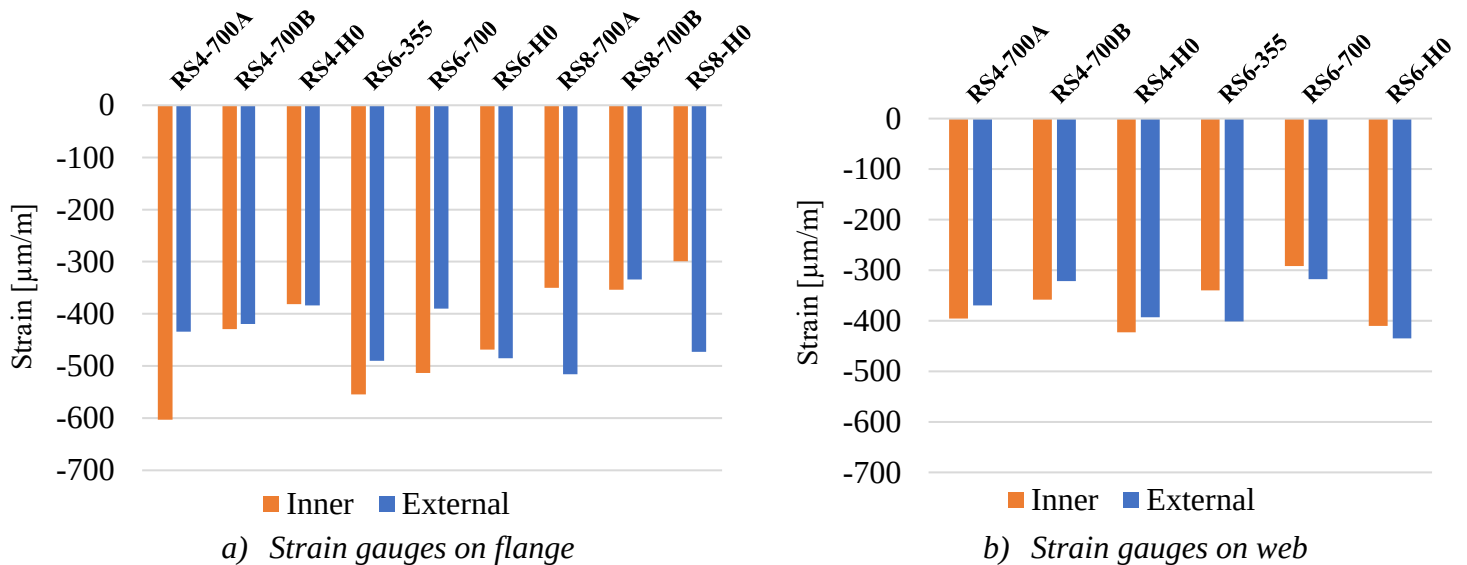


Fig. 46 - Axial strains [μm/m] measured by inner and external strain gauges on a) flange, b) web

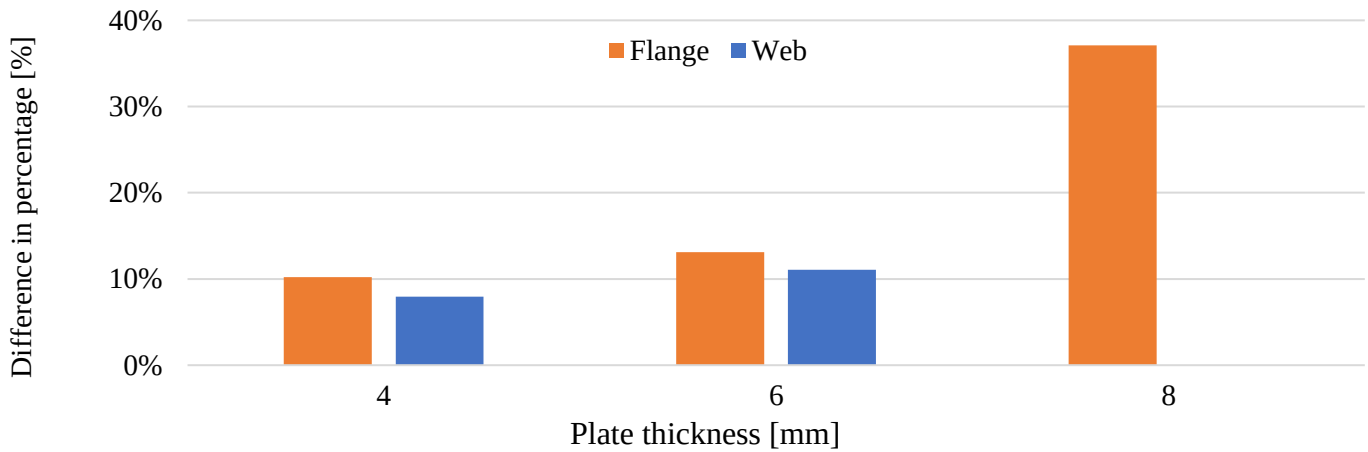


Fig. 47 - Percentage difference between the measured strains of the internal and external strain gauges for different thicknesses

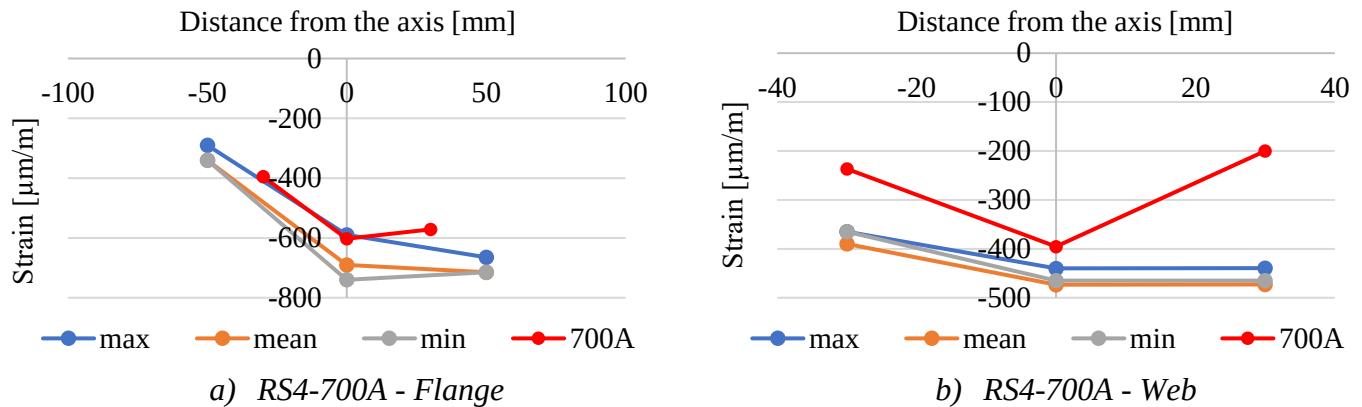


Fig. 48 - Correlation of BAM extensometer measurements (min, mean and max) with strain gauge measurements on a) flange and b) web of RS4-700A specimen

It is important to note that at the time of writing, the contour method of the specimens is in progress, which can help draw further conclusions about generated residual stresses and by the manufacturing process. However, before we get the results of the contour method, it is possible to compare the results of BAM extensometer measurement and strain gauges measurement. The results of the BAM extensometer measurement and the strain gauge measurement are plotted in a common coordinate system, as shown in **Fig. 48** for the RS4-700A specimen. The diagrams of the measurement results for each specimen are summarized in the **Appendix E**. A comparison of the strains measured by the two methods at the centre of the plate shows that the greatest agreement for both the web and the flange was for the RS4 specimens (**Fig. 49**). With increasing plate thicknesses, the difference between the results of the two methods increases. For RS4 specimens, the difference in the strains of the flange is 9.8-12.7% compared to the strain gauge results. The same value for RS8 specimens is 6.3%-47.8%. It can also be concluded that the difference between the deformations of the non-welded plate (flange) measured by the two methods is smaller than that of the welded plate (web). The average difference between the results is 21.2% for flange and 28.7% for web.

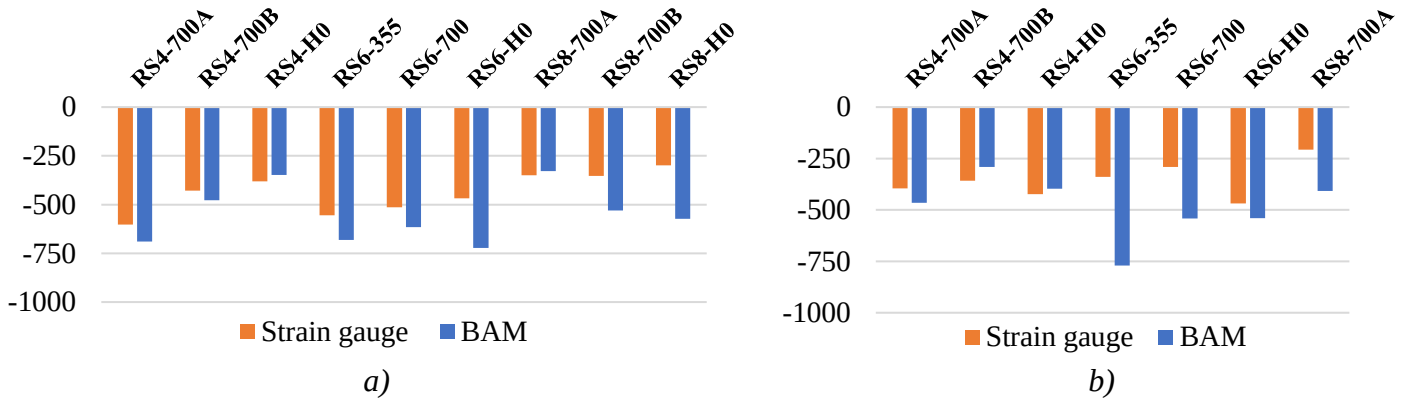


Fig. 49 - Measured axial strain at the axis of the a) flange and b) web based on BAM and strain gauge measurement

6.1 Deformed shape measurement

To measure local geometric imperfections, i.e., out-of-flatness, we used a specially designed mobile device with an inductive transmitter. The instrument, driven by an electric motor, moves along a track of a box section fixed at both ends. It is essential to prevent movement of both the locking section track and the measured specimen during the measurement. For this purpose, the test piece is supported to prevent wobbling, and the track guiding the gauge is clamped at the support points.

The instrument measures the horizontal distance taken by the transmitter as it rolls over the test piece surface and the change in vertical distance between the measured surface and the box section track. Thus, when processing grains, each horizontal point can be associated with a vertical point, along the measured line. With the right number and direction of measurements, the deformed plane can be created. In each case, the inductive transmitter was started in one of the box sections enclosing the measured specimen, leaving a gap of 10 to 15 centimetres between each element. This arrangement allowed measurements to be taken along the entire length of the test piece and facilitated the processing of the measurement results. During the measurement, the data was recorded at a sampling frequency of 50 Hz. An outline of the experimental setup is shown in **Fig. 50**.

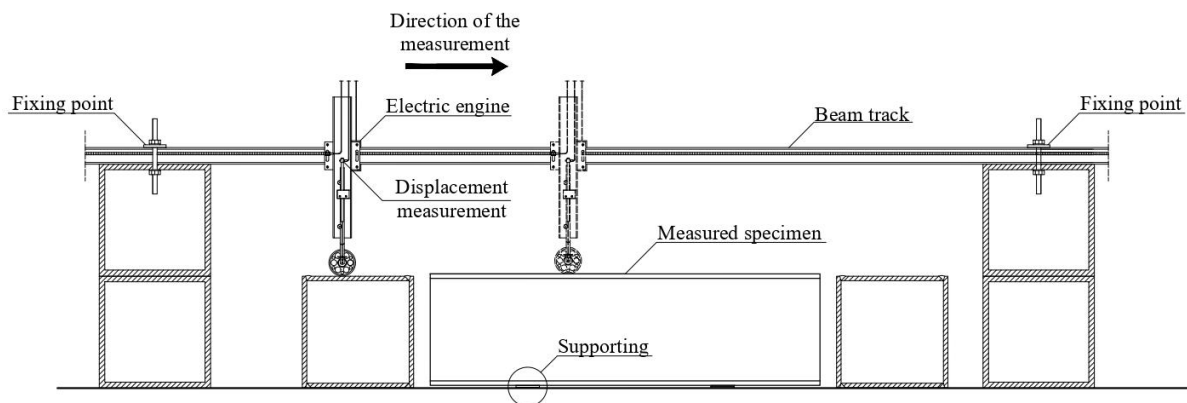


Fig. 50 - Sketch for the measurement set-up

Measurements of the deformed shape were taken along 5 longitudinal lines and two transverse lines on each flange and web, as shown in **Fig. 51**. For the longitudinal lines, L1, L2, L3, L4 and L5, the measurement direction was the same as the welding direction. For the transverse directions, T1 is the cross section at the beginning of the weld and T2 is the cross section at the

end of the weld. For the transverse directions, the measurement direction was always from the direction of L5 to L1.

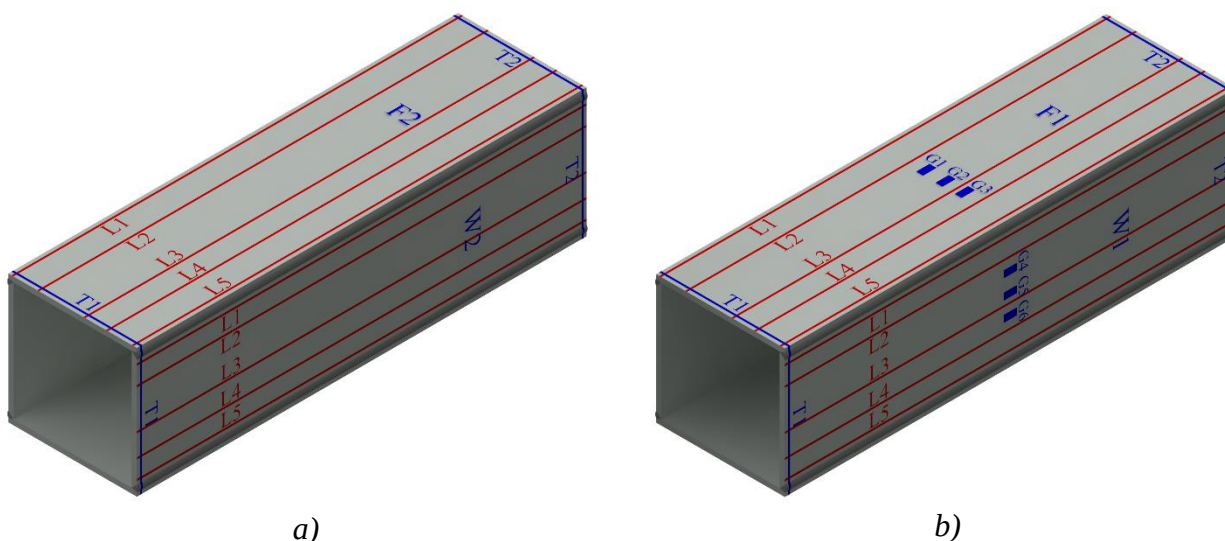


Fig. 51 - Longitudinal and transverse measuring lines of shape measurement

In documenting the measurements, it was necessary to be able to identify the individual plates, so the following designations were used in the measurements:

- F1: flange with strain gauge, non-welded plate
- F2: flange without strain gauge, non-welded plate
- W1: web with strain gauge, welded plate
- W2: web without strain gauge, welded plate

By processing the measured data, the deformations are plotted per constituent plate for RS4 specimens, as shown in **Fig. 53**. Typical out-of-flatness magnitudes vary between -1.5 mm and +0.4 mm; thus, the measured maximum is around $b/150$, which is even larger than the equivalent geometric imperfection for panels and subpanels ($b/200$) in EN 1993-1-5. On the other hand, it is in accordance with the functional tolerances of EN 1090-2 since it is $b/100$ and $b/150$ for Classes 1 and 2 (**Fig. 52**), respectively.

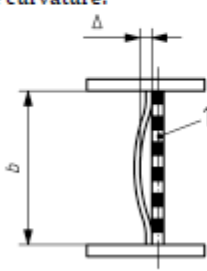
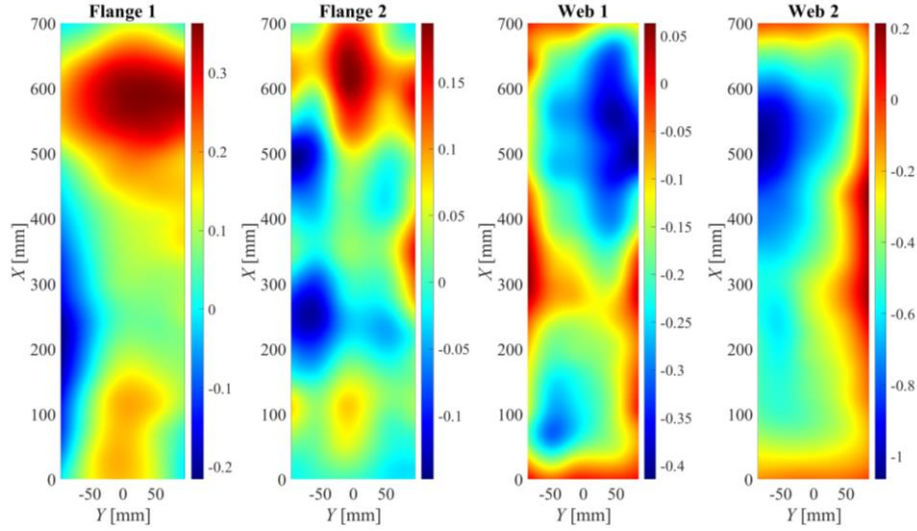
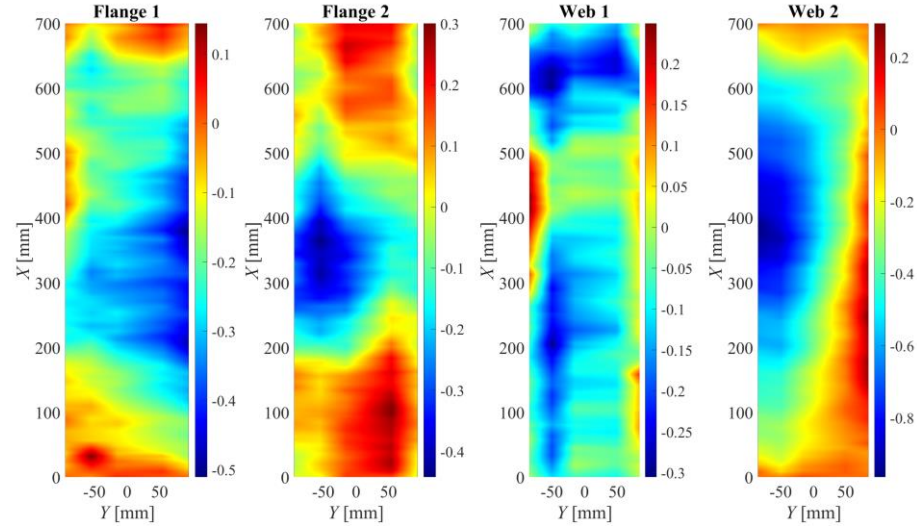
No	Criterion	Parameter	Essential tolerances Permitted deviation Δ	Functional tolerances Permitted deviation Δ	
			Class 1 and 2	Class 1	Class 2
7	Plate curvature: 	Deviation Δ over plate height b :	$\Delta = \pm b / 200$ if $b/t \leq 80$ $\Delta = \pm b^2 / (16\,000\,t)$ if $80 < b/t \leq 200$ $\Delta = \pm b / 80$ if $b/t > 200$ but $ \Delta \geq t$ (t = plate thickness)	$\Delta = \pm b / 100$ but $ \Delta \geq 5\text{ mm}$	$\Delta = \pm b / 150$ but $ \Delta \geq 3\text{ mm}$

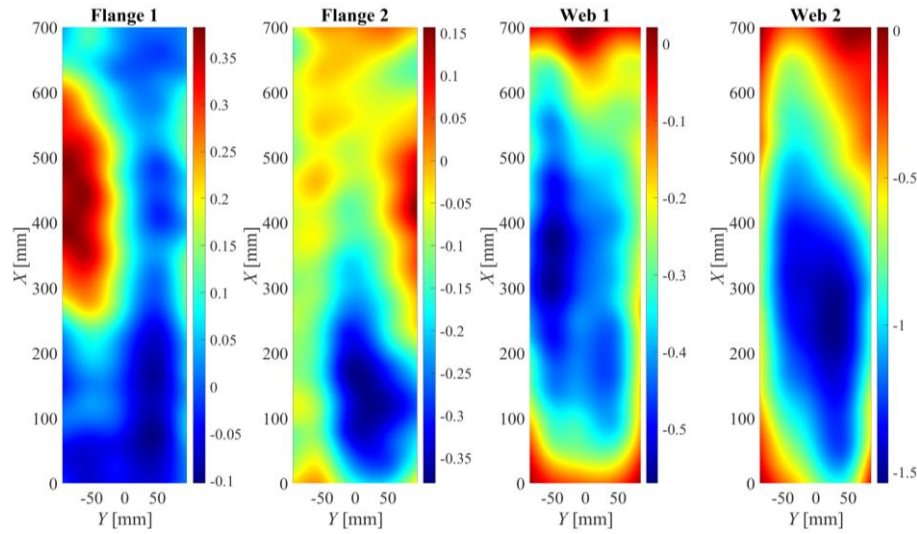
Fig. 52 - Tolerances for local distortions of welded panels in EN 1090-2



a) RS4-H0



b) RS4-700A



c) RS4-700B

Fig. 53 - Results of out-of-flatness measurements for RS4 specimens

3.7 Mechanical properties of base materials

To determine the strength properties of the material, tensile tests can be carried out on specimens taken from box sections, but the manufacturer also provides data on the material. The manufacturer specifies, among other properties, the ultimate strength (R_m) and yield strength (R_{eH}) for NSS. If no clear yield strength can be identified, the proof strength $R_{p0.2}$ is added, which is the stress at 0.2% elongation. The summarizing table of the strength properties of the base material is shown in **Table 9** based on inspection certificates.

Table 9 - Yield strength and tensile strength of base materials

Specimens	Steel grade	R_{eH} [MPa]	R_m [MPa]
RS4-700A	S700MC E	753	829
	S700MC E	753	829
RS4-700B	S700MC E	753	829
	S700MC E	753	829
RS4-H0	S355MC	402	469
	S700MC E	746	797
RS6-355	S355J2+N	446	570
	S355J2+N	446	570
RS6-700	S700MC E	749 ($R_{p0.2}$)	833
	S700MC E	749 ($R_{p0.2}$)	833
RS6-H0	S355J2+N	446	570
	S700MC E	749 ($R_{p0.2}$)	833
RS8-700A	S700MC E	738	827
	S700MC E	738	827
RS8-700B	S700MC E	738	827
	S700MC E	738	827
RS8-H0	S355MC	400 ($R_{p0.2}$)	486
	S700MC E	738	827

3.8 Chemical composition of base materials

Knowledge of the chemical composition of the base materials used in the manufacture of test specimens is useful and necessary for several points of view. The factor that can be used to characterize steel base material is the so-called carbon equivalent. In the literature, there are several formulae for calculating this factor of the material based on chemical composition, yield strength, etc. Thus, novel equations (e.g., **Eqs. (15)-(18)**) have been developed over time to improve the accuracy for different types of steel:

$$CE = C + \frac{Mn}{6} + \frac{Cr+Mo+V}{5} + \frac{Cu+Ni}{15} \quad (15)$$

$$CEM = C + \frac{Si}{25} + \frac{Mn+Cu}{20} + \frac{Cr+V}{10} + \frac{Mo}{15} + \frac{Ni}{40} \quad (16)$$

$$CET = C + \frac{Mn+Mo}{10} + \frac{Cr+Cu}{20} + \frac{Ni}{40} \quad (17)$$

$$CEV = C + \frac{Mn}{6} + \frac{Cu+Ni}{15} + \frac{Cr+Mo+V}{5} \quad (18)$$

The most common equation is the CE, which is adopted by the International Institute of Welding (IIW). Another method of calculating the carbon equivalent is the so-called CEM, but it is important, the carbon equivalent CEM can only be used under the very limited conditions of the short cooling time range (2 to 6 s) and the narrow validity range of the chemical composition. The most currently comprehensive carbon equivalent for the prevention of cold cracking is the carbon equivalent CET was formulated by Uwer und Höhne in 1991. It is important to note that the literature does not recommend using CET for high strength materials. The calculation of the EN 10025-1 carbon equivalent value (CEV) is based on the IIW recommendation, so its calculation is the same as the IIW's CE factor. The method of calculation of the carbon equivalent values indicated on the certificates of the steel materials used in the research is the CEV factor method. [37-38]

The chemical composition of the base materials is summarized in **Table 10**, with calculated solidus temperatures of the material. The carbon equivalent values (CEV) of each base material is also shown in the table. From a welding modelling point of view, knowledge of the chemical composition is also necessary to know the solidus and liquidus temperatures. As we mentioned before the solidus temperature (T_s) is the highest temperature at which an alloy is completely solid, and the liquidus temperature (T_L) is the lowest temperature at which an alloy is completely liquid. It is important to note that the calculation of the solidus and liquidus temperatures of the high solids and nominal solids considered in this research is different, and there are several recommendations in the literature on the subject [34]. The solidus and liquidus temperatures of normal strength steel material can be calculated from the carbon content as follows [34]:

$$T_s = 1527 - 181.356C \quad (19)$$

$$T_L = 1530 - 80.581C \quad (20)$$

A large number of additional formulas for calculating solidus and liquidus temperatures can be found in the literature, but it is important to note that the accuracy of these formulae depend largely on the chemical composition of the product. In 2013, Gryc et al. [39] published a study focusing on the calculation of solidus and liquidus temperatures of different steel materials. The solidus and liquidus temperatures of steels were provided by thermal analysis, literature formulae and Computherm thermodynamic software. In their study, they summarized the formulae that showed the smallest deviation from the results of the thermal analysis considered as the standard. When calculating the liquidus temperature of steel, **Eq. 21** was found to be the most accurate for higher carbon contents of 0.25%, while **Eq. 22** was found to be the most accurate for lower carbon contents of 0.04%. In studies, **Eq. 23** has been used to determine the solidus temperature, but its accuracy was much lower than the formulae developed in the literature for calculating the liquidus temperature. In general, it can be concluded that the variability of the calculated values compared to the thermal analysis of steel materials is due to the alloying element content of the steel grades investigated [39].

Table 10 - Chemical composition of the base materials

	C%	Si%	Mn%	P%	S%	Al%	Nb%	CEV
S355J2+N	0.19	0.21	1	0.015	0.007	0.036	0.002	0.4
S355MC	0.061	0.01	0.69	0.011	0.004	0.028	0.027	0.2
S700MC	0.055-	0.02-	1.83-	0.009-	0.002-	0.039-	0.052-	0.4
	0.062	0.03	1.93	0.014	0.002	0.058	0.063	
	V%	Ti%	Cu%	Cr%	Ni%	Mo%	N%	$T_s [^{\circ}C]$
S355J2+N	0.001	0.001	0.016	0.018	0.01	0.006	0.006	1514.69
S355MC	0.006	0	0.011	0.05	0.03	0.003	0.005	1513.48
S700MC	0.01-	0.099-	0.01-	0.02-	0.03-	0-0.1	0.004-	1505.66-1505.78
	0.05	0.11	0.2	0.5	0.04		0.005	

3 Measurements

$$T_L = 1535 - 73C - 3Mn - 12Si - 28P - 30S - 7Cu - 1Cr - 3.5Ni - 3Al - 1Sn - 2Mo - 18Ti - 2V - 1.8Co \quad (21)$$

$$T_L = 1536 - 251C - 12.3Si - 6.8Mn - 123.4P - 183.9S - 3.3Ni - 1.4Cr - 3.1Cu - 3.6Al \quad (22)$$

$$T_S = 1536 - 251C - 12.3Si - 6.8Mn - 123.4P - 183.9S - 3.3Ni - 1.4Cr - 3.1Cu - 3.6Al \quad (23)$$

4 Development of numerical model

Nowadays, it is a remarkable demand to speed up and improve the frequently used manufacturing processes such as welding. Welding technologies are generally developed by experiments and specimen tests, the computational methods are still rarely used in this procedure. We should mention that the application of Computer-aided Engineering opportunities is more efficient and economical than experiments. To perform numerical simulations is faster and easier than to carry out welding experiments, especially when dealing with large-scale welded structures. As Goldak and Akhlaghi [34] denoted before, in the automotive industry the number of prototypes has been significantly reduced applying Computer-aided Engineering sources. However, it should be mentioned that prototypes are still necessary in reduced number to validate simulations.

Developing a sustainable virtual manufacturing process is a good option to get information about the deformations and the residual stress distribution during welding process, so we can reach the optimal residual stress and deformation relation. Furthermore, with specified optimal manufacturing conditions we can reduce waste in workshops as well. Numerical simulations can play an important role in the development of production quality and design of sustainable structures. However, it must be declared that computations still have boundaries.

The used numerical modelling method is an uncoupled thermomechanical analysis. During the modelling process, an appropriate heat source model, thermal and mechanical material properties, and thermal and mechanical boundary conditions have to be defined. The numerical model used in this research is suitable for parametric studies, after its parameters and variables have been properly adjusted and validated with experimental results. The thermal analysis of these numerical models can be used to predict the induced temperature in the specimen during welding, and the mechanical analysis of the models can be used to determine deformations and residual stresses resulting from welding.

4.1 Finite element types

The applied numerical framework utilizes solid elements. SOLID70, a thermal solid element, has a three-dimensional thermal conduction capability. The element has eight nodes with a single thermal degree of freedom at each node. SOLID185, the equivalent structural solid element, has eight nodes with three translational degrees of freedom at each node. Solid elements with pure displacement formulation and full integration with B-bar method are used in the vicinity of the weld. Elements with enhanced strain formulation are applied in the remaining domains.

4.2 Material properties

4.2.1 Thermal material model

The used temperature-dependant thermal material model in the simulation is based on EN 1993-1-2. This standard does not include microstructural changes and phase proportion evolution directly. One of the most important thermal material properties is density, which is considered to be 7850 kg/m^3 as a constant in the simulation according to the standard. In reality, it is not a constant value because of the changing material volume, but this approximation has a low effect on the simulation results.

Other thermal material properties are the specific heat, which gradient is shown in **Fig. 54** as a function of temperature, which has a peak point at 735°C . This peak is due to the phase transformations between $\alpha\text{-Fe}$ and $\gamma\text{-Fe}$ where the lattice structure changes as also shown in **Fig. 54**. The standard considers specific heat to be constant after 1200°C , but during welding the

temperature can be higher, so this effect should be treated. Latent heat due to solidification or melting can be handled by implementing the effective specific heat to the model. The effective specific heat is given by **Eq. 24**:

$$c_{\text{eff}}(T) = \begin{cases} c_s, & T < T_s \\ c_s + \frac{L}{T_l - T_s} \cdot \frac{T - T_s}{T_l - T_s}, & T_s \leq T \leq T_l \\ c_l, & T > T_s \end{cases} \quad (24)$$

where L is the latent heat (270000 J/kg) while c_s and c_l are the solidus and liquidus specific heat, while T_s (solidus temperature) is the highest temperature at which an alloy is completely solid, and T_l (liquidus temperature) is the lowest temperature at which an alloy is completely liquid. The applied enthalpy, instead of using specific heat and density directly, is defined by **Eq. 25**, which is used due the rapid changes in the effective specific heat curve [40]. The standard does not distinguish between thermal response of different steel grades.

$$H(T) = \int_0^T \rho(T) \cdot c(T) dT \quad (25)$$

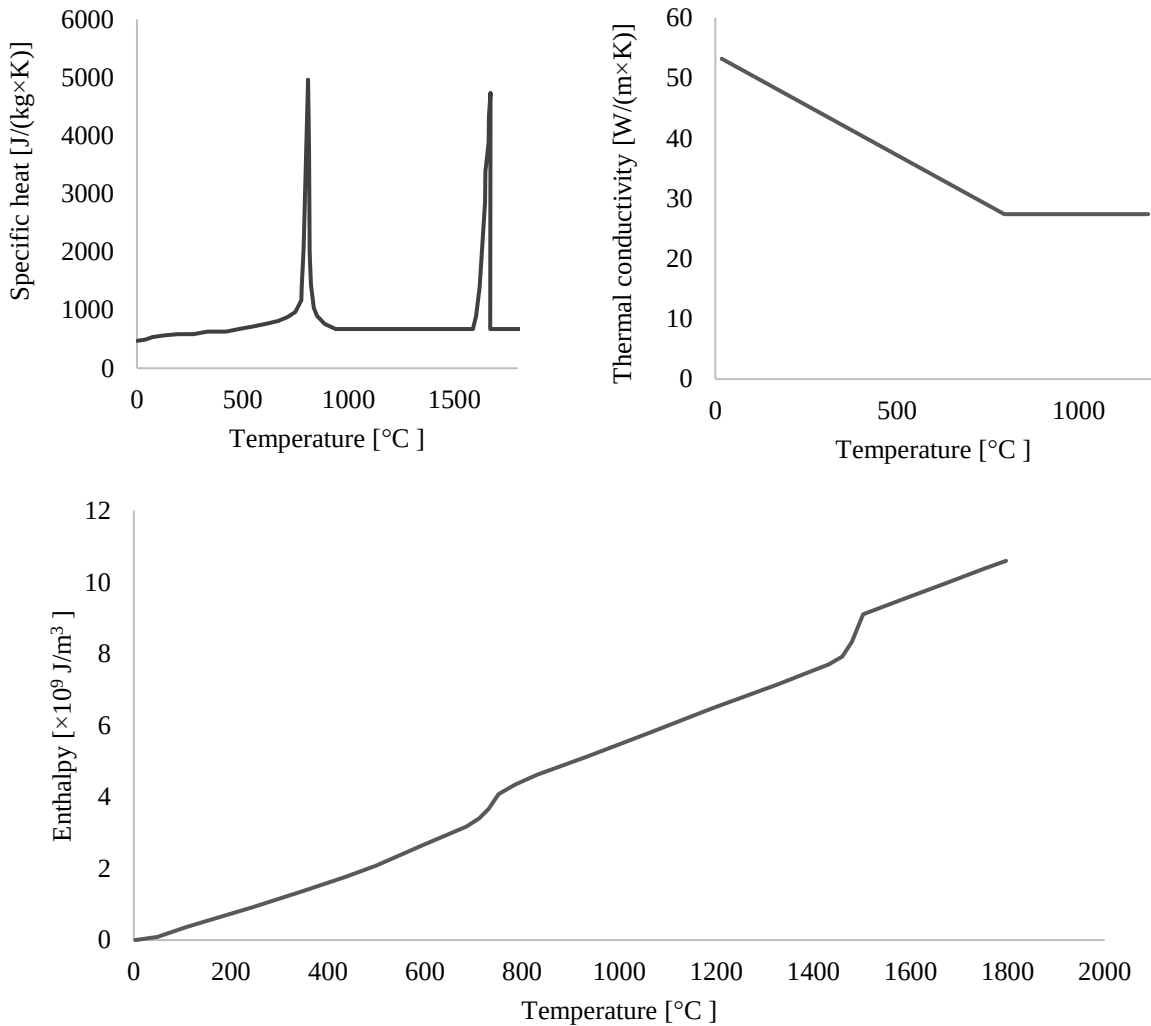


Fig. 54 - Thermal material properties of normal and high strength steels in the simulations

4.2.2 Mechanical material model

Numerical modelling requires the Poisson's ratio, thermal strains, Young's modulus, yield strength and stress-strain curves as a function of temperature in the mechanical analysis. Poisson's ratio is assumed to be constant during the simulation with a value of 0.3. The thermal strains of the workpiece can be calculated with **Eq. 26**:

$$\varepsilon_{\text{ther}}(T) = \frac{\Delta l}{l}(T) = \alpha(T) \cdot (T - T_r) \quad (26)$$

where T_r is the reference temperature and $\alpha(T)$ is the temperature-dependent thermal expansion coefficient. Reference temperature is 20°C for base material and 1200°C for melted material. Most of the mechanical material properties change with temperature (**Fig. 55**) according to EN 1993-1-2, which is taken into account in modelling by the reduction factors of the Eurocode for normal strength steels. Temperature-dependent stress-strain curves at elevated temperatures are based on the model described in Annex A of EN 1993-1-2 applying the yield strength values of inspection certificates and Young's modulus ($E = 210$ GPa) at room temperature. A multilinear isotropic hardening model is used in the simulations with von Mises yield criterion and associative flow rule.

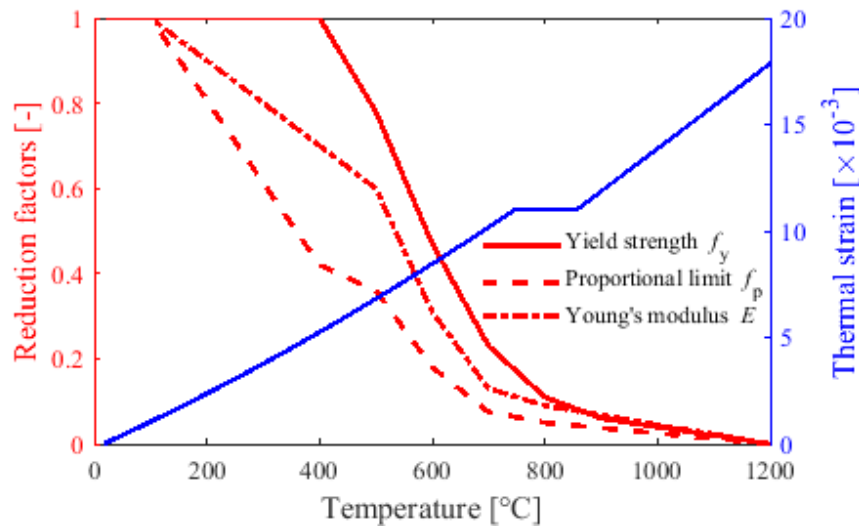


Fig. 55 - Mechanical material properties of NSS in the simulations based on [41]

In this research, Ramberg-Osgood material model was used to model high strength steels. In Ramberg-Osgood material model, the relation between strain ε and stress σ is described by **Eq. 27**:

$$\varepsilon = \frac{\sigma}{E_\theta} + 0.002 \left(\frac{\sigma}{f_{p0.2\theta}} \right)^n \quad (27)$$

where n is taken as 14 for high strength steels based on the material tests of Somodi [42] while E_θ and $f_{p0.2\theta}$ are temperature-dependent Young's modulus and proof strength, respectively. However, the same reduction factors are used for HSS as for NSS. Young's modulus at room temperature for HSS is assumed to be $E = 200$ GPa.

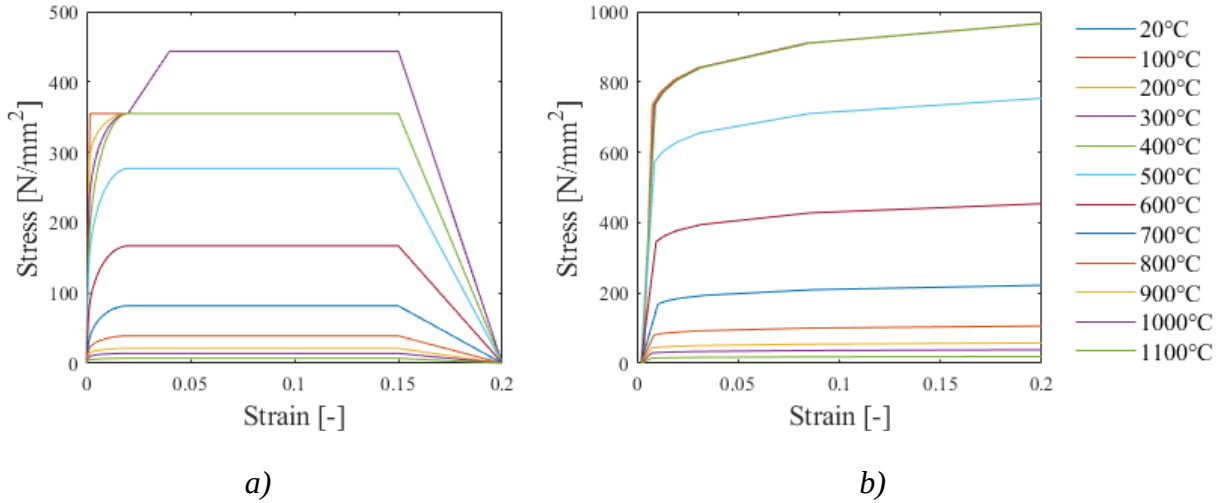


Fig. 56 – Stress-strain diagram of a) NSS material and b) HSS material

Filler material addition is modelled in the developed ANSYS code with the combination of ‘birth and death’ and ‘quiet element’ techniques according to [41] in order to deal with melting and solidification during welding. The ‘birth and death’ procedure is used in the heat transfer analysis for inactive weld passes, which means that the thermal conductivity is multiplied by 10^{-6} for deactivated elements. In the subsequent mechanical analysis, the ‘quiet element’ technique is used which means all elements are active from the beginning of the calculation. Young’s modulus of 1000 MPa is used for both not yet deposited and melted material, while linear thermal expansion coefficient is taken as zero; thus, thermal strain free weld bead finite elements are ensured before welding. After cooling below the zero strength temperature (1200°C), the weld metal uses the same stress-strain curves as the base material made of high strength steel since welding consumable with a guaranteed minimum proof strength of 690 MPa is applied in the experiments.

4.3 Boundary conditions and loads

In the thermomechanical analysis, it is also necessary to specify thermal and mechanical boundary conditions and loads. To simulate the thermal phenomenon during welding, an appropriate heat source model of the welding process needs to be specified for describing heat generation body loads in conjunction with thermal boundary conditions. In addition, in order to predict the residual stresses and deformations generated by the welding process, the mechanical boundary conditions must be given.

4.3.1 Thermal boundary condition

Thermal boundary conditions have to be defined in the heat transfer analysis. These boundary conditions are the ambient temperature, the initial temperature of the specimen, and the factors of the heat loss, such as the convective heat transfer coefficient and emissivity for simulating radiative heat transfer. The applied convective heat transfer coefficient is $25 \text{ W/(m}^2\cdot\text{K)}$, while the emissivity ε is 0.8. The proper simulation procedure also requires the selection and calibration of a heat source model that fits the welding process. First of all, the modelled heat input must be calculated by Eq. 28:

$$Q = \eta UI \quad (28)$$

where η is the thermal efficiency of welding, U is voltage, and I is current. In addition, Goldak's double ellipsoidal heat source model (**Fig. 57**) is used for arc welding simulation in this study, in which front and rear ellipsoids can be calibrated separately. **Eqs. 29-30** determine the power density distribution in the front and rear quadrants for a double ellipsoidal heat source model, respectively

$$q_f(x, y, z) = q_{\max} \cdot e^{-\frac{3x^2}{c_f^2} - \frac{3y^2}{a^2} - \frac{3z^2}{b^2}} \quad (29)$$

$$q_r(x, y, z) = q_{\max} \cdot e^{-\frac{3x^2}{c_r^2} - \frac{3y^2}{a^2} - \frac{3z^2}{b^2}} \quad (30)$$

where parameters c_f , c_r , b and a are the dimensions of the heat source model in each direction.

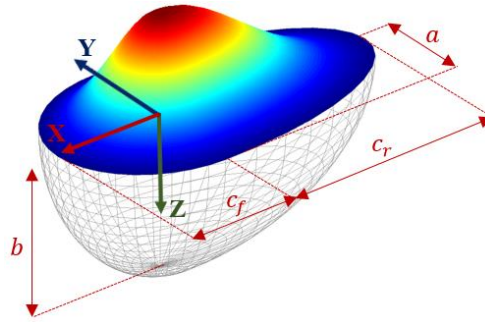


Fig. 57 - Notations of the double ellipsoidal heat source model [41]

4.3.2 Mechanical boundary conditions

The mechanical boundary conditions of the welded test specimen have a major influence on the deformations and the residual stress during welding. Stiffer boundary conditions will cause less residual deformation and higher residual stress, while ensuring free dilatation will cause more deformation with lower residual stress in the specimen. Because of this stress-strain correlation, it is important that the boundary conditions are chosen appropriately. In the welding simulation, it is important to avoid rigid body motion in the modelling. The used mechanical boundary conditions are shown in **Fig. 58**, which are in accordance with the experimental layout.

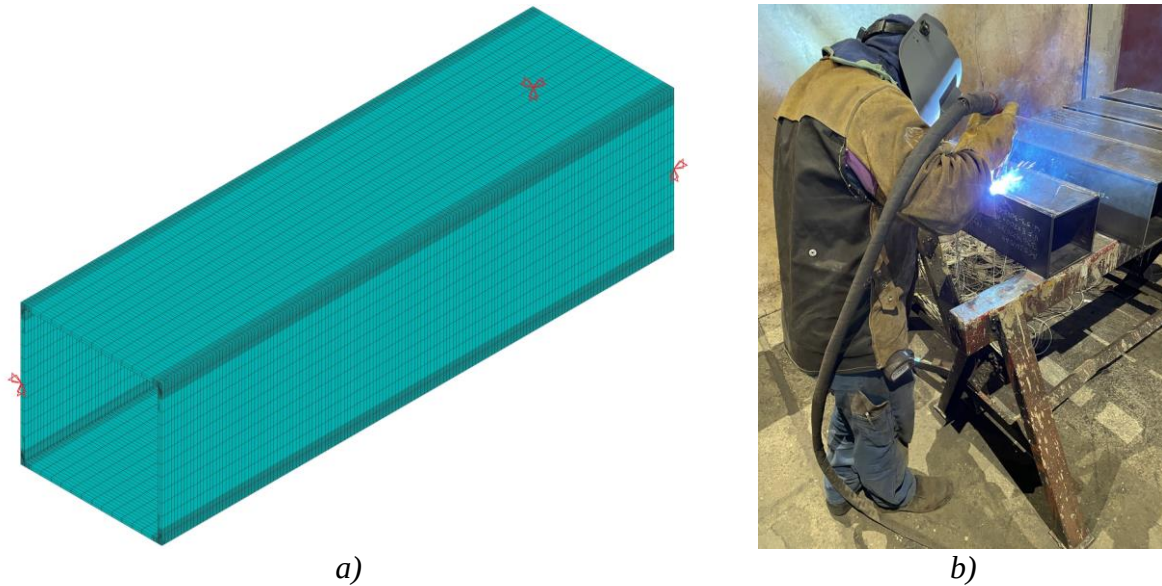


Fig. 58 - a) Mechanical boundary conditions in the developed model and b) supports during experiments

4.4 Finite element mesh

Choosing the right mesh size is essential for a finite element model. For welding simulations, a denser mesh size distribution is required in the heat affected zone (HAZ) and a less dense mesh size distribution away from the weld point. In order to select the appropriate mesh size, a mesh sensitivity study was performed using four finite element meshes. Different finite element mesh sizes were used in the weld, in the heat affected zone and outside of the heat affected zone. Outside of the HAZ, in all cases, two finite elements are defined along the thickness. Further properties of the investigated finite element meshes are summarised in **Table 11**, while the finite element meshes are shown in **Fig. 59**. Because the results of the mesh sensitivity test are not affected by the welding sequence, it is not necessary to model the entire cross-section. For this reason, a quarter of the cross-section was modelled by applying double symmetry; thus, achieving a shorter calculation time. It is important to mention that, in some cases, the specified element sizes may differ from the element sizes used in the model due to the location of the keypoints in the geometric model, sometimes the element sizes of the model are adapted to the location of the existing keypoints when the finite element mesh is created.

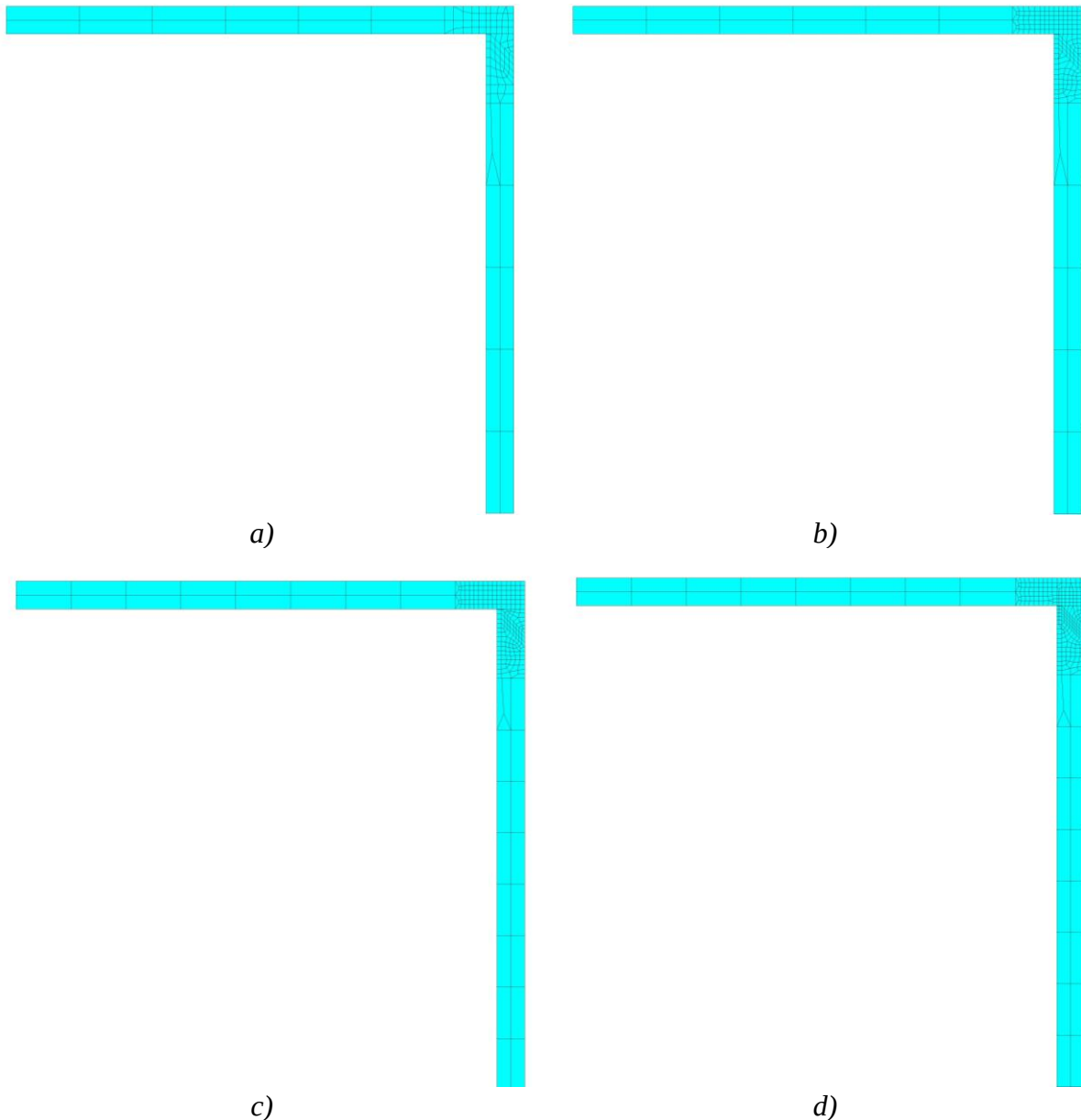


Fig. 59 - Elements of the mesh sensitivity study: a) Mesh-1, b) Mesh-2, c) Mesh-3, d) Mesh-4

Table 11 - Properties of the finite element meshes

Mesh type	Mesh-1	Mesh-2	Mesh-3	Mesh-4
Element size in weld	$t/4$	$t/5$	$t/6$	$t/7$
Element size in HAZ	$t/3$	$t/5$	$t/6$	$t/6$
Element size outside of HAZ	$3t$	$3t$	$2t$	$2t$

To evaluate the finite element meshes and to select the appropriate mesh size, compressive residual stress is determined in the middle cross section at the mid-point of the flange for each model. Results are plotted in a common coordinate system with the number of elements of the models. The resulting compressive residual stress versus number of elements diagram was used to select the finite element mesh that was sufficiently accurate, with the shortest possible calculation time. **Fig. 60** shows the diagram of the mesh sensitivity study. The results show that the percentage difference between the results of the finite element model with the largest number of elements and the model with the smallest number of elements is 2.49%. It is noted that based on this deviation; all finite element meshes are sufficiently accurate. In order to minimize the computation time, Mesh-1 was selected and used in the subsequent ones, which has a reasonable accuracy based on the mesh sensitivity analysis. **Fig. 61** shows the global model and the selected finite element mesh.

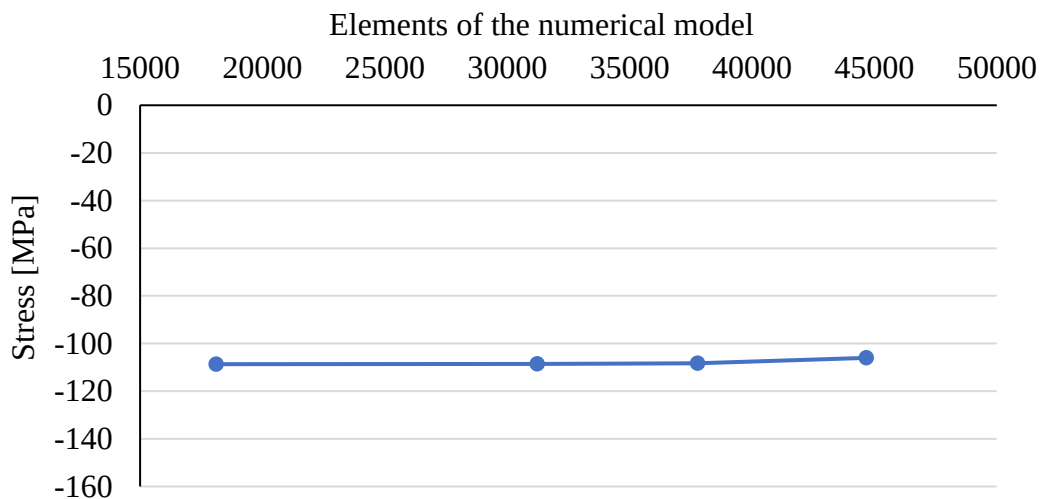


Fig. 60 - Result of the mesh sensitivity study

In the following, the selected finite element mesh was applied to the numerical model of each specimen, so that the applied element is $t/4$ in the seam, $t/3$ in the HAZ zone, $3t$ in the transverse direction outside the HAZ zone, while $t/2$ is along the plate thickness. The finite element mesh divides the numerical model along the longitudinal axis into 160 parts. Using the appropriate finite element mesh, the number of elements of the RS4, RS6 and RS8 specimens is 76 360, 78 080 and 86 636 respectively.

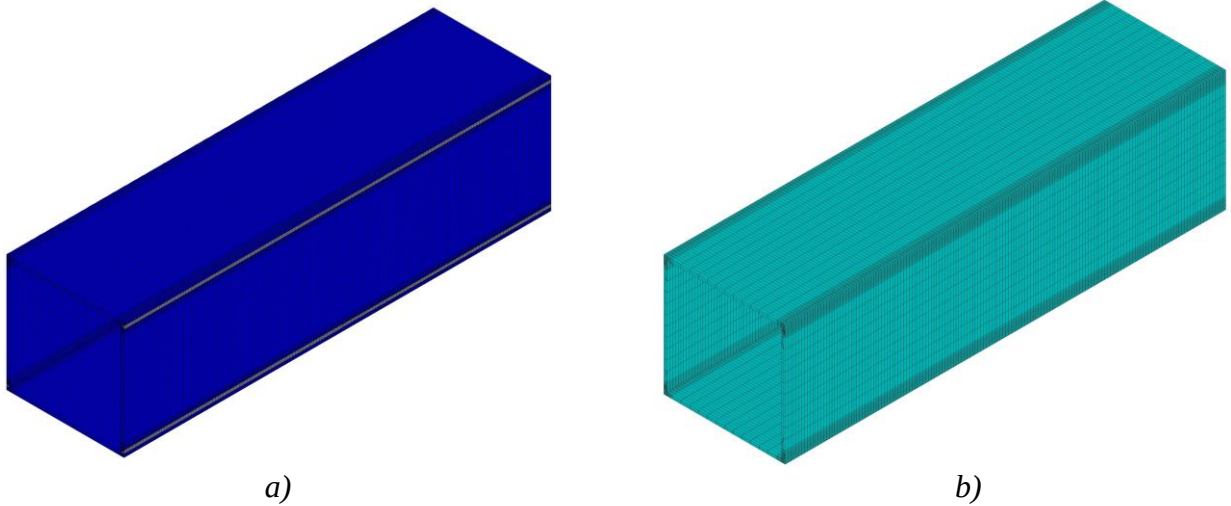


Fig. 61 - a) Finite element model with active (blue) and inactive (grey) elements when starting the analysis and b) chosen finite element mesh of the numerical model

5 Verification and validation of the numerical model

In this chapter of the thesis, results of the thermomechanical analyses of the test specimens are presented, including the temperature fields during welding, distortions and residual stresses. Finally, measurement results are compared with the numerical model results to assess the accuracy of the finite element model. This assessment is both important for evaluating the performance of the numerical model and relevant for subsequent parametric studies.

5.1 Results of the thermal analysis

Although the results of the thermal analysis cannot be used to validate the model, they provide essential information about the functioning of the numerical model and are important for the calibration of the model, which will be discussed later. **Fig. 62** shows temperature fields during the welding simulation, while **Fig. 63** shows the middle cross-section of the numerical model of the RS4-700A specimen at the time instant of the heat source model passes where grey zones indicate molten material (i.e., fusion zone and weld pool with maximum temperature larger or equal to liquidus temperature T_{liq}), which is assumed to be verified, while it will be validated based on macrographs. Figures of the other test specimens are given in **Appendix F**. With these pictures we can examine the size of the heat-affected zone and fusion zone. The size of these zones is mainly influenced by the parameters of the double ellipsoid model, welding parameters, and the plate thicknesses.

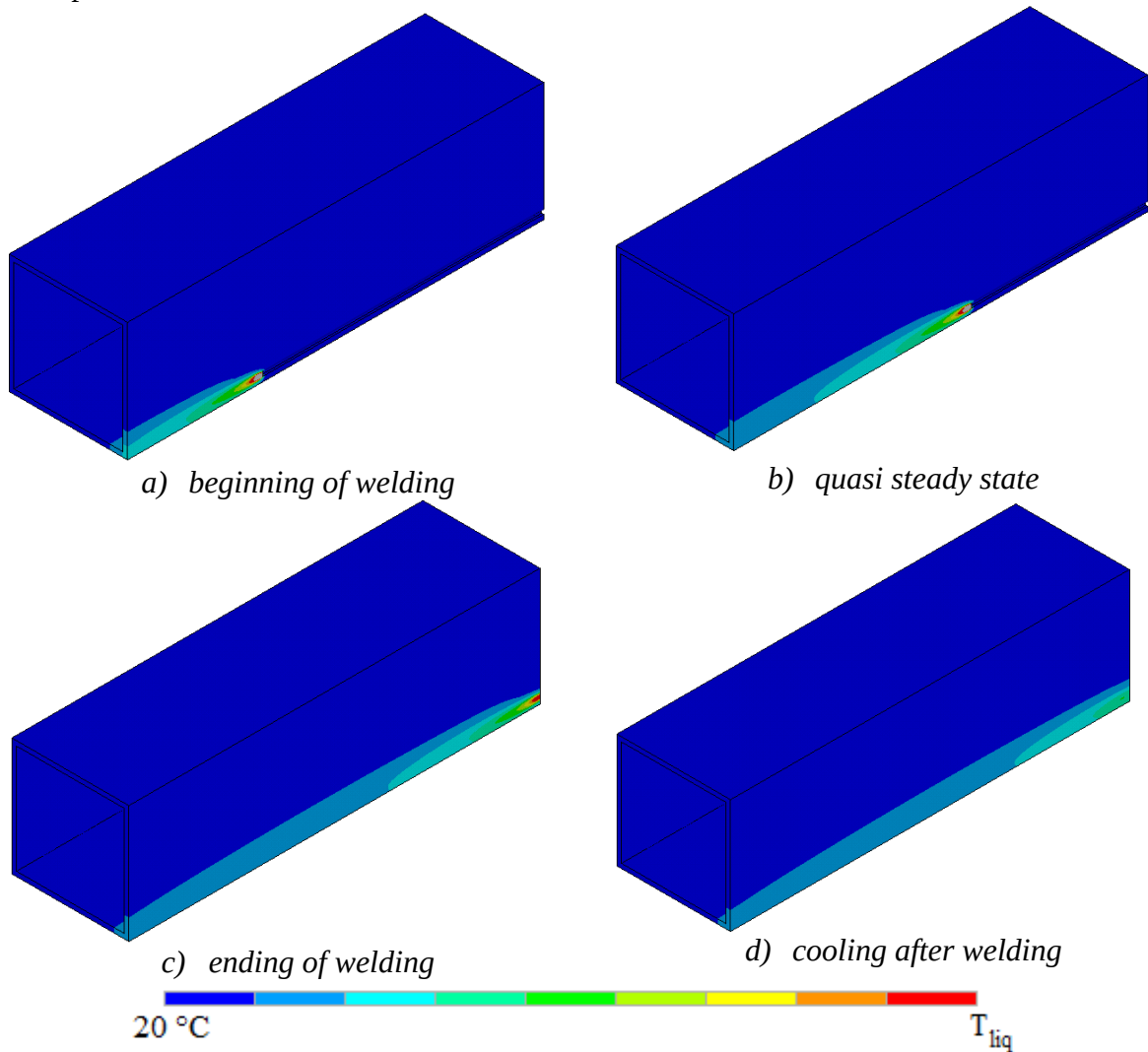


Fig. 62 - Schematic temperature fields during welding using the numerical model

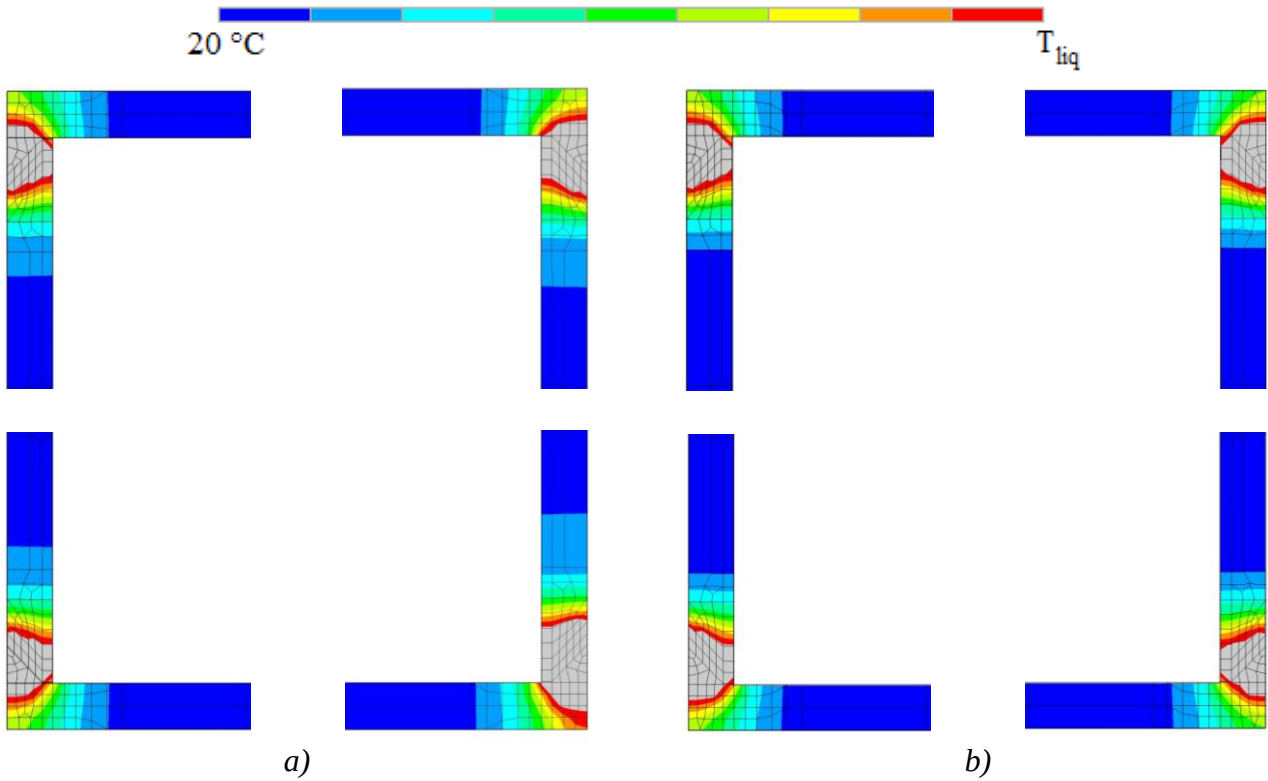


Fig. 63 - Fusion zones (grey) of specimens a) RS4-700A and b) RS4-700B

5.2 Results of the mechanical analysis

The most important result of the welding simulation, beyond the results of the thermal analysis, are the distortions and residual stress distributions. In the present study, the most relevant extractable result is the longitudinal elastic strains of the model, which can be used to validate the numerical model, with the results of the measurements presented before in **Chapter 3**. The longitudinal elastic strains shown in **Fig. 64** provide important information; distortions of the global model and the flange and web shown in **Fig. 65** are also essential. As expected, the longitudinal strains are the greatest in and around the weld seam, as this is where the heat input was greatest. In addition, as can be seen from the global model deformations, the welding process caused twisting of the specimen.

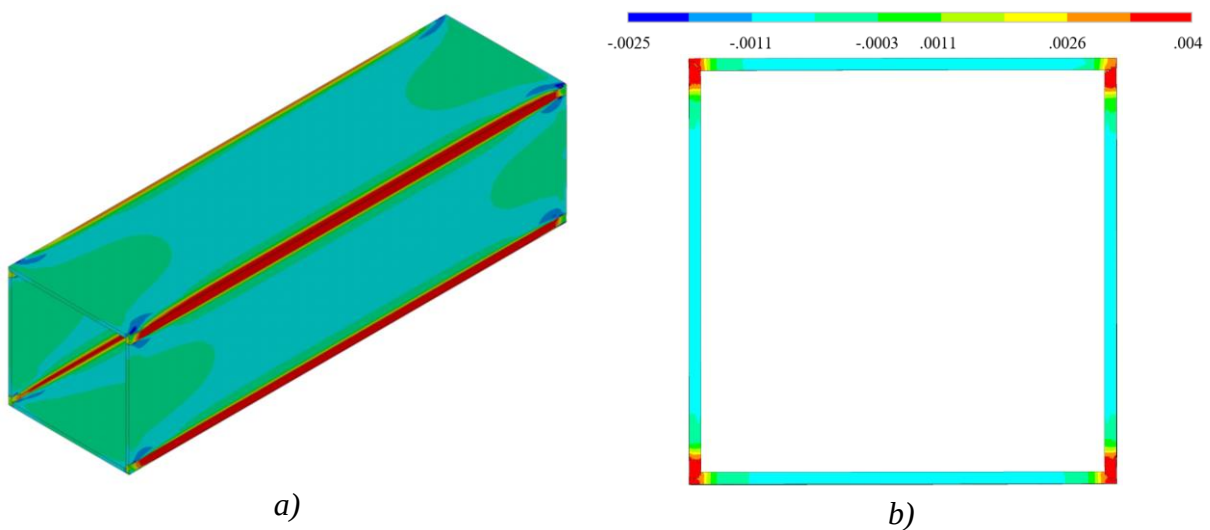


Fig. 64 - Elastic axial strains [-] of RS6-700 specimen showing the a) global model, and b) middle cross-section

5 Verification and validation of the numerical model

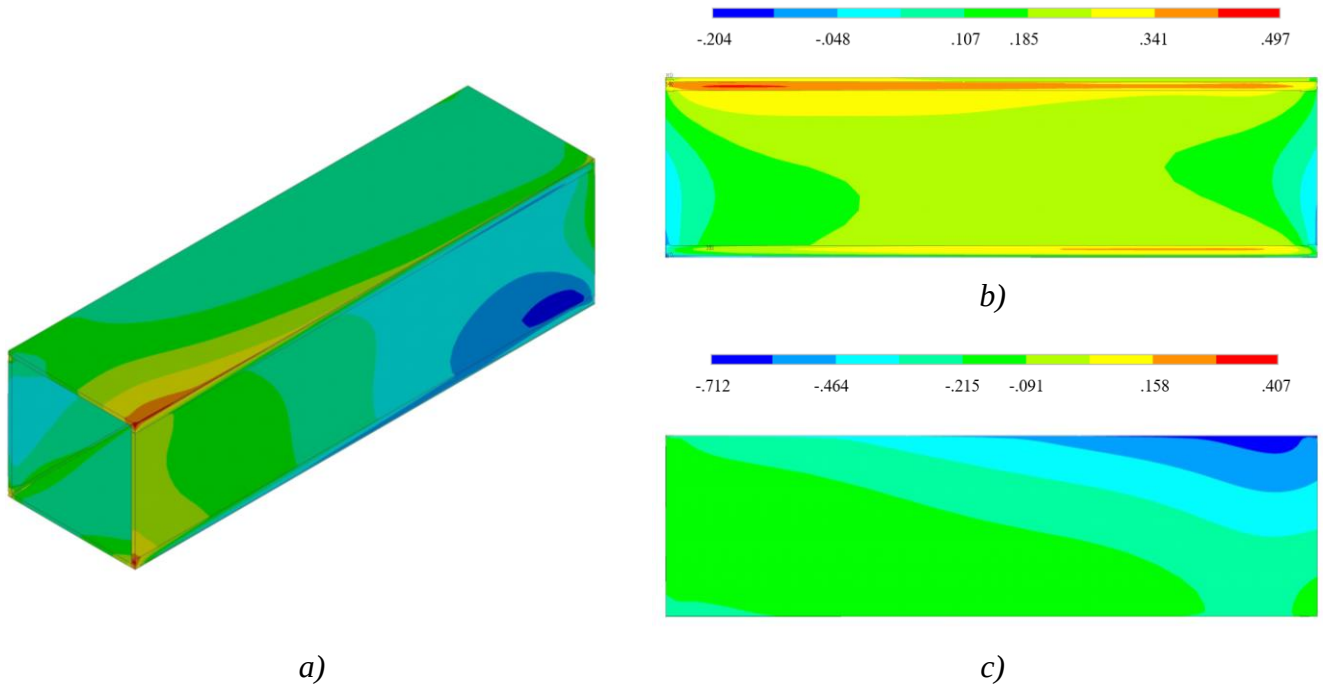


Fig. 65 - a) Total distortions [mm] of the RS6-700 specimen showing a) global model, b) transverse distortions [mm] of web, and c) vertical distortions [mm] of flange

The third important result that can be obtained from the numerical model is the residual stress distribution. The von Mises residual stress distribution for the numerical model of sample RS6-700 is shown in **Fig. 66**, which shows that the residual stresses near the weld are as high as the yield strength of the material. Furthermore, there are disturbed zones around the ends of the specimen, while the stress distribution is more uniform in the centre of the specimen. This is the reason why strains of the middle cross-section are measured in the experiments and this cross-section is used in model validation. The von Mises and longitudinal residual stress distributions of all the nine specimens are summarized in **Appendix G**.

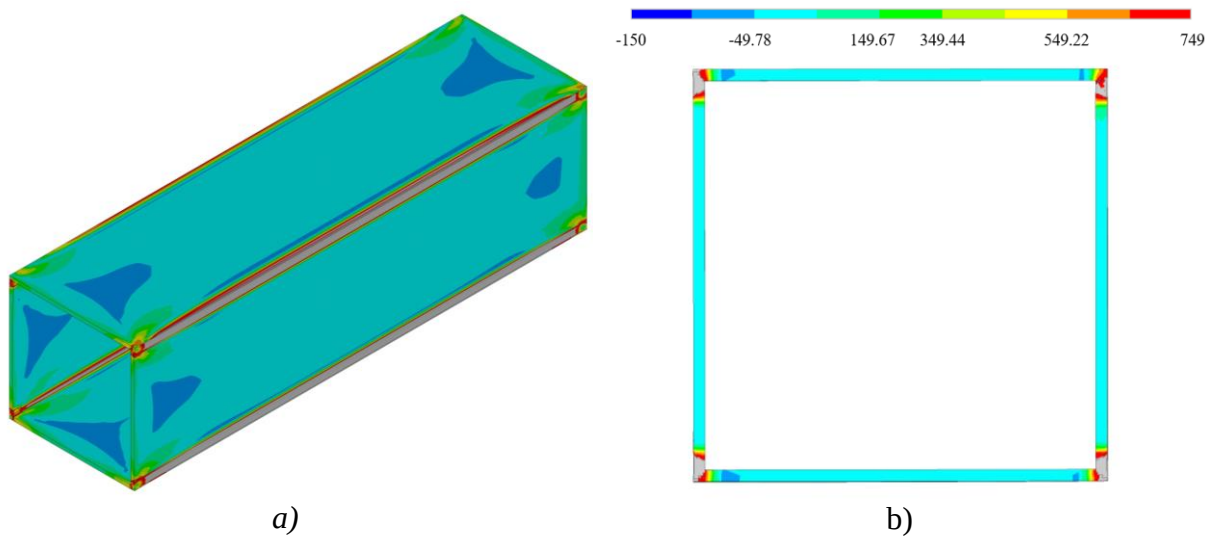


Fig. 66 - Von Mises residual stress [MPa] distribution of RS6-700 specimen showing the a) global model, and b) middle cross-section

5.3 Numerical result correlation with experimental results

The results of the numerical model can be compared with some of the experimental results. We can compare the results of the BAM extensometer and strain gauges with the axial deformations of the numerical model in the central cross-section of the specimens. In addition, we can compare the deformation measurement results with the residual deformations of the numerical model, but we should mention that the imperfections generated by the welding process are purely represented in the model, while the sum of imperfections generated by each manufacturing process is represented in the test specimen measurement results.

5.3.1 BAM strain-measuring extensometer

To compare the numerical model results with the BAM strain-measuring extensometer's results, the measurement results are plotted in a common coordinate system. These plots can be found in **Appendix H** for each of the test specimens tested. **Fig. 67** shows the axial strains of the RS6-H0 specimen at the middle cross section based on the BAM extensometer and the numerical model.

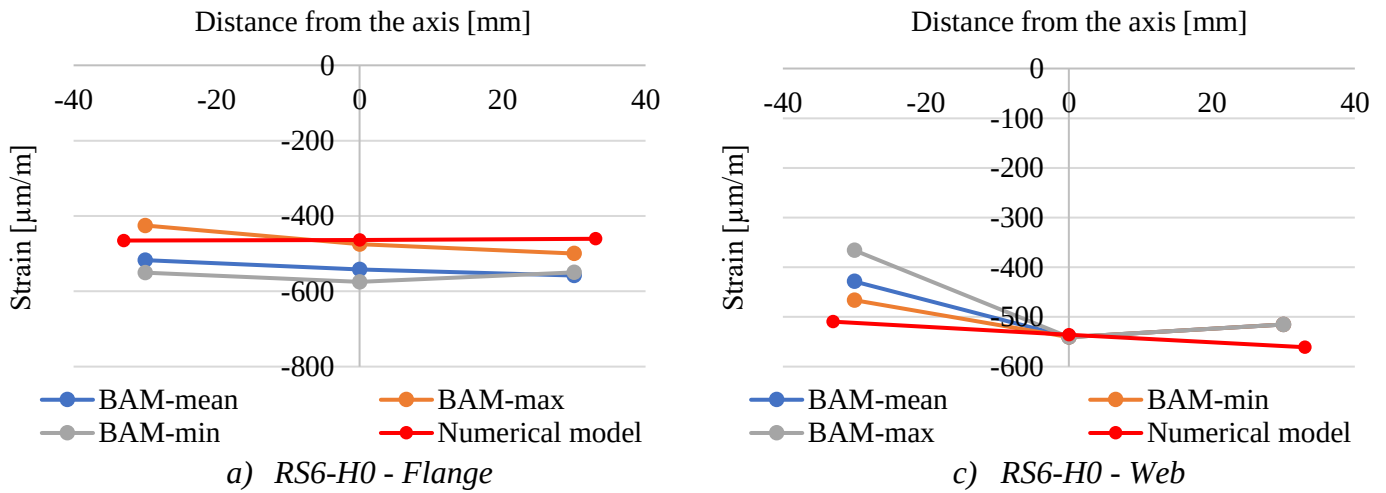


Fig. 67 - Axial strains [$\mu\text{m/m}$] of the RS6-H0 specimen at the middle cross section based on the BAM extensometer measurement and the numerical model on a) flange and b) web

5.3.2 Strain gauge-based measurement

To compare the numerical model results with the strain gauge-based measurement results, results are plotted in a common coordinate system. These plots can be found in **Appendix I** for each of the test specimens. **Fig. 68** shows the axial strains of the RS4-700B specimen at the middle cross-section based on strain gauges and the numerical model.

The numerical model can predict the strains of the flange with an accuracy of 0.71% - 21.36% compared to the strain gauge results. For the strains of the web, it can predict with an accuracy of 7.12% - 48.14%, also compared to the results of the strain gauges. On average, the model can do this with an accuracy of 25.87% for the web plate and 8.32% for the flange. The difference between the strains from numerical model and the deformations measured by strain gauges shown in **Fig. 69-70**.

5 Verification and validation of the numerical model

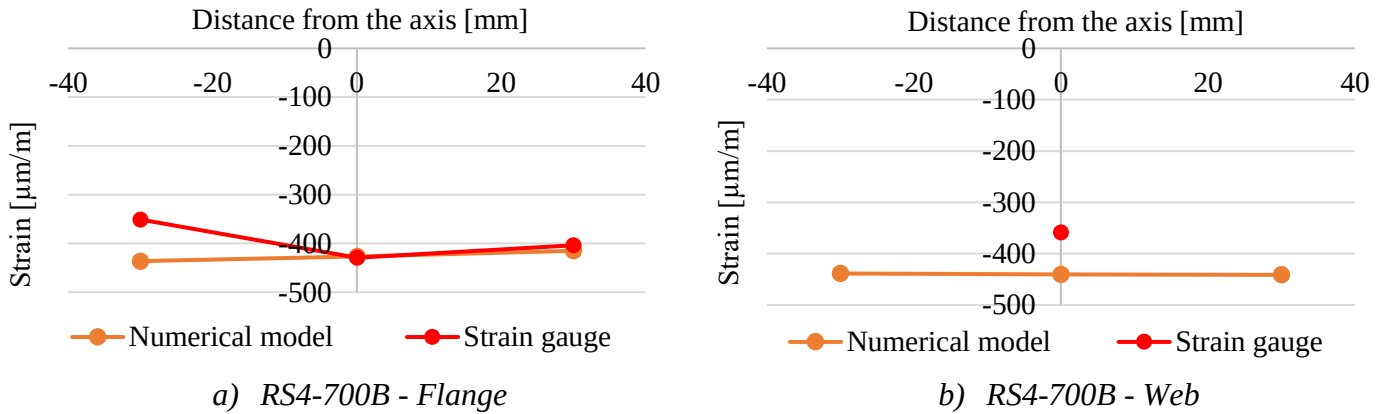


Fig. 68 - Axial strains $[\mu\text{m/m}]$ of the RS4-700B specimen at the middle cross section based on strain gauges measurement and the numerical model on a) flange and b) web

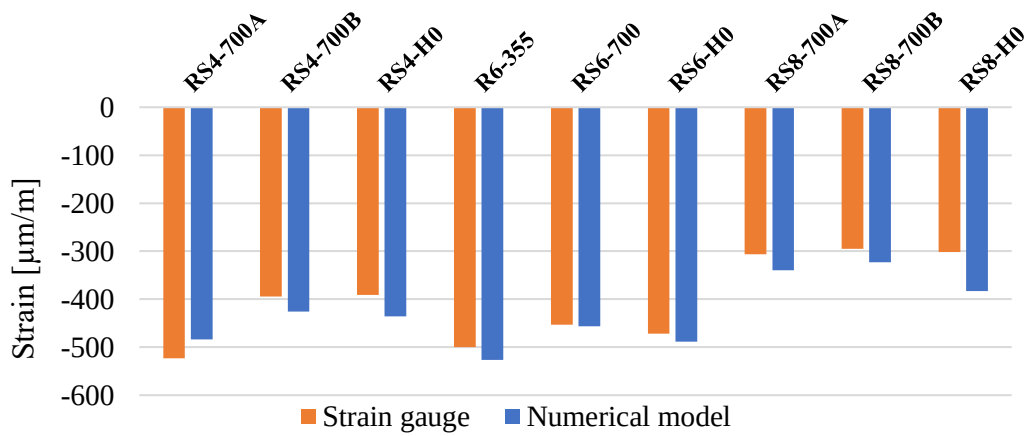


Fig. 69 - Difference between the strains from numerical model and the deformations measured by strain gauges on flange

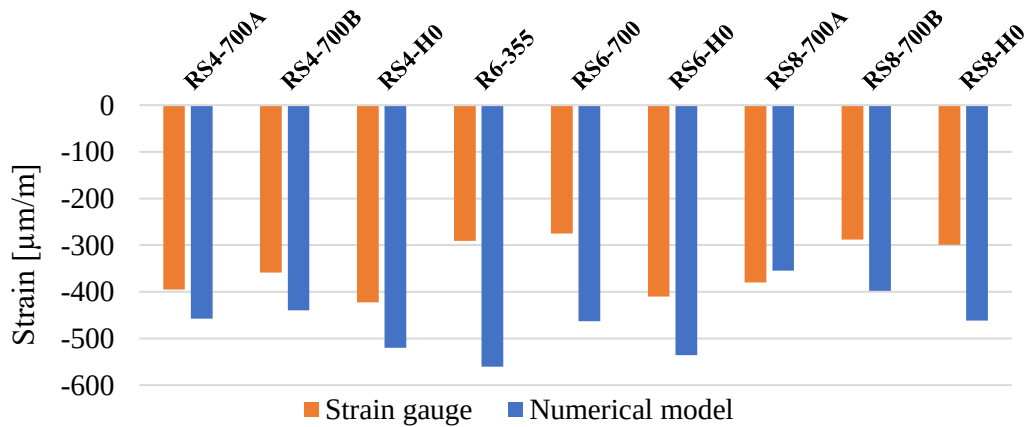


Fig. 70 - Difference between the strains from numerical model and the deformations measured by strain gauges on web

6 Parametric study

Parametric studies with a validated numerical model are very important to understand how the changing properties affect the residual stress distribution of the closure sections. The present research aims to investigate the effect of different steel grades and the behavior of hybrid sections by parametric analysis. In accordance with these objectives, a parametric study was carried out with NSS, HSS and hybrid box section.

6.1 Elements of a parametric study

During the mentioned parametrical study, nine box-section was investigated. The width and the height of the box sections was 220 mm, the wall thickness was 6 mm, and the length of the specimens was 800 mm. All the specimens had the same geometrical properties, consequently the width/thickness ratio of the cross-sections is 33.3 in all cases. Since the cross-sectional dimensions of the test specimens are identical, so the welds are formed in the same way. All the specimens' weld type are single-bevel butt weld, which corresponds to the welding seam of the test specimens shown earlier. The cross-sections of the parametrical study are made with one weld pass.

Table 12 - Geometrical parameters and steel grades in the parametric study

Elements of the parametrical study	Steel grade	
	Flange	Web
RS-P-235	S235	S235
RS-P-275	S275	S275
RS-P-355	S355	S355
RS-P-460	S460	S460
RS-P-700	S700	S700
RS-P-960	S960	S960
RS-P-H1	S460	S355
RS-P-H2	S700	S355
RS-P-H2	S960	S355

As already mentioned, the parametric study focuses on the effect of changes in material quality. In line with this the tested specimens consist of three types of normal strength steel (S235, S275, S355) and three types of high strength steel (S460, S700, S960). Six cross-sections consisted only one material type, and three hybrid section consisted of a normal and a high strength material. The hybrid cross sections are made with a high strength flange (S460, S700, S960) and a normal strength web (S235, S275, S355). The strength of the welding consumable in the parametric test is equal to the strength of the cross-section material. In hybrid cross-sections the strength of the welding consumable was equal to the cross-section's high strength steel. The material properties of the nine virtually tested box sections are summarized in **Table 12**. In the same way as the geometric data, all the material properties used with nominal values in the numerical model.

6.2 Description of the numerical model

The numerical model of the parametric study differs from the already presented numerical model in one feature. This important difference is the use of double symmetry in modelling, which means that only a quarter of the cross-section is modelled the effect of welding sequence is not investigated in the parametric study. The geometrical model of the parametric study is

showed in **Fig. 71a**. As a result of the modelling procedure, the seams of the entire box section are produced together, and their welding parameters are identical. An important advantage of this modelling procedure is that it effectively reduces the calculation time. On the other hand, it requires special adjustment of boundary conditions, which will be discussed later. Simultaneous welding also affects the residual stress distribution of the model, resulting in higher heat input and higher residual stresses. The positive impact of the procedure is that it reduces the distortion due to the welding sequence.

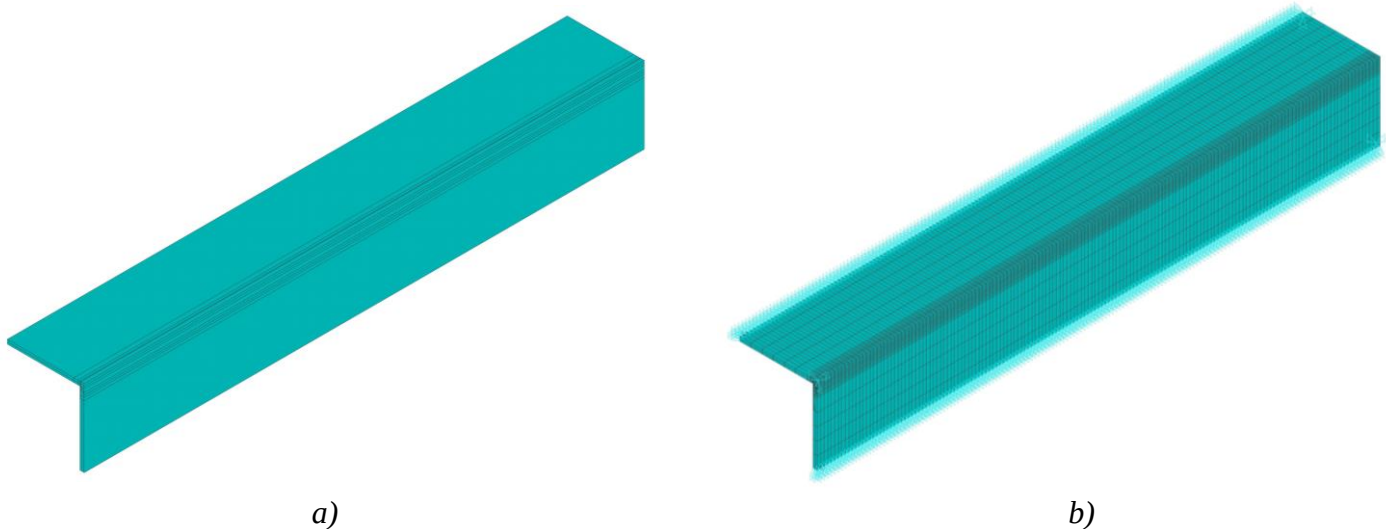


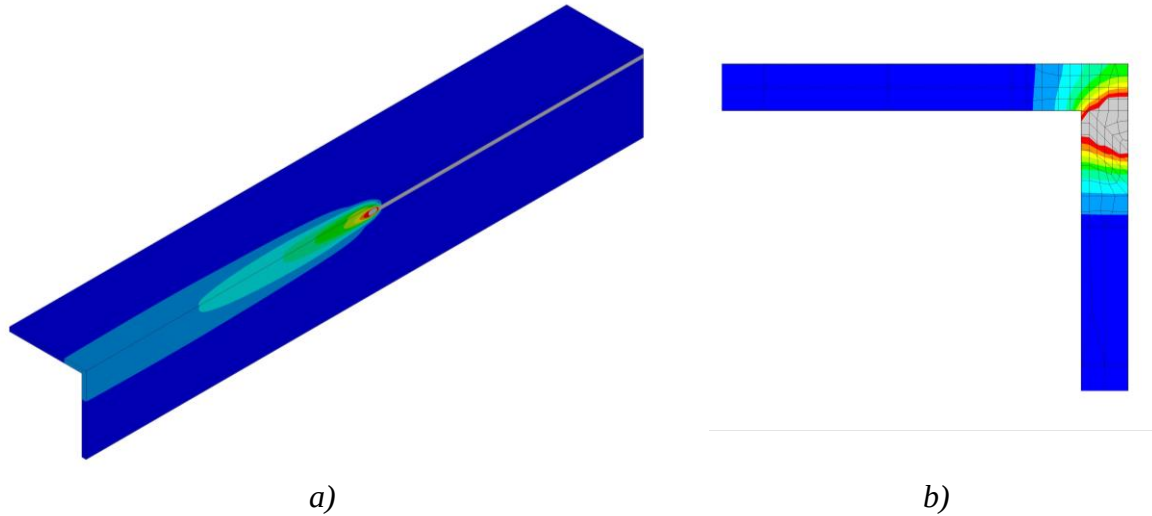
Fig. 71 - a) Geometrical model of the parametric study and b) mechanical boundary condition of the meshed model

The thermal and mechanical model was the same as the numerical model of the experimental specimens. Ramberg-Osgood material model was used to model high strength steels, while multilinear isotropic hardening material model, with yielding plateau below 400°C, was used for normal strength steel. The weld metal uses the same stress-strain curves as the base material made of high strength steel due to equivalent filler metal. When defining thermal boundary conditions, the effect of symmetric modelling must be taken into account, so no heat exchange surfaces are modelled in the planes of symmetry. Since the symmetry plane is not affected by the heat source used, it is not necessary to modify the heat source model presented earlier. For the parametric study, the net heat input is 0.74 kJ/mm, calculated with the formula $q = \eta UI/v$. Both the initial ambient temperature for the parametric procedure and the initial temperature of the test specimen are 25°C. When specifying mechanical boundary conditions, it is necessary to specify the support conditions of the cross-section. We must define support to prevent global displacement, i.e., rigid body motion, of the model, and it is also necessary to support the surfaces of the planes of symmetry, as it is shown in **Fig. 71**. All the properties of the finite element mesh used in the parametric study (**Fig. 71b**) are the same as the finite element mesh already presented, which was selected using mesh sensitivity study.

6.3 Results of the parametric study

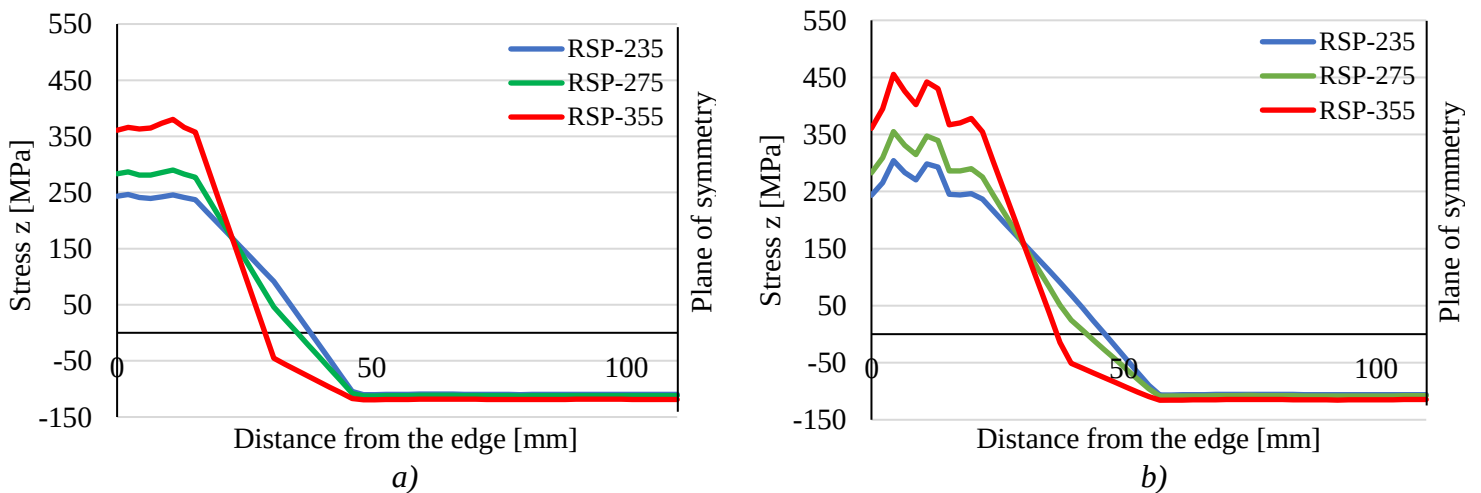
Although the focus of the research is not directly on the evaluation of thermal analysis results; however, temperature fields provide essential information for checking thermal analysis. **Fig. 72a** shows temperature fields on the quarter model during the welding simulation, while **Fig. 72b** shows the middle cross-section of the numerical model in the parametric study at the time of the heat source passing instantly. Grey zones indicate molten material. In the evaluation of the thermal results, the liquidus temperature of the base material was estimated at 1500°C, without

knowing the exact chemical composition. Due to double symmetry, specimens have the same melting zones.



a) b)
Fig. 72 - Thermal results of the parametric study

Further relevant results of the welding simulation model are included in the mechanical analysis. The parametric analysis focuses on the longitudinal and von Mises residual stress distributions of the specimens (**Fig. 76-81**). In addition, the plots in **Fig. 73-75** show the longitudinal stress magnitudes for the flange and the web on the outer surface of the specimen. At point 0 on the horizontal axis of the diagrams, the stress value at the edge of the cross-section is shown, and at the end point, the stress value at the centre of the cross-section is shown. The end of the horizontal axis is the plane of symmetry of the cross-section. By examining the residual stress curves of the parametrical study, several conclusions can be drawn regarding the effect of steel grade. The maximum tensile stress of the plates exceeds the yield strength of the material in all cases tested, both at the flange and at the web. Furthermore, the increase in the maximum tensile stress of the flange plates tracks well the increase in the yield strength of the base material, which is also clearly observed in **Fig. 82**. The same trend is no longer observed for the maximum compressive residual stresses of the flanges. As can be seen in **Fig. 82**, the maximum tensile stresses of the plates are slightly higher in the webs than in the flanges in all cases. The reason for this is the location of the weld seam, which causes a higher and more concentrated heat input in the web plate than in the flange.



a) b)
Fig. 73 - Longitudinal residual stress (Stress z) magnitudes of the a) flanges and b) webs in NSS sections of the parametric study

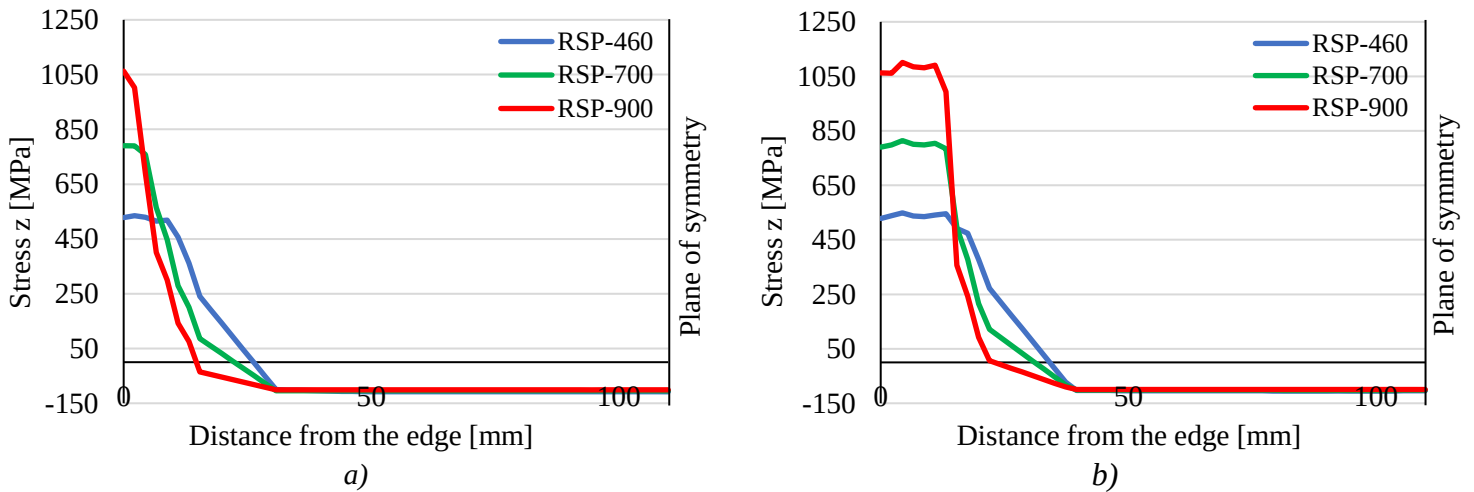


Fig. 74 - Longitudinal residual stress (Stress z) magnitudes of the a) flanges and b) webs in HSS sections of the parametric study

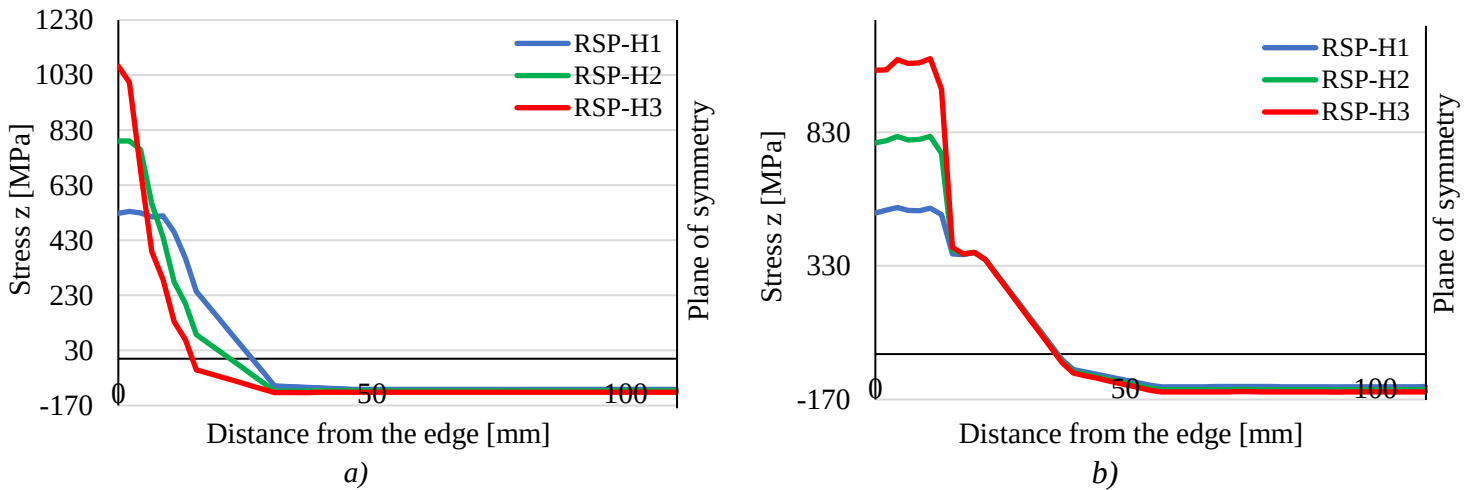
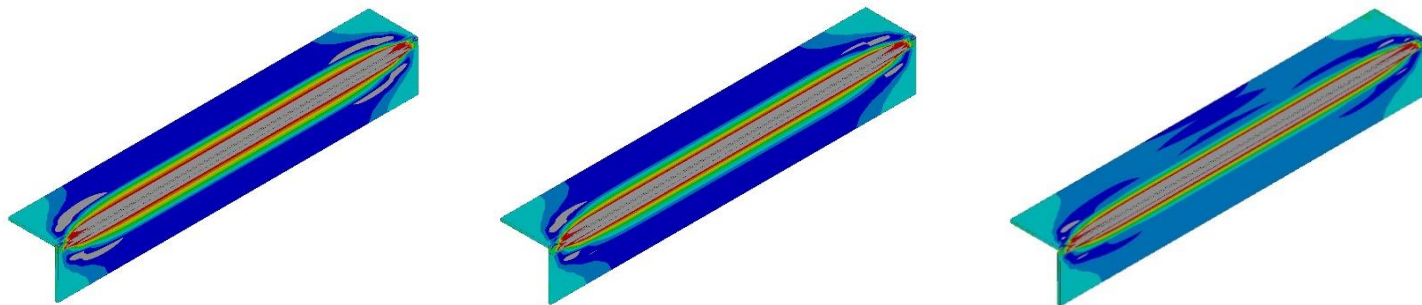


Fig. 75 - Longitudinal residual stress (Stress z) magnitudes of the a) flanges and b) webs in hybrid sections of the parametric study

The residual stress curves further show that a stress plateau appears along the edges of the webs, also due to the location of the weld and the design of the cross-section. Near the edge, the material of the high-strength flange and the high-strength weld is present, and in this zone of the plate, a relatively high heat input is typical. It is important to note that the high heat input in this zone causes disturbances in the uniform residual stress, which is most pronounced in the case of NSS sections due to the low yield strength of the material. For flanges, the appearance of the tensile stress plateau of the edges, depends on the steel grade of the base material. For higher yield strength, a zone of uniform tension with minimal width can be seen, while for lower yield strength a wider zone can be seen. In the case of hybrid sections, the jump in the web tensile stress curves should be highlighted. The explanation of the stress jump near the weld can be explained by the change in steel grade. Indeed, the material of the numerical model changes in the vicinity of the jump from a normal strength web material to a weld material welded with a high strength filler material.

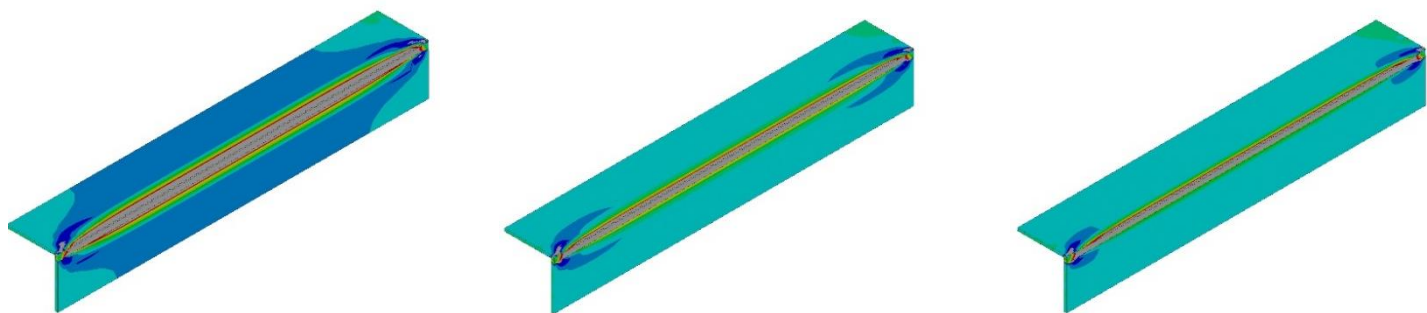
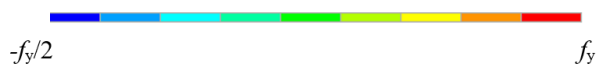


a) RS-P-235 – σ_z

b) RS-P-275 – σ_z

c) RS-P-355 – σ_z

Fig. 76 - Longitudinal residual stress (σ_z) distribution in NSS sections of the parametric study

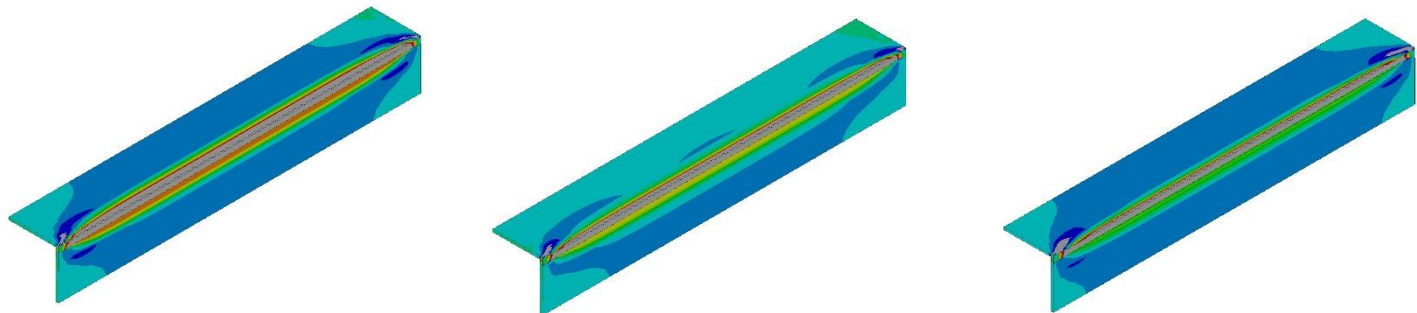


a) RS-P-460 – σ_z

b) RS-P-700 – σ_z

c) RS-P-960 – σ_z

Fig. 77 - Longitudinal residual stress (σ_z) distribution in HSS sections of the parametric study

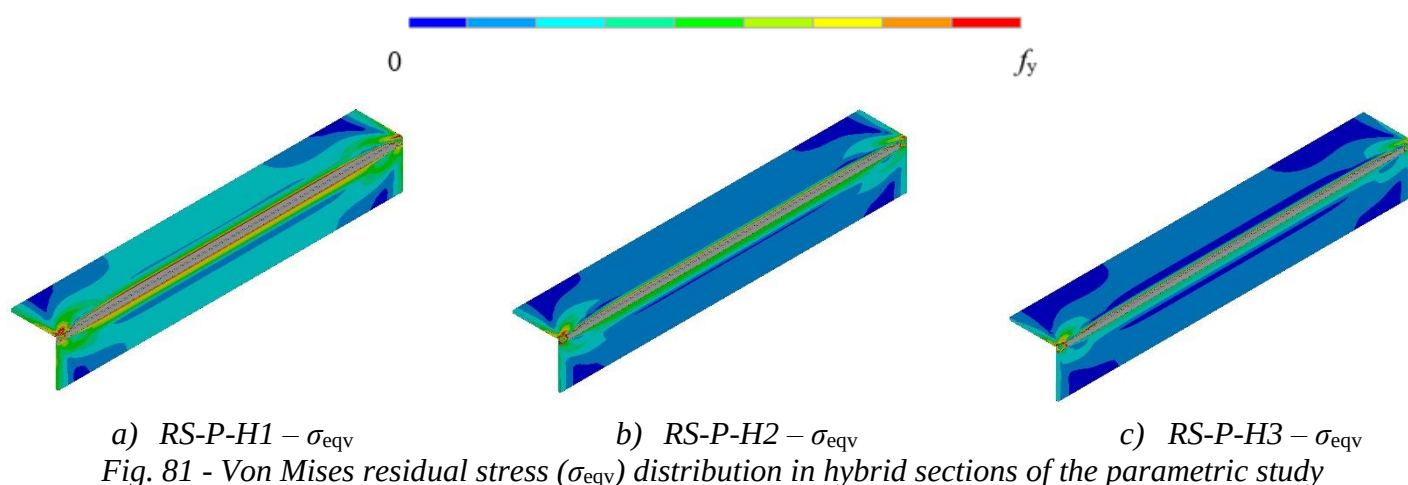
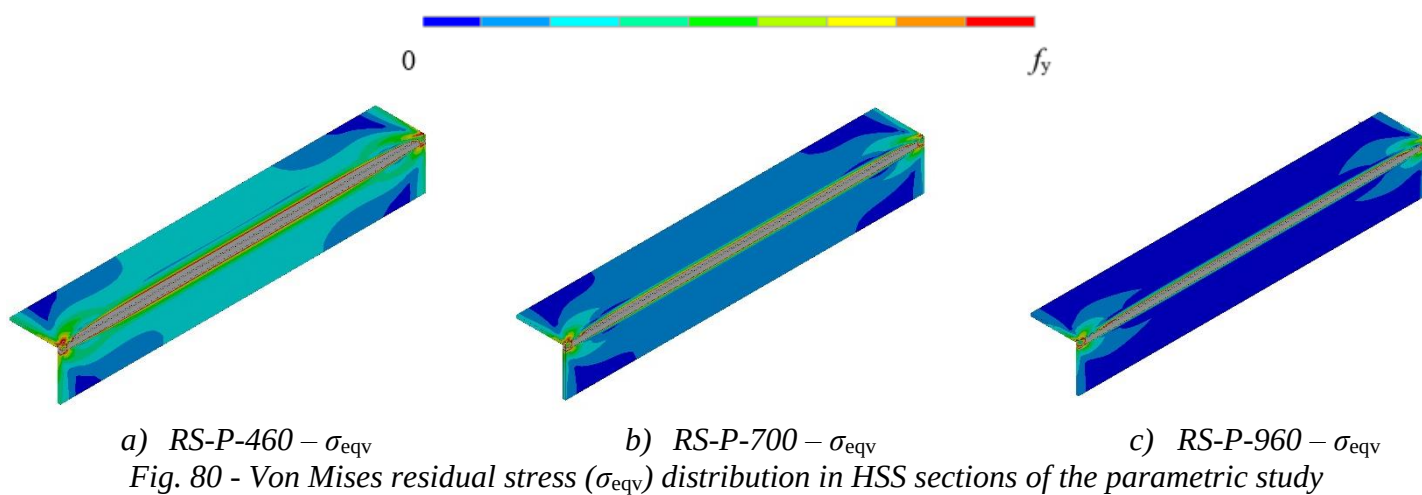
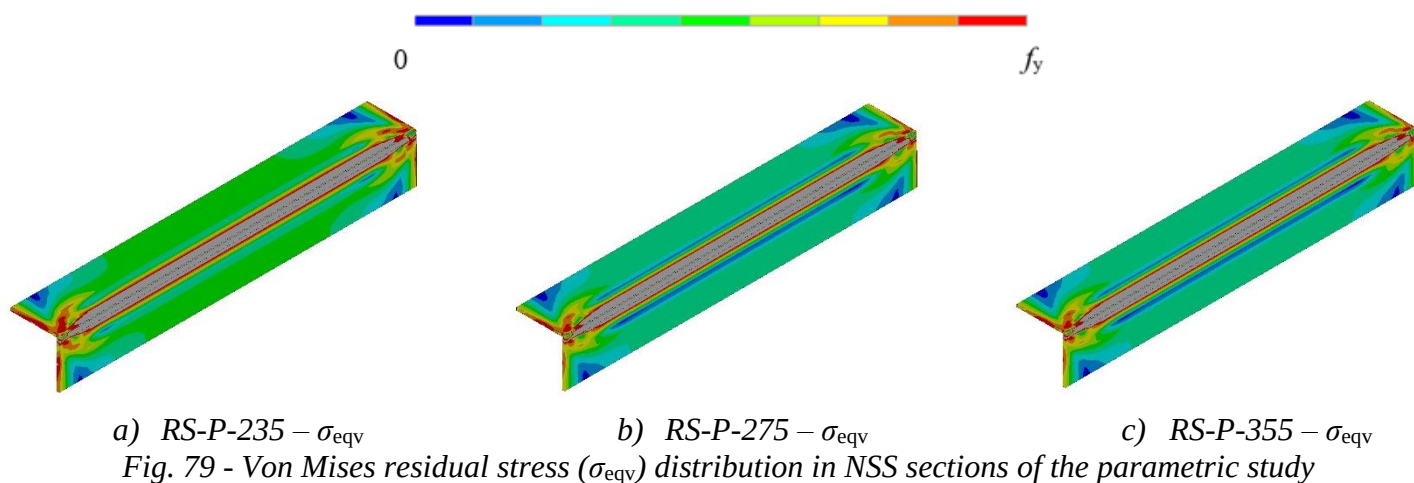


a) RS-P-H1 – σ_z

b) RS-P-H2 – σ_z

c) RS-P-H3 – σ_z

Fig. 78 - Longitudinal residual stress (σ_z) distribution in hybrid sections of the parametric study



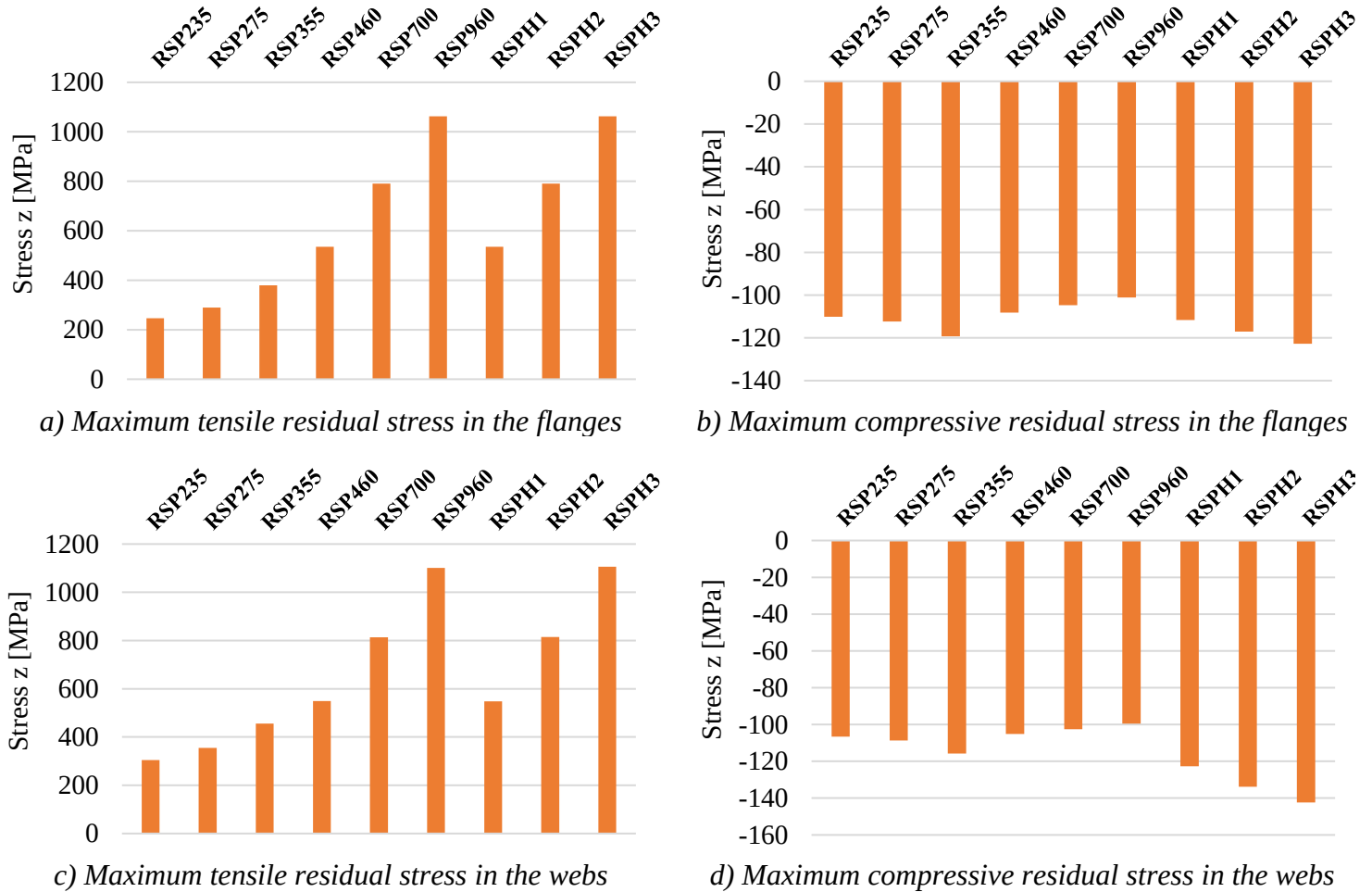


Fig. 82 - Maximum tensile and compressive residual stresses in the a-b) flanges and c-d) webs

An important point of the research is to evaluate the accuracy and applicability of the residual stress models presented earlier. For this purpose, a comparative analysis was carried out using compressive residual stresses calculated using the residual stress models presented in this study. Some of these residual stress models can be applied to NSS sections, others to HSS sections, while none of the models is recommended for hybrid sections. **Fig. 83-85** show the difference between the calculated compress residual stress and the parametrical models maximal compress residual stress in the middle cross-section. None of the presented residual stress models distinguish between the stress distributions of the flange and the web. Most of the models treat steel grade, i.e., yield strength, as a variable, while Ban's two formulae (**Eq. 3-4**) and Kövesdi and Somodi's two formulae (**Eq. 7-10**) depend only on geometric properties. It is important to point out that two versions of Kövesdi and Somodi's formulae are included in the analysis of results, which differ in terms of the constants used in the formulae.

The ECCS light weld model's formula (**Fig. 19**) grossly underestimates the compressive stress of NSS sections. The accuracy of the model is much improved under the heavy weld assumption for NSS sections, but consistently grossly overestimates the stress of HSS sections. The Chinese model (**Fig. 20**) overestimates the compressive residual stress in all cases, especially for HSS sections. Among the tested models for NSS sections, the ECCS's heavy weld formula (**Fig. 19**) provided the highest accuracy, with 11-38%.

6 Parametric study

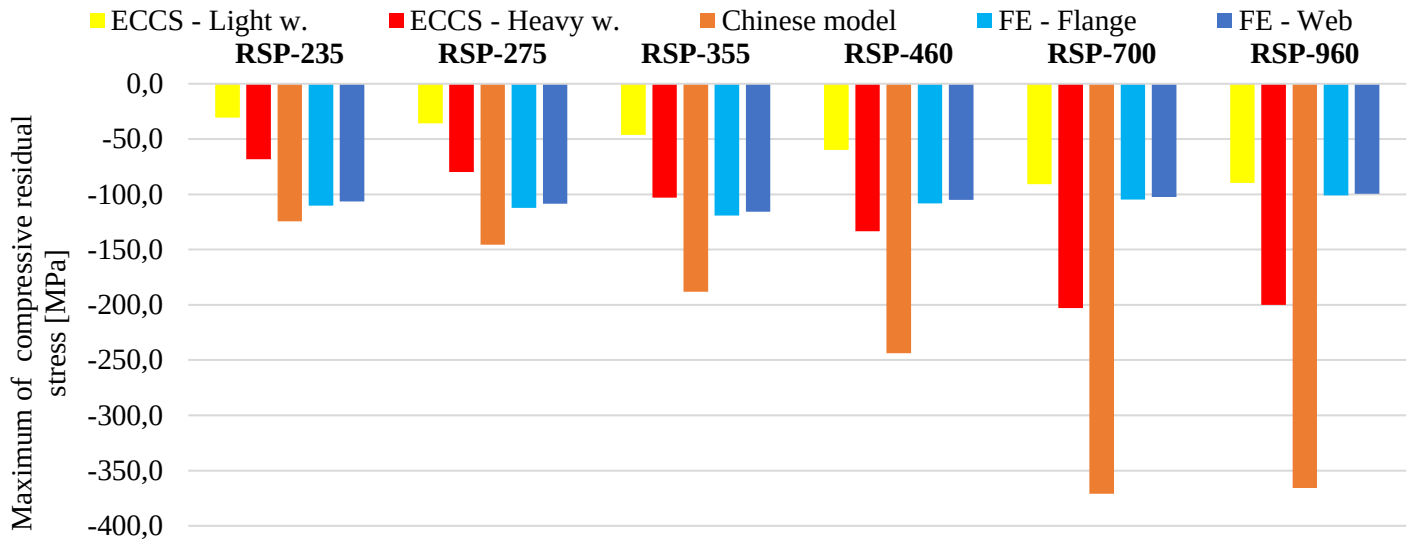


Fig. 83 - Results of residual stress models and parametric analysis (FE) – NSS specimens

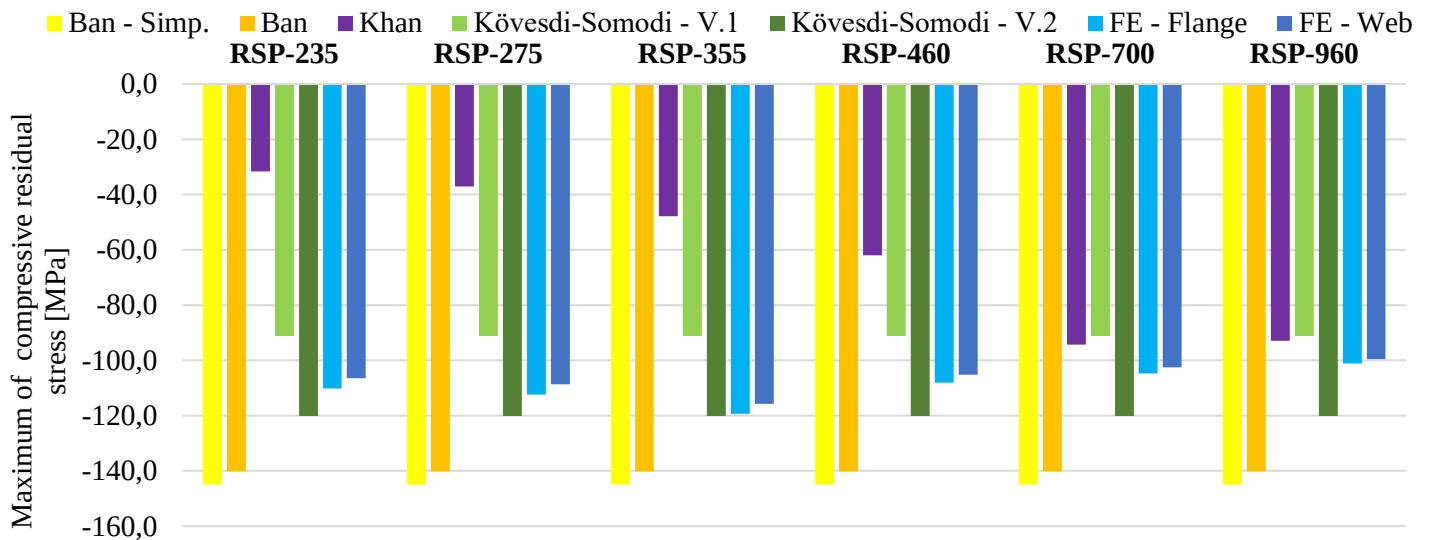


Fig. 84 - Results of residual stress models and parametric analysis (FE) – HSS specimens

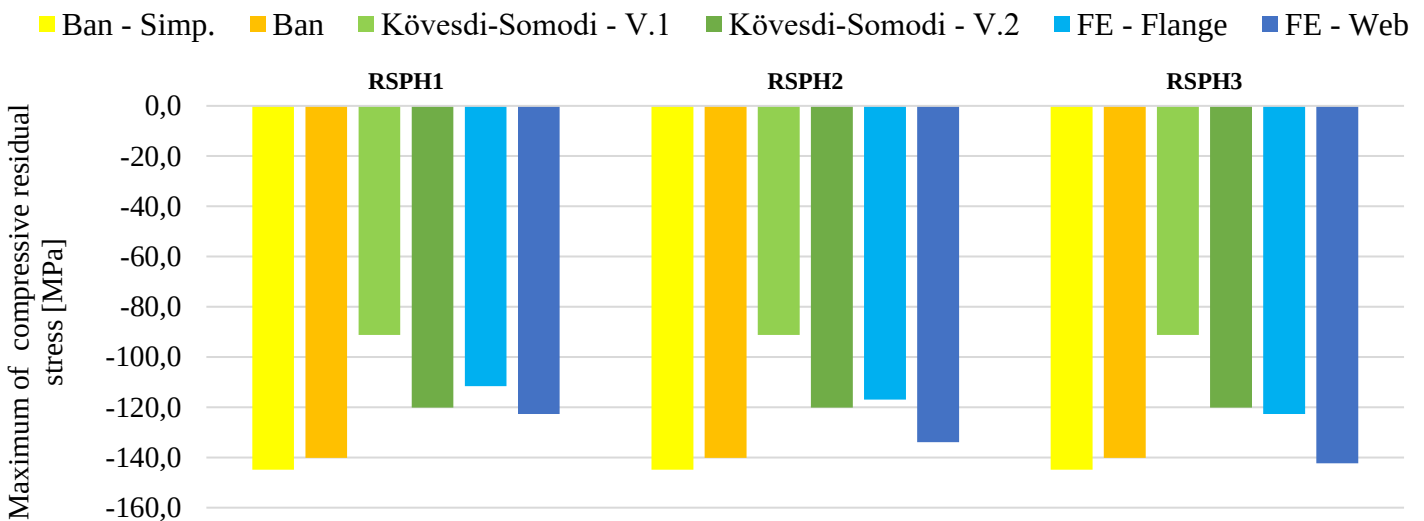


Fig. 85 - Results of residual stress models and parametric analysis (FE) – Hybrid specimens

A comparison of the results of the HSS models with the numerical results is shown in **Fig. 83**. As can be seen from the diagram, Ban's formula (**Eq. 4**) and its simplified version (**Eq. 3**) overestimate the compressive stress on the cross-section in all cases considered. The accuracy of the model is 21-46% in the cases investigated. As can be seen from the diagram, the model results are independent of the steel grade of the section under investigation. In contrast, Khan's formula (**Eq. 6**) treats the material quality of the section as a variable. The model grossly underestimates the compress residual stress of NSS sections, but its accuracy is much improved for HSS sections. Kövesdi and Somodi's residual stress models overestimated the compressive self-stress in all cases, but overall, this model had the highest accuracy, with 0.7-20.7%. Overall, it can be concluded that, among the tested models, Kövesdi and Somodi 2nd formula (**Eq. 9-10**) was the most accurate for sections made purely with S235, S275, S355, and S460 material, and can be applied with 15-20% accuracy for sections made with S700 and S960 material. It can also be shown that Khan's formula (**Eq. 6**) is most accurate for sections using pure S700 and S960 steel, but grossly underestimates the compressive stress of the cross-section in the lower strength cases.

Although none of the presented models is recommended for calculating the residual stress distribution of hybrid box sections, in some cases reasonable accuracy can be also achieved with these models. The results of the models with the compressive stress of the parametrical study's sections are shown in **Fig. 84**. Of the models, only those are shown whose results do not depend on the steel grade of the section. As can be seen from the diagram, the second formula of Kövesdi and Somodi (**Eq. 9-10**) is able to predict the compressive residual stresses with the highest accuracy for hybrid sections, with 7.6-15.4%.

7 Conclusions

As an introduction, the thesis summarizes possibilities of welded box-section assemblies using flat and rolled plates. The diploma work also discusses the most common welding processes, their properties and their effects on the welded product. Since the manufacturing process has a major impact on the residual stress distribution of the product, the possibility of measuring residual stress is an important issue. This work summarises the most common destructive, non-destructive, and semi-destructive measurement techniques, their advantages and limitations. In addition to the measurement of the residual stress, an important issue in design is the accuracy of the residual stress models and limits of their applicability. Therefore, the thesis also deals with the topic of residual stress models that can be used to estimate the residual stress distribution of normal, and high strength steel box sections. In addition to the residual stress models, the paper presents some welding simulation models available in the literature, with their basic properties, settings and structural layout.

Besides the literature review, the diploma work includes the description of measurements made on the test specimens, the presentation and validation of the developed welding simulation model, and the parametric study of NSS, HSS and hybrid sections. During the experimental tests, the geometric data and welding parameters of nine welded box-sections were recorded, together with the geometric data of the welding pools. A comparison of the welding parameters and the weld pool dimensions shows that increasing the heat input causes an increase in the weld pool width, while there is a larger scatter for semi-axis length of the weld pool. To measure the residual stress of the specimens, BAM extensometer and strain gauge-based measurements were performed. The measurement results have been used to validate the numerical model of the research, while important conclusions can be drawn from the measurement results as well. Based on the evaluation of the measurement results, it can be concluded that absolute value of compressive residual strains (and thus stresses) in the flange decrease by increasing the width-to-thickness ratio, while steel grade has minor importance. In addition, it can be also concluded that as plate thickness increases, the strain measured on the external strain gauges deviates at an increasing rate from the value measured on the internal gauge; thus, bending becomes more relevant. In addition to measuring residual stresses, the out-of-flatness of the constituent plates were measured with a mobile measuring device and the results were processed. It can be concluded that maximum out-of-flatness was around $b/150$, which is even larger than the equivalent geometric imperfection for panels and subpanels ($b/200$) in EN 1993-1-5. On the other hand, it is in accordance with the functional tolerances of EN 1090-2 since it is $b/100$ and $b/150$ for Classes 1 and 2, respectively. Mechanical and chemical properties of the base materials were recorded.

Partly using these data and based on the results of the strain gauge-based measurements, a validated numerical model was developed. Based on the results of a parametric study focusing on the effect of combining steel grades, the following conclusions can be drawn:

- The maximum tensile stress of the plates exceeds the yield strength of the material in all cases tested, both at the flange and at the web.
- The increase in the maximum longitudinal tensile stress of the flange plates tracks well the increase in the yield strength of the base material.
- The maximum tensile stresses of the plates are higher in the webs than in the flanges.
- A stress plateau appears on the stress curves in the webs, near the edge, due to the location of the weld and the design of the cross-section, while for flanges the appeared stress plateau depends on the steel grade. For higher yield strength, a zone of uniform

tension with minimal width can be seen, while for lower yield strength a wider zone can be seen.

- In hybrid sections, there is a jump in the stress curve of the web near the edges due to the change from high strength steel weld material to normal strength steel web material.

Furthermore, the results of the parametric study were also used to evaluate the residual stress models of the literature. Based on the comparison of these results lead to the following conclusions:

- Among the tested models for NSS sections, the ECCS's heavy weld formula provided the highest accuracy.
- Among the tested models, second formula of Kövesdi and Somodi (**Eq. 9-10**) was the most accurate for sections made purely from S235, S275, S355, and S460 steel grades.
- Khan's formula (**Eq. 6**) is most accurate for sections using pure S700 and S960 steel, but grossly underestimates the compressive stress of the cross-section in the lower strength cases.
- Although none of the presented models is recommended for calculating the residual stress distribution of hybrid box sections, it can be seen that the second formula of Kövesdi and Somodi (**Eq. 9-10**) is able to predict the compressive residual stresses with accuracy of 7.6-15.4%.

8 References

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Appendices

Appendix A – Inspection certificates



WESTFÄLISCHE DRAHTINDUSTRIE GMBH
Werk Hamm
WESTFÄLISCHE LÜNTENAUER GEBETE • POSTFACH 1311 • 59067 Hamm
www.wdi.de

Georg Meier
Kontakt: 02381 2764-34 • Fax: 02381 2764-35
E-Mail: meier@wdi.de

ABNAHMEPRÜFZEUGNIS
nach EN 10204/3.1

Hegont Kft.
Grassalkovich ut. 255
H 1239 Budapest

Ihre Bestellung vom: 18.06.2014 Per Mail:
Lieferadresse: Hegont Kft.
Grassalkovich ut. 255
H 1239 Budapest

Auftrags-Nr.: 187963 **Pos.: 8,0** **LS-Nr.: 757350** **L-Menge: 2.250 kg**

Artikel: 107972 SG-Draht VIK3 MoNi
verpackt 15 kg lage-prüfs
Körbgröße 15 kg lage-prüfs
Dressur: MIN 2000 mm

Chemische Analyse in %
Charge: 834901 conform: A1026

C	Si	Mn	P	S	Cr	Ni	Mo	Cu-Steel	Al
,09	,78	1,76	,006	,007	,15	1,17	,359	,02	,001

As	Ti	Sn	V	N
,004	,008	,001	,001	,0040

Drahtelektrode: EN ISO 16834 – A G 69 4 M Mn3Ni1Mo / AWS A 5.28 ER100 S-G

Mechanisch-technologische Werte einer typischen Charge nach EN ISO 16834

Festigkeit (MPa) 770
Streckgrenz (MPa) 690
Bruchdehnung (%) 17
Kerbschlagarbeit (J) 47 bei -40 °C

Westfälische Drahtindustrie GmbH
Schweißtechnik
Qualitätswesen

Abnahmebeauftragter

Dieses Dokument wurde durch ein DV-System erstellt und ist gemäß DIN EN 10204, Abschn. 5 ohne Unterschrift gültig.

Inspection certificate according to EN 10204-3.1

U.S. Steel Košice s.r.o.
Výrobný areál, 85 Strojní
044 54 Košice
SLOVAK REPUBLIC
Your order: SR-2020/211

Metallurgical Certificate No: 20/315495 01

Size: 6,000 x 1500,0 x 6000,0 mm
EN 10051/10

Pos: 18
Net Weight: 7 540 kg 873
Weight: 7 629 kg 812

Standard: EN 10225-2/04
Delivery No: 30254203

Unit No: 3820607 **Heat:** 3820607 **Unit No:** 3820607 **Heat:** 3820607

M E C H A N I C A L T E S T R E S U L T S

Min.	Max.	Coll No
3820607	3820607	3820607

C71

CHEMICAL COMPOSITION

Min.	Max.	Heat No
3820607	3820607	3820607

C70

PROCES of steel production: LD-PROCES; Continuous casting; Controlled rolling mode.
DOI inspection of surface appearance, shape and dimensions was conducted.
The results meet the requirements.

U.S. Steel Košice s.r.o.
Výrobný areál, 85 Strojní
044 54 Košice
SLOVAK REPUBLIC
Your order: SR-2020/211

Abnahmebeauftragter

Dieses Dokument wurde durch ein DV-System erstellt und ist gemäß DIN EN 10204, Abschn. 5 ohne Unterschrift gültig.



AINESTODISTUS TEST REPORT

EN 10 204-3.1 (2004)

2/3

78916K-001

22.01.2022

Tilauksen Purchaser
SSAB POLAND SP. Z O.O.
UL. KOLEJOWA 15
55-020 ZORAWINA POLAND
Tilauksen Order No.
4501327042

Tilauksen Order Confirmation
78916K

Vastaanottaja Consignee
SSAB POLAND SP. Z O.O.
UL. KOLEJOWA 15
55-020 ZORAWINA POLAND
Asiakkaan markki Shipping mark

Päivämäärä Date
24.01.2022
Valmistajan markki
Mark of the Manufacturer



Lap Grade
STREX 700 MC E

Lisävaatimukset Additional requirements

Jalustavälillä haggelöadit
Oxygen steel, continuous casting
Fully killed, Fine grain practice

Laatuvaatimukset Quality Specifications
HIGH STRENGTH FORMABLE STEEL MEETS REQ. OF EN10149-2 S700MC

Pos. Item	Substans kanta no Cast. test No	T-tila Cond	Velokoe Test	Tensile test										Täivutuskoet Bend test			Huom Nb	Päästö Tempering °C				
				K2	°C	RPO2 MPa	RT05 MPa	REL MPa	REH MPa	1	RM MPa	2	3	A %	RE / RM	RM * A5			RAZ %	Keskiaarno Average	K5	D = X1
010	87572	021	TM	32		749					833			20					32	2.0		
020	87952	041	TM	32		752					838			20					32	2.0		
030	87569	041	TM	32		770					838			20					32	2.0		
040	87572	011	TM	32		738					821			20					32	2.0		

K2: 30-CENTRE, LONGITUDINAL
K5: 30-120 MM WIDE BEND TEST

TM-THERMOMECH. TREATED

Pos. Item	Substans kanta no Cast. test No	Isokoe Impact test	K3	°C	Kokkelauso Average			FA %			LE (mm)			Specimen Unbroken			Erikoiskokeet Special tests			Huom Nb	Päästö Tempering °C	
					1	2	3	1	2	3	1	2	3	1	2	3	K4	°C	1			2
010	87572	021	133	-040	32	40	39	37														
020	87952	041	133	-040	32	36	44	37														
030	87569	041	137	-040	37	37	40	38														
040	87572	011	135	-040	66	68	55	63														

FA = Sitkeämurtuman osuus Shear fracture appearance
LE = Poikittainen laajenema Lateral Expansion

K3: 133-CH-VISO-VUJ,5X10,CENTRE, LONGIT, KV600 137-CH-VUJ, TX10,CENTRE, LONGIT, KV600 135-CH-VISO-VUJ, 7,5X10,CENTRE, LONGIT, KV600

Raabe Steel Works

Tämän todistuksen, että toimitus on tilausvahvistuksen mukainen.
We hereby certify that the material described above has been tested and complies with the terms of the order confirmation.

Testaus ja tarkastus Testing and Inspection

Minna Valkama

MINNA VALKAMA
Valtuutettu tarkastaja Authorized inspection representative

Yhtiön nimi Company Name: SSAB Europe Oy
Kotipaikka Registered Office: HAMMENLINNA

Osoite Address: PL 93, P.O. Box 93
FIN-02101 RAABE, FINLAND

Puhelin Telephone: 020 5911
+358 20 5911

Y-tunnus Business ID: 2389445-7



ANALYYSITODISTUS ANALYSIS CERTIFICATE ANALYSEBESCHEINIGUNG COMPOSITIO CHIMIQUE CERTIFICAT СЕРТИФИКАТ АНАЛИЗА

3/3

78916K-001

22.01.2022

Substans kanta no Cast. test No	Koe nro Test No	Positio Pos.	Cehi Ceq	Analyyti %	Chemical composition %	Chemisch Zusammensetzung %	Composition Chimique %	Analyse %												Päivämäärä Date Datum Date	AMH
No. of samples No. of coudeurs	Pos. No.	Pos. No.	Pos. No.	C	SI	MN	P	S	AL	NB	V	TI	CU	CR	NI	MO	B	24.01.2022			
87572	010	.40	.055	.03	1.93	.014	.002	.039	.052	.051	.099	.019	0.05	0.03	.007	.0002					
87952	020	.41	.060	.03	1.94	.012	.001	.037	.052	.051	.097	.013	0.05	0.04	.004	.0003					
87569	030	.40	.055	.02	1.91	.014	.002	.040	.049	.052	.099	.014	0.05	0.03	.005	.0002					
87572	040	.40	.055	.03	1.93	.014	.002	.039	.052	.051	.099	.019	0.05	0.03	.007	.0002					

CEQ-C+Mn+V+(Cr+Mo+V)/5+(Ni+Cu)/15

Raabe Steel Works

Testaus ja tarkastus Testing and Inspection
Prüfung und Kontrolle

Minna Valkama

MINNA VALKAMA
Valtuutettu tarkastaja Authorized inspection representative

Yhtiön nimi Company Name: SSAB Europe Oy
Kotipaikka Registered Office: HAMMENLINNA

Osoite Address: PL 93, P.O. Box 93
FIN-02101 RAABE, FINLAND

Puhelin Telephone: 020 5911
+358 20 5911

Y-tunnus Business ID: 2389445-7

Steel manufactured and supplied by Raabe Steel Works is free from radiation.
Производство на металлургическом заводе «Raabe Steel Works» и поставка
эксклюзивно сталь не излучает радиацию



AINESTODISTUS TEST REPORT

EN 10 204-3.1 (2004)

3/6
78423K-001 A
07.01.2022

Tilaaaja Purchaser
SSAB POLAND SP. Z O.O.
UL. KOLEJOWA 15
55-020 ZORAWNA POLAND
Tilauksen nro Order No.
4501320675
Laji Grade
S355MC

Tilauksen vahvistus Order Confirmation
78423K

Lisävaatimukset Additional requirements

Vastaanottaja Consignee
SSAB POLAND SP. Z O.O.
LUKOWSKA 79
64-600 CIEPRZYŃ POLAND
Asiakkaan merkki Shipping mark
G.P. 3.11

Päivämäärä Date
10.01.2022
Valmistajan merkki
Mark of the Manufacturer
Jalkavalmiutus happesta
Oxygen steel, continuous casting
Fully killed, Fine grain practice



Laatuvaatimukset Quality Specifications
HIGH YIELD STRENGTH FORMABLE FINE-GRAIN STEEL

Pos. Item	Sulatus, Cast test No	Tila Cond	Vetokoe K2	Tensile test °C	RPO2 MPa	RT05 MPa	REL MPa	REH MPa	1	RM MPa	2	3	A %	50	80	200	RE / RM	RM * A5	1	RAZ %	2	3	Keskiarvo Average	Tavutustulos Bend test K5	D = X1	Huom Nb	Päästi Tempering °C
010	83814	040	TM	32	396					469		33												32	0.5		
020	83814	040	TM	32	396					469		33												32	0.5		
030	86309	031	TM	32	400					486		30												32	0.5		
030	86309	051	TM	32	395					479		30												32	0.5		
040	81732	010	TM	32	403					476		31												32	0.5		
040	84255	050	TM	32	401					473		32												32	0.5		

K2: 32-CENTRE, LONGITUDINAL
K5: 32-120 MM WIDE BEND TEST

TM-THERMOMECH. TREATED

Raabe Steel Works

Tilauksen vahvistus Testing and Inspection

Täten todistamme, että toimitus on tilauksen vahvistuksen mukainen.
We hereby certify that the material described above has been tested and complies with the terms of the order confirmation.

Minna Valkama
Valtuutettu tarkastaja
Authorized inspection representative

Yhtiön nimi Company Name: SSAB Europe Oy
Kotipaikka Registered Office: HAMMENLINNA

Osoite Address: PL 63, P.O. Box 93
FIN-02101 RAAHE, FINLAND

Puhelin Telephone: 020 5911
+358 20 5911

Y-tunnus Business ID: 2389445-7



AINESTODISTUS TEST REPORT

EN 10 204-3.1 (2004)

4/6
78423K-001 A
07.01.2022

Tilaaaja Purchaser
SSAB POLAND SP. Z O.O.
UL. KOLEJOWA 15
55-020 ZORAWNA POLAND
Tilauksen nro Order No.
4501320675

Tilauksen vahvistus Order Confirmation
78423K

Lisävaatimukset Additional requirements

Vastaanottaja Consignee
SSAB POLAND SP. Z O.O.
LUKOWSKA 79
64-600 CIEPRZYŃ POLAND
Asiakkaan merkki Shipping mark
G.P. 3.11

Päivämäärä Date
10.01.2022
Valmistajan merkki
Mark of the Manufacturer
Jalkavalmiutus happesta
Oxygen steel, continuous casting
Fully killed, Fine grain practice



Laatuvaatimukset Quality Specifications
HIGH STRENGTH FORMABLE STEEL MEETS REQ. OF EN10149-2 S500MC

Pos. Item	Sulatus, Cast test No	Tila Cond	Vetokoe K2	Tensile test °C	RPO2 MPa	RT05 MPa	REL MPa	REH MPa	1	RM MPa	2	3	A %	50	80	200	RE / RM	RM * A5	1	RAZ %	2	3	Keskiarvo Average	Tavutustulos Bend test K5	D = X1	Huom Nb	Päästi Tempering °C
050	86664	041	TM	32	529					604		25												32	1.0		
050	86666	021	TM	32	515					584		27												32	1.0		

K2: 32-CENTRE, LONGITUDINAL
K5: 32-120 MM WIDE BEND TEST

TM-THERMOMECH. TREATED

KS: 30~120 MM WIDE BEND TEST																									TM-THERMOECH. TREATED									
Pos. item	Sulatus Cast test No	Isokuo K3	Impact test °C	1	2	3	Keskiarvo Average	W (mm)	FA %			LE (mm)			*Specimen Unbroken			Erikoiskokeet K4 °C	Special tests			Huom Nb	Päästi Tempering °C											
									1	2	3	1	2	3	Keskiarvo Average	1	2		3	Keskiarvo Average	1			2	3	Keskiarvo Average								
FA = Sirkelmurtuman osuus Shear fracture appearance																									LE = Poikittainen laajeneminen Lateral Expansion									
050	86664	041	133	-020	83	83	85																											
050	86666	021	133	-020	96	93	109	99																										
K3: 133-CH-VISO-V(J) SX10.CENTRE.LONGIT.KV600																																		

K3: 133-CH-VISO-VUJ 5X10, CENTRE, LONGIT. XY600

FA = Etäisyyden mittaus Shear fracture appearance

LE = Poikittaisen laajenema Lateral Expansion

Raabe Steel Works

Tilauksen vahvistus Testing and Inspection

Täten todistamme, että toimitus on tilauksen vahvistuksen mukainen.
We hereby certify that the material described above has been tested and complies with the terms of the order confirmation.

Minna Valkama
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Yhtiön nimi Company Name: SSAB Europe Oy
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FIN-02101 RAAHE, FINLAND

Puhelin Telephone: 020 5911
+358 20 5911

Y-tunnus Business ID: 2389445-7

SSAB		ANALYYSITODISTUS ANALYSIS CERTIFICATE ANALYSEBESCHEINIGUNG COMPOSITIO CHIMIQUE CERTIFICAT СЕРТИФИКАТ АНАЛИЗА																5/6 78423K-001 A 07.01.2022	
Sulatus nro Cast No Schmelzen Nr. No de couler № Плавки	Koe nro Test No Essai No № Проб	Positi- on Item Poste №	Coke Ceq Ceq Ceq	Analyysi % Chemical composition % Chemisch Zusammensetzung % Composition Chimique % Анализ пробы % (%ppm)														Päivämäärä Date Datum Date Data 10.01.2022	AMH
				C	SI	MN	P	S	AL	NB	V	TI	CU	CR	NI	MO	N	B	
83814	010	.19	.056	.01	0.70	.009	.004	.036	.029	.006	.000	.011	0.04	0.03	.003	.003	.0002		
83814	020	.19	.056	.01	0.70	.009	.004	.036	.029	.006	.000	.011	0.04	0.03	.003	.003	.0002		
86309	030	.19	.061	.01	0.69	.011	.004	.028	.027	.006	.000	.011	0.05	0.03	.003	.005	.0001		
81732	040	.19	.058	.02	0.69	.008	.005	.035	.027	.005	.001	.014	0.04	0.03	.002	.004	.0000		
84255	040	.19	.058	.01	0.70	.008	.005	.034	.026	.008	.000	.014	0.04	0.04	.004	.004	.0000		

CEQ=C+Mn/S+(Cr+Mo+V)/5+(Ni+Cu)/15

Raahe Steel Works

Testaus ja tarkastus
Prüfung und Kontrolle
Essais et Contrôle
Испытание и контроль качества

Steel manufactured and supplied by Raahe Steel Works is free from radiation.
Производство на металлургическом комбинате «Raahe Steel Works» и поставленная заказчику сталь не содержит радиацию.

Minna Valkama

MINNA VALKAMA
Valtuutettu tarkastaja
Sachverständiger
Authorized inspection representative
Inspector/autorité
Уполномоченный инспектор

Osake Address: PL 93, P.O. Box 93
FIN-82101 RAAHE, FINLAND

Puhelin Telephone: 020 5911
+358 20 5911

Y-tunnus Business ID: 2389445-7

SSAB		ANALYYSITODISTUS ANALYSIS CERTIFICATE ANALYSEBESCHEINIGUNG COMPOSITIO CHIMIQUE CERTIFICAT СЕРТИФИКАТ АНАЛИЗА														6/6 78423K-001 A 07.01.2022					
Sulatus nro Cast No Schmelzen Nr. No de couler № Плавки		Koe nro Test No Essai No № Проб	Positi- on Item Poste №	Coke Ceq Ceq Ceq	Analyysi % Chemical composition % Chemisch Zusammensetzung % Composition Chimique % Анализ пробы % (%ppm)														Päivämäärä Date Datum Date Data 10.01.2022		AMH
					C	SI	MN	P	S	AL	NB	V	TI	CU	CR	NI	MO	N	B		
86664		050	.29	.055	.02	1.22	.012	.003	.060	.046	.082	.017									
86666		050	.28	.052	.02	1.21	.012	.002	.059	.043	.079	.016									

CEQ=C+Mn/S+(Cr+Mo+V)/5+(Ni+Cu)/15

Raahe Steel Works

Testaus ja tarkastus
Prüfung und Kontrolle
Essais et Contrôle
Испытание и контроль качества

Steel manufactured and supplied by Raahe Steel Works is free from radiation.
Производство на металлургическом комбинате «Raahe Steel Works» и поставленная заказчику сталь не содержит радиацию.

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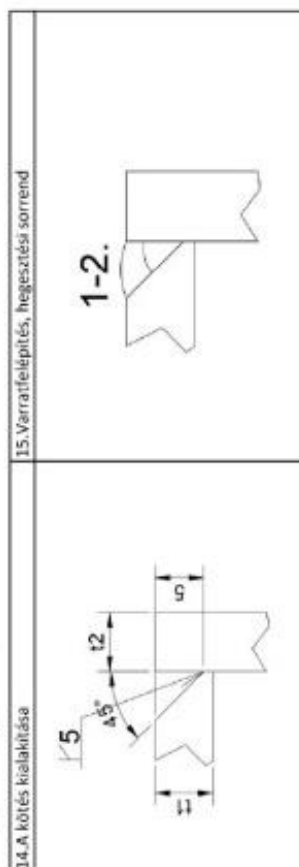
Appendix B - Welding Procedure Specifications

1. Gyártói hegesztési utasítás (Az EN ISO 15609-1:2020 szerint)

2. Az üzem helye: Budapest
3. WPS (hegesztési utasítás) száma: WPS 168/2022
4. WPQR (heg. techn. jóváhagyási ív) száma:
5. Gyártó: Acélhidak Kft.
7. Hegesztési eljárás: 135
8. Kötéstípus: BW
9. A varratelőkészítés és a tisztítás módszere: revétlenítés, köszörülés
10. Az alapanyag megnevezése: t1=S700MC, t2=S700MC
11. Anyagvastagság: t1=6 mm, t2=6 mm
12. Külső átmérő:
13. Hegesztési helyzet: PA

Minősítő:

TÜV Rheinland Intercert Kft.
Budapest



14. A kötés kialakítása

15. Varratfelépítés, hegesztési sorrend

16. Hegesztéstechnológiai adatok

17.	18.	19.	20.	21.	22.	23.	24.	25.
Varrator /réteg	Hegesztési eljárás	A hozaganyag mérete	Áramerősség, A	Feszültség, V	Az áram neve és polaritása	Húzóerő-tollási sebesség cm/min	Hegesztési sebesség cm/min	Hőbevitel kJ/cm
1.	135	Ø 1,2	230-240	22-23	DCEP	8-9	30	8,8
2.	135	Ø 1,2	280-290	28-29	DCEP	9-10	40	10,2

26. A hozaganyag beszerelése és kereskedelmi megnevezése: Mn3Ni1Mo (EN ISO 16834)

WDI MoNI SG

27. Esetleges különleges szárítás: -

28. Védőgáz vagy fedőpor: M21 (82% Ar + 18% CO2)

29. Megtámasztás: -

30. Védőgáz mennyisége: 14 l/min

31. A gyökérfaragás részletei: -

32. Előmelegítési hőmérséklet: -

33. Közbeső hőmérséklet: max. 250 °C

Dátum: 2022.05.26

34. Hegesztés utáni hőkezelés: -

35. Idő, hőmérséklet, módszer: -

36. Felmelegítési és lehűlési sebesség: -

37.

Készített
hegesztő szakmérnök, EWE/IWE

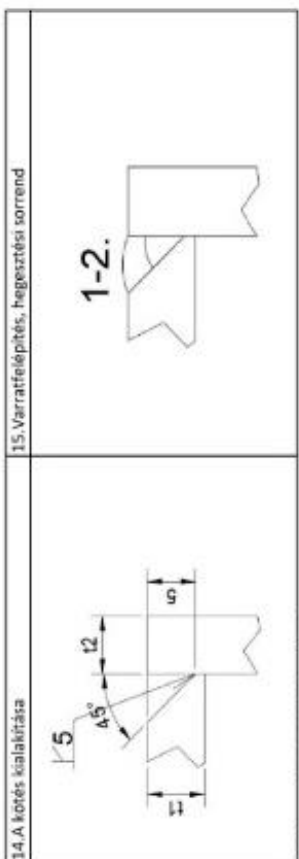


1. Gyártói hegesztési utasítás (Az EN ISO 15609-1:2020 szerint)

2. Az üzem helye: Budapest
3. WPS (hegesztési utasítás) száma: WPS 167/2022
4. WPQR (heg. techn. jóváhagyási ív) száma:
5. Gyártó: Acélhidak Kft.
7. Hegesztési eljárás: 135
8. Kötéstípus: BW
9. A varratelőkészítés és a tisztítás módszere: revétlenítés, köszörülés
10. Az alapanyag megnevezése: t1=S355J2+N, t2=S355J2+N
11. Anyagvastagság: t1=6 mm, t2=6 mm
12. Külső átmérő:
13. Hegesztési helyzet: PA

Minősítő:

TÜV Rheinland Intercert Kft.
Budapest



14. A kötés kialakítása

15. Varratfelépítés, hegesztési sorrend

16. Hegesztéstechnológiai adatok

17.	18.	19.	20.	21.	22.	23.	24.	25.
Varrator /réteg	Hegesztési eljárás	A hozaganyag mérete	Áramerősség, A	Feszültség, V	Az áram neve és polaritása	Húzóerő-tollási sebesség cm/min	Hegesztési sebesség cm/min	Hőbevitel kJ/cm
1.	135	Ø 1,2	230-240	22-23	DCEP	8-9	30	8,8
2.	135	Ø 1,2	280-290	28-29	DCEP	9-10	40	10,2

26. A hozaganyag beszerelése és kereskedelmi megnevezése: Mn3Ni1Mo (EN ISO 16834)

WDI MoNI SG

27. Esetleges különleges szárítás: -

28. Védőgáz vagy fedőpor: M21 (82% Ar + 18% CO2)

29. Megtámasztás: -

30. Védőgáz mennyisége: 14 l/min

31. A gyökérfaragás részletei: -

32. Előmelegítési hőmérséklet: -

33. Közbeső hőmérséklet: max. 250 °C

Dátum: 2022.05.26

34. Hegesztés utáni hőkezelés: -

35. Idő, hőmérséklet, módszer: -

36. Felmelegítési és lehűlési sebesség: -

37.

Készített
hegesztő szakmérnök, EWE/IWE



**1. Gyártói hegesztési utasítás
(Az EN ISO 15609-1:2020 szerint)**

Minősítő:
TÜV Rheinland Intercert Kft.
Budapest

2. Az üzem helye: Budapest
3. WPS (hegesztési utasítás) száma: WPS 172/2022

5. Gyártó:	Acélhidak Kft.	
7. Hegesztési eljárás:	135	
8. Kötéstípus:	BW	
9. A varratelőkészítés és a tisztítás módszere:		revetlenítés, köszbrülés
10. Az alapanyag megnevezése:	t1=S700MC, t2=S700MC	
11. Anyagvastagság:	t1=4 mm, t2=4 mm	
12. Külső átmérő:	-	
13. Hegesztési helyzet:	PA	

14.A kötés kialakítása	15.Varratfelépítés, hegesztési sorrend
	

16. Hegesztéstechnológiai adatok

47.	46.	45.	44.	43.	42.	41.	40.	39.	38.	37.
Varratör -főleg	Hegesztési eljárás	A horaganyag mérete	Áramerősség, A	Feszültség, V	Az áram néme és polaritása	Húzóerős- telési sebesség cm/min	Hővezetl KJ/cm	23.	22.	21.
1.	135	Ø 1.2	230-240	22-23	DCEP	8-9	30	8.8		

26.A hozaganyag besorolása és kereskedelmi megnevezése:

WDI MoNi SG

27. Esetleges különleges száritás: -

28. Védőgáz vagy fedőpor: M21 (82% Ar + 18% CO₂)

högföldvédelem:

29. Megtámasztás: -

30. Védőgáz mennyisége: 14 l/min

31. A gyökérfagás részletei: -
32. Előmelegítési hőmérséklet: -
33. Közbenő hőmérséklet: **max. 250 °C**
34. Hegesztés utáni hőkezelés: -
35. Idő, hőmérséklet, módszer: -
36. Felmelegítés és lenűlési sebesség: -

37.  Magyar László
Hegyzőközlöny, EWF/IWE

1. Gyártói hegesztési utasítás
(Az EN ISO 15609-1:2020 szerint)

Minősítő:
TÜV Rheinland Intercert Kft.
Budapest

2. Az üzem helye: Budapest

1. WPQR (fig. techn. jóváhagyási jkv) száma:	
5. Gyártó:	Acellidák Kft.
7. Hegesztési eljárás:	135
8. Kötéstípus:	BW
10. Az alapanyag megnevezése:	t1=S35MC, t2=S700MC
t1-t1. Anyagvastagság:	t1=4 mm, t2=4 mm
t2-t2. Külső átmérő:	-
13. Hegesztési helyzet:	PA

14. A kötés kialakítása	
15. Varratleírás, hegesztési sorrend	

16. Hegesztéstechnológiai adatok

8.7.	8.8.	8.9.	8.10.	8.11.	8.12.	8.13.	8.14.	
Varrósor /réteg	Hegesztési ellátás	A hozaganyag mérté	Áramerősség, A	Feszültség, V	Az áram néme és polaritása	Huzalele- tolási sebesség cm/min	Hegesztési sebesség cm/min	Hőbevitel kJ/cm
1.	135	Ø 1,2	230-240	27-23	DCEP	8-9	30	8,8

26.A. Hozaganyag besorolása és kereskedelmi megnevezése: **Mn3Ni1Mo (EN ISO 16834)**

WIDI MoNi SG

27.És esetleges különleges száritás: -

28. Védőgáz vagy fedőpor: M21 (82% Ar + 18% CO₂)

hagyfördővelem:

29. Megtámasztás:

31. A gyökfaragás részletei: -
32. Előmelegítési hőmérséklet: -
33. Kőzetbelső hőmérséklet: **max. 250 °C**
34. Hegesztés utáni hőkezelés: -
35. Idő, hőmérséklet, módszer: -
36. Felmelegítési és lehűlési sebesség: -

37.  Magyar László
húgócsigolyák, hernék, EWE/IWE

**1. Gyártói hegesztési utasítás
(Az EN ISO 15609-1:2020 szerint)**

2. Az üzem helye:	Budapest
3. WPS (megszérségi utasítás) száma:	WPS 169/2022
4. WPOR (meg. techn. jóváhagyási kv) száma:	
Működő:	TÜV Rheinland Intercert Kft.
	Budapest

5.Gyártó: **Acélhidak Kft.**

7. Hegesztési eljárás: 135

8. Köröstimpus: BW

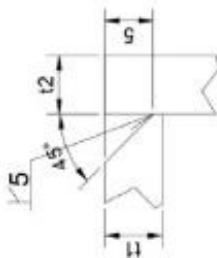
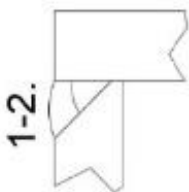
9. A varratelőkészítés és a tisztítás módszere:

10. Az alapanyag megnevezése: t1=S355J2+N, t2=S700MC

11. Anyagvastagság: $t_1=6\text{ mm}, t_2=6\text{ mm}$

12. Külső átmérő:

13. Hegesztési helyzet: PA

14. A kötés kialakítása			15. Varratfelépítés, hegesztési sorrend											
														
16. Hegesztéstechnológiai adatok														
17. Varratór /réteg	18. Hegesztési eljárás	19. A hozaganyag mérete	20. Áramerősség, A	21. Feszültség, V	22. Az áram fajla és polaritása	23. Huzalele- tolási sebesség	24. Hegesztési sebesség cm/min	25. Hőbevitel KJ/cm						
1.	135	Ø 1,2	230-240	22-23	DCEP	8-9	30	8,8						
2.	135	Ø 1,2	280-290	28-29	DCEP	9-10	40	10,2						

26.A hozaganyag besorolása és kereskedelmi megnevezése:
Mn3Ni1Mo (EN ISO 6834)

WDI MoNi SG

Egyéb adatok: -

28. Védőgáz vagy fedőgáz: M21 (82% Ar + 18% CO₂)

hagyfűdővédelem:

29. Megtámasztás: -

30. Védőgáz mennyisége: 14 l/min

31. A gyökkifaragás részletei: -

32. Előmelegítési hőmérséklet: -

33. Közbenő hőmérséklet: max. 250 °C

Datum: 2022.05.26

34. Hegesztés utáni hőkezelés:

35. Idő, hőmérséklet, módszer: -

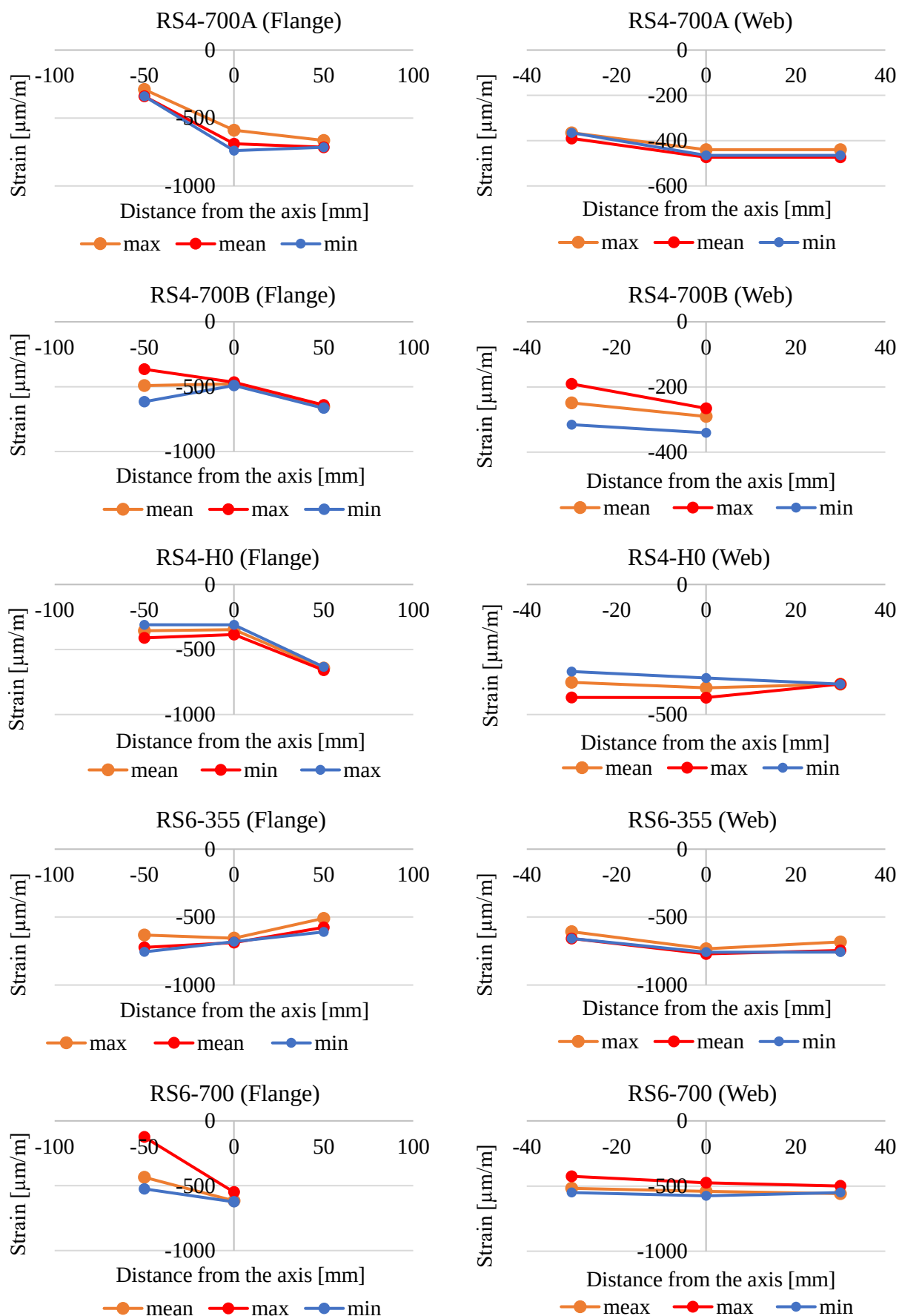
36. Felmelegítési és lehűlési sebesség: -

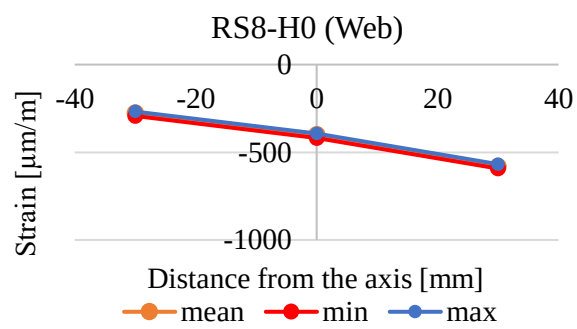
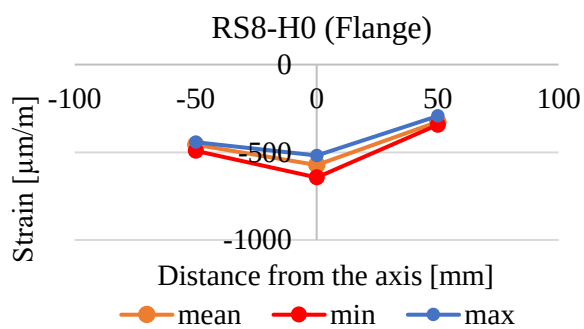
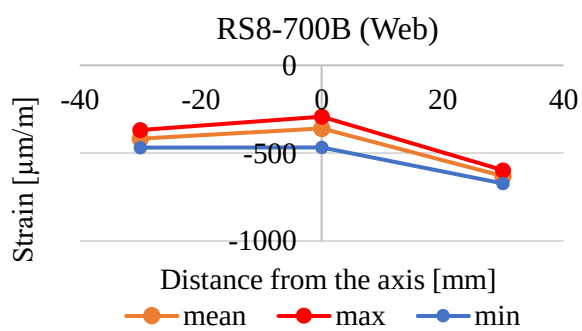
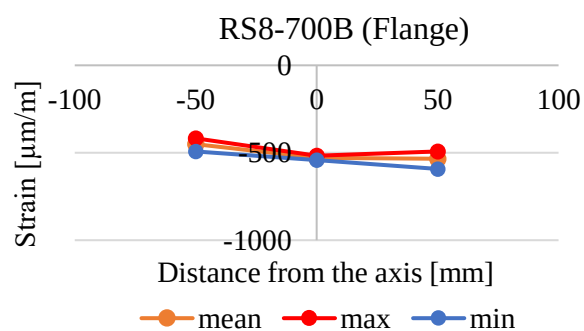
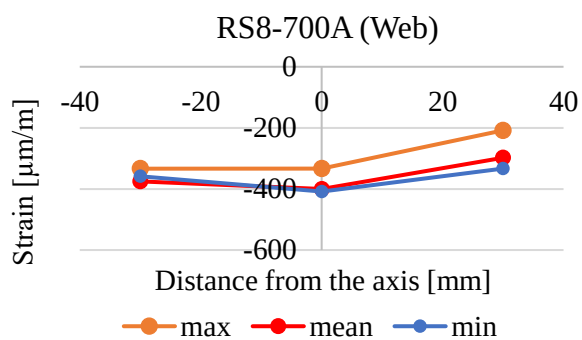
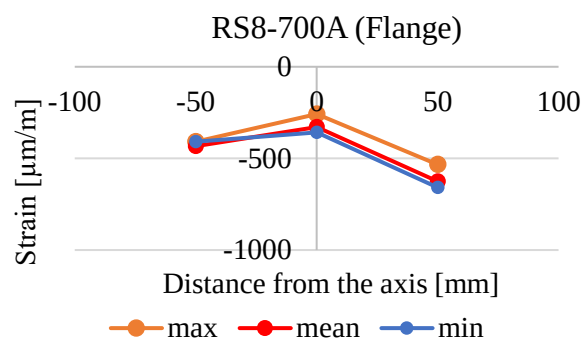
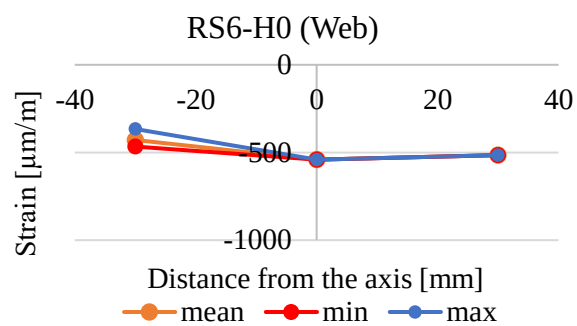
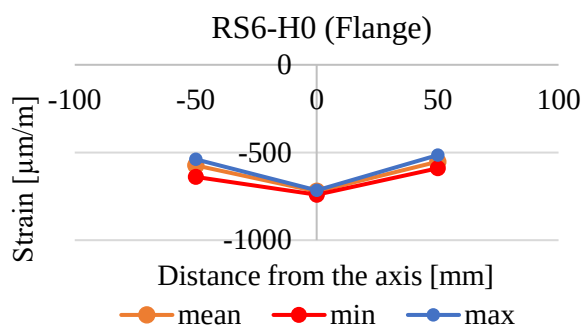
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Készítette

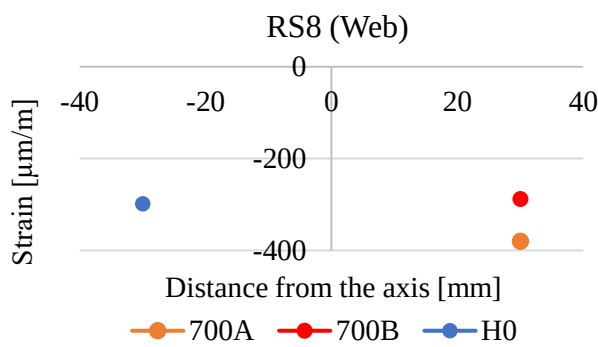
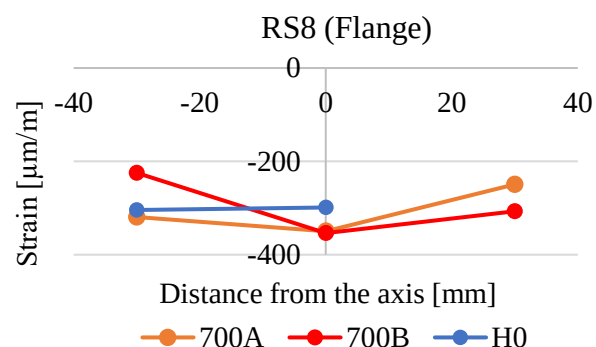
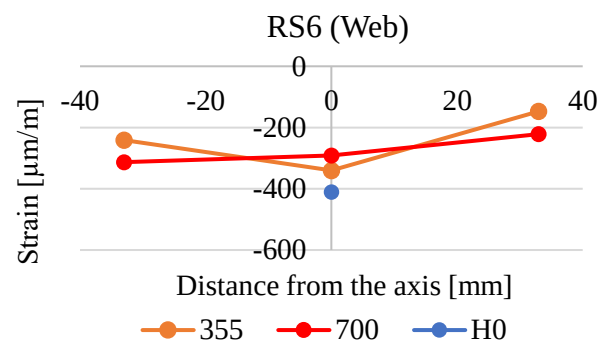
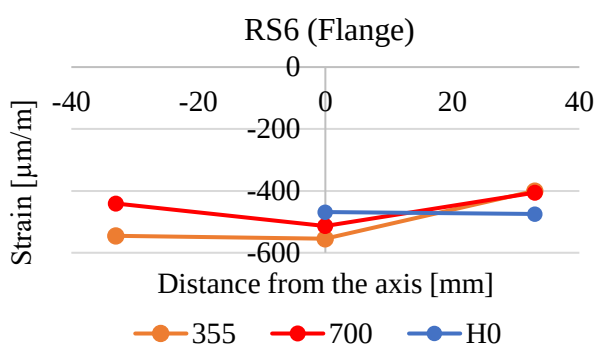
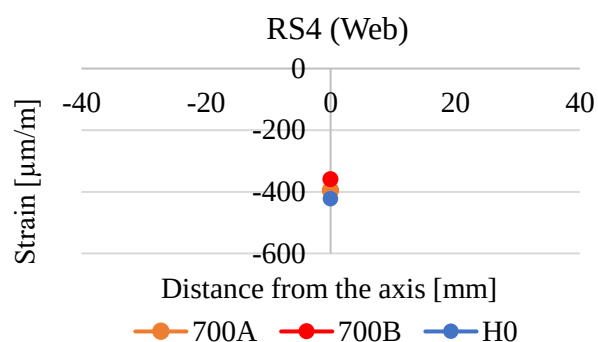
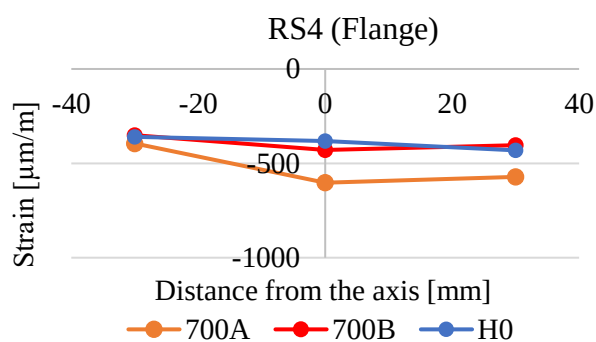
hegesztő szaktárménők, ÉMKE/IVE

Appendix C – Results of BAM extensometer measurements

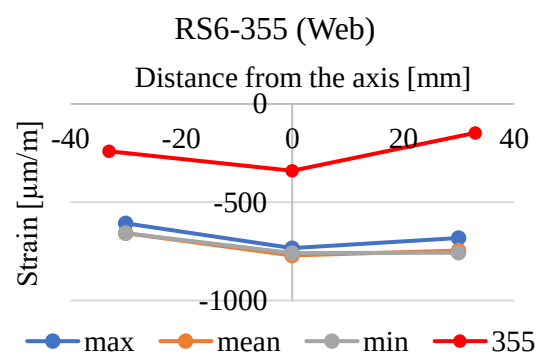
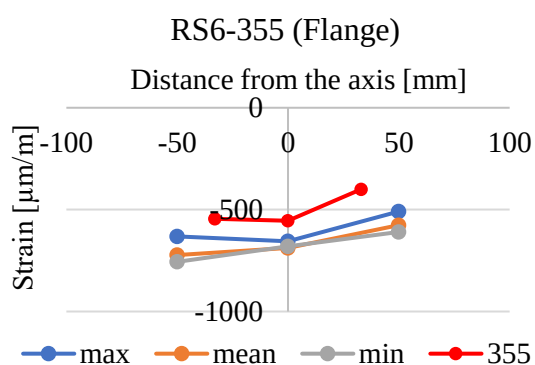
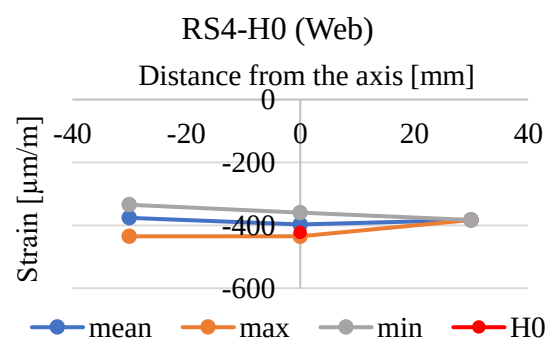
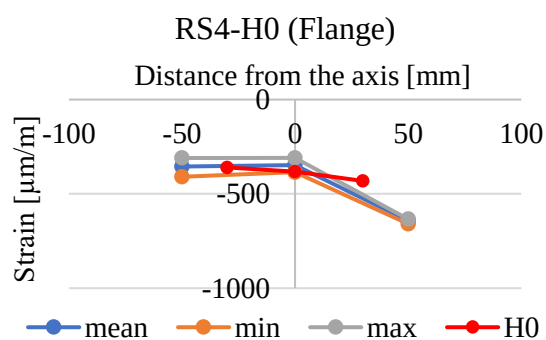
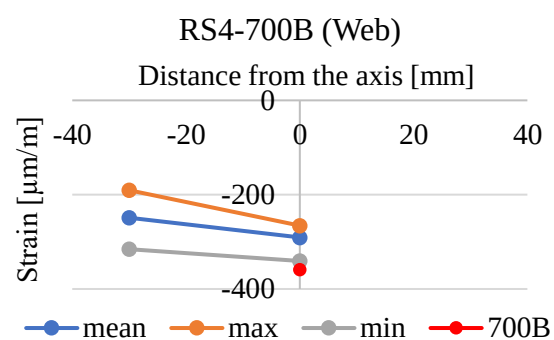
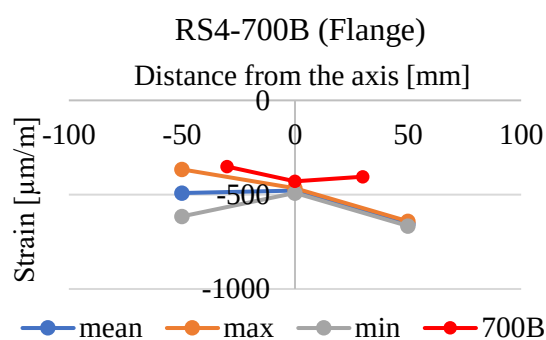
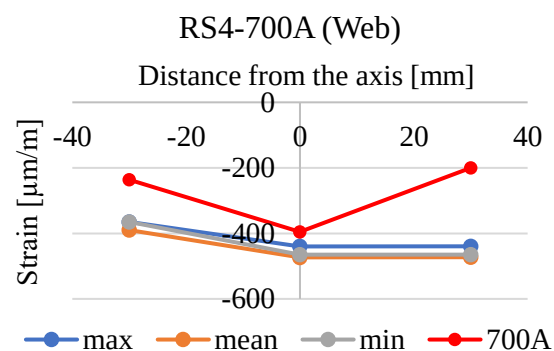
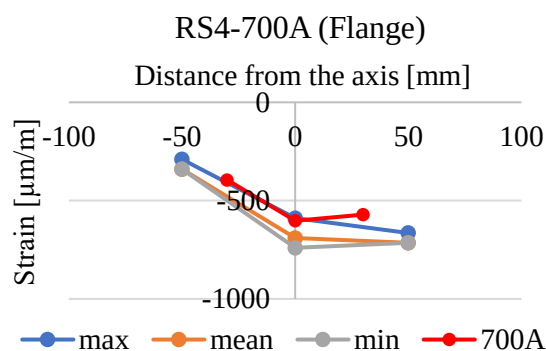


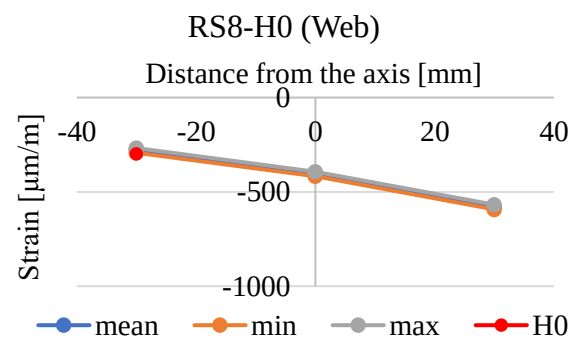
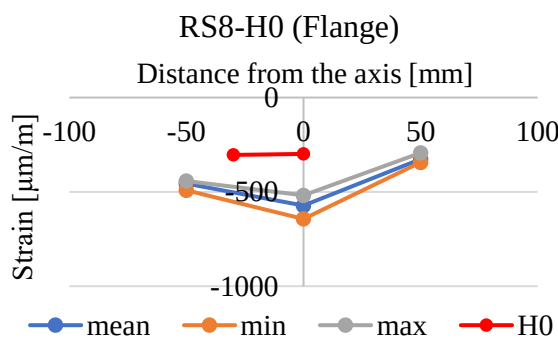
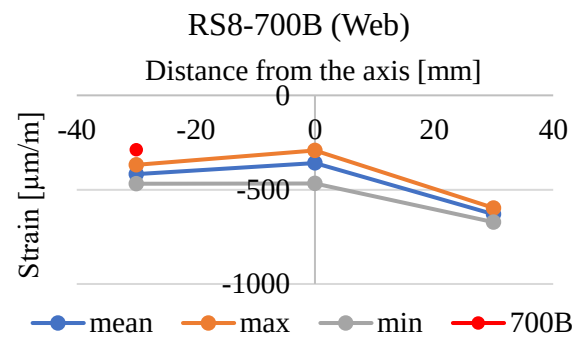
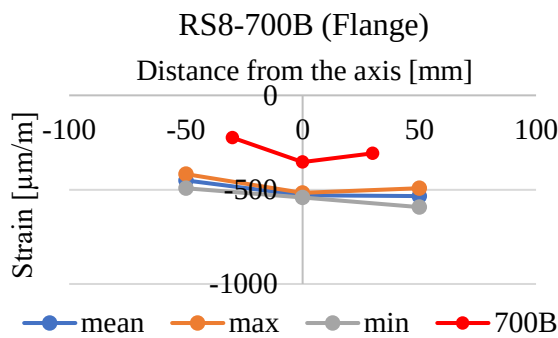
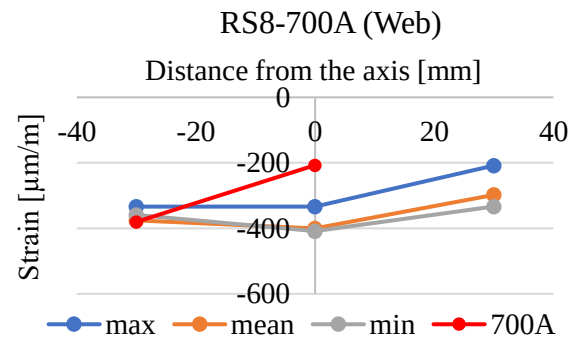
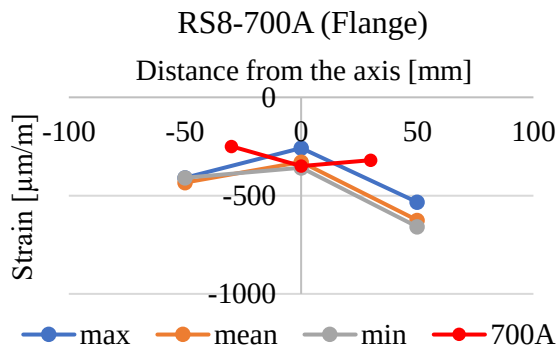
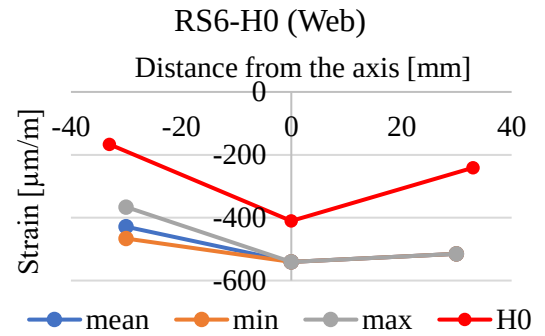
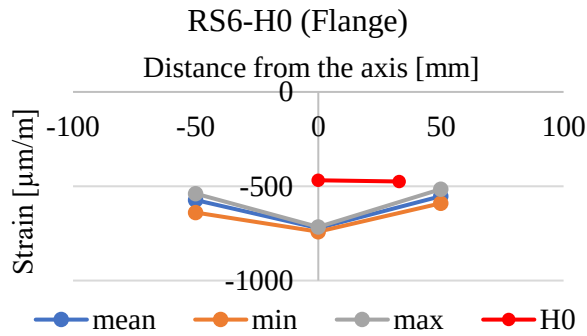
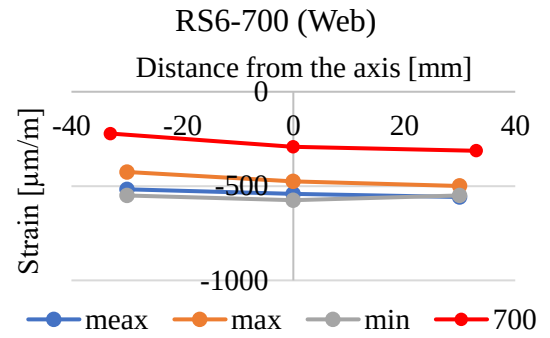
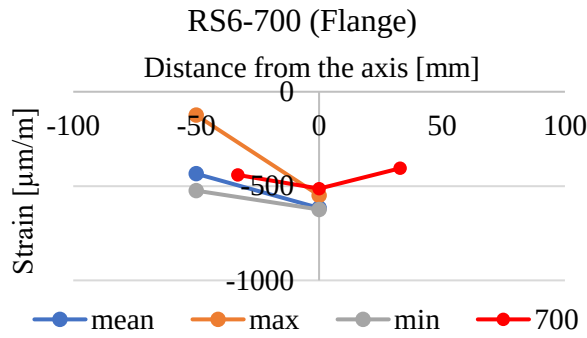


Appendix D – Results of the strain gauges measurements

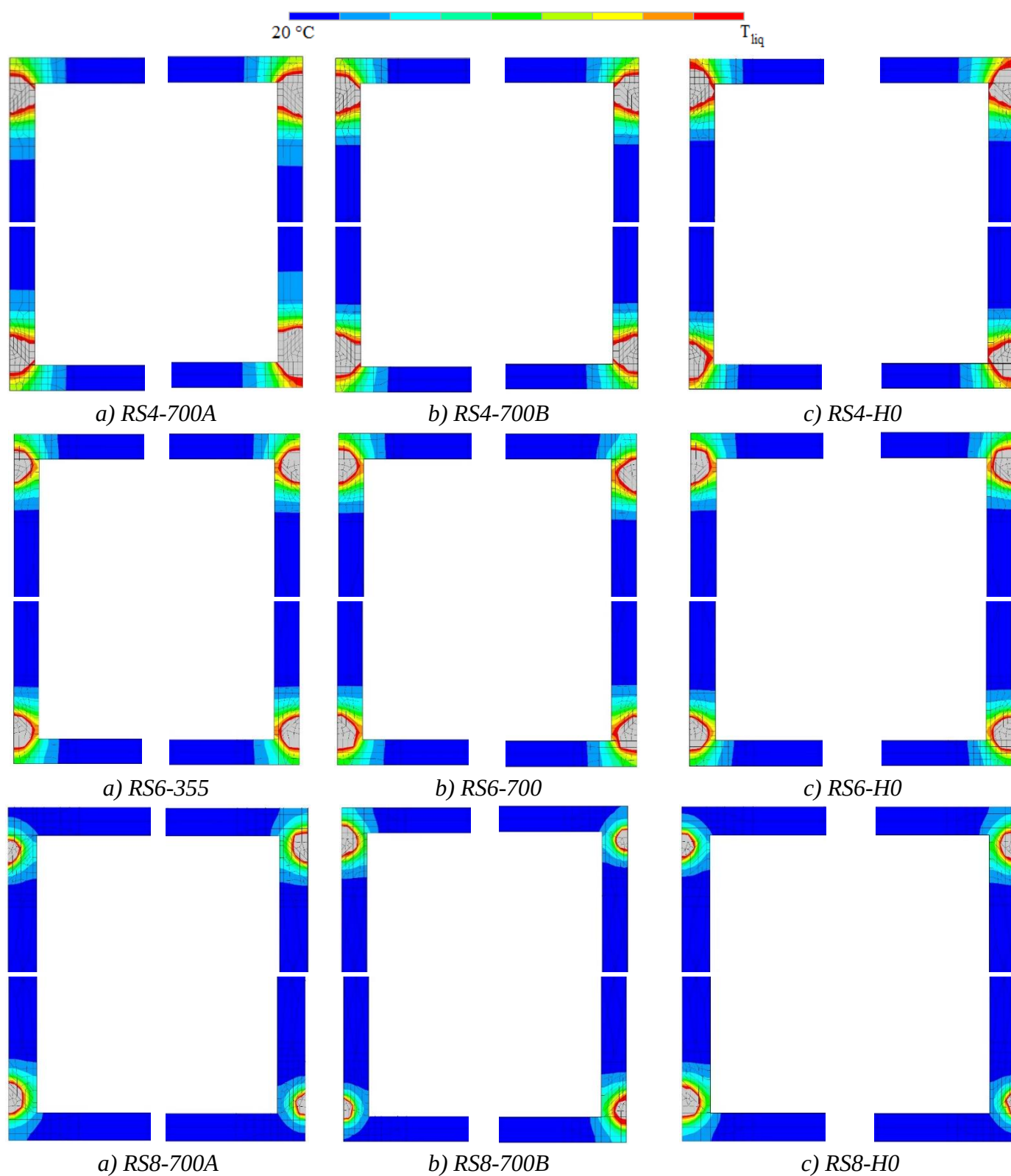


Appendix E – Results of BAM and strain gauge-based measurements

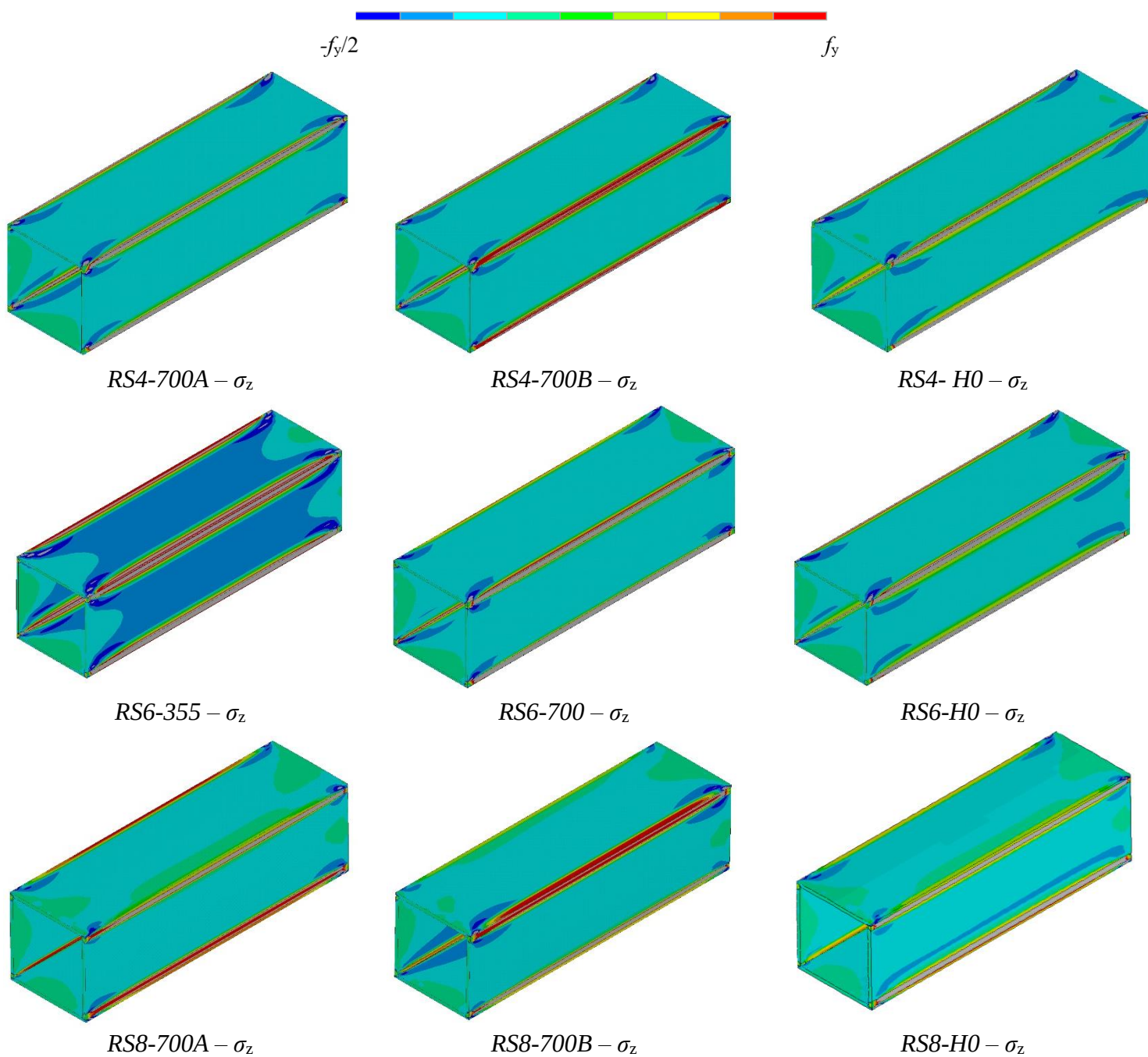


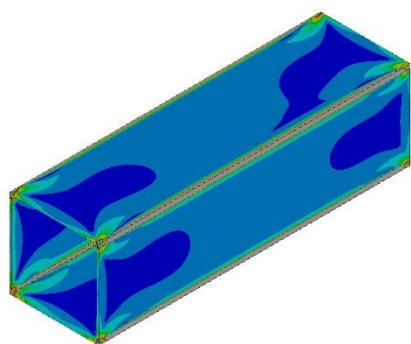


Appendix F - Fusion zones of the tested specimens

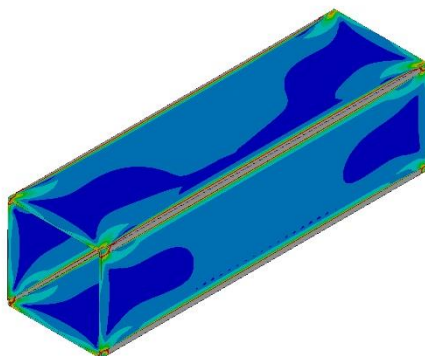


Appendix G – Longitudinal (σ_z) and von Mises (σ_{eqv}) residual stresses

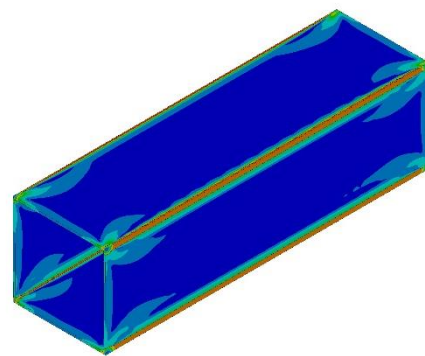




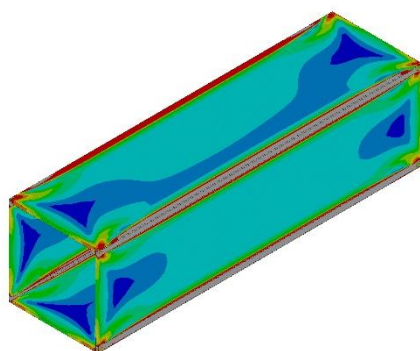
RS4-700A – σ_{eqv}



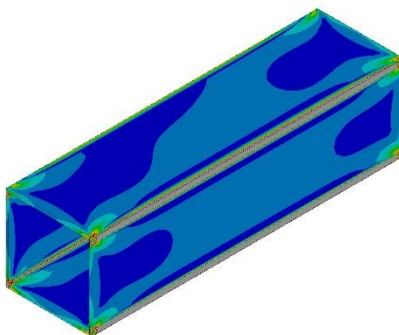
RS4-700B – σ_{eqv}



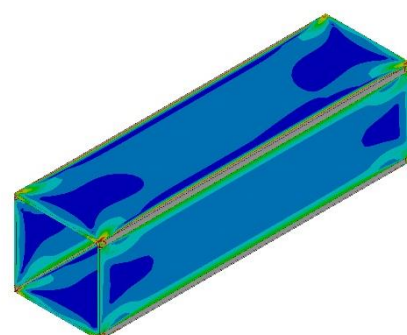
RS4-H0 – σ_{eqv}



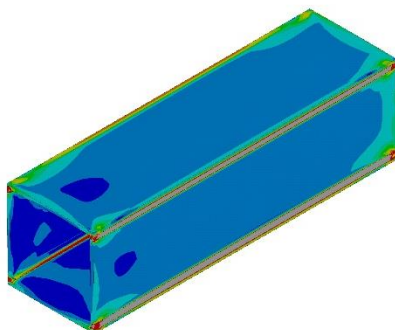
RS6-355 – σ_{eqv}



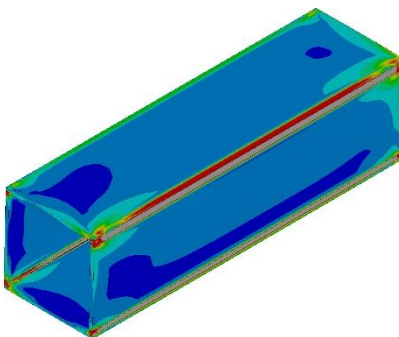
RS6-700 – σ_{eqv}



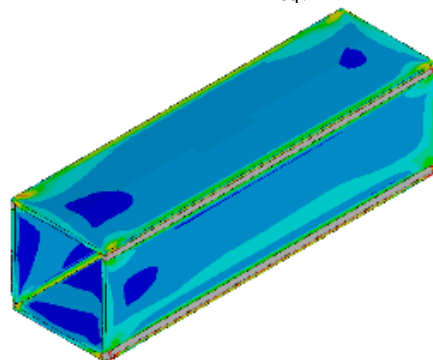
RS6-H0 – σ_{eqv}



RS8-700A – σ_{eqv}

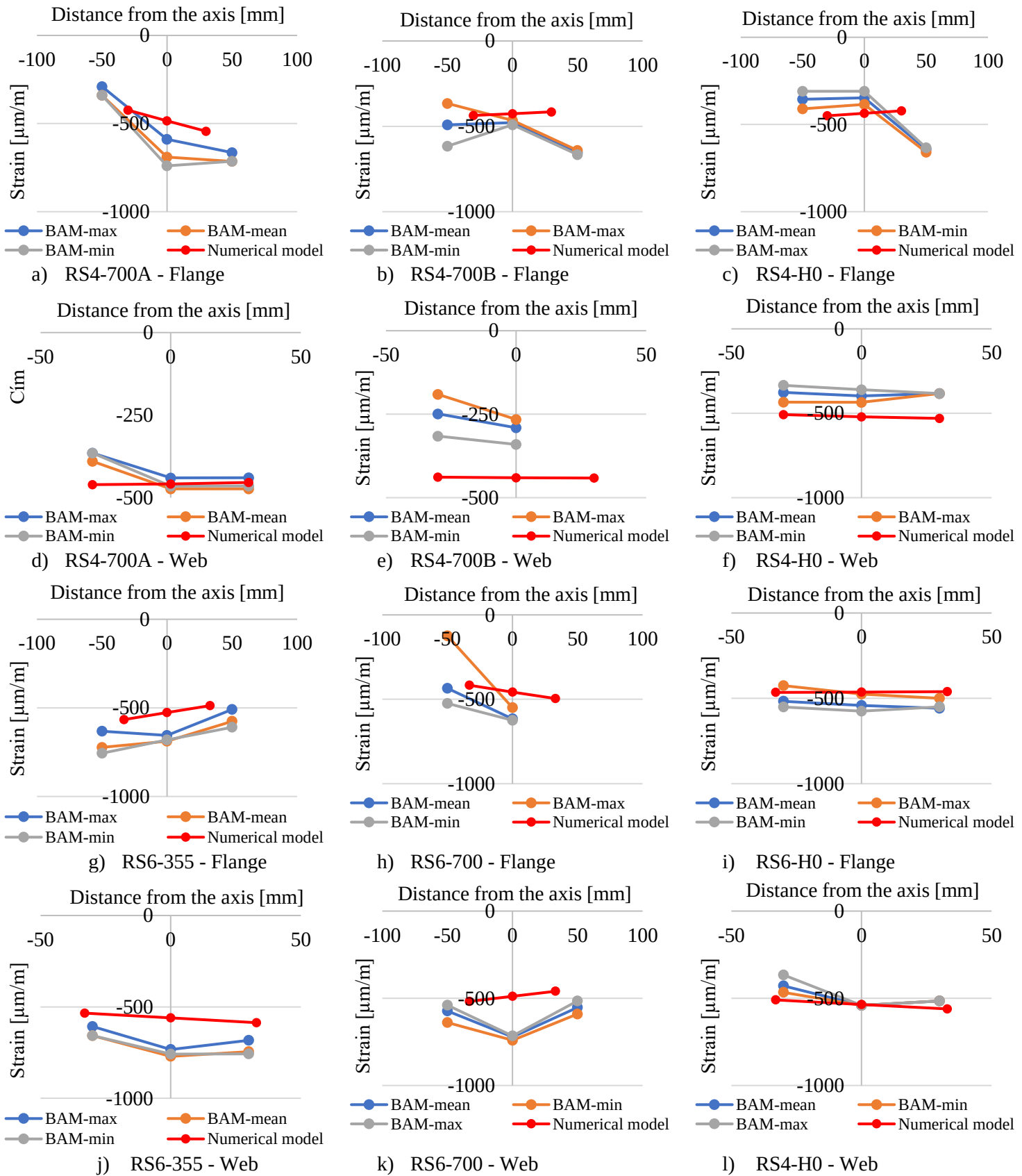


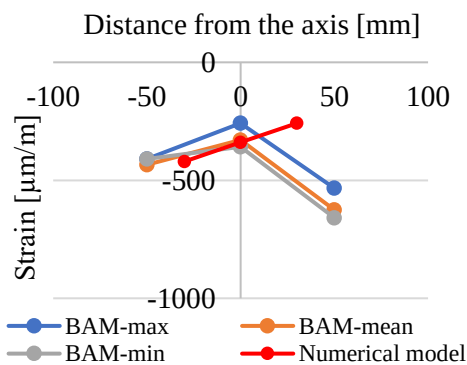
RS8-700B – σ_{eqv}



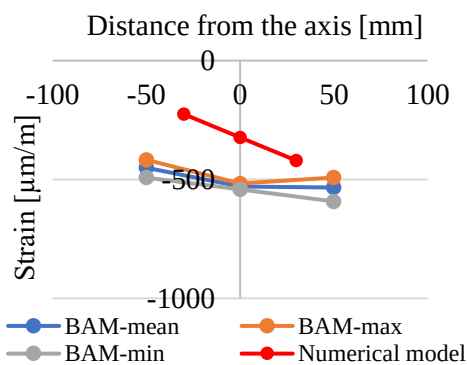
RS8-H0 – σ_{eqv}

Appendix H – Results of BAM measurements and numerical models

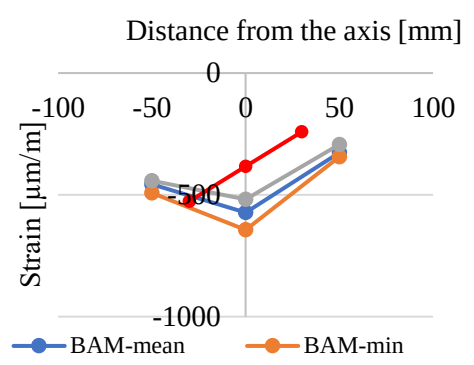




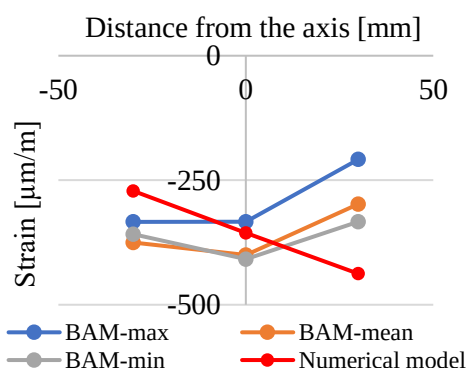
m) RS8-700A - Flange



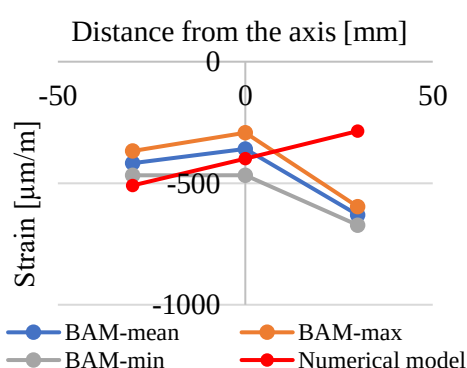
n) RS8-700B - Flange



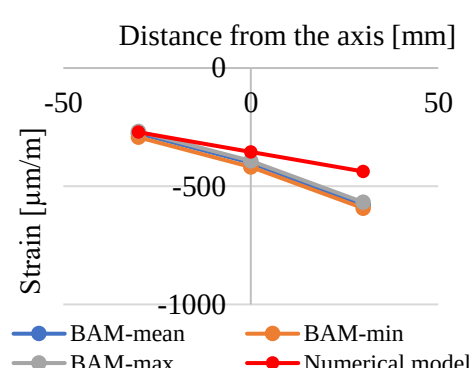
o) RS8-H0 - Flange



p) RS8-700A - Web

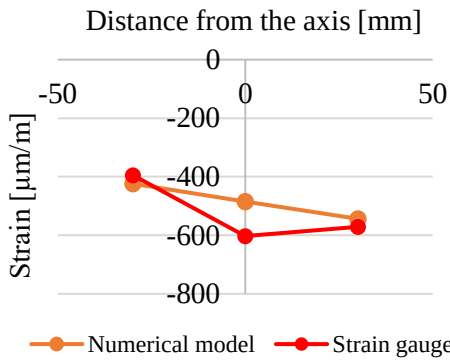


q) RS8-700B - Web

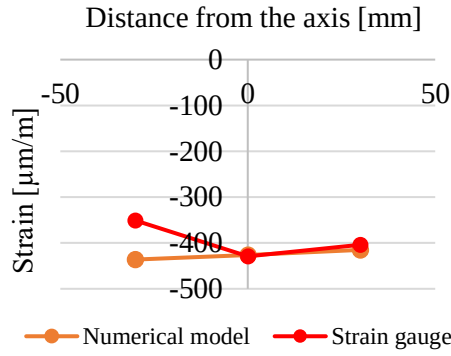


r) RS8-H0 - Web

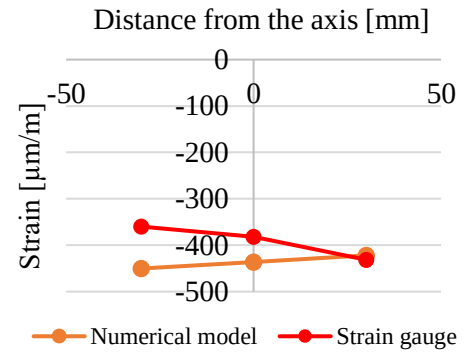
Appendix I – Results of strain gauge-based measurements and numerical models



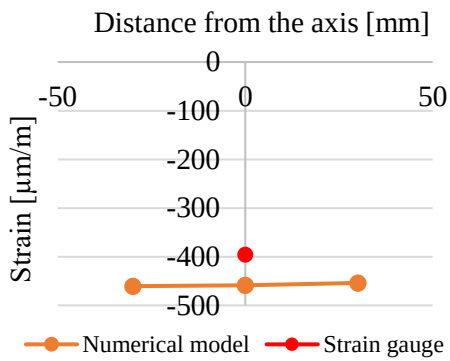
a) RS4-700A - Flange



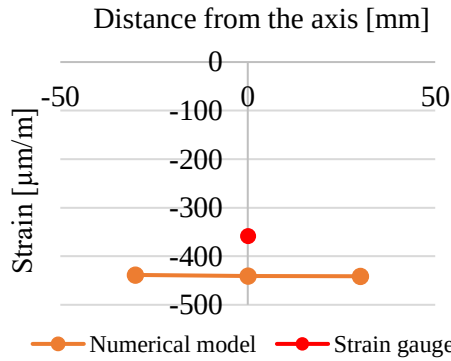
b) RS4-700B - Flange



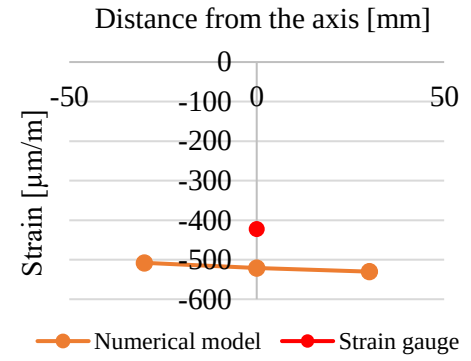
c) RS4-H0 - Flange



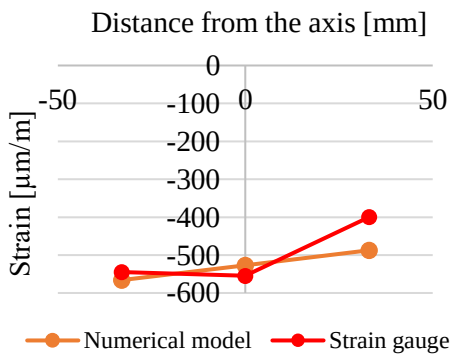
d) RS4-700A - Web



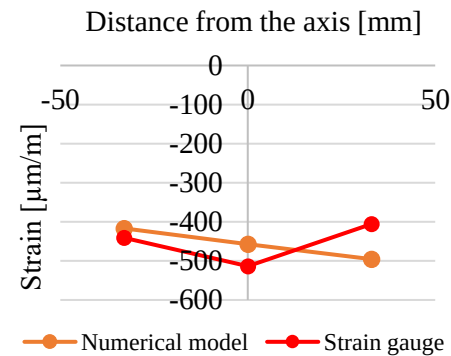
e) RS4-700B - Web



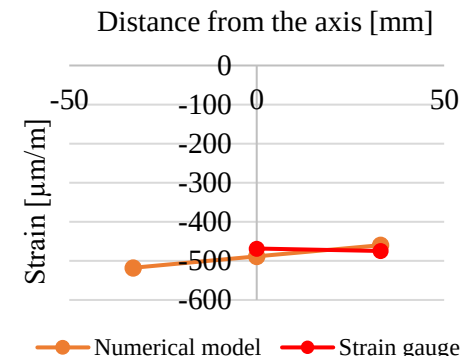
f) RS4-H0 - Web



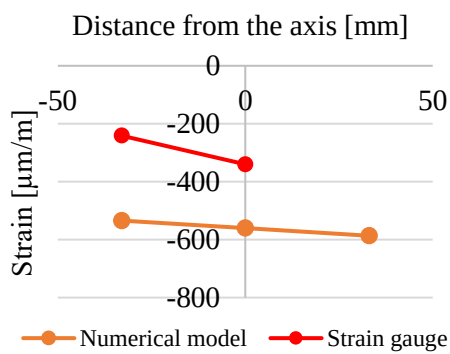
g) RS6-355 - Flange



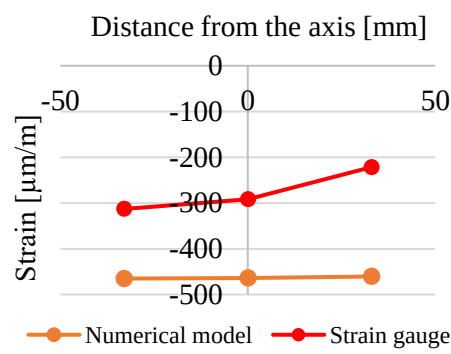
h) RS6-700 - Flange



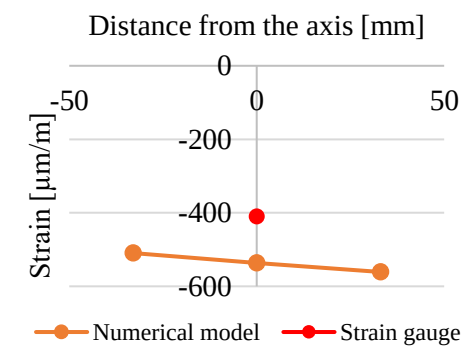
i) RS6-H0 - Flange



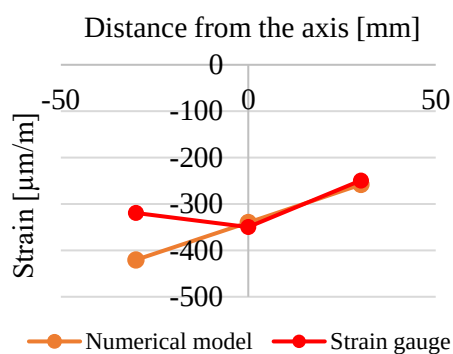
j) RS6-355 - Web



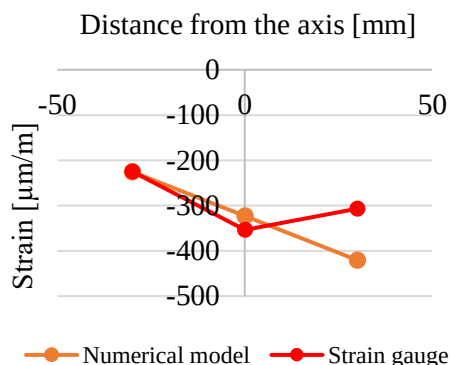
k) RS6-700 - Web



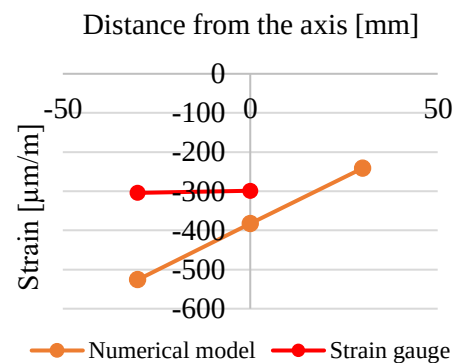
l) RS6-H0 - Web



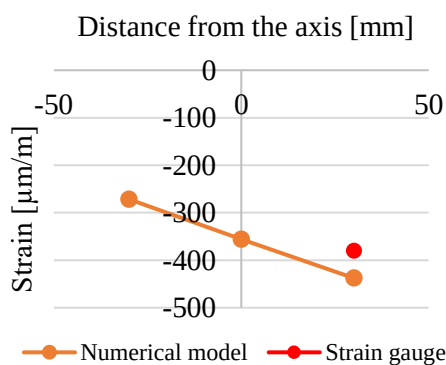
m) RS8-700A - Flange



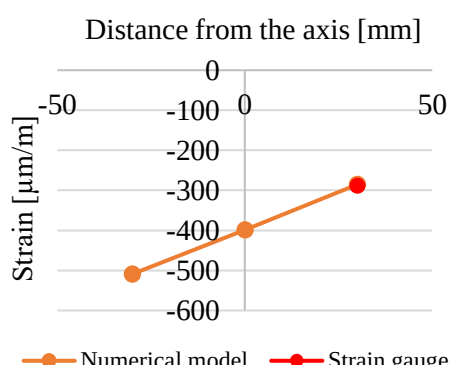
n) RS8-700B - Flange



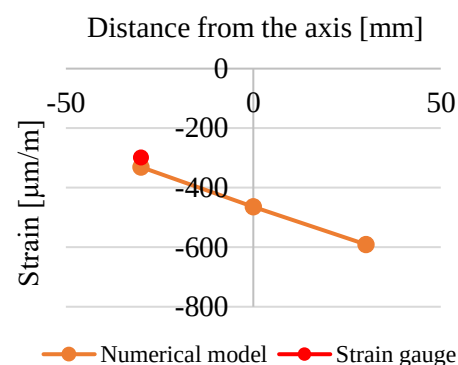
o) RS8-H0 - Flange



p) RS8-700A - Web



q) RS8-700B - Web



r) RS8-H0 - Web