WELDING OF THICK STEEL PLATES UNDER SITE CONDITIONS

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INTRODUCTION

In comparison to factory production construction site welds - as found e.g. in steel bridges (see Fig. 1a) - are carried out under difficult conditions. Especially for thick plates, construction site welds put high demand not only to the executing company but also to the engineer. For the design of construction site welds taking into account the site conditions, so far only insufficient decision support tools are available. Factors such as the weld shrinkage of the components, the distortion and the residual stress state can particularly influence the production process as well as the structural safety. Nowadays, the construction of large steel structures mainly is realized using modular factory production. The assembly to an overall structure has to be performed under variable conditions at the construction site. For welding of thick plates multi-layer welding is used (see Fig. 1b). In previous research on the welding of thick plates and their simulation constant laboratory conditions were used as boundary conditions during the experimental weld examinations. Systematic studies on welding of thick plates under site conditions will be presented considering a variable temperature range (+20 °C, 0 °C, -10 °C). The article presents test results from the experimental part at the climate chamber as well as numerical calculations with the help of welding simulation and non-linear structural analysis. Results are given and compared with traditional engineering models. Advises for future problems will be presented.

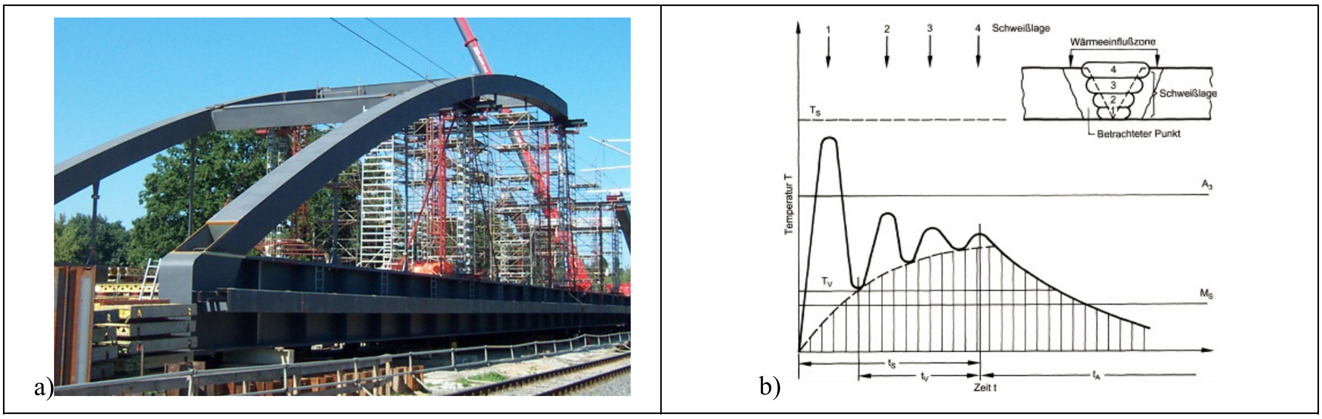


Fig. 1: a) Tied Arch Bridge [1], b) Increase in Temperature in HAZ during multi-layer welding [2]

1 CONSTRUCTION SITE WELDS – ASSEMBLY JOINTS

1.1 Location of assembly joints

As shown in [3] the location of assembly joints varies dependent on the particular case. From a static point of view the ideal location leads to points with low or zero stress level, such as the point of zero moment for a certain load case. On the other hand, dimensions are often limited by delivery lengths or restrictions of weight due to means of transportation or the location of the construction site. Mostly the design process is significantly influenced by such economic factors. During the investigations the boundary conditions free-free (e.g. main beam), free-rigid (e.g. initial arc, cross girder connection) and rigid-rigid (e.g. closing segments) were analyzed.

1.2 Type of assembly joints

Apart from the location of assembly joints, the detailed design of the weld and the welding sequence are of importance. Fig. 2 shows 3 different types of joints. For I-girders in bridge constructions of large span U- or Z-joints are commonly used. Due to the more favorable execution, the Z-joint is applied mostly [4]. Fillet welds are kept open to a certain length (usually 900-1500 mm) until all butt joints are welded. Dependent on the boundary conditions and the plate thickness the respective length may vary. Thereby it is aimed to keep the cross sections as elastic as possible during welding. A strong restriction of deformation generally leads to high residual stress levels, and can favor cracks or other failure modes.

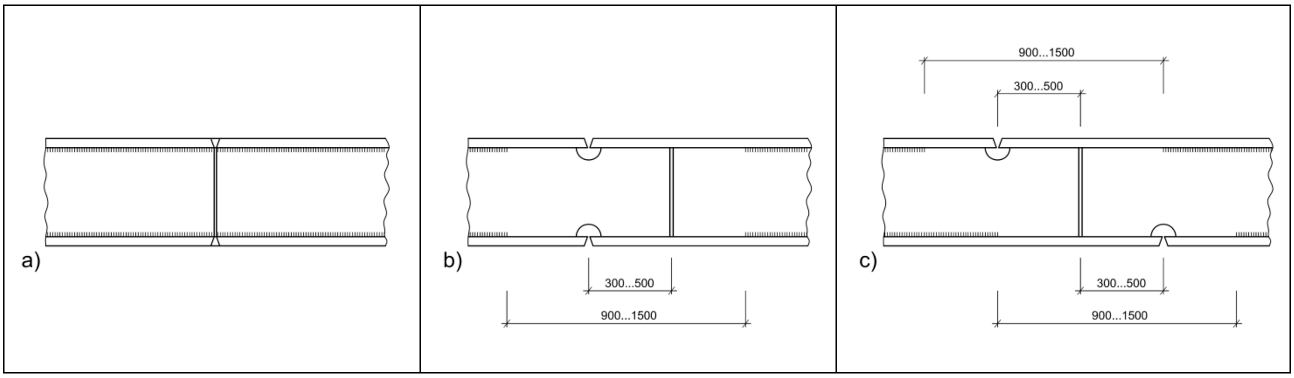


Fig. 2: Execution types of joints: a) Butt- Joint, b) U-joint, c) Z-Joint

2 EXPERIMENTAL PROCEDURE

2.1 Part Demonstrator

As stated in 1.2, the most common joint type is the Z-joint, see Fig. 2c. The manufacturing of components, referred to as part demonstrator, took part under manufacturing conditions, see Fig. 3. The base material was chosen as P355NL2 and S460NL. The joining was carried out by MAG-welded, single-pass fillet welds with a throat thickness of 5 mm. During the process temperature and deflections were measured. After manufacturing the residual stress state was determined using mobile x-ray diffractometer. The results are important for the calibration and validation of the model presented in 4.1.

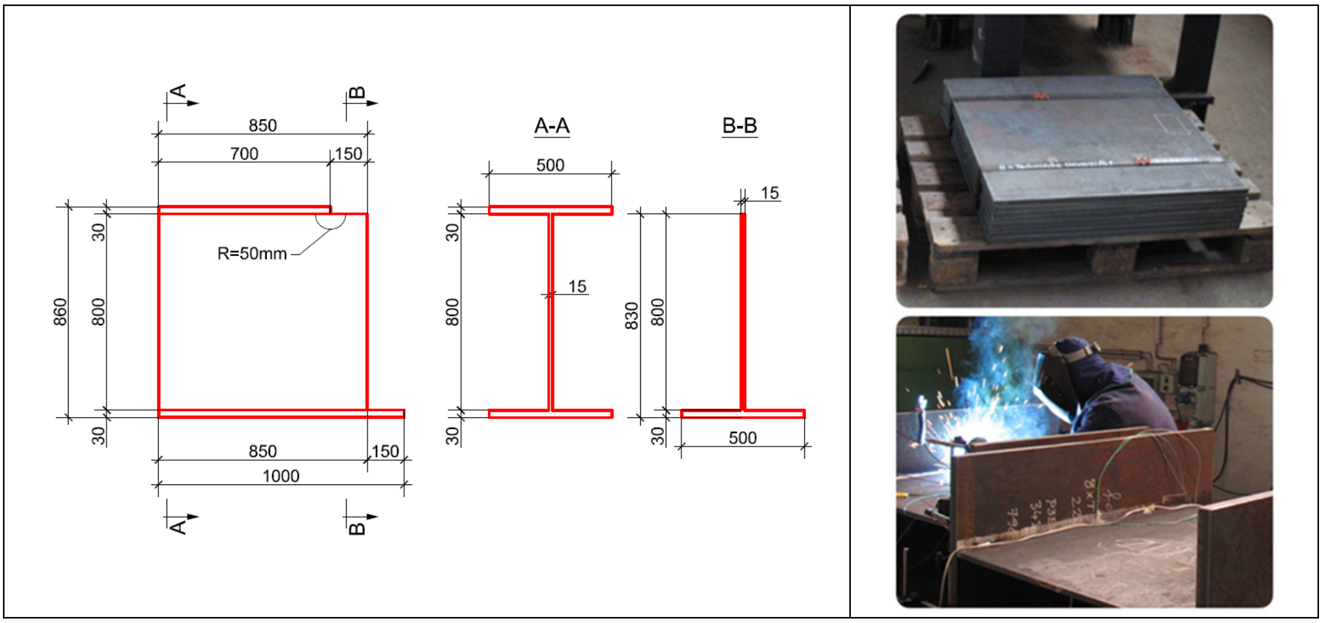


Fig. 3: Part Demonstrator (PD): Geometry and Manufacturing

2.2 Demonstrator, Variation of Ambient Temperature

After the fabrication of components, the assembly was performed at the climate chamber, choosing different climatic conditions. In cooperation with industrial partners the examined temperature range was set to -10 °C, 0 °C and +20 °C. To apply realistic boundary conditions the components were fixed to a special frame construction. For the frame design the transverse shrinkage of butt welds was investigated by various shrinkage models. The transport to the climate chamber was realized using a modified rail vehicle, see Fig. 4.

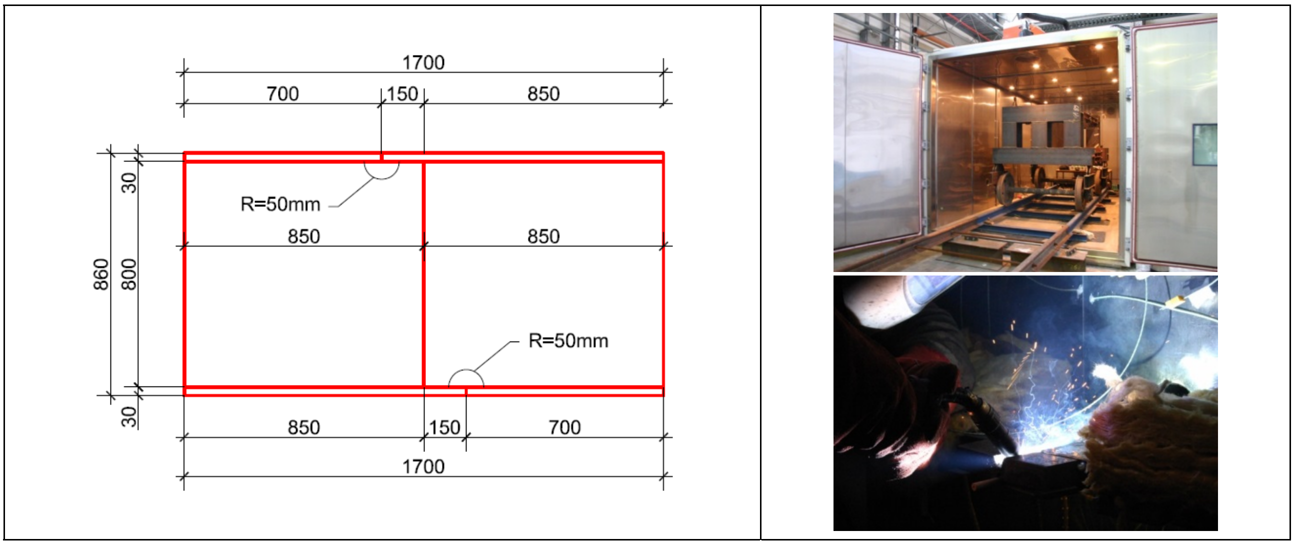


Fig. 4: Demonstrator (D): Geometry and Manufacturing

All specimens were equally preheated ($T_V \geq 100$ °C). In order to achieve steady temperature level around the weld, heating mats had to be used. For multi-layer welding the intermediate layer temperature has to be checked ($T_Z \leq 200$ °C). During and after assembly measurements were carried out. Fig. 5 shows the comparison of longitudinal and transverse residual stresses at -10 °C and RT (+20 °C). As can be seen, the ambient temperature has no significant influence on the final stress state, provided that the welding was performed accordingly (preheating temperature, intermediate layer temperature). For further investigations the temperature influence can be neglected.

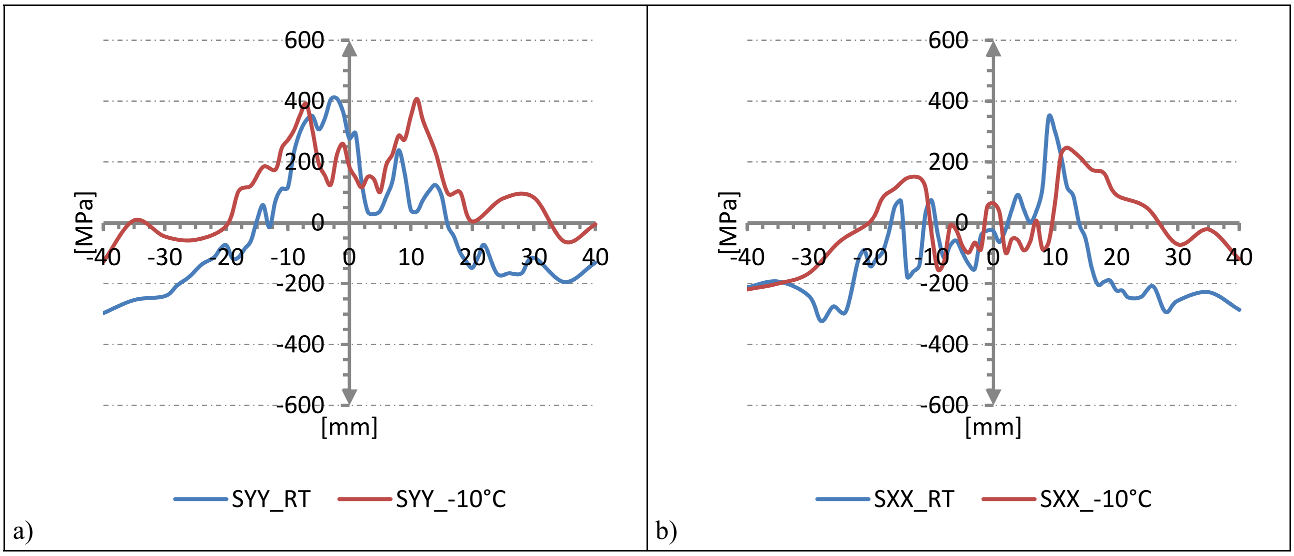


Fig. 5: a) Longitudinal and b) Transverse Welding Stresses at Different Temperature Levels (RT: +20 °C, -10 °C)

3 ENGINEERING MODELS

There are only few engineering models for the approach of the residual stress state. Fig. 6 shows two common models. The first model is proposed in [5], see Fig. 6a. Thereby the distribution and magnitude of stress is only dependent on the geometry and the yield strength. The second model is based on the calculation of a plastic width [6], see Fig. 6b. The idea is based on the assumption that the stress state is mainly caused by the shrinkage of the weld seam and the HAZ, which can be compared with the prestressing of a tendon.

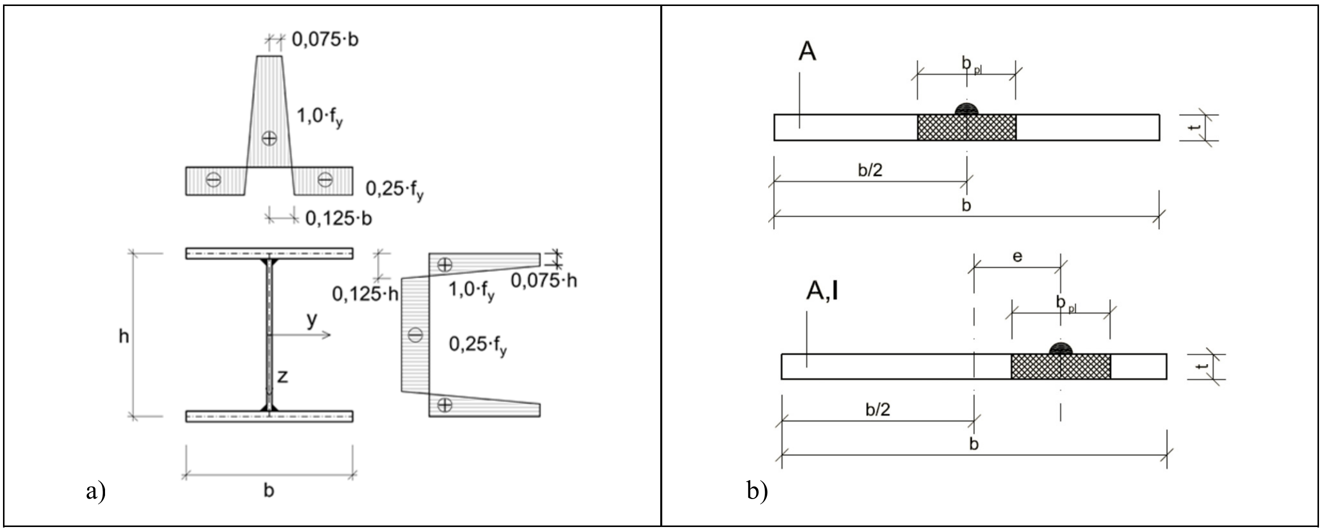


Fig. 6: Engineering Models: a) ECCS-84 [5], b) Shrinkage Model, Okerblom -58 [6]

4 WELDING SIMULATION

4.1 Part Demonstrator

For the comparison and evaluation of the engineering models a welding simulation was performed with Sysweld by ifs Braunschweig [7]. Fig. 7 shows the residual stress state of the part demonstrator (PD) after welding the two fillet welds.

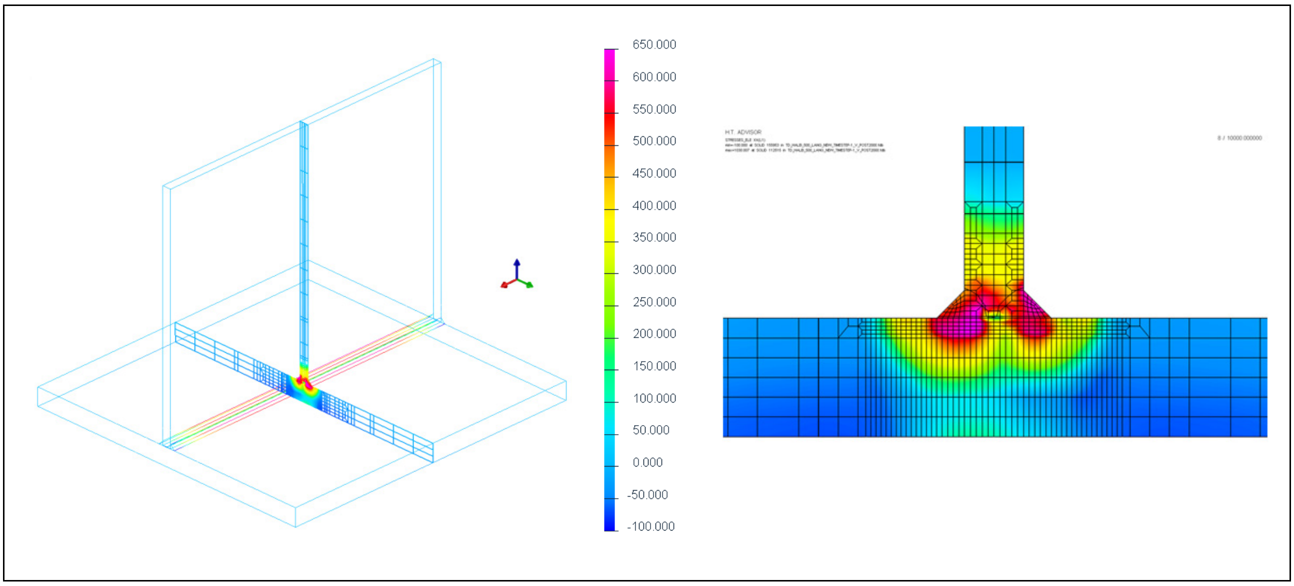


Fig. 7: Welding Simulation (PD): Longitudinal Welding Stresses, MPa [7]

In Fig. 8a the stress state at the bottom of the flange resulting from the simulation and the experimental determination is compared. As can be seen, course and magnitude of results are in good agreement Fig. 8b shows the comparison of simulation and assumed model. Especially for thick plates a strong gradient over the thickness can be noted, which leads to strong deviations around the weld center. However, for stability analysis focus is put on the approximation of compressive residual stress, resulting from equilibrium condition. Fig. 8b shows, that the thickness gradient is only existent close to the weld. Therefore the assumption of constant stress level over the thickness seems adequate. However, course and magnitude of compressive residual stress are approximated insufficient, which leads to underestimation of load capacity. Investigations have proven that the residual stress state strongly depends on the given boundary conditions such as manufacturing parameters and the material grade. Deviations generally increase with an increase in yield strength.

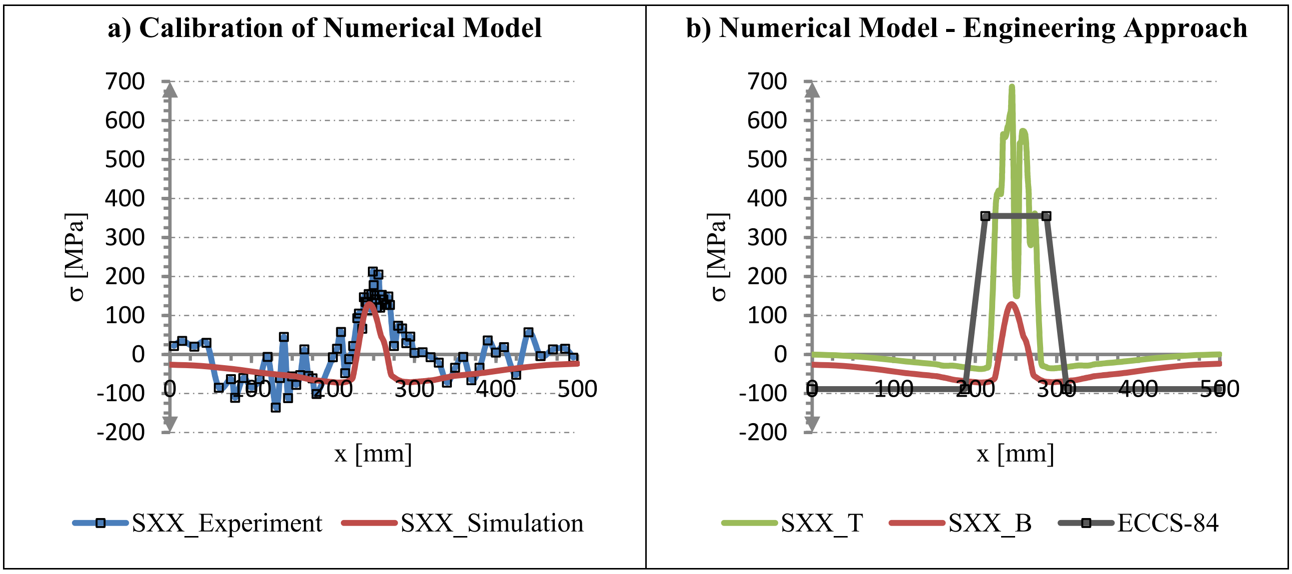


Fig. 8: Comparison of Experiment, Welding Simulation and Engineering Model for the PD [7]

4.2 Demonstrator

In Fig. 9 part of the simulation results for the demonstrator (D) is shown. As an example longitudinal (Fig. 9a) and transverse stress (Fig. 9b) at the upper flange are presented. The bead sequence was simplified with 6 layers for the flange and 3 layers for the web. The calculation was performed with Sysweld by the IFS Braunschweig [7]. For the calibration and validation of the model the experimental results from 2.2 were used; the comparisons have shown satisfying agreement. For further calculations results were simplified, using blockwise or trapezoidal approximation.

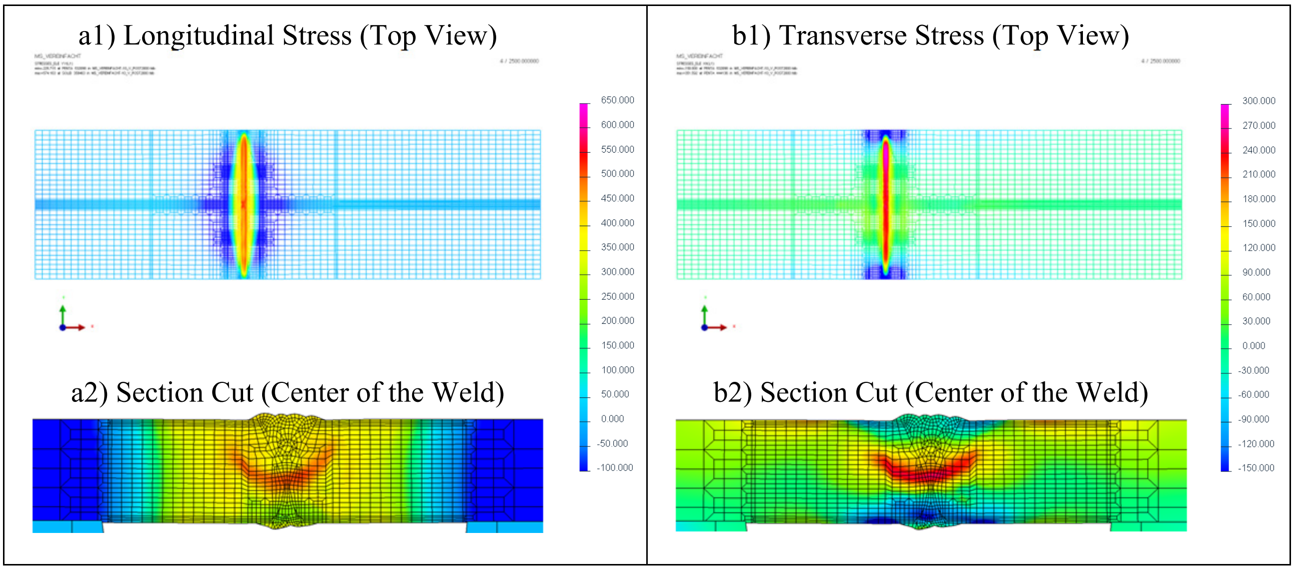
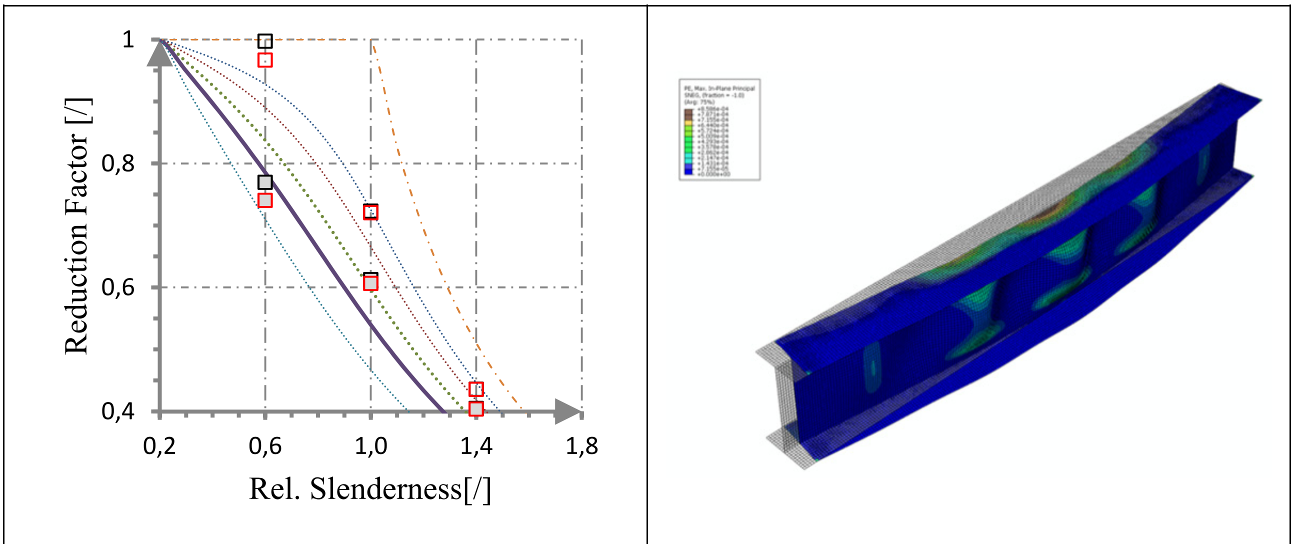


Fig. 9: Welding Simulation (D): Residual Stress Distribution for the Flange, MPa [7]

Based on the simplified models numerical calculations have been carried out, investigating the influence of the assembly joint on the structural behaviour. For all investigations influence was below 5 %. The necessity of consideration of such discontinuity areas is dependent on the particular case.

5 NON-LINEAR STRUCTURAL ANALYSIS AND CONCLUSION

Extensive load capacity calculations, investigating the influence of different aspects, especially the effects of different residual stress models, have been carried out. Results are included in [7]. Fig. 10 shows exemplary results for flexural buckling, comparing results without and with residual stress as well as the influence of additional local distortion. It can be seen that the residual stress state mainly influences the lower and medium slenderness range. Calculations have shown that the magnitude of load capacity strongly depends on the approach. Partially deviations reached values up to 15 %, compared to the results using the simplified approach proposed by [5]. Tendency shows that deviations increase with an increase in yield strength. This underlines the necessity of realistic models, especially as high strength steel is being used. For an adequate approximation, constructive, manufacturing and material aspects have to be taken into account. As far as the simplified approach is used, results equal more or less with the proposed values by the standard (EC3), as can be seen in Fig. 10.



a) Comparison with EC3 (European Buckling Curves)

b) Exemplary Yield Zone Pattern at Failure (0,6)

Fig. 10: Nonlinear Load Capacity Calculation: Flexural Buckling about Weak Axis [7]

6 ACKNOWLEDGMENT

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KEYWORDS: Assembly Joints; Residual Stress Distribution, Welding Simulation, Load Capacity

ABSTRACT

In comparison to factory production construction site welds - as found e.g. in steel bridges (see Fig. 1a) - are carried out under difficult conditions. Especially for thick plates, construction site welds put high demand not only to the executing company but also to the engineer. For the design of construction site welds taking into account the site conditions, so far only insufficient decision support tools are available. Factors such as the weld shrinkage of the components, the distortion and the residual stress state can particularly influence the production process as well as the structural safety. Nowadays, the construction of large steel structures mainly is realized using modular factory production. The assembly to an overall structure has to be performed under variable conditions at the construction site. For welding of thick plates multi-layer welding is used (see Fig. 1b). In previous research on the welding of thick plates and their simulation constant laboratory conditions were used as boundary conditions during the experimental weld examinations. Systematic studies on welding of thick plates under site conditions will be presented considering a variable temperature range (+20 °C, 0 °C, -10 °C). The article presents test results from the experimental part at the climate chamber as well as numerical calculations with the help of welding simulation and non-linear structural analysis. Results are given and compared with traditional engineering models. Advises for future problems will be presented.

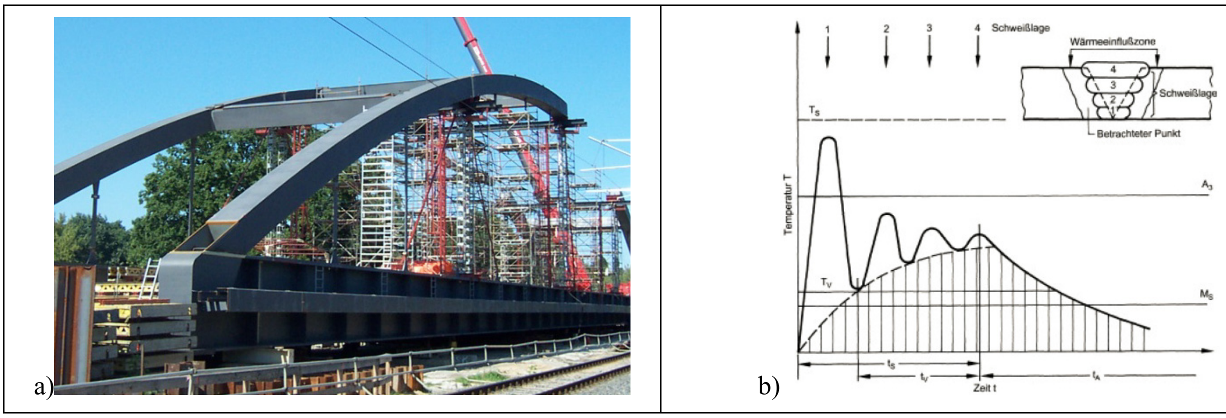
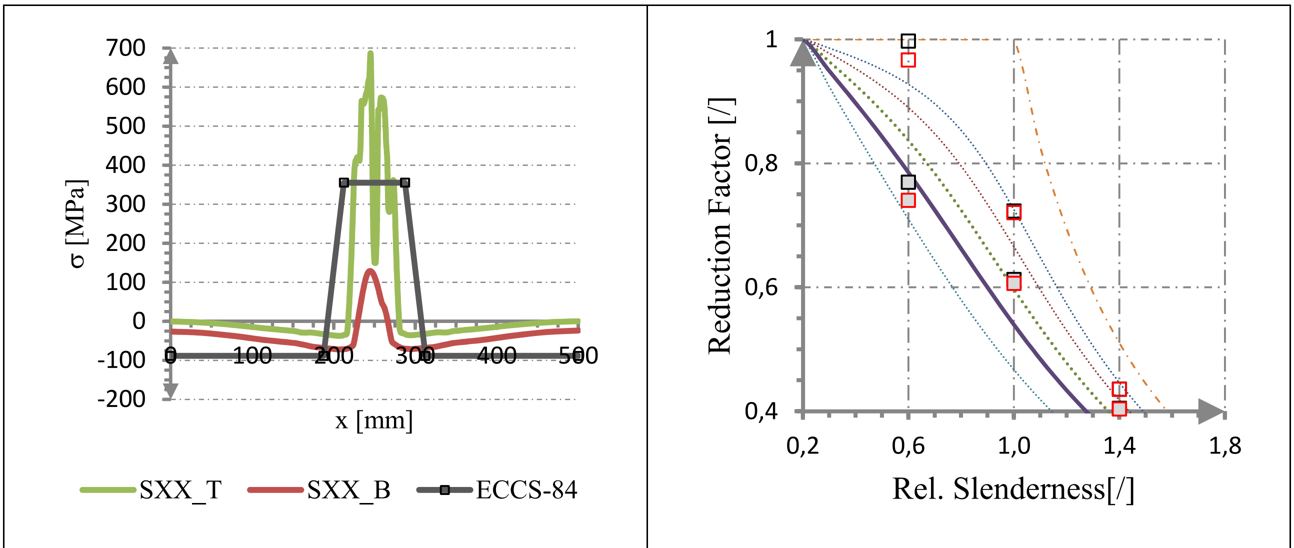


Fig. 1: a) Tied Arch Bridge [1], b) Increase in Temperature in HAZ during multi-layer welding [2]

CONCLUSIONS

In practice the Z-joint is a commonly used joint type. A large experimental and numerical research program was performed to investigate the magnitude and influence of welding imperfections resulting from the production of components as well as from the assembly. For the latter special focus was put on variable temperature conditions. Measurements on examined specimens have shown that the ambient temperature has no significant influence on the final stress state, provided that the welding was performed accordingly (preheating temperature, intermediate layer temperature). A welding simulation was performed with Sysweld by the IFS Braunschweig [4]. For structural calculations results were simplified, using blockwise or trapezoidal approximation. For all investigations influence of the assembly joint was below 5 %. The necessity of consideration of such discontinuity areas is dependent on the particular case.

For the fabrication of components existent engineering models were examined and compared with the results of welding simulation, see Fig. 2a. Extensive load capacity calculations, investigating the influence of different aspects, especially the effects of different residual stress models, have been carried out. Results are included in [4]. Fig. 2b shows exemplary results for flexural buckling, comparing results without and with residual stress as well as the influence of additional local distortion. It can be seen that the residual stress state mainly influences the lower and medium slenderness range. Calculations have shown that the magnitude of load capacity strongly depends on the approach. Partially deviations reached values up to 15 %, compared to the results using the simplified approach proposed by [3]. Tendency shows that deviations increase with an increase in yield strength. This underlines the necessity of realistic models, especially as high strength steel is being used. For an adequate approximation, constructive, manufacturing and material aspects have to be taken into account. As far as the simplified approach is used, results equal more or less with the proposed values by the standard (EC3), as can be seen in Fig. 2b.



a) Welding Simulation - Engineering Approach

b) Comparison with EC3 (European Buckling Curves)

Fig. 2: a) Comparison of Simulation and Model, b) Nonlinear Load Capacity Calculation: Flexural Buckling (z-z) [4]

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