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

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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.

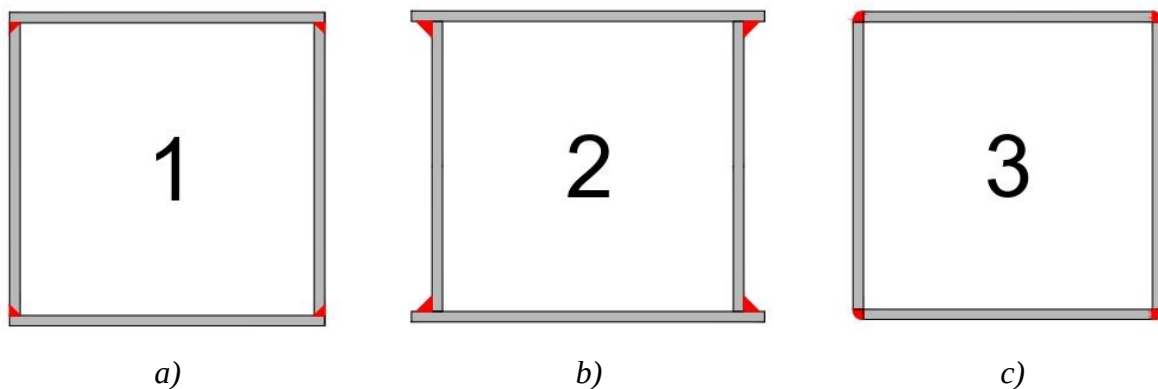


Fig. 1 - Cross-sections of box sections using flat plates

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.

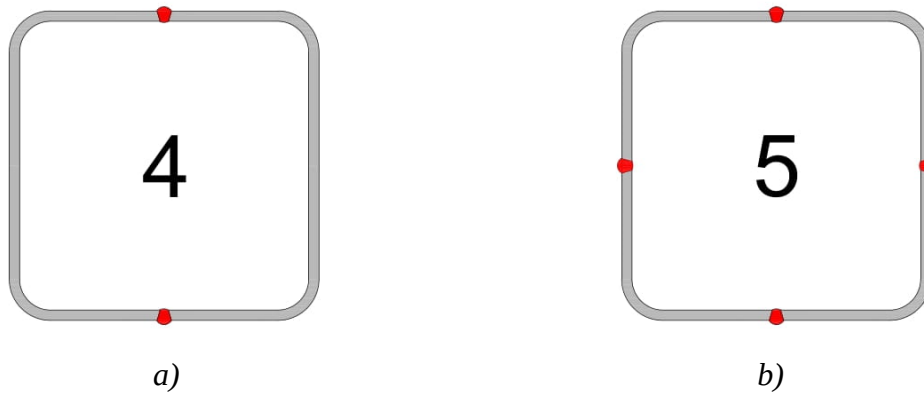


Fig. 2 - Cross-sections of box sections using cold-formed profiles

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.

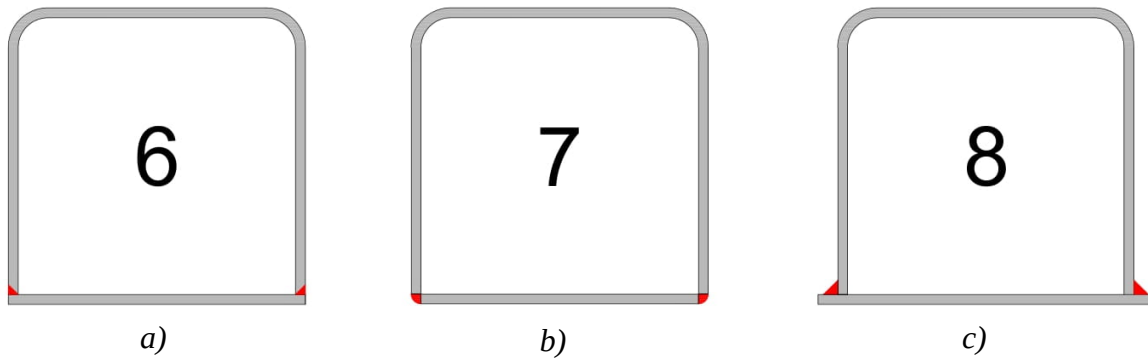


Fig. 3 - Cross-sections of box sections using flat and cold-formed plates

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**.

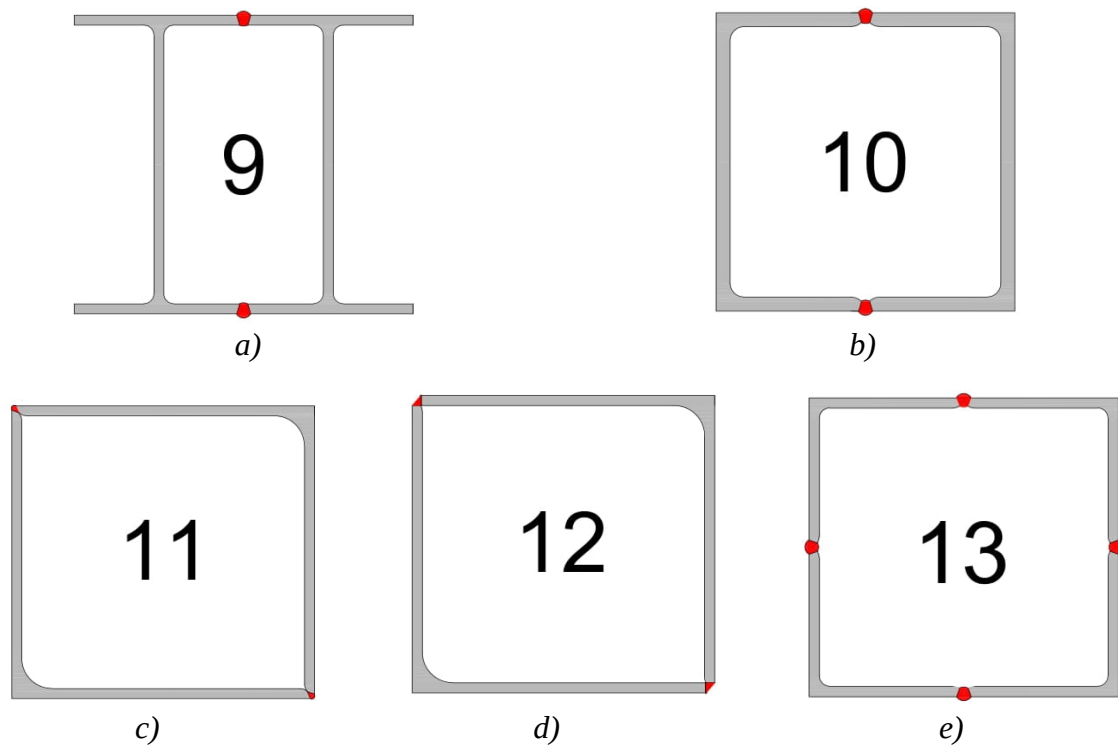


Fig. 4 - Cross-sections of box sections using hot rolled shapes

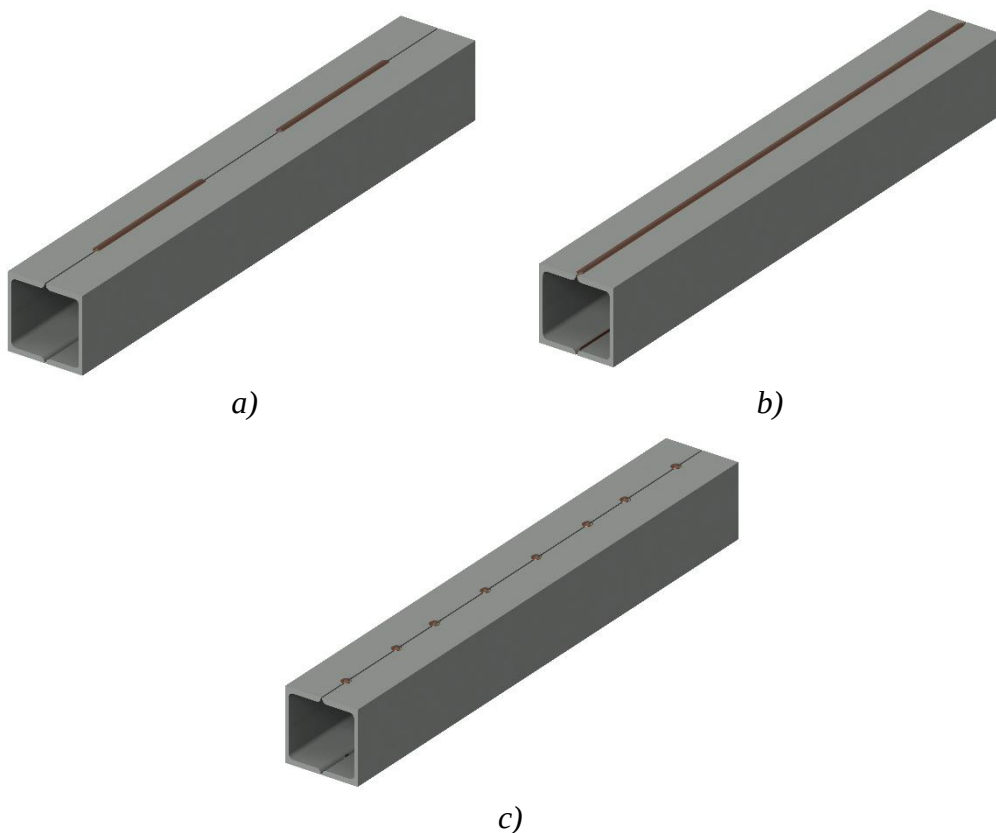


Fig. 5 - Different welding types: box section with a) intermittent, b) continuous, and c) tack welds

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**.

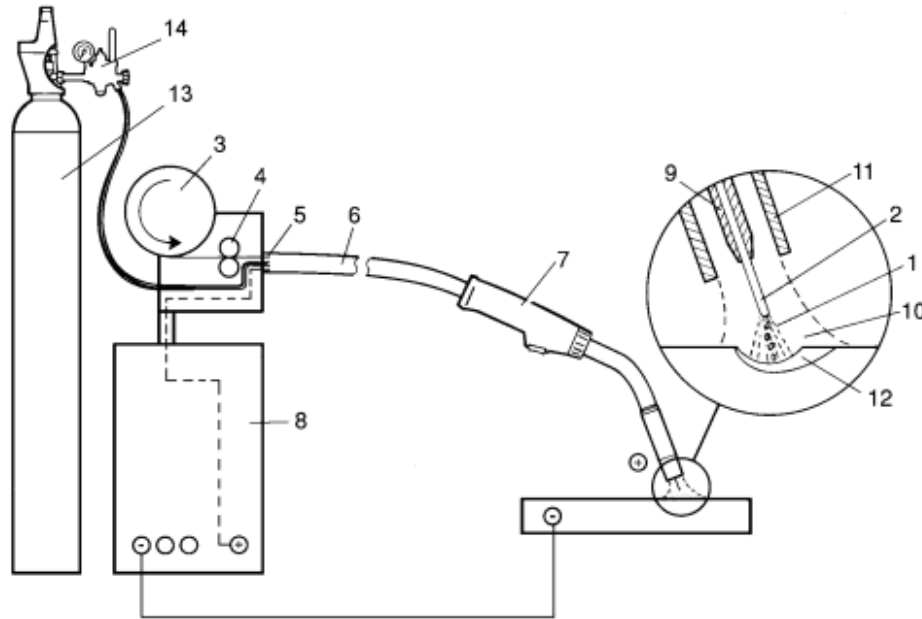


Fig. 6 - Schematic drawing of MIG/MAG welding process [2]



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.

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. 8**. 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.

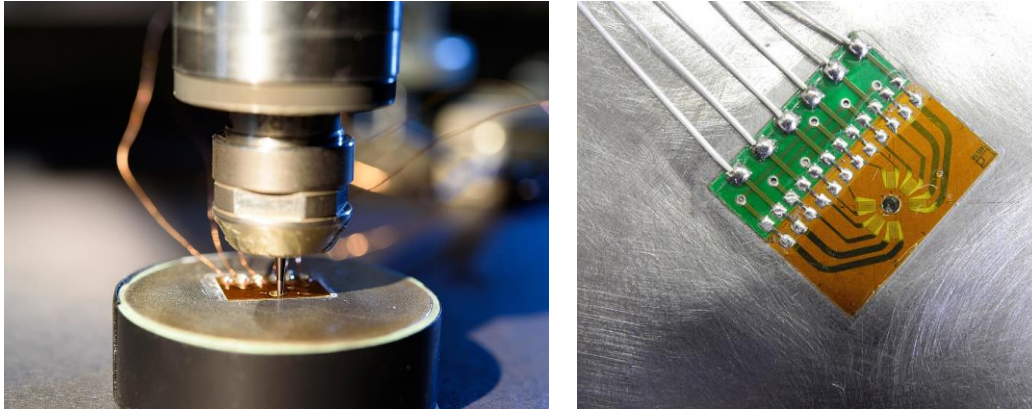


Fig. 8 - Hole-drilling measurement method setup [4]

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. [5] 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. 9**, 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. EQ9 - Deep hole method [6]

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. 10**. 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. [7] 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.

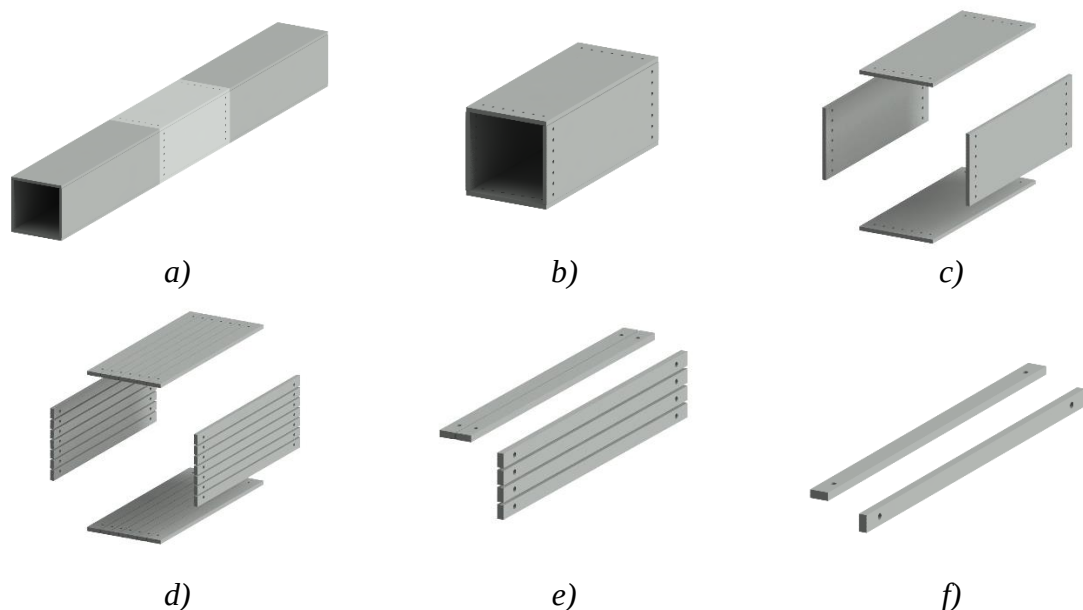


Fig. 10 - Process of sectioning method: a) drill gauge holes, b) cut off the two ends, c) cut the section into plates, d) cut plates into thick strips, e) and f) separate thick strips into experimental strips based on [8]

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. 11**.

- 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 coordinate 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.

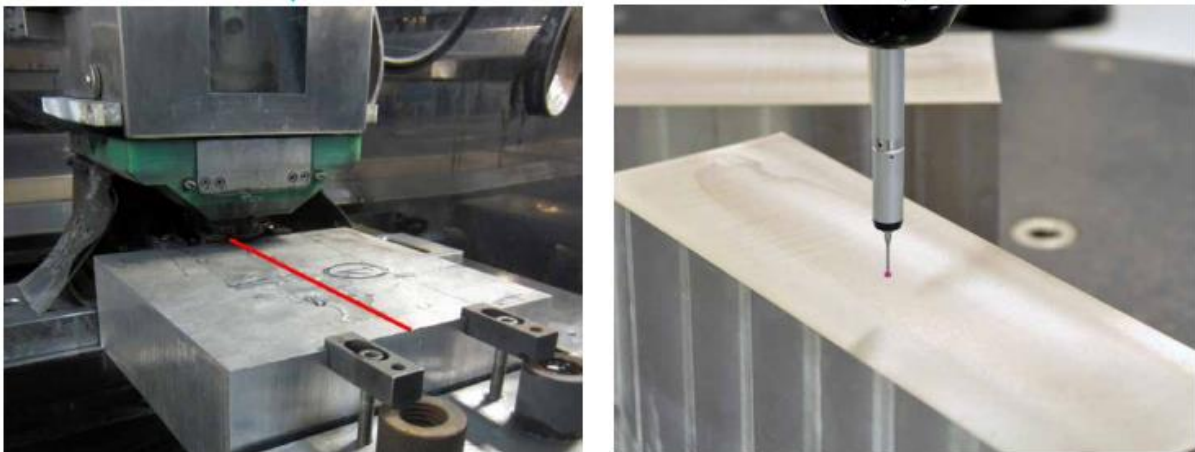


Fig. 11 - Contour method for residual stress measurement [9]

Other destructive methods can be also distinguished which are summarized in **Fig. 12**. 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.

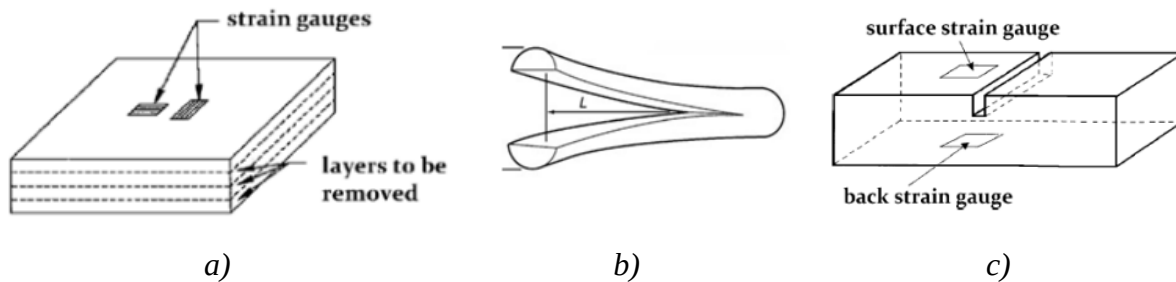


Fig. 12 – Other less used techniques: a) layer removal, b) slitting and c) splitting [10]

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. 13a**, 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. 13b**.

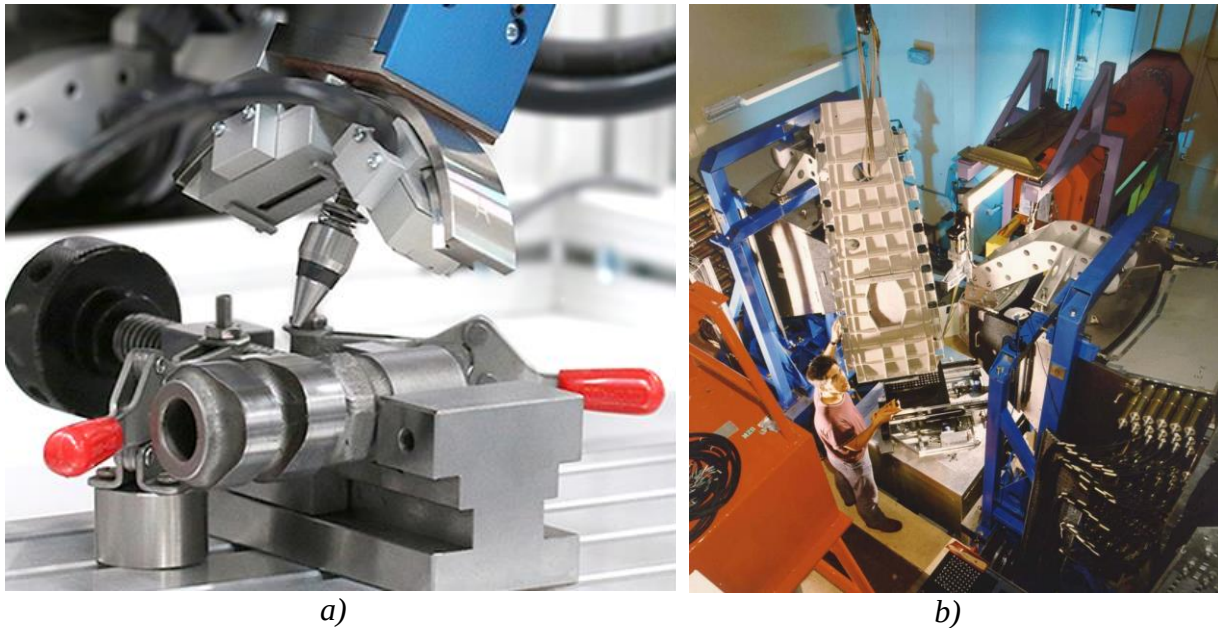


Fig. 13 – a) X-ray diffraction method [11] and b) ENGIN-X neutron diffractometer [12]

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. 14a**. Some scientific articles can be found on the literature, which are focused on BMN method. Stewart et al. [13] 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. [14] 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.



Fig. 14 – a) Barkhausen magnetic noise [11] and b) ultrasonic [15] measurement methods

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. 14b**. 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.

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

[16] were derived experimentally and theoretically, the models are shown in **Fig. 15**. 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.

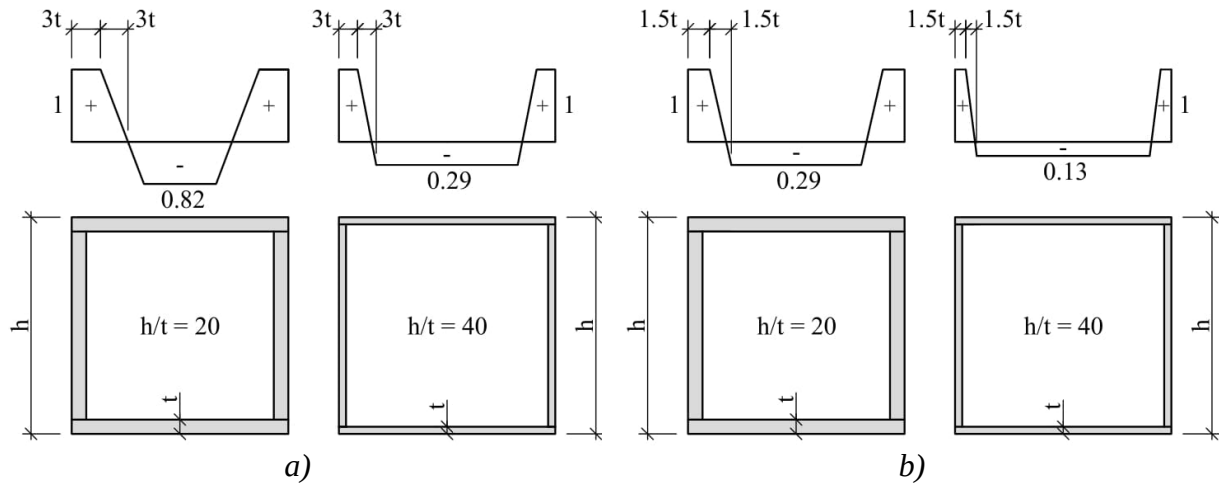


Fig. 15 - ECCS residual stress models for heavy welds (a) and light welds (b) based on [17]

The Chinese standard [18] 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. 16**.

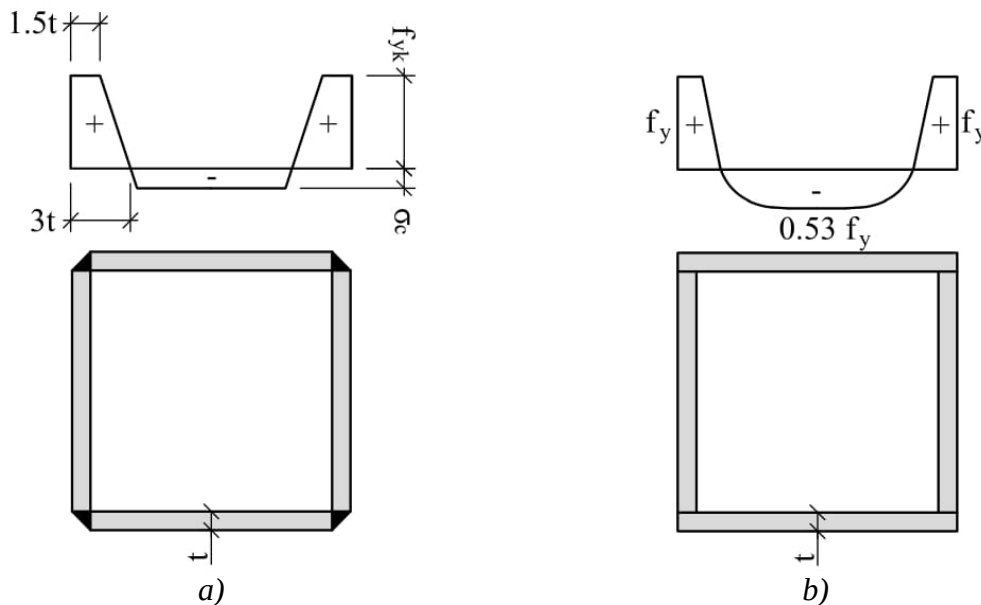


Fig. 16 - Chinese (a) and Swedish (b) residual stress models for box sections based on [19]

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.

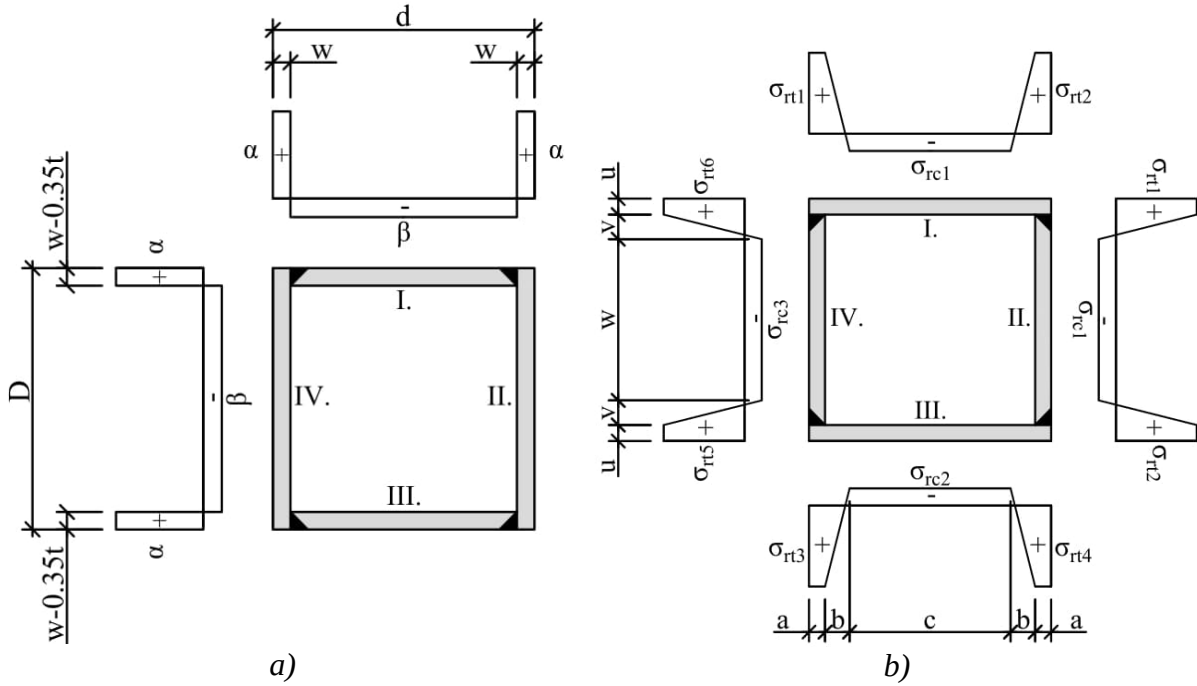


Fig. 17 - a) Proposed residual stress model by Wang et al. [20], b) proposed residual stress model by Ban et al. [8]

In 2012, Wang et al. [20] 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. 17a**, 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. [8] 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. 17b**. 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. 17b**, 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.

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

In 2015, Li et al. [21] 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. 18a**, 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. [20], 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.

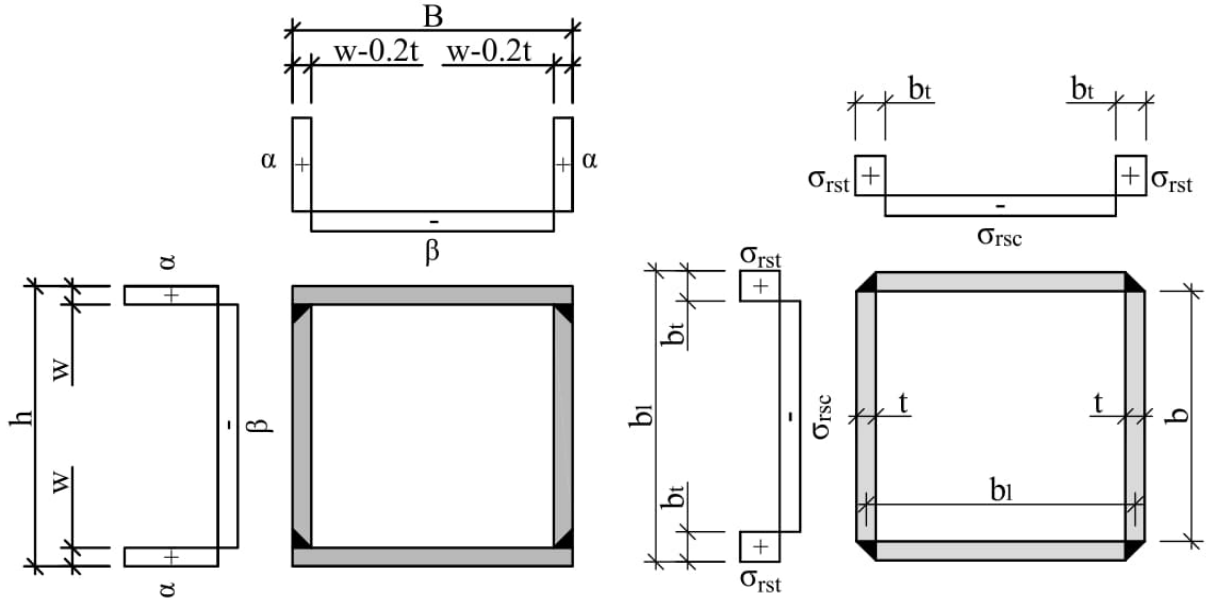


Fig. 18 - a) Proposed residual stress model by Li et al. [21] and b) Ban et al. [22]

Khan et al. [22] 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. 18b**. The tensile stress distribution width b_t can be determined by stress equilibrium as shown in **Eq. (4)**, where b_1 is the width of a plate from the weld centre, and t is the thickness of the plate as shown in **Fig. 18b**.

$$b_t = \frac{b_1 \sigma_{rsc}}{2(\sigma_{rst} + \sigma_{rsc})} \quad (4)$$

$$\sigma_{rsc} = f_y 3.6607 \left(\frac{b_1}{t} \right)^{-0.924} \quad (5)$$

Kövesdi and Somodi [19] 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. 19**). 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. (6-7)**.

$$t \leq 5 \text{ mm: } \sigma_{rc} = 70 - 21t + t^2 - [2900 - 3600 \cdot (t - 5)] \cdot [b/t]^{-1} \quad (6)$$

$$t \geq 5 \text{ mm: } \sigma_{rc} = 70 - 21t + t^2 - [2900 - 290 \cdot (t - 5)] \cdot [b/t]^{-1} \quad (7)$$

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. (8)**. The width c of the triangle part of the residual stress model can be calculated based on the geometrical equation given by **Eq. (9)**. 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.

$$L_c = \frac{\sigma_{rt} (b - t + 2a)}{2 \cdot |\sigma_{rt}| + \sigma_{rt}} \quad (8)$$

$$c = \frac{b - t - 2a - L_c}{2} \quad (9)$$

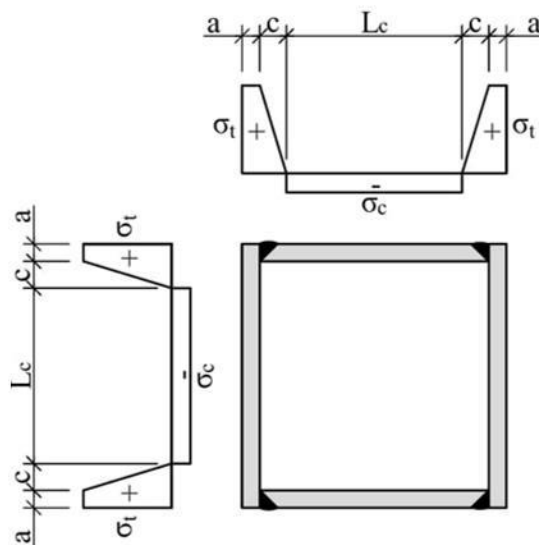


Fig. 19 - Proposed residual stress model by Kövesdi and Somodi [19]

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. [23] 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 [24] 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 $1200 \text{ }^\circ\text{C}$, 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. [25] 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. 20a**. The presented paper used the same thermal boundary conditions, and temperature-dependant material models as [23]. The paper used one weld pass for thin plates ($t \leq 8 \text{ mm}$), 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. 20b** 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.

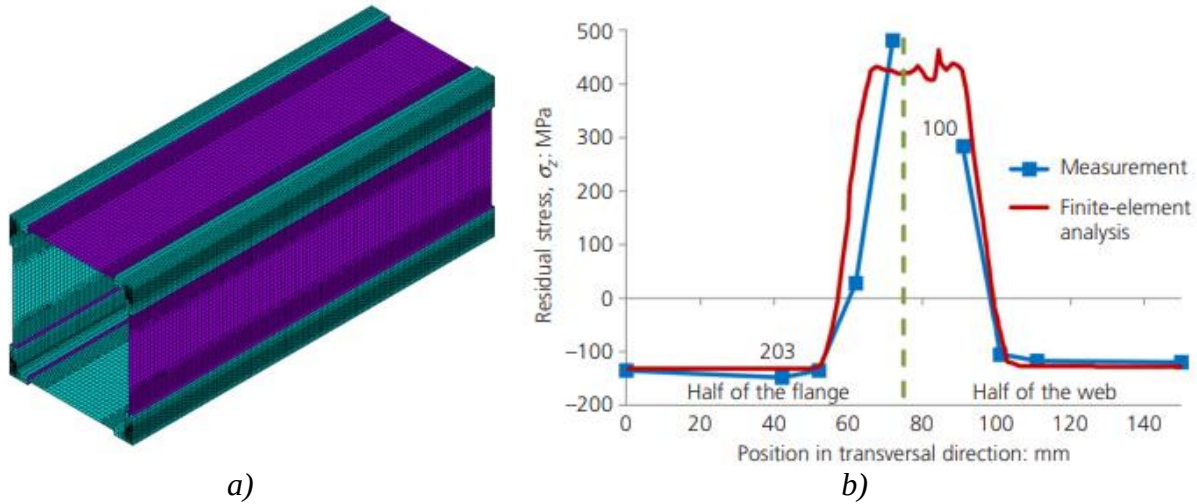


Fig. 20 - a) Numerical model of the box section analysed and b) comparison between finite element results and test results by Somodi et al. [25]

In 2022, Xiao et al. [17] 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. 21a** 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. 21** 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.

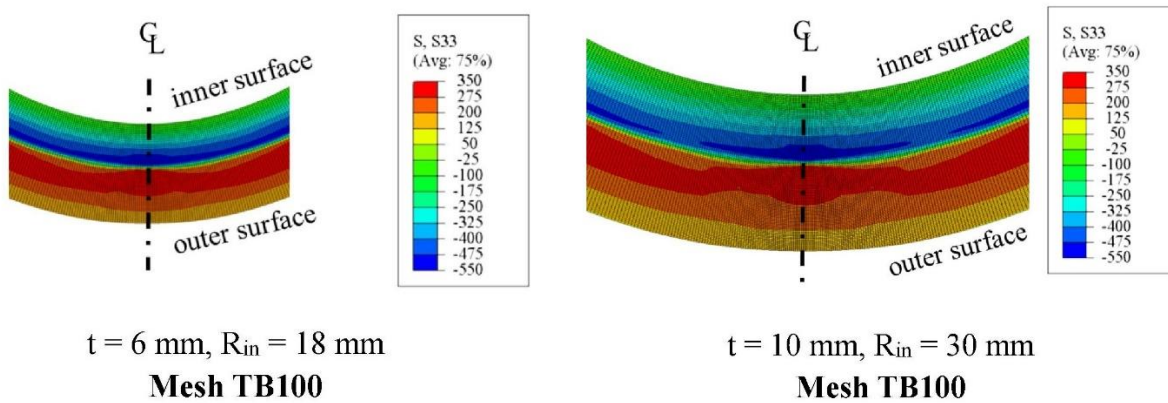


Fig. 21 - Longitudinal residual stresses due to transverse bending of the cold-formed profile to be welded [17]

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 [24] 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. 22** 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. 23** 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.

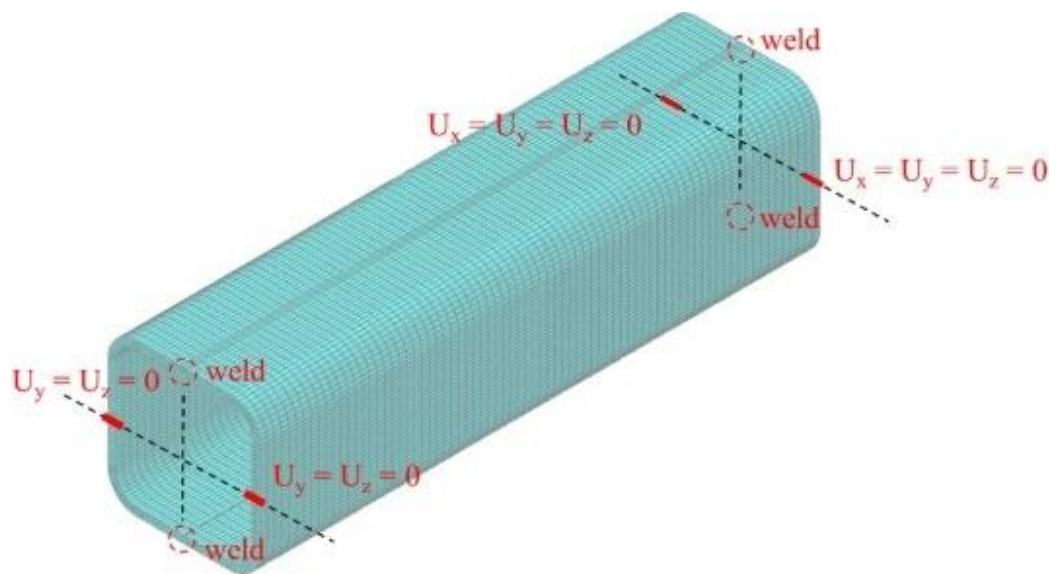


Fig. 22 - Numerical models of the box sections with the applied mechanical boundary conditions [17]

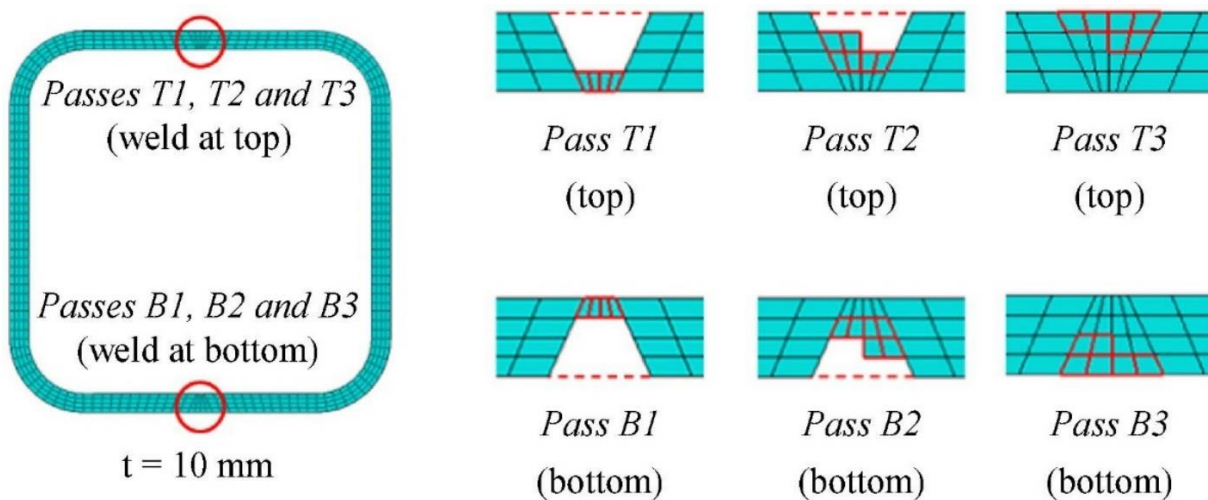


Fig. 23 - Multi-pass welding during modelling [17]

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. 24**.

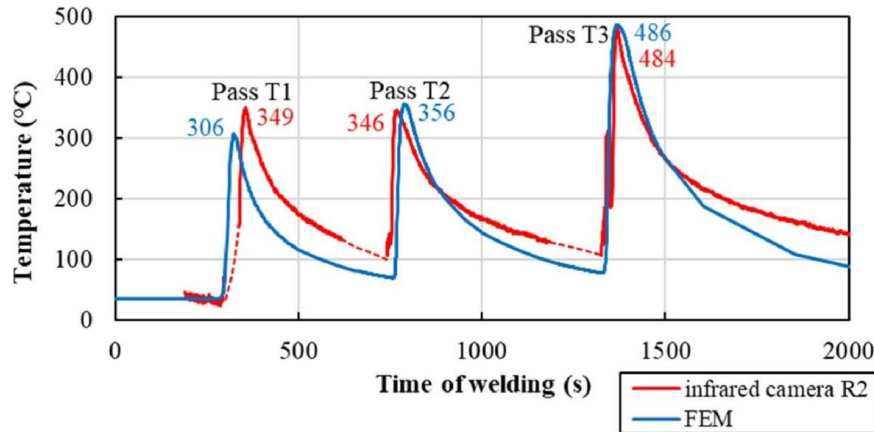


Fig. 24 - Results of the thermal analysis [17]

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. 25**. **Fig. 26** illustrates cross-sectional view of longitudinal stresses, induced by transverse bending and longitudinal welding, in the developed numerical model after an exact calibration.

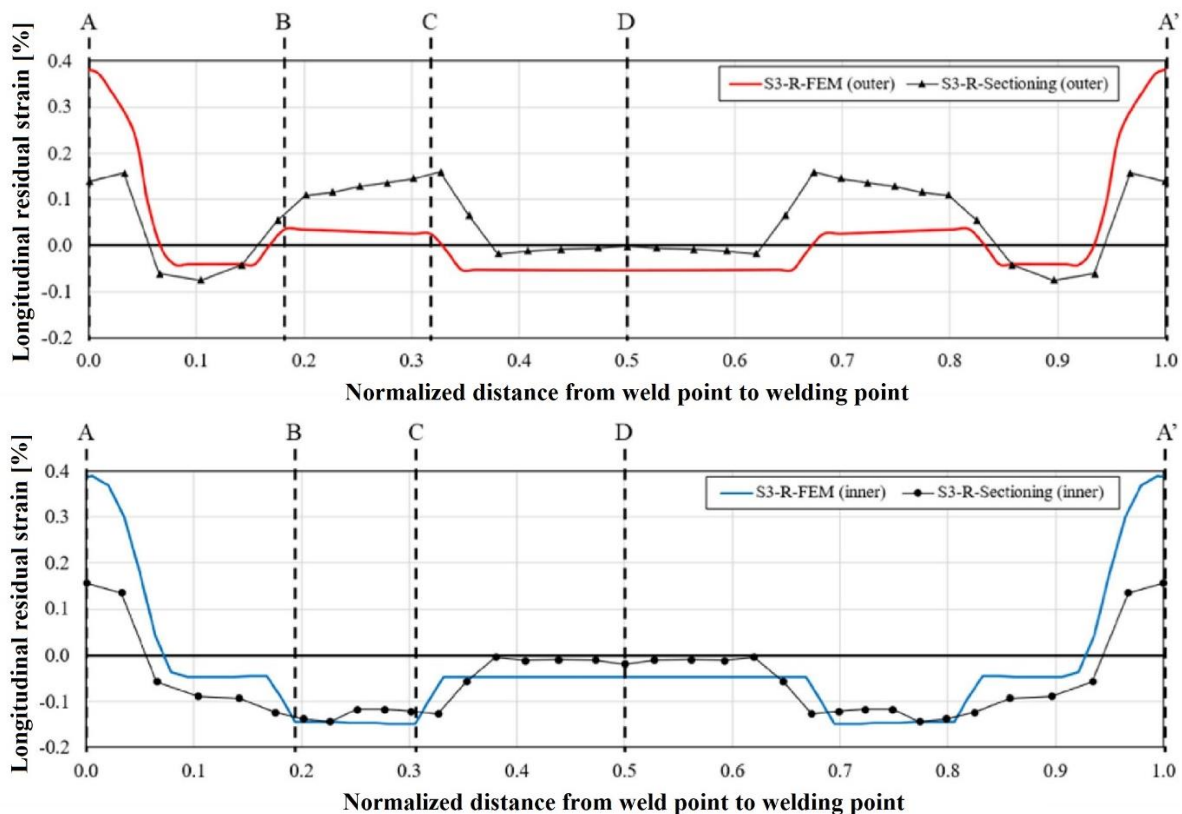


Fig. 25 - Experimental and numerical (FEM) residual stresses based on [17]

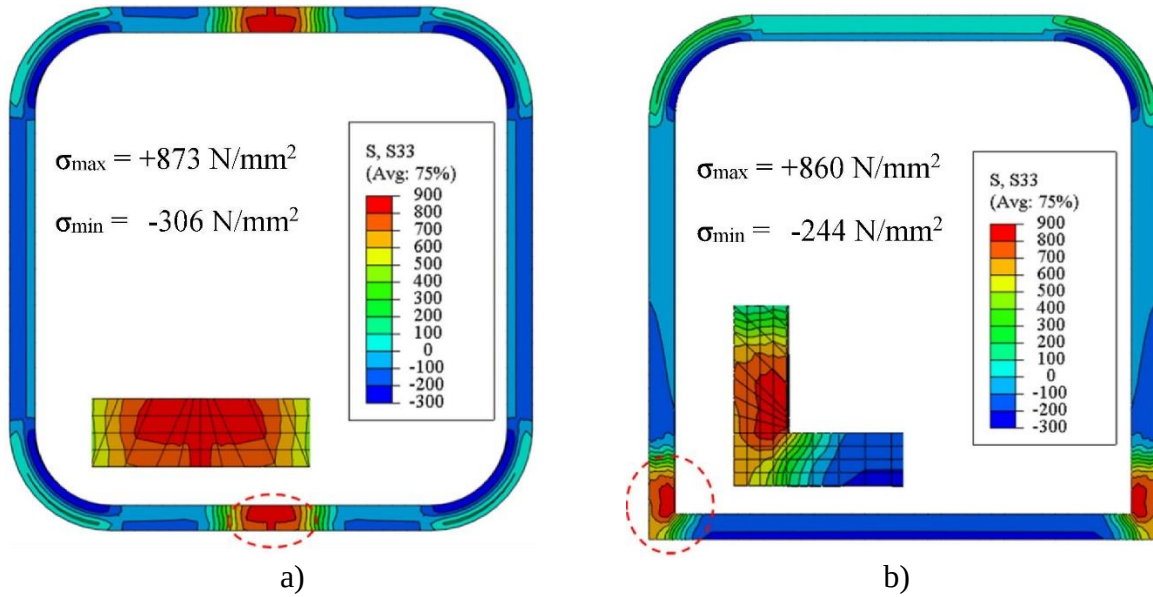


Fig. 26 - Plots of the FEM-based longitudinal residual stresses in two types of welded box sections: a) using two C profiles and b) a U-profile with a flat plate [17]

Jiang et al. [26] 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. 27). 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 [27]–[29]. 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 $25 \text{ W/(m}^2\cdot\text{K)}$ and the emissivity ε was 0.2. The chosen heat source model was the double ellipsoidal heat source model introduced by Goldak and Akhlaghi [30]. 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. (10).

$$\dot{\varepsilon}^{cr} = \frac{A \cdot q^n [(m+1) \cdot \varepsilon^{cr}]^m}{(m+1)} \quad (10)$$

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.

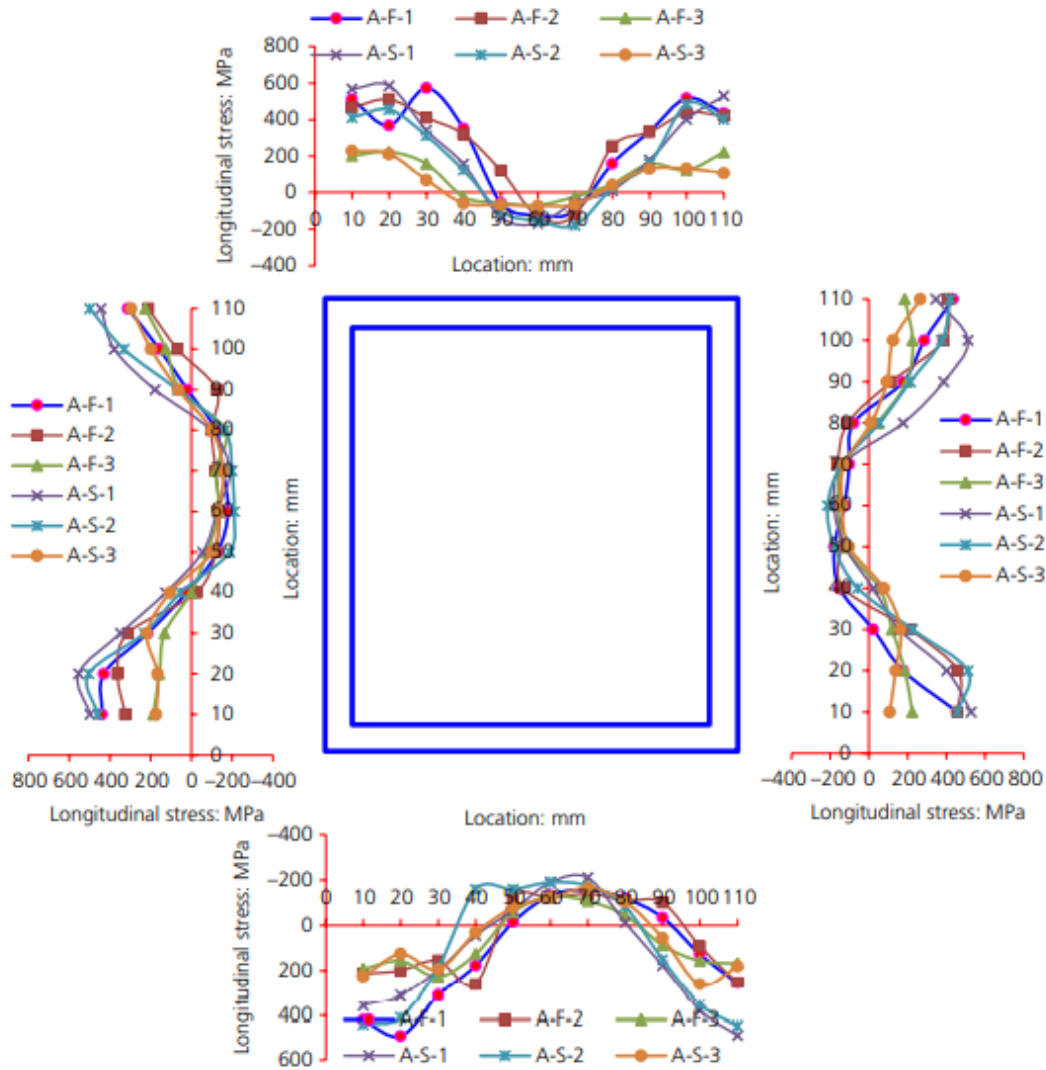


Fig. 27 – Computed longitudinal residual stress distribution from simulation [26]

The residual stress profiles from the numerical models are shown in **Fig. 27**, 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. 28** 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 three steel grades (S355, S460, 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

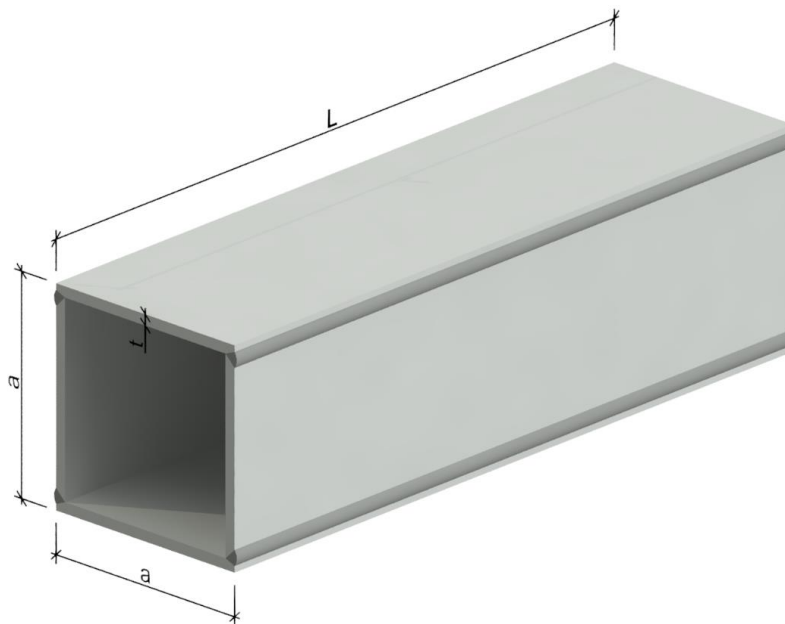


Fig. 28 - Sketch of the modelled specimen

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. 29**.

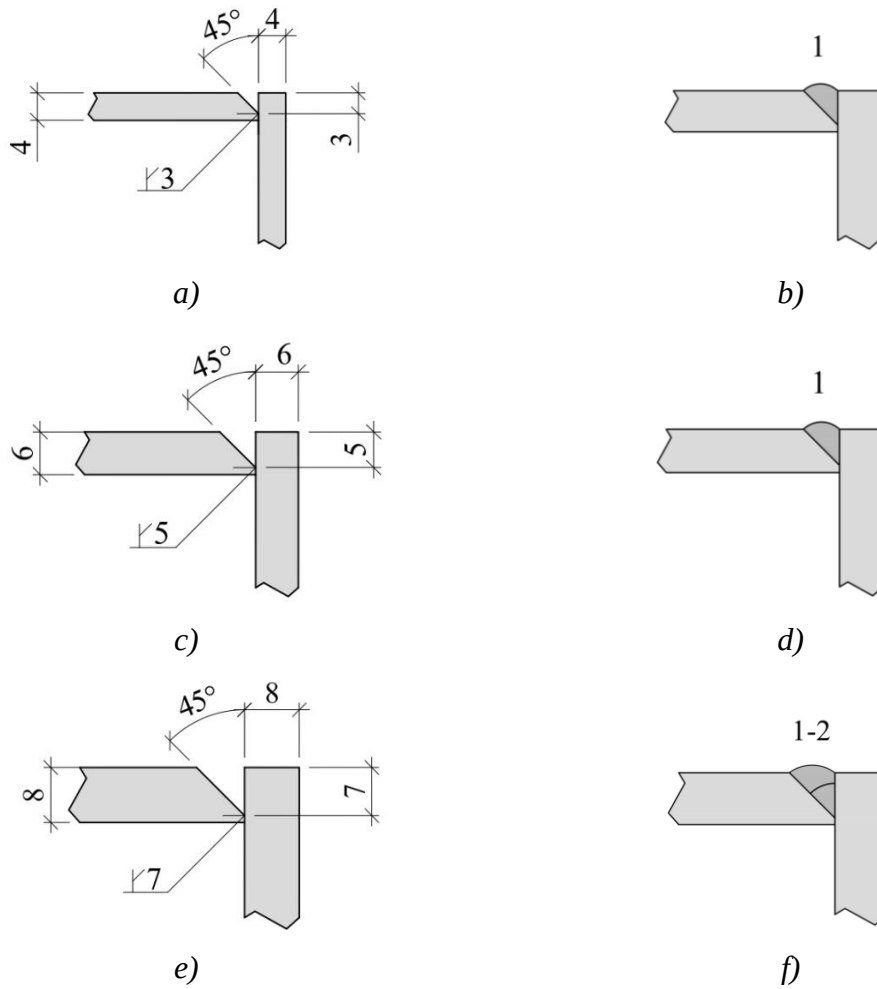


Fig. 29 - Sketch of the modelled specimen

As mentioned above, plate thickness of test specimens varies, so the plates are made with different edge preparation and weld sizes summarized in **Fig. 29** 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.

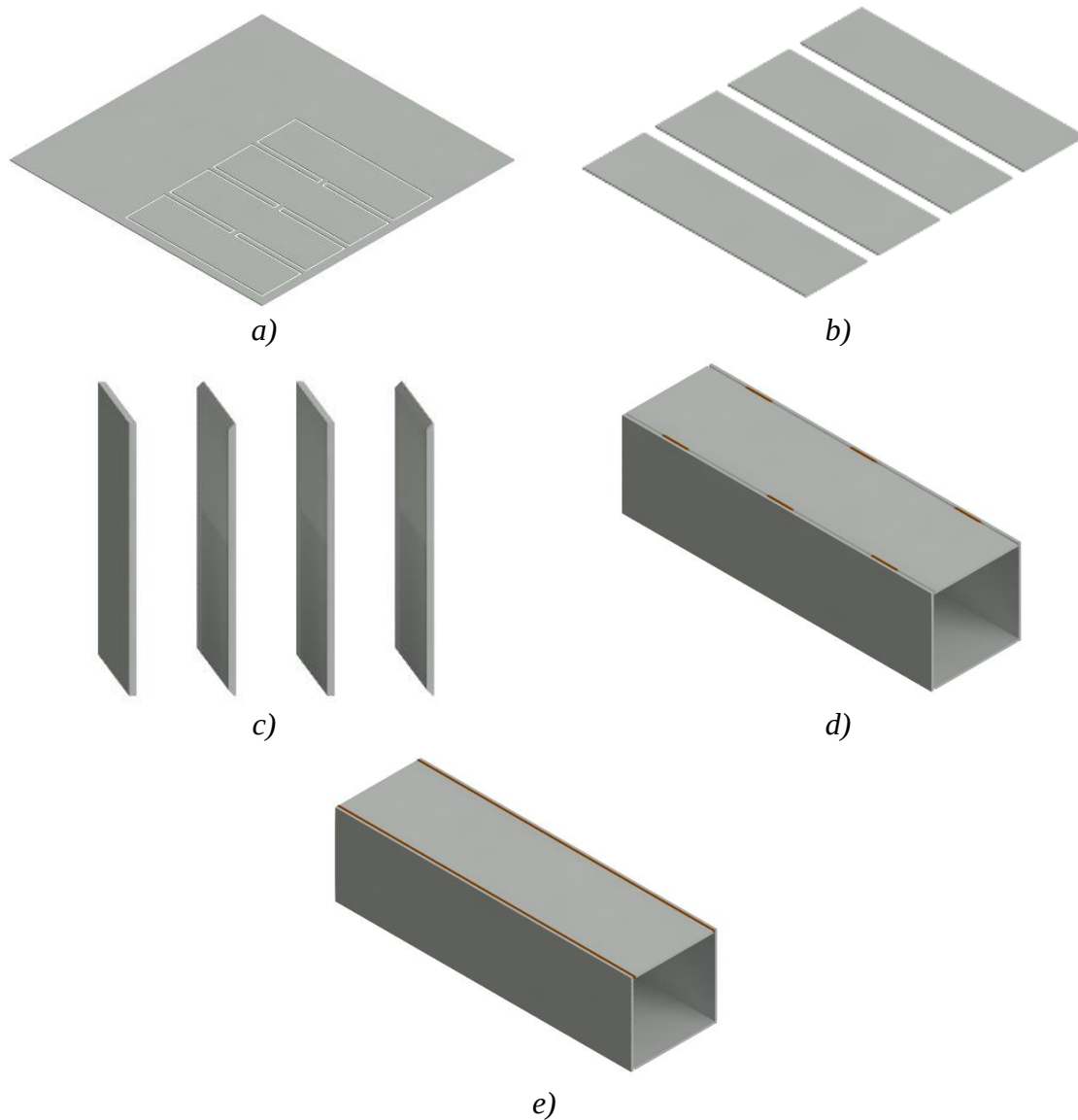


Fig. 30 - Manufacturing process: a) plasma cutting of constituent plates, b) separation of constituent plates, c) edge preparation, d) tack welding, and e) welding of the box section

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. 30**.

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 G**. 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. 31**.

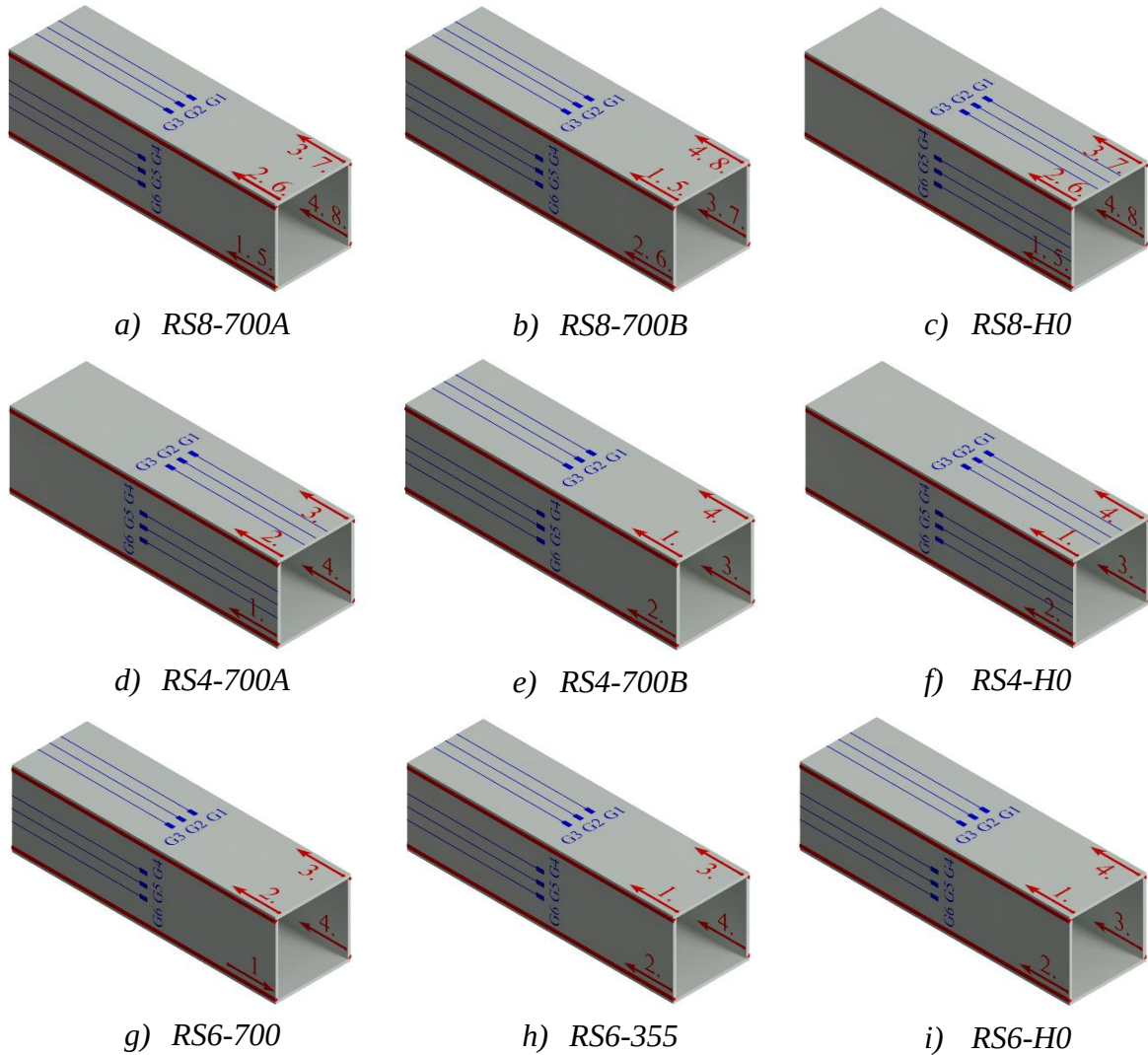


Fig. 31 - The welding sequence of the specimens in accordance with strain gauge positions

Tables in **Appendix A** 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 G**.

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. Tables in **Appendix B** summarize the measured geometrical data.

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. 32**. To define the size of the weld pool, the three geometric dimensions shown in **Fig. 33** are required. Since the dimension of the semi-ellipsoid in front of the source cannot be measured, the assumption of Goldak et al. [31] is followed for c_r and c_f using **Eq. (11)**. Tables in **Appendix C** summarize the weld pool parameters for each weld.

$$c_r = 4c_f \quad (11)$$

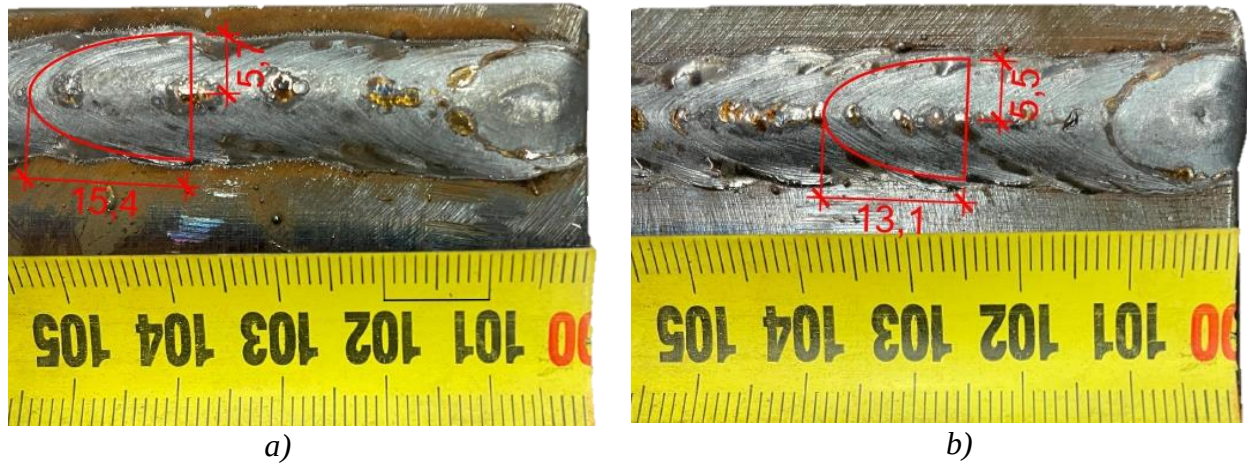


Fig. 32 - Measuring the size of weld pools

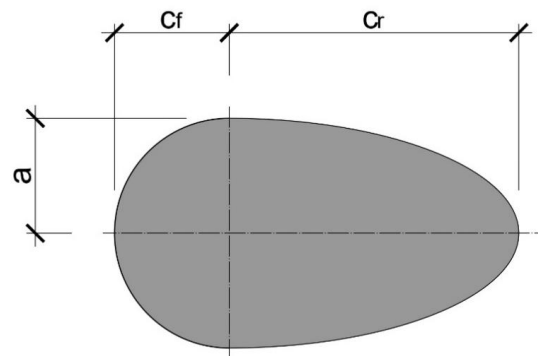


Fig. 33 - Geometrical parameters of the weld pool

By recording the welding parameters and the geometric dimensions of the weld pool, the relationship between these parameters can be investigated. Diagrams in **Fig. 34** 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.

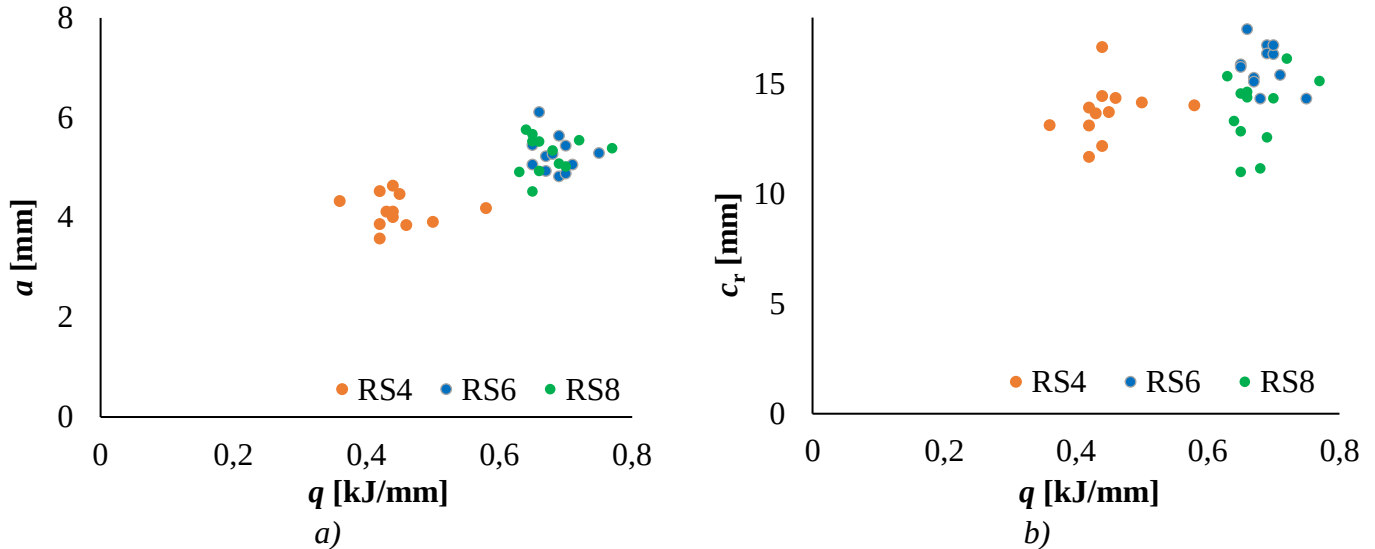


Fig. 34 – Relationship between total heat input and a) weld pool width and b) semi-axis length of rear ellipsoid

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. [32]

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. 35**. 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

3 Measurements

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.

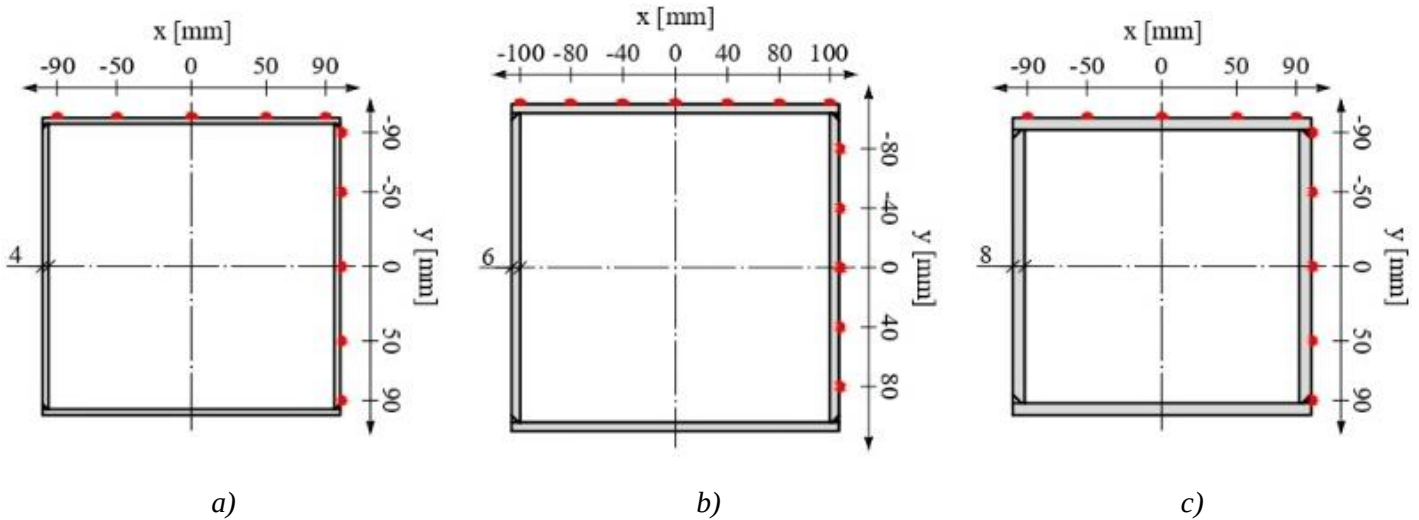
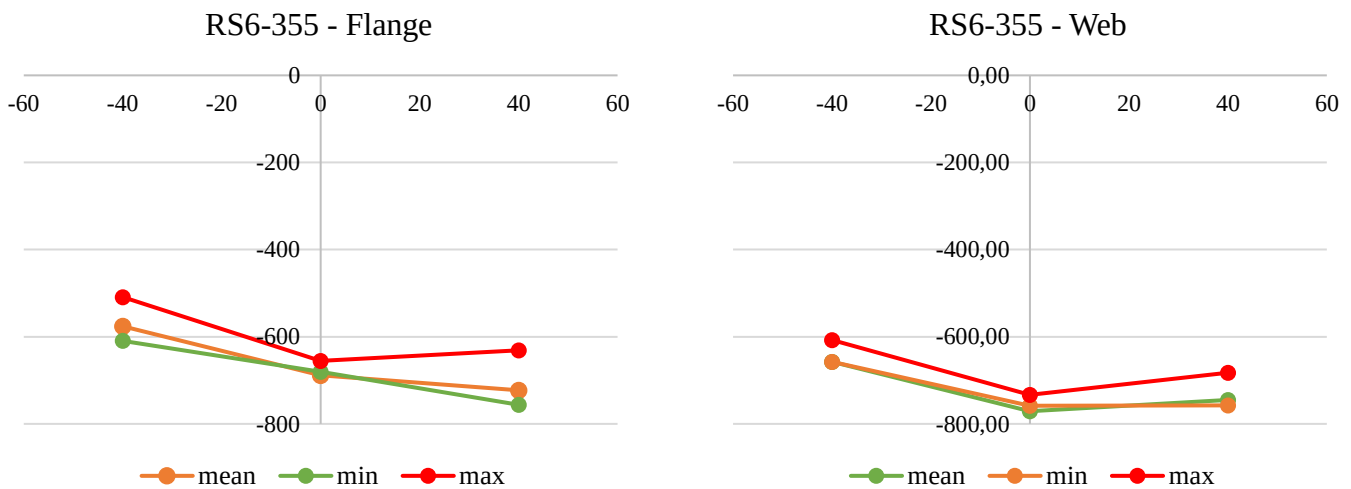


Fig. 35 - Sketch of BAM strain-measuring extensometer's measuring points: a) RS4 specimens b) RS6 specimens c) RS8 specimens



a) RS6-355 flange b) RS6-355 web
Fig. 36 - Axial strains [$\mu\text{m/m}$] with BAM strain-measuring extensometer - RS6 specimen

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. 36** summarize the measured and corrected strains for RS6-355 specimen, whose are sufficiently far from the HAZ zone. The plots of the measurement results for all the specimens are shown in **Appendix D**. 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. 37** 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 $350\ \Omega$ resistance were used in total.

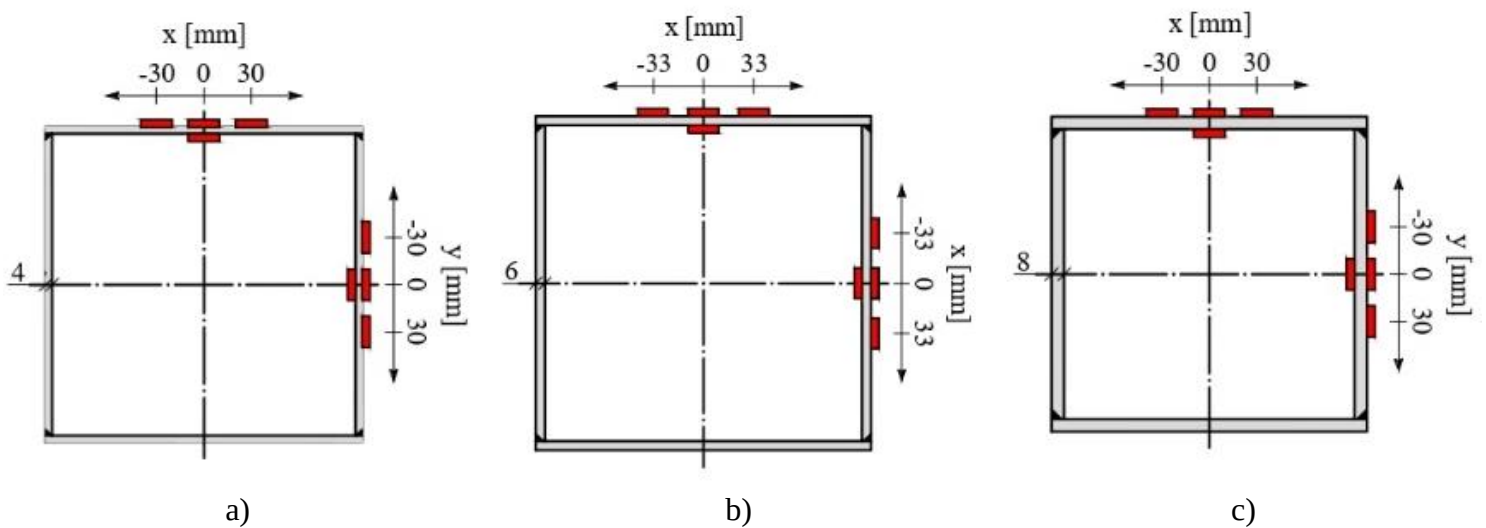


Fig. 37 - Sketch for the positions of strain gauges: a) RS4 specimens, b) RS6 specimens, and c) RS8 specimens

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. 38** and **Fig. 39**, 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 [19]. It is clearly shown that strains are smaller in the webs than in the flanges due to the position of single-bevel butt welds.

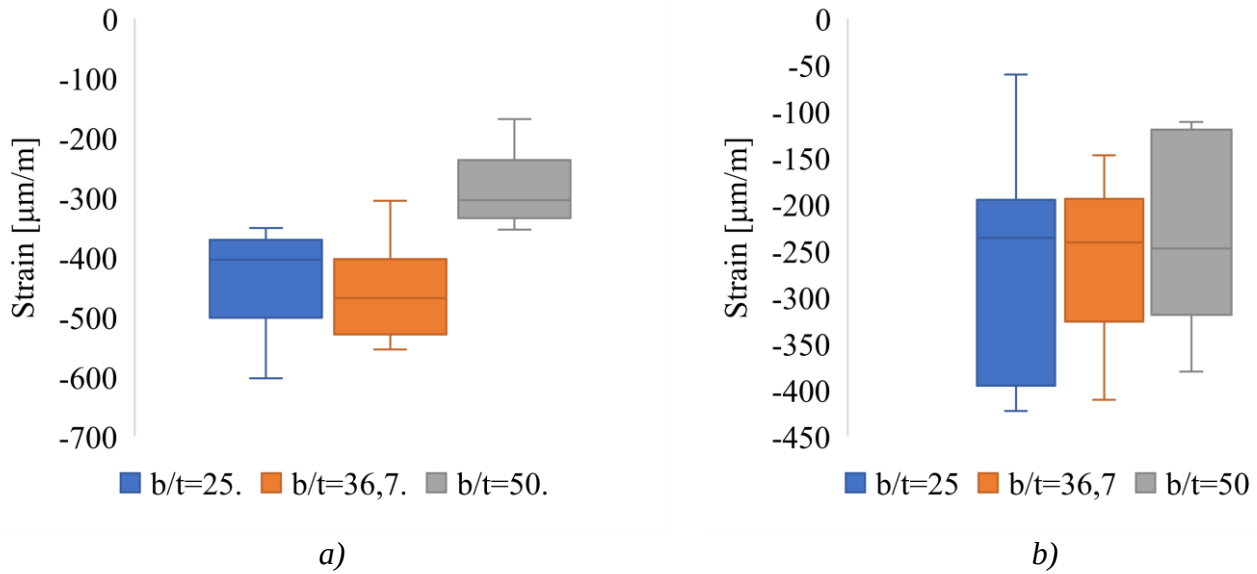


Fig. 38 - Measured residual strain ranges of different b/t parameters on a) flange, and on b) web

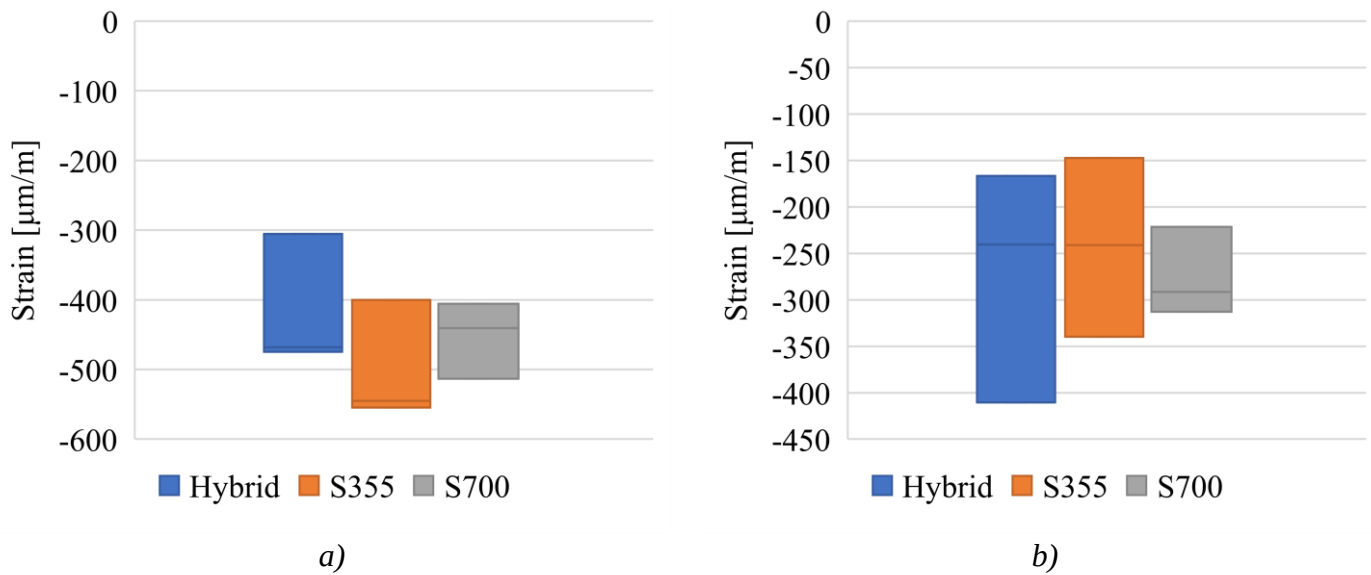


Fig. 39 - Measured residual strain ranges of different steel grades on a) flange, and on b) web

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. 40**. 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. 41**, 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.

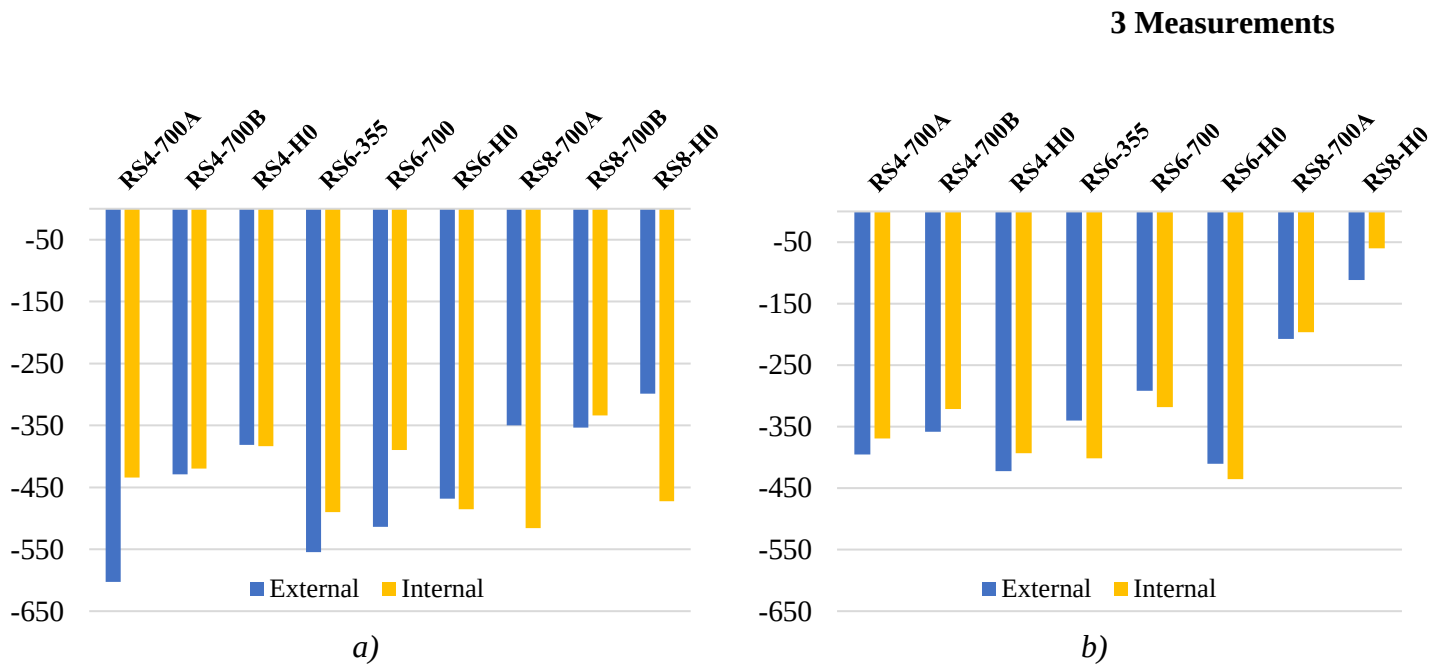


Fig. 40 - Axial strains [$\mu\text{m/m}$] measured by inner and external strain gauges on a) flange, b) web

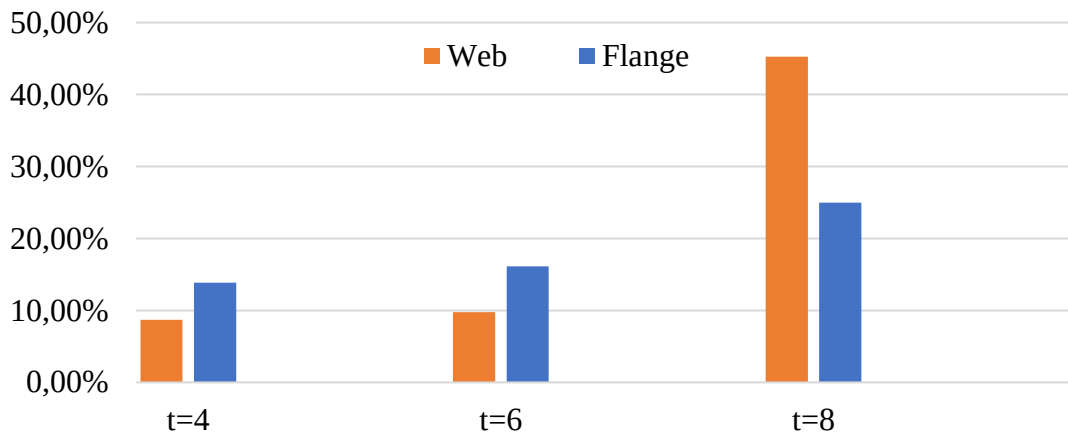


Fig. 41 - Percentage difference between the measured strains of the internal and external strain gauges for different thicknesses

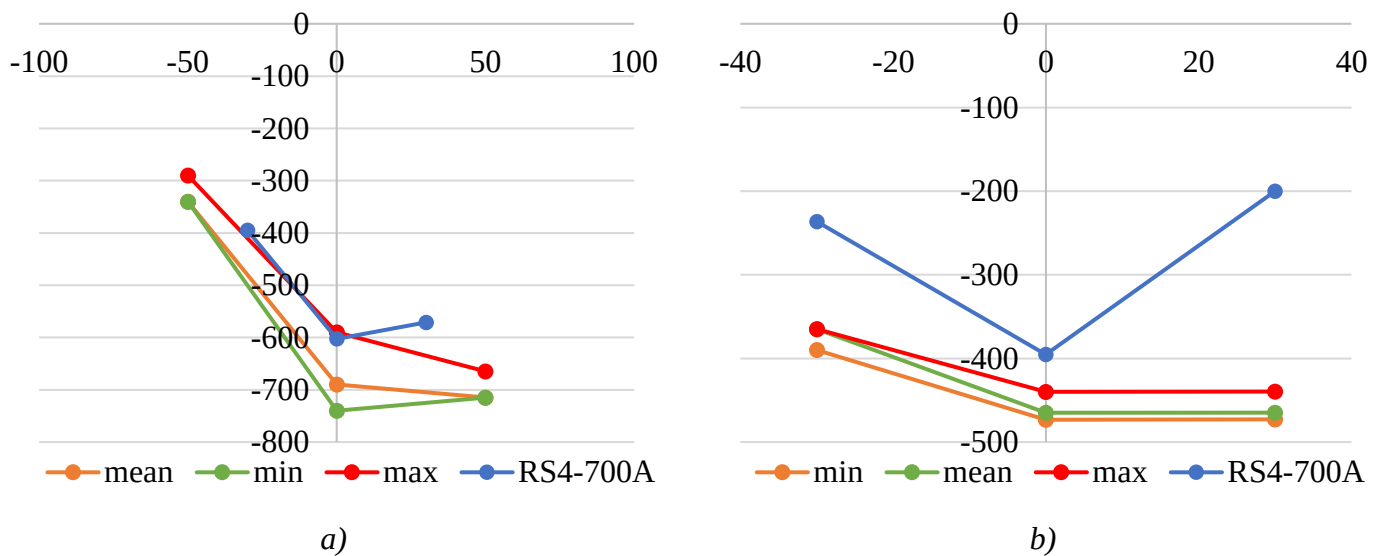


Fig. 42 - Correlation of BAM extensometer measurements (min, mean and max) with strain gauge measurements on a) flange and b) web of RS4-700A specimen

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. 42** for the RS4-700A specimen. The diagrams of the measurement results for each specimen are summarized in the **Appendix D**. 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. 43**). 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 9.9-12.6% 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 21.7% for flange and 29.9% for web.

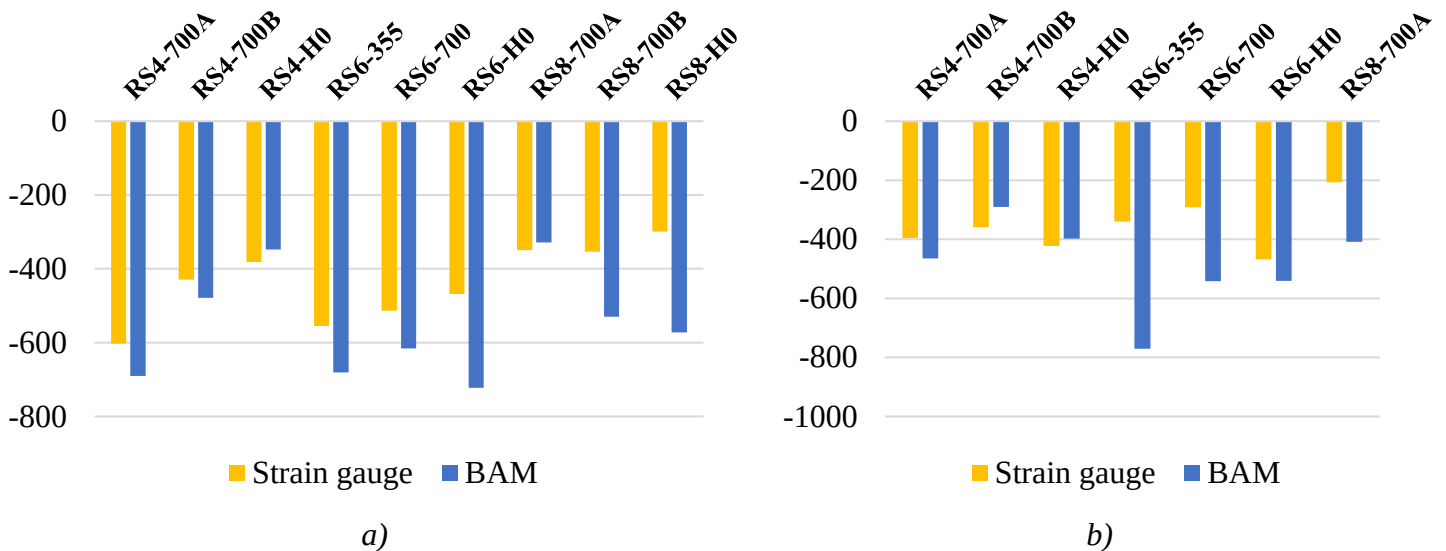


Fig. 43 - Measured axial strain on axis of the a) flange and b) web based on BAM and strain gauge measurement

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 **Appendix E** based on inspection certificates.

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. (12)-(15)**) have been developed over time to improve the accuracy for different types of steel:

$$CE = C + \frac{Mn}{6} + \frac{Cr+Mo+V}{5} + \frac{Cu+Ni}{15} \quad (12)$$

$$CEM = C + \frac{Si}{25} + \frac{Mn+Cu}{20} + \frac{Cr+V}{10} + \frac{Mo}{15} + \frac{Ni}{40} \quad (13)$$

$$CET = C + \frac{Mn+Mo}{10} + \frac{Cr+Cu}{20} + \frac{Ni}{40} \quad (14)$$

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

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. [33] [34]

The chemical composition of the base materials is summarized in table of **Appendix E**, 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 [30]. The solidus and liquidus temperatures of normal strength steel material can be calculated from the carbon content as follows [30]:

$$T_s = 1527 - 181.356C \quad (16)$$

$$T_l = 1530 - 80.581C \quad (17)$$

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. [35] 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. 18** was found to be the most accurate for higher carbon contents of 0.25%, while **Eq. 19** was found to be the most accurate for lower carbon contents of 0.04%. In studies, **Eq. 20** 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. [35]

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

$$T_L = 1536 - 251C - 12.3Si - 6.8Mn - 123.4P - 183.9S - 3.3Ni - 1.4Cr - 3.1Cu - 3.6Al \quad (19)$$

$$T_S = 1536 - 251C - 12.3Si - 6.8Mn - 123.4P - 183.9S - 3.3Ni - 1.4Cr - 3.1Cu - 3.6Al \quad (20)$$

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 [30] 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.

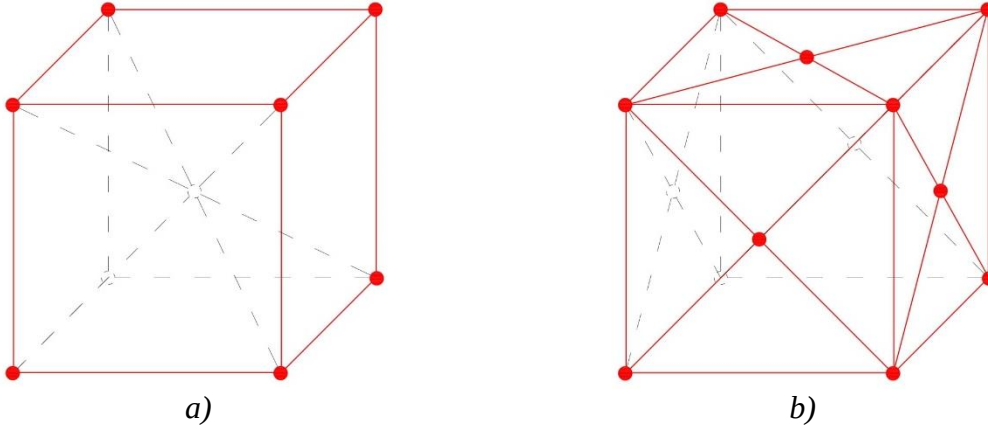


Fig. 44 - Crystal lattices: a) structure of α -Fe b) structure of γ -Fe

Other thermal material properties are the specific heat, which gradient is shown in **Fig. 32** as a function of temperature, which has a peak point at 735°C. This peak is due to the phase transformations between α -Fe and γ -Fe where the lattice structure changes as shown in **Fig. 31**. 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. 11**:

$$c_{\text{eff}}(T) = \begin{cases} c_s, & T < T_s \\ c_s + \frac{L}{T_l - T_s} \cdot \frac{T - T_s}{T_l - T_s}, & T_s \leq T \leq T_l \\ c_l, & T > T_s \end{cases} \quad (11)$$

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. 12**, which is used due the rapid changes in the effective specific heat curve [36]. Thermal material properties of both NSS and HSS are summarized in **Fig. 32** since the standard does not distinguish between thermal response of different steel grades.

$$H(T) = \int_0^T \rho(T) \cdot c(T) dT \quad (12)$$

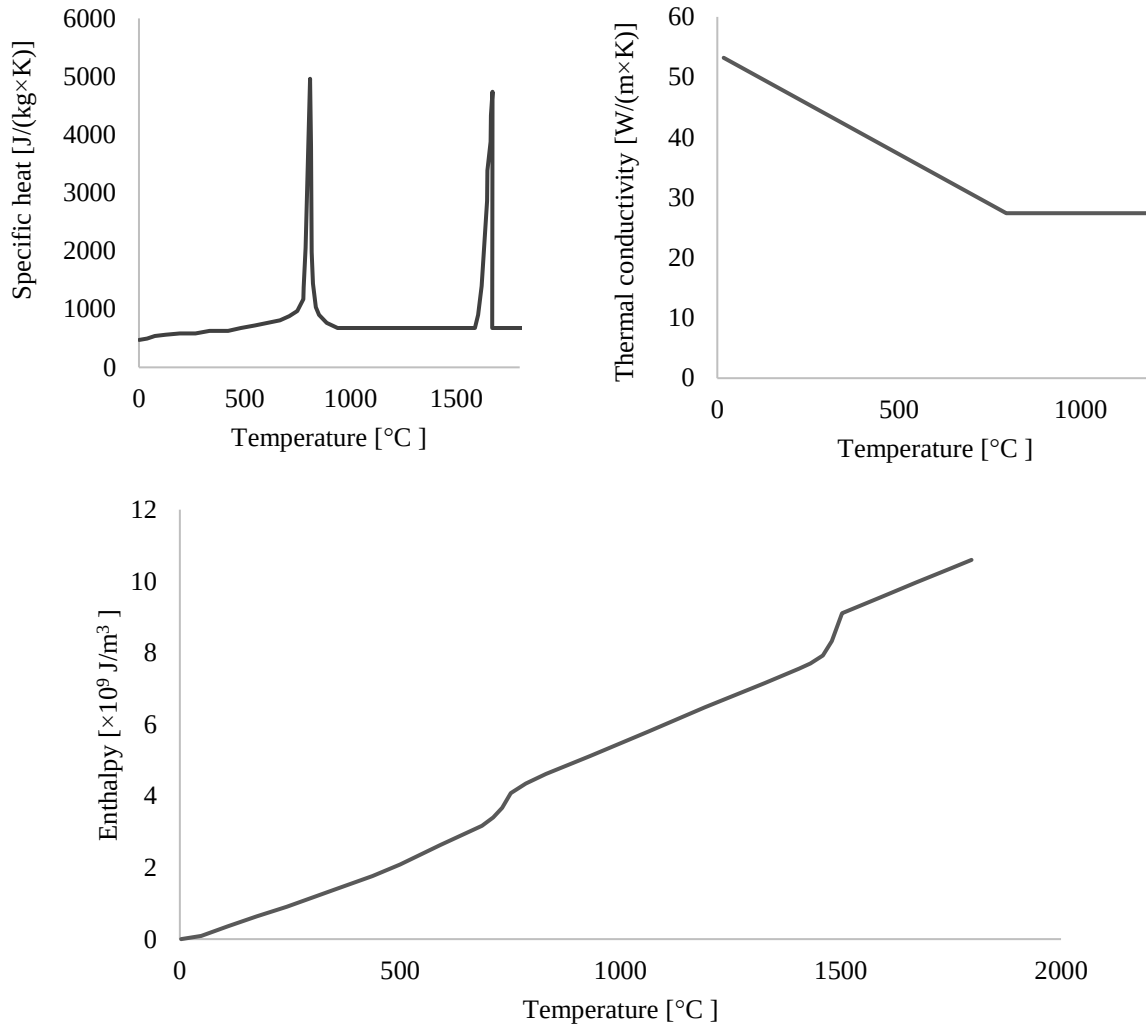


Fig. 45 - Thermal material properties of normal and high strength steels in the simulations

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. 13**:

$$\varepsilon_{\text{ther}}(T) = \frac{\Delta l}{l}(T) = \alpha(T) \cdot (T - T_r) \quad (13)$$

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. 33**) 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.

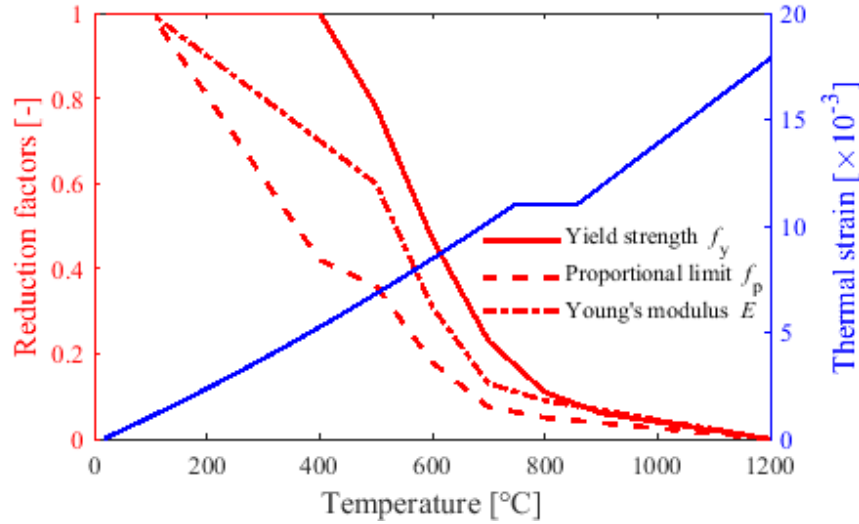


Fig. 46 - Mechanical material properties of NSS in the simulations based on [37]

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. 14**:

$$\varepsilon = \frac{\sigma}{E_{\theta}} + 0.002 \left(\frac{\sigma}{f_{p0.2\theta}} \right)^n \quad (14)$$

where n is taken as 14 for high strength steels based on the material tests of Somodi [47], 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.

Filler material addition is modelled in the developed ANSYS code with the combination of 'birth and death' and 'quiet element' techniques according to 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 $25 \text{ W}/(\text{m}^2 \cdot \text{K})$, 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. 15**:

$$Q = \eta UI \quad (15)$$

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. 34**) is used for arc welding simulation in this study, in which front and rear ellipsoids can be calibrated separately. **Eqs. (16)-(17)** determine the power density distribution in the front and rear quadrants for a double ellipsoidal heat source model, respectively

$$q_f(x, y, z) = q_{\max} \cdot e^{-\frac{3x^2}{c_f^2} - \frac{3y^2}{a^2} - \frac{3z^2}{b^2}} \quad (16)$$

$$q_r(x, y, z) = q_{\max} \cdot e^{-\frac{3x^2}{c_r^2} - \frac{3y^2}{a^2} - \frac{3z^2}{b^2}} \quad (17)$$

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

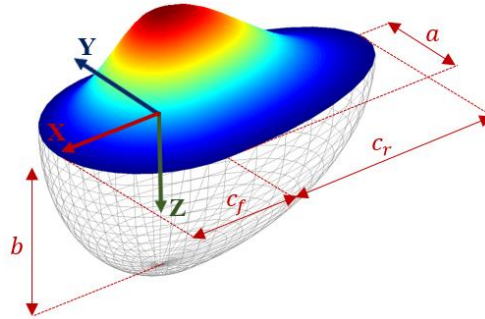


Fig. 47 - Notations of the double ellipsoidal heat source model [37]

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. 35**, which are in accordance with the experimental layout.

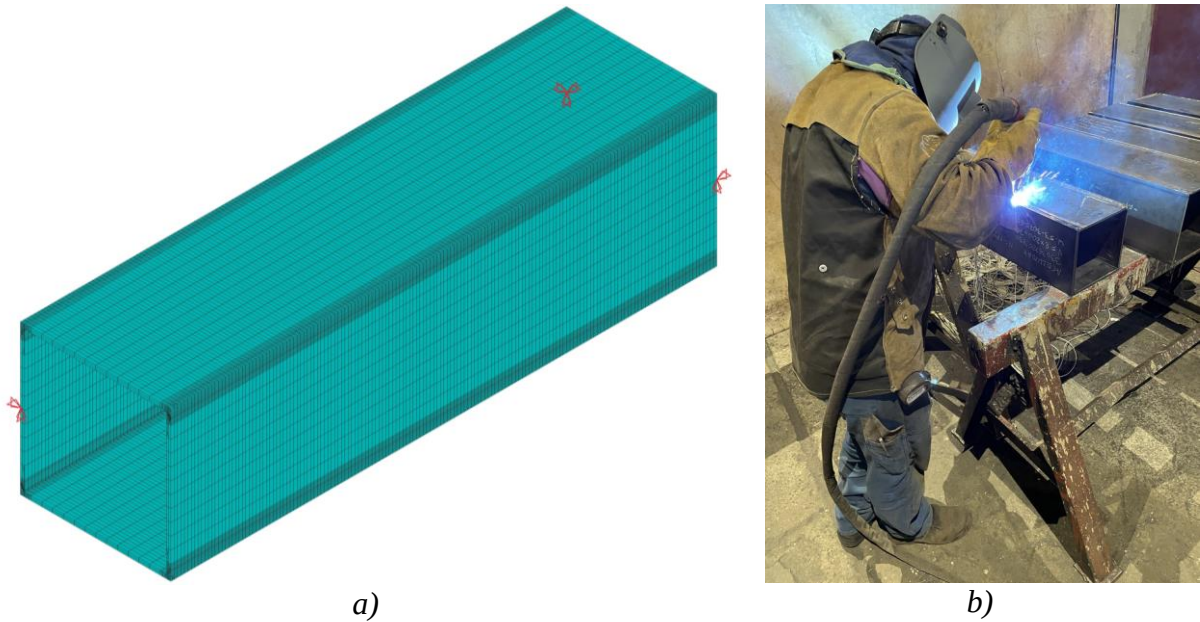


Fig. 48 - a) Mechanical boundary conditions in the developed model and b) supports during experiments

4.4 Finite element mesh

Choosing the right mesh size is essential for a finite element model. In the case of weld simulation, a denser mesh size distribution in the heat-affected zone (HAZ) and less dense further from the weld are required, as shown in **Fig. 36**. Outside the HAZ, two finite elements are defined through the thickness for each specimen. The finite element mesh divides the test specimens along their longitudinal axis into 160 parts. For RS6 and RS4 specimens, the flange was divided into six parts through the thickness and the web into four parts in the HAZ, while seven elements through the thickness of the web is used for RS8. The finite element mesh of the flange of RS8 specimens is identical to that of RS6 and RS4. The finite element mesh of the numerical model of the RS6-355 sample is shown in **Fig. 36**. Number of finite elements of RS4, RS6 and RS8 specimens are 76 360, 78 080 and 76 636, respectively.

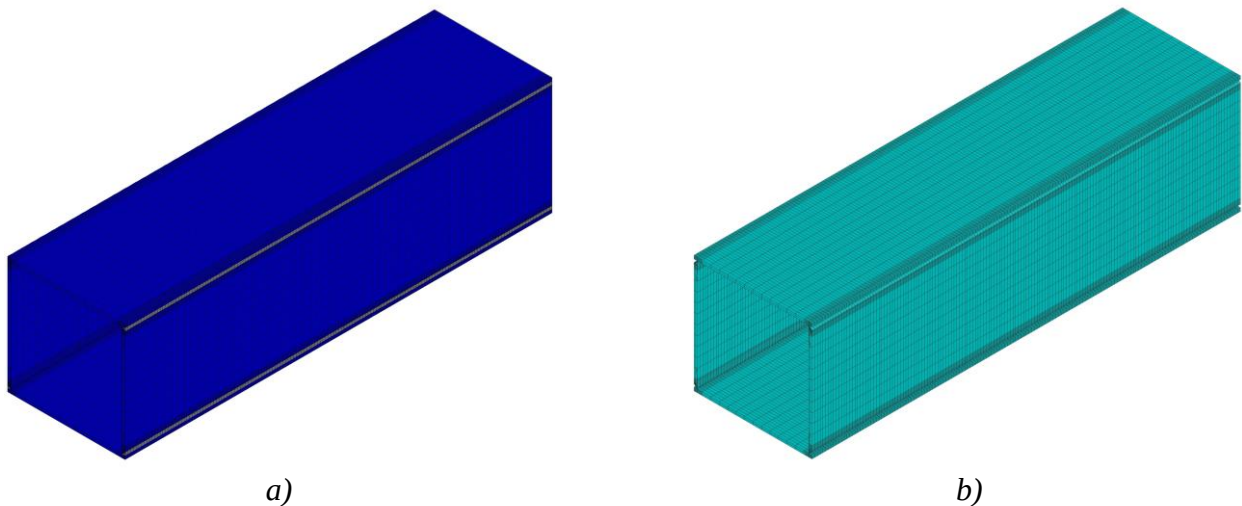


Fig. 49 - a) Finite element model with active (blue) and inactive (grey) elements when starting the analysis and b) finite element mesh of the numerical model

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 future parameter 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. 50** shows temperature fields during the welding simulation, while **Fig. 51** 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 B**. 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.

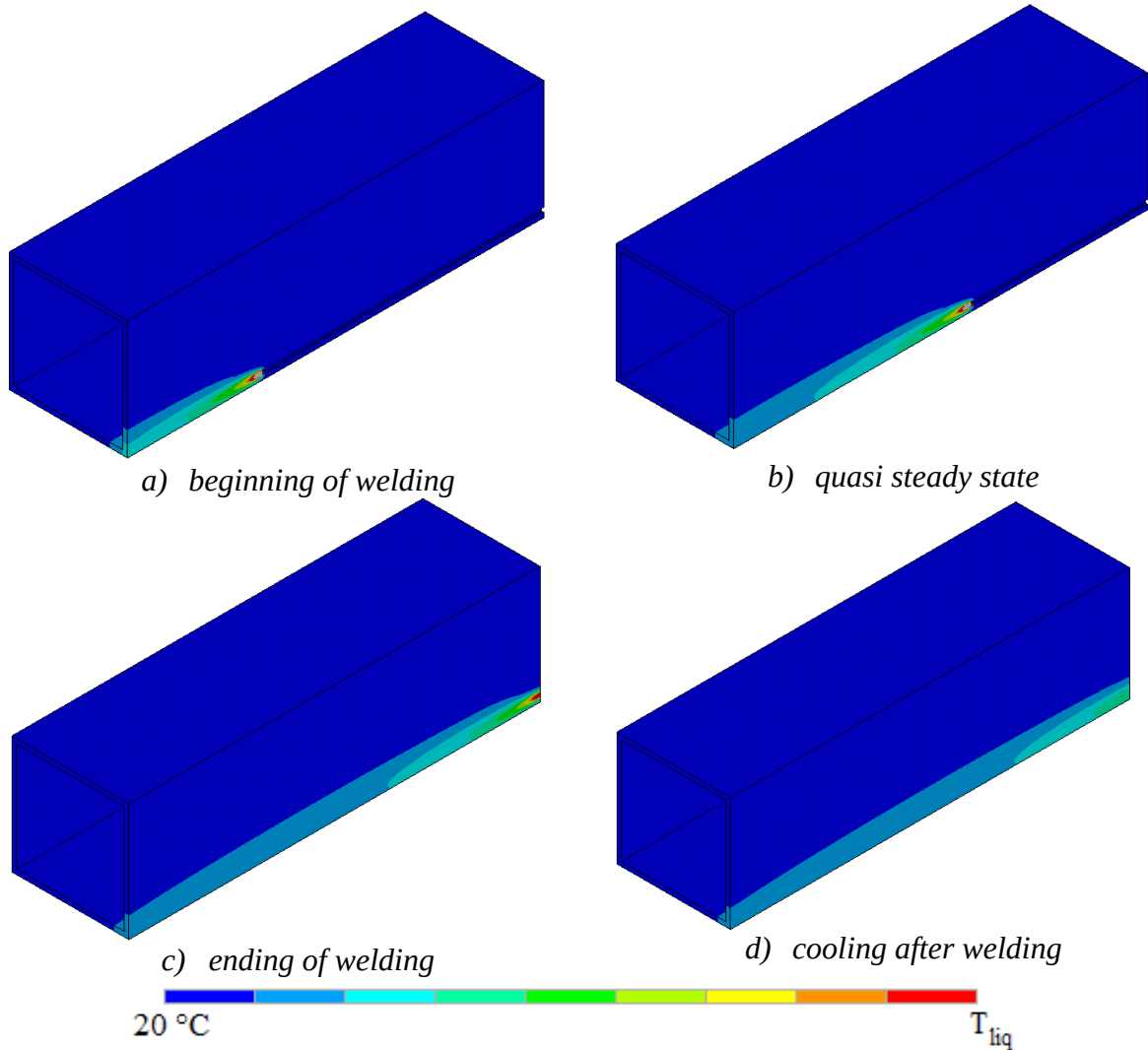


Fig. 50 - Schematic temperature fields during welding using the numerical model

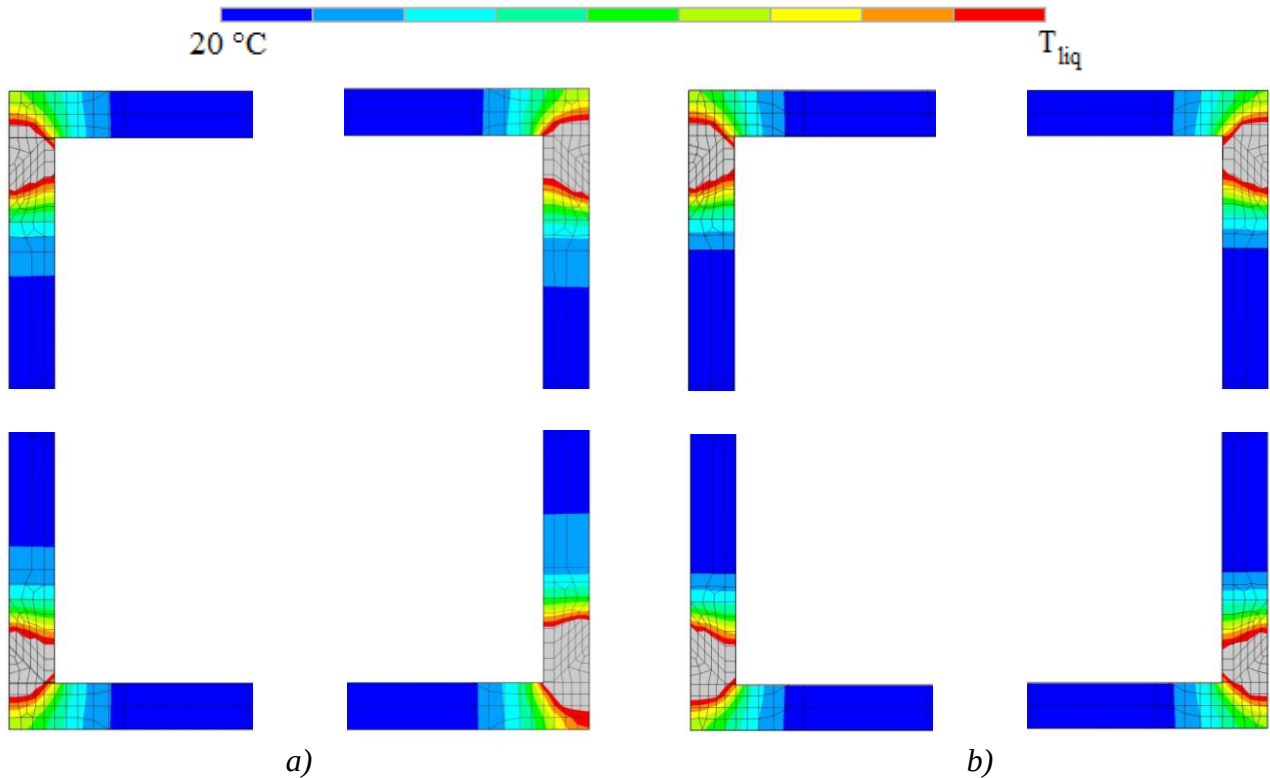


Fig. 51 – Fusion zones (grey) of specimens a) RS4-700A and b) RS4-700B

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. 52** provide important information; distortions of the global model and the flange and web shown in **Fig. 53** 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.

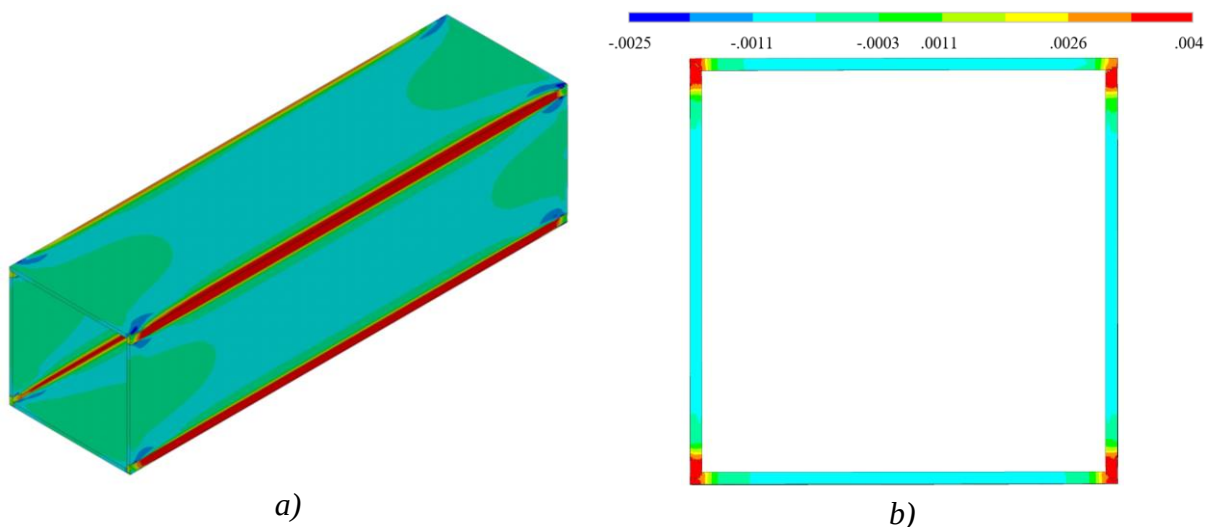


Fig. 52 - Elastic axial strains [-] of RS6-700 specimen showing the a) global model, and b) middle cross-section

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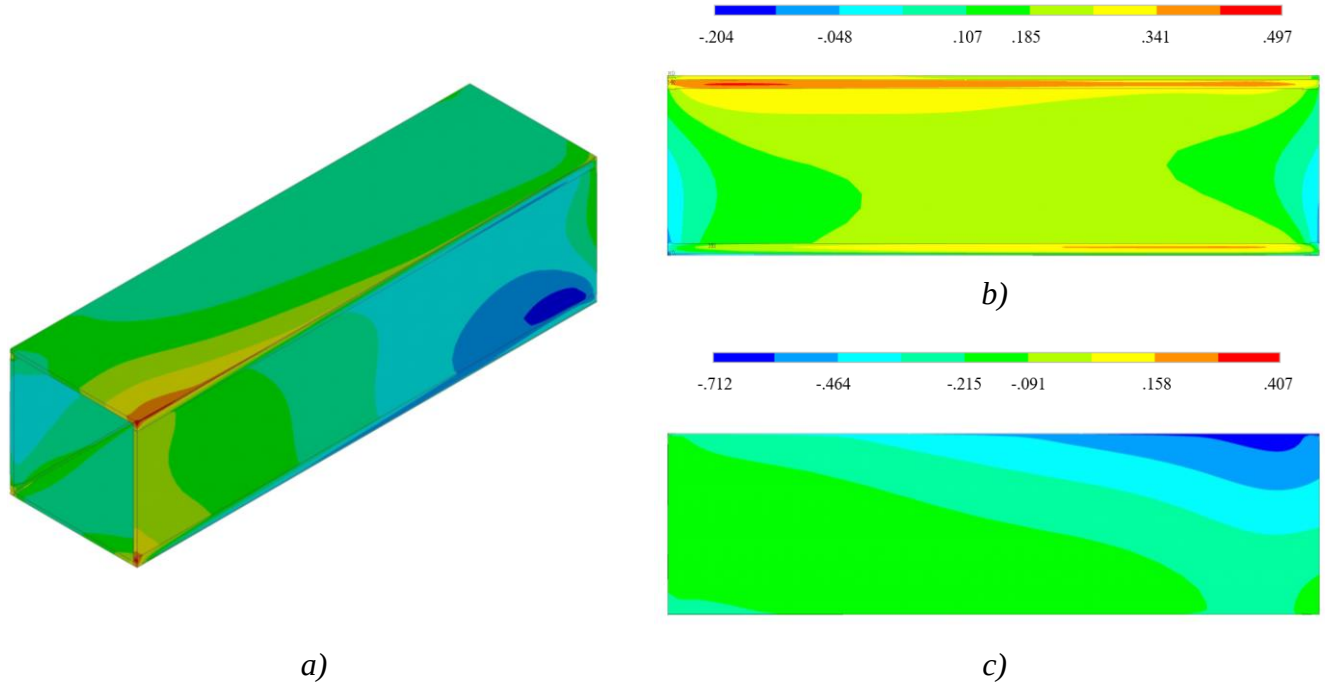


Fig. 53 - a) Total distortions [mm] of the RS6-700 specimen showing a) global model, b) transverse distortions [mm] of web, and c) vertical distortions [mm] of flange

The third important result that can be obtained from the numerical model is the residual stress distribution. The von Mises stress distribution for the numerical model of sample RS6-700 is shown in **Fig. 54**, 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 we measured the strains of the middle cross-section in the experiments and use this cross section in model validation.

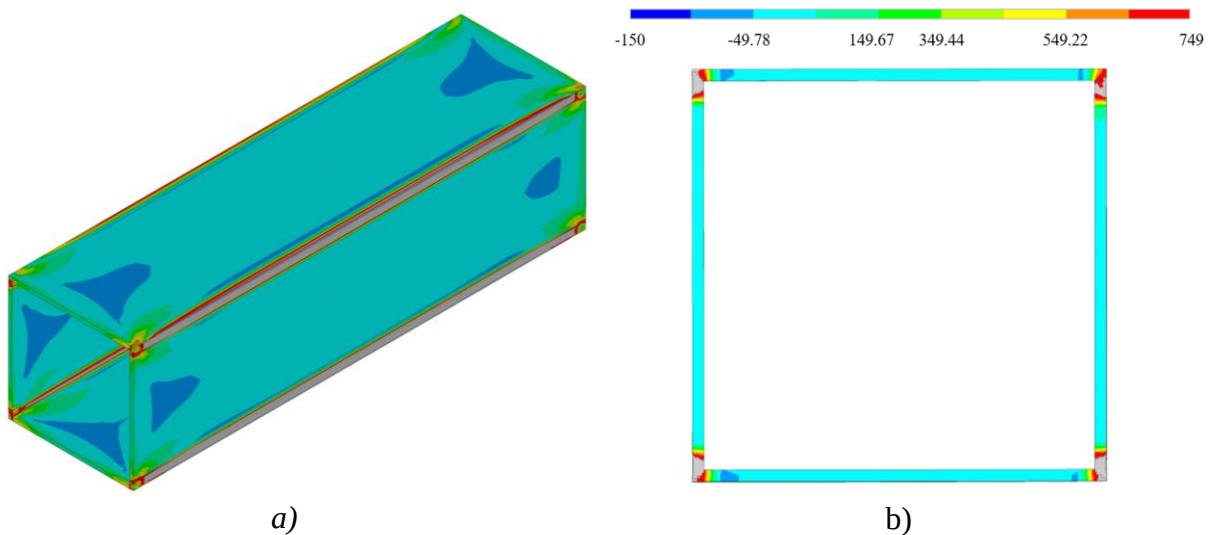


Fig. 54 - Von Mises stress [MPa] distribution of RS6-700 specimen showing the a) global model, and b) middle cross-section

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 D** for each of the test specimens tested. **Fig. 55** shows the axial strains of the RS6-355 specimen at the middle cross section based on the BAM extensometer and the numerical model.

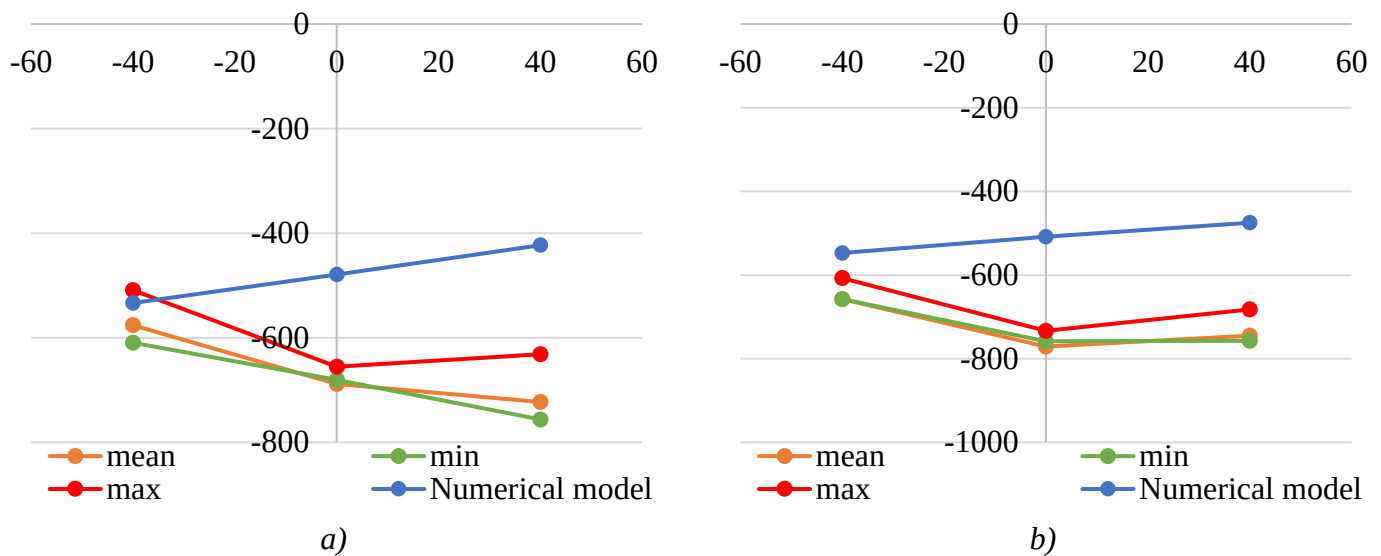


Fig. 55 - Axial strains [$\mu\text{m/m}$] of the RS6-355 specimen at the middle cross section based on the BAM extensometer measurement and the numerical model on a) flange and b) web

5.3.2 Strain gauge-based measurement

To compare the numerical model results with the strain gauges-based measurements' results, the measurement results are plotted in a common coordinate system. These plots can be found in **Appendix D** for each of the test specimens tested. **Fig. 56** shows the axial strains of the RS6-H0 specimen at the middle cross section based on strain gauges measurement and the numerical model.

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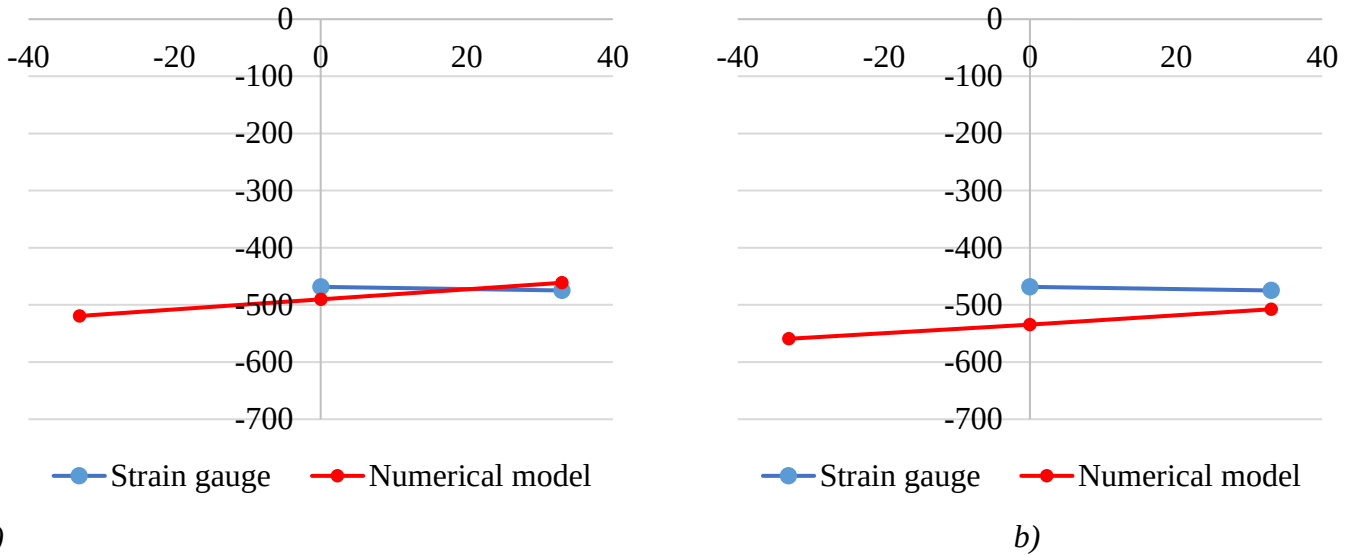


Fig. 56 - Axial strains [$\mu\text{m/m}$] of the RS6-H0 specimen at the middle cross section based on strain gauges measurement and the numerical model on a) flange and b) web

The numerical model can predict the strains of the flange on the middle with an accuracy of 0.65% - 31.0% compared to the strain gauge results. For the strains of the web, it can predict with an accuracy of 16.12% - 41.0%, also compared to the results of the strain gauges, in the axis of the plate. On average, the model can do this with an accuracy of 27.92% for the web plate and 14.96% for the flange.

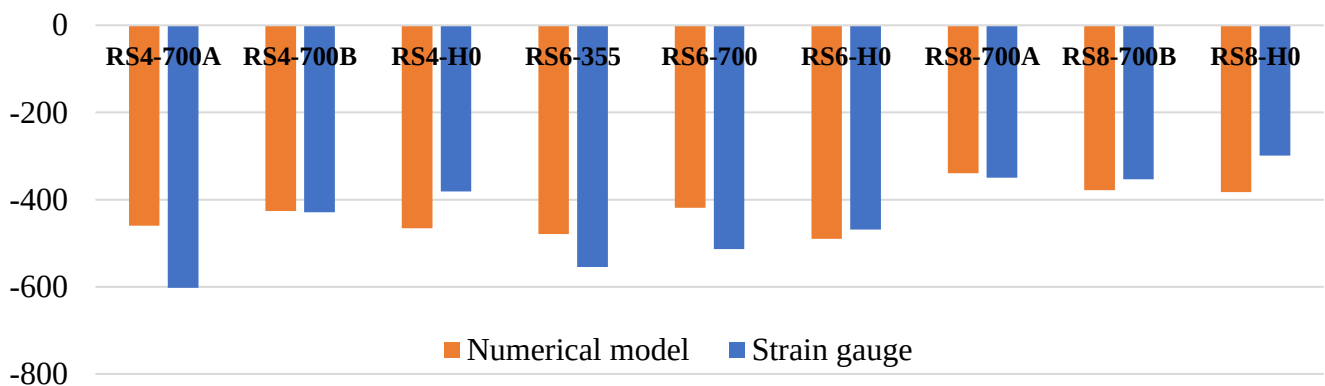


Fig. 57 - Difference between the strains from numerical model and the deformations measured by strain gauges in the axis of flange

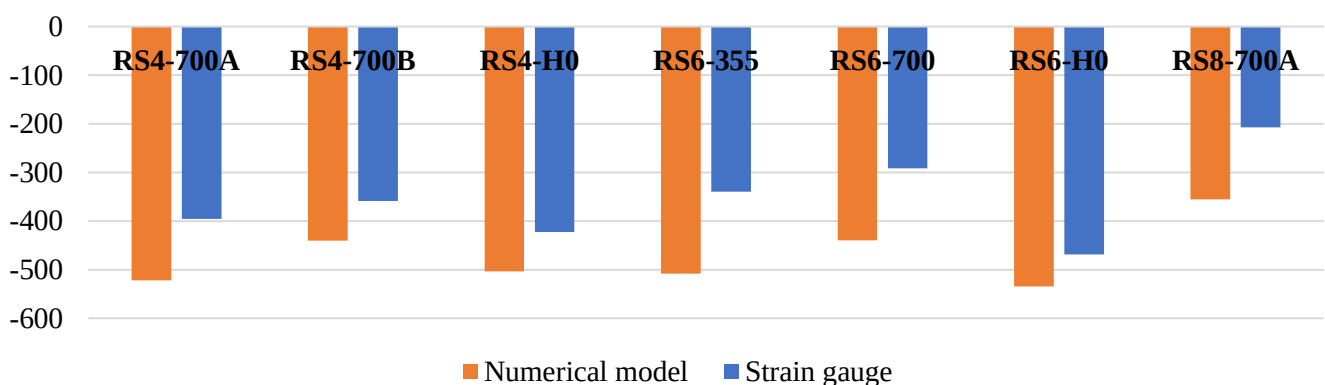


Fig. 58 - Difference between the strains from numerical model and the deformations measured by strain gauges in the axis of web

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