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Advanced residual stress assessment of plate girders through welding simulation

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Abstract

This article provides an impression on potentials in applying nowadays welding simulation tools in construction design. This is carried out exemplary on plate girders from two structural steel grades. The calculated residual stresses are compared with measurements by sectioning method. It has been repeatedly stated that present Eurocode models fail to approximate the residual stresses. Especially for high strength steel (HSS) only limited information is available on realistic occurring residual stresses in typical I-girders. The investigations are aimed to give further guidance on these values. A few proposals on advanced models are discussed.

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1. Introduction

Welded I-girders are used in many applications in steel construction, especially a tailored mixture of different plate thicknesses is difficult to manufacture by rolling. The ultimate limit state of plate girders under compression or bending is significantly influenced by the present imperfections. Load influencing imperfections are mainly geometric deviations from the ideal shape and residual stresses (both due to assembly or weld manufacturing). The following sections are referred to the influence of residual stresses only. The general influence of residual stresses on structural

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members is to cause premature yielding leading to a loss of stiffness and a reduction in load-carrying capacity [1]. Typical yield zone patterns of an I-shape section at ultimate limit state (ULS) are presented exemplary for pure compression and 3-point bending in Figure 1. Both cases show broadly comparable yielding over wide areas of the corresponding side of the chords in compression. Hence, the residual stress amplitudes near the chord edges are of importance. Previous studies have shown that the reduction in load-carrying capacity is particularly noteworthy in the lower and medium slenderness range [1]. For the residual stresses, the recommendation from Eurocode only reads that a typical residual stress pattern (reflecting the “mean” expected values) must be included. This recommendation is independent of the type of loading and does not suggest any specific residual stress pattern. The decision on the type of pattern which fits best (and safe-sided) for a particular problem must be taken by the designer.

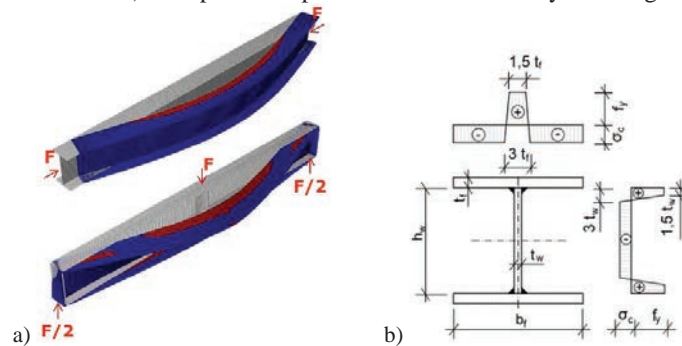


Fig. 1. a) Typical yield zone patterns at ULS for pure compression and 3-point bending; b) Typical distribution of residual stresses for design purposes [2].

The formation of residual stresses in steel girders occurs primarily during the section production process, e.g. due to cutting (especially thermal cutting processes involve intense local heating and rapid cooling) and all types of welding. In this paper, the latter is investigated. Tensile and compressive longitudinal stresses are observed in all welded girders in a quite regular fashion. Models can be found e.g. in the Swedish provisions for the design of bridges [2] and in several works of the ECCS [3,4]. The residual stress pattern is characterized by longitudinal stresses acting symmetrically on the cross-sectional area of the plate girder, whereas boundaries are often determined by geometrical parameters. A general recommendation which model should be used is not possible, because no information on the validity range is available (except for the maximum plate thickness in [2]). Hence, their match is random for the most part.

The amplitudes in compression (referred to the yield stress) and especially the distribution near the edges are the main influencing factors on the load-bearing capacity. For narrow chords the distribution is simplified as a constant. Thus, the values can be calculated from equilibrium if the sum of tensile residual stresses is known. Those must be referred in some way to the material grade, the plate thickness and the weld heat input (or an equivalent parameter) [1]. The attempt to establish a correlation only with the profile shape or the dimensions (such as originally by [3]) seems connected with the fact that this procedure applies to rolled sections, and is therefore probably developed historically. For rolled sections the temperature field is initially homogeneous. The subsequent zonal change in temperatures causes residual stresses. However, these relations cannot be used for welding (locally concentrated heat).

It should be added also that present models are based on (very few) specimens from mild structural steel [5]. For such steel the residual stresses close to the weld are typically assumed to meet the nominal yield stress in tension. For high-strength steel (HSS) less information is available. Clarin [6] noticed that, when considering the steel grades with higher grades, the tensile residual stresses seem to be lower in comparison to the yield stress. Nevertheless, no firm conclusion has been drawn yet. As a temporary recommendation it is suggested to use 500 MPa as an upper limit even if the actual yield stress is higher [7]. Ban [8] suggests tensile residual stresses at 75 % of the nominal yield stress for S460. This also implies that the residual stress effects would be less severe on the structure response for HSS. However, more experimental data are in need to conform the research conclusions. Apart from that no data are reported.

2. Experimental and numerical results

This study is aimed to examine the differences of S355 and S690 experimentally as well as numerically to give further recommendations. In the following, results are shown exemplary for one constellation of thicknesses and welding parameters each in S355J2+N and S690QL. The chords are 150 mm and the web is 220 mm in all cases. The investigated thicknesses are 25 mm in the chords and 15 mm in the web. The edge preparation was carried out using waterjet cutting to reduce initial stresses prior to welding. The welding method is MAG. The filler materials are commercially available G4Si1 for S355 and Mn4Ni1,5CrMo for S690. The electrical power for the weld process was kept constant at 330 A and 33 V. The welding speed is 49 cm/min. The specimens are part of a wider program on all together 8 MAG and 4 SMA welded specimens in cooperation with the BAM Federal Institute of Materials Research and Testing. All welds are one-layer fillet welds deposited subsequently after each other. Process is fully mechanized. Figure 2 shows macrosections of the examined case for S355 and S690. It can be noticed that the dimensions, especially weld penetration and heat affected zone (HAZ) are quite comparable. Throat thickness is 5 mm on average.

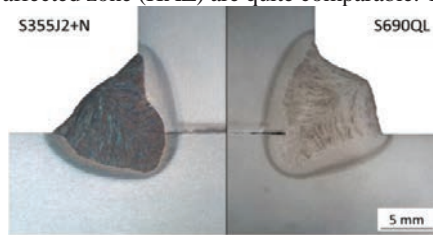


Fig. 2. Exemplary macrosections for S355 (left) and S690 (right) with the previously prescribed parameters.

2.1. Residual stress measurement by sectioning method

The measurement of residual stresses by sectioning method has been used for long time to measure typically longitudinal residual stresses in large structural components. The girders are vertically sectioned by saw cutting [9]. Each sectioning causes the assimilation of residual stresses in the remaining girder section by relaxation processes. The occurring mechanical (elastic) relaxation strains are measured by strain gauges. The (longitudinal) residual stresses are calculated by Eq. 1.

$$\sigma_1 = \frac{E}{1-\nu^2} \cdot (\varepsilon_1 + \nu \cdot \varepsilon_2) \quad (1)$$

Where, σ is the calculated longitudinal stress (in MPa), ε is the measured relaxed elastic strain. The index 1 indicates the longitudinal direction in the direction of the weld seam. The index 2 indicates the transverse direction. E is the Young's modulus (210000 MPa) and ν is the Poisson's ratio (0,3).

To obtain reliable results, it is important to perform a careful preparation of the test piece such as proper location of the test section, strain gauges locations and cutting positions. The strain gauges were applied in longitudinal and transverse direction of each girder at mid length. All together 24 strain gauges (at 12 measuring positions) were used for one quarter of the section assuming a more or less symmetrical distribution of residual stresses. With 3 positions on each inner (i) and outer side (o) of one half of either the chords or the web. A partial (i.e. stepwise) sectioning was realized. An optimized sectioning procedure was developed based on the first fully instrumented specimen. In the next step, X-ray diffraction (XRD) will be used to superpose unreleased stresses and especially to increase the density of measuring points. This part is in progress. In the following, reference is taken only to the stresses by sectioning.

2.2. Results by sectioning method

The results for the chord are given in Figure 3. On average, the absolute values of compressive residual stresses are on the same level. However, the variation of compressive residual stresses through the thickness tends to be

stronger for S690. With reference to the yield stress (i.e. normalized stresses), S690 shows a favorable behavior compared to S355. For the tensile stresses no conclusion can be drawn yet as values are too far from the weld and the density of points is low.

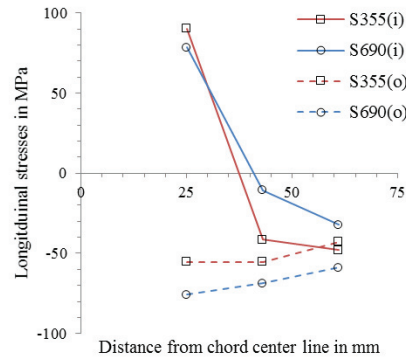


Fig. 3. Residual stresses by sectioning for S355 and S690 for the inner (i) and outer side (o) of the chords.

2.3. Welding simulation model

Experimental results are typically limited in accessibility (e.g. it is not possible to take a look inside the component) and number of points. A simulation aims to increase the density of information and helps to create a complete understanding of the process. It enables the user to access the meaning of certain phenomena or parameters by simply turning them on or off and therefore allows for a more targeted optimization (regardless of whether for academic or industrial applications). However, a calibration of the model is usually necessary. As for the part of the so called structural welding simulation, the macro behavior under local heat input is simulated [1]. This has made a large progress in recent years and has been used in various industrial applications (mainly in mechanical engineering). Basically, the calculation can be realized by any multi-purpose software (Ansys, Abaqus) or using specialized software tools. The specific calculation in this study was carried out using specialized software (Simufact.Welding, V. 5.0.0).

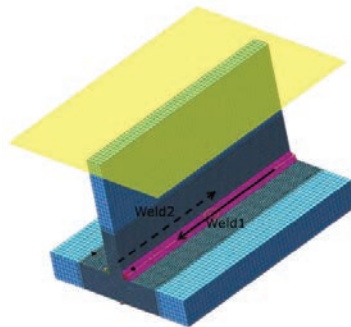


Fig. 4. Numerical model of half girder with symmetry about the web.

The implemented model is shown in Figure 4. In a first approach, half of the section is modelled with symmetry about the web (assuming that due to the web height opposite fillet welds do not affect one another significantly). The length of the model is 200 mm. No gap is modelled (parts are assumed to be one solid piece). The element edge length in the weld seam close area (chosen by 40 mm in here) is 1 mm. Far from the weld, elements are 5 mm. An optimized mesh may be used. However, the mesh is intended for use at variable weld heat input. The element types are assigned automatically by the software. For the thermal analysis 8-node heat transfer bricks are used (MSC.MARC, element 43),

8-node isoparametric bricks are used for the mechanics (element 7). The total number of elements is 565.000. The sequencing was simplified. Pause times between welds were not taken into account, because temperatures are already dropped at the end of each track (due to the plate thicknesses). The time stepping is set adaptive, i.e. variable time steps are applied to all welding and cooling cycles. And the end time is 250 s in all models.

The materials are taken from the software library as S355J2G3 and S690QL. In a first approach, single phase models (SPM) are used, i.e. that phase transformation effects on the mechanical solution are neglected. Effects on the temperature distribution such as latent heat are included though. In terms of global compressive residual stresses this assumption is sufficient as a first approximation. Comparative calculations for S355 in [1] have shown that the implementation of a multi-phase model (MPM) does not influence the result significantly. The stress-strain behavior was scaled based on tensile tests. This is important (and generally recommended) since especially the yield stress has a strong influence on the exteriors of the plastic zone, and consequently also on the compressive residual stresses.

2.4. Numerical results

The calculated longitudinal residual stresses are given in comparison to the measured values in Fig. 5 a) and b). It should be considered that the measured values by sectioning method represent “global” stresses released over a certain volume. In contrast, values at the exteriors of the model are plotted for the numerical model. Therefore, the agreement must be evaluated on average. A good correlation with the compressive residual stresses is noticed. However, the tensile residual stresses are currently questionable. The effect of phase transformations needs to be added (in progress).

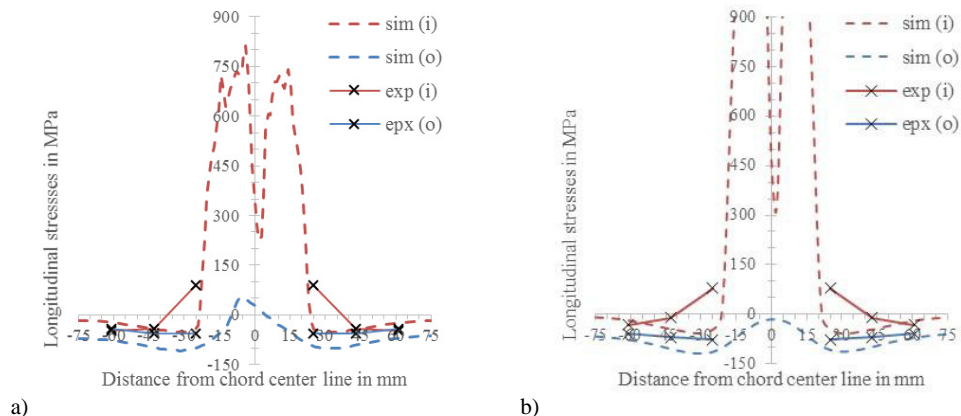


Fig. 5. Longitudinal residual welding stresses on the inner (i) and outer side (o) of the chords for S355 (a) and S690 (b).

The numerically calculated compressive residual stresses seem to be at a similar level (irrespective of the grade). The same was noticed in Fig. 3. Hence, the importance of longitudinal residual welding stresses is significantly reduced for S690. It should be highlighted that the calculation time even though to various simplifications is at a few days, in here between 5 to 6 days. Domain decomposition method (DDM) was used with 4 domains in longitudinal direction. Computer was a standard working station (2x Intel Xeon E5-2670, 64 GB RAM). Thus, a simplified modelling procedure is absolutely required. For further steps, reference is taken to the numerical model.

3. Proposed modeling procedure

3.1. Simplified models

The comparison with recently available simplified models for design led to the result that none of the models gives a sufficient agreement. The model proposed by the ECCS in [3] is outdated since the compressive residual stresses are introduced as a constant ($\sigma_c = 0,25 \cdot f_y$). It may be used in case that other models lead to higher residual

stresses. Due to narrow chords in this example e.g. the model by BSK 99 [2] (which led to relatively good agreement in [1]) results in significantly overestimated compressive residual stresses. A lower boundary for the width should be added. If the compressive stresses are plotted with reference to the plate thicknesses a more or less linear increase can be noticed in the range up to 40 mm. This is to be questioned generally. It is more likely that the tendency is opposite.

The approach by [4] is based on Okerblom's model [10] and a few modifications to simplify the original equations. The application to I-girders is based on plausibility considerations. Generally, the model takes into account all relevant parameters including the weld distortion induced initial strain effects. However, it was found in [11] that the deviations between experiment and predicted values with this model are as high as 80-120 % in some cases. Nevertheless, the Okerblom approach (shrinkage model) might be a good basis for the development of an advanced theory.

3.2. Advanced models

An advanced analytical model is available by the combined analytical-numerical hybrid shrinkage model proposed by [12]. The model has been developed to calculate the weld-induced distortion in large structural components (which is still a major problem in welding technology). However, no record was taken of the residual stresses yet. A coupling with a subsequent structural analysis is promising, but has not been focused either. The basic idea of this (and similar) models is a reduction of the complex thermo-mechanical problem to the mechanical level. The shrinkage force used in this context may be illustrated by a tendon which is prestressed and applied eccentrically to the structure. Such force can be associated with the longitudinal and transverse direction (for the case investigated here the transverse direction can be neglected). The shrinkage force and its load application point are calculated analytically based on an iterative procedure. Subsequently the force is applied to the global FE-model and a linear elastic analysis is carried out. Such force will cause meaningless compressive residual stresses in the weld seam close area. Therefore, the better way is to implement an adequate (inherent) strain distribution. The inherent strain can be taken as the plastic strain [13]. The shrinkage force is essentially the volume integral of these strains.

An exemplary calculation for the girder S355 is shown in Figure 6. The residual stresses close to the weld and in adjacent parts of the structure are given with the correct signs. The magnitudes in compression seem to be valid in comparison to the results in Fig. 5 a), but more time is needed for verification with thermo-elasto-plastic FE-models. The implemented data are the widths of the plastic zone (originating from the center of the fillet), the size of plastic strains and the application points needed to distribute the strains through the thickness. The values were calculated based on a T-joint with one fillet (only longitudinal strain was taken into account). The same values were applied to all welds. This requires a symmetric distribution of residual stresses. If the initial stresses (due to the first weld) are taken into account for the second weld and so on, this would result in a non-symmetric stress state (and a remaining bending distortion). For the previous assumptions, no bending occurs due to symmetry. The calculation time for this example is at a minute or less. Thus, such approach is of particular interest (especially for large structural components).

A direct way is to compute the plastic strains numerically using either 2-D or 3-D thermo-elasto-plastic analysis on finite element models of simple weld geometry or a representative structure part. Those are subsequently mapped to the elastic full structure FE-model. Both procedures are essentially the same, just the way the plastic strains are computed is different.

For practical calculations of e.g. frameworks a reduction of this model to a simple beam model is of interest. In Ansys, BEAM188 can be used for that. This element type allows defining a section by an arbitrary multi-material user-mesh. It is known that for an elastic analysis the elastic strains ε and the temperature change ΔT are coupled via the thermal expansion coefficient α . This means that a known initial strain distribution can be defined alternatively via fictitious thermal expansion coefficients and a unit temperature change. This principle was realized at first in several test runs. A test section with such user mesh and one weld is shown in principle in Figure 7. The residual stresses and the global deformations are given with the right sign. The verification of such model is recently in progress.

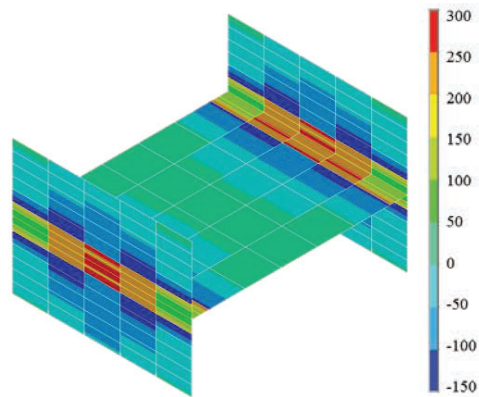


Fig. 6. Calculated longitudinal residual stresses (in MPa) using the hybrid shrinkage model, Ansys, V. 14-5.

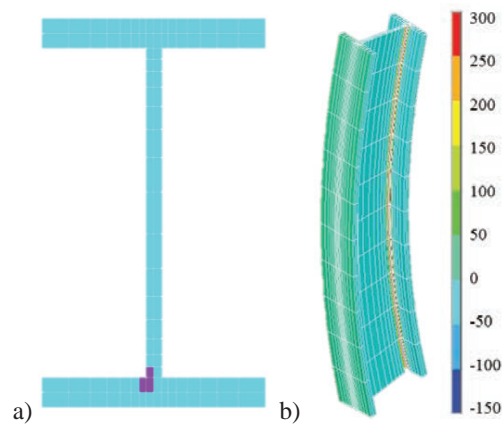


Fig. 7. a) Multi-material user section (BEAM 188); b) Longitudinal residual stresses (in MPa) and bending deformations (automatic scaling), Ansys, V. 14-5.

For a fast approximation of the dimensions of the plastic zone, the maximum temperature isotherms may be used. A thermal analysis is comparatively fast and the thermo-physical properties are widely reported (and are quite constant for all low-alloyed structural steel grades). The corresponding temperatures can be estimated based on bar theory, Eq. 2 and 3. The relevant strain is at ε_y (below no remaining stresses after cooling) and $2 \cdot \varepsilon_y$ (tensile residual stresses at yield stress). Generally, the temperature difference (in K) to cause plastic strain is the greater, the higher the yield stress (in MPa) and the lower the Young's modulus (in MPa) and the thermal expansion coefficient (in 1/K).

$$\Delta T_2 = \frac{2 \cdot \varepsilon_y}{\alpha} = \frac{2 \cdot \sigma_y}{\alpha \cdot E} \quad (2)$$

$$\Delta T_1 = \frac{\sigma_y}{\alpha \cdot E} \quad (3)$$

This leads to the conclusion that the plastic zone must narrow with an increase in strength (the temperatures are more or less identical at otherwise the same conditions). The relevant temperature isotherms for S690 are e.g. almost twice as high as for S355. This explains also why a stronger gradient is noticed for S690. On average, this relates

with reduced tensile residual stresses, and hence reduced compressive residual stresses (both with respect to the yield stress).

4. Conclusion

A basic study on a welded I-girder from two structural steel grades was presented. Experimental (and numerical) results have shown the decreased importance of longitudinal residual welding stresses for S690. Absolute residual stress values were found to be on a similar level as for S355. This underlines the necessity to adjust on the recent buckling classification as given in Eurocode 3. It was also shown that numerical calculations are able to reproduce the residual stresses. However, the effort is still not in a practically applicable range. For that, simplified models are still in need. For a reliable statement on the residual stresses, it is necessary to define the validity range which is missing for present Eurocode models. For an advanced assessment of residual stresses some more recent (plasticity based) theories were discussed. For an implementation in the civil engineering sector further investigations are however necessary. Nevertheless, those models seem suitable for a subsequent calculation of load-carrying capacity. Thus, the study provides a first valuable step on future studies in the structural level as well as for the development of a simplified model.

Acknowledgements

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