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Combining Sectioning Method and X-Ray Diffraction for Evaluation of Residual Stresses in Welded High Strength Steel Components

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Abstract. Residual stresses and distortions in welded I-girders for steel construction are relevant when evaluating the stability of steel beams and column members. The application of high strength steels allows smaller wall thicknesses compared to conventional steels. Therefore, the risk of buckling has to be considered carefully. Due to the lack of knowledge concerning the residual stresses present after welding in high strength steel components conservative assumptions of their level and distribution is typically applied. In this study I-girders made of steels showing strengths of 355 MPa and 690 MPa were welded with varying heat input. Due to the dimension of the I-girders and the complex geometry the accessibility for residual stress measurement using X-ray diffraction was limited. Therefore, saw cutting accompanied by strain gauge measurement has been used to produce smaller sections appropriate to apply X-ray diffraction. The stress relaxation measured by strain gauges has been added to residual stresses determined by X-ray diffraction to obtain the original stress level and distribution before sectioning. The combination of both techniques can produce robust residual stress values. From practical point of view afford for strain gauge application can be limited to a number of measuring positions solely to record the global amount of stress relaxation. X-ray diffraction can be applied after sectioning to determine the residual stresses with sufficient spatial resolution.

Introduction

This work is part of an ongoing research project on recommendations for the implementation of welding imperfections in the numerical analysis of welded thick-walled I-girders. One focus is put on welding residual stresses and their impact on the stability of specific components. Simulation approaches for capacity design are often quite conservative due to lack of knowledge concerning important input parameters [1]. For example, welding residual stresses are often assumed to be tensile up to the yield strength in the heat affected zone (HAZ). This is not the case especially when welding high strength steels which show a stress reducing effect due to solid state phase transformations [2-3]. The resulting extent of equilibrium compressive residual stresses is important for the ultimate load. But experimental proofs of spatially resolved residual stresses for welded thick-walled I-girders are difficult to obtain due the limited accessibility of such structures. Especially the HAZ adjacent to the weld restricts local measurements as it is covered by the parallel chords even in large scale I-girders. The sectioning method is an established technique to determine residual stresses in larger structures. Strain gauges are applied on the surface of the specimen. Sectioning by saw cutting leads to stress/strain relaxations which are recorded by strain gauges locally. Applying a large

number of strain gauges the stress relaxation can be calculated accurately. The spatial resolution is in principle limited by the geometry of the strain gauge. In the present work the sectioning method was combined with residual stress determination by X-ray diffraction (XRD). For this purpose the I-girders were cut just to the size until the areas of interest were accessible by XRD. The final residual stresses were determined by simply summing up the stresses found by sectioning and subsequent XRD.

Experimental

Welding. Full-scale specimens welded at a steelwork company were used. The high strength steels S355J2+N and S690QL (minimum yield strength: 355 MPa, respectively 690 MPa) were welded by gas metal arc welding (GMAW). The plate thicknesses were 20 mm for the chords and 10 mm for the web plate. Fillet welding was performed using strength matching filler materials in a single layer. Important parameters are shown in Table 1. Two heat inputs were applied varied mainly by the welding speed.

Table 1: Welding parameters

Sample	Material	Current [A]	Voltage [V]	Welding speed [cm/min]	Heat input [kJ/cm]
355L	S355J2+N	328	33	64	10.1 (low)
355H		329	33	40	16.3 (high)
690L	S690QL	343	33	64	10.6 (low)
690H		338	33	40	16.7 (high)

Sectioning. Sectioning was performed using a conventional band saw. The sections are indicated in Fig. 1. The cutting strategy was chosen from preliminary tests taking into account the strain gauge response and also literature recommendations [4]. The strains were recorded longitudinally and transversely to the welding direction. From these strains the stresses in longitudinal direction were calculated.

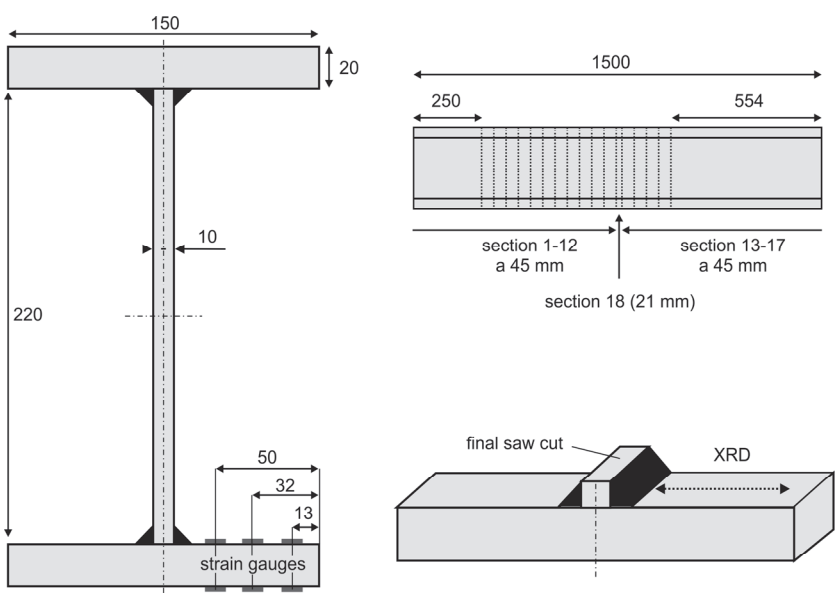

Figure 1: Schematic of sectioning, position of the strain gauges and measuring position for XRD

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The first section had a length of 250 mm. From cut number two on the sections had lengths of 45 mm. Cut number twelve was located directly adjacent to the strain gauges. The second half of the beam was then cut beginning from the other side. Section number 13 had a length of 554 mm. Sections 14 to 17 showed again lengths of 45 mm. The resulting section number 18 which carried the strain gauges then resulted in a length of 21 mm. From this last section the chords were cut from the fillet and used for final residual stress measurement by XRD as shown in Fig 1.

X-ray diffraction. The residual stresses in longitudinal direction were determined using the $\sin^2\psi$-method. Measuring and evaluation parameters are given in Table 2. The measurements were performed along a line starting adjacent to the weld covering the HAZ and the base material. Up to 19 points were chosen along a distance of 50 mm (see Fig 1). The measurement was made at the welded side and also at back side of the chords at similar positions.

Table 2: Measuring and evaluation parameters for residual stress analysis by XRD

Focus	2 mm
Radiation	CrKα
Diffraction line	Ferrite: 211
E{211} and ν{211}	220.000 MPa and 0.28

Results and Discussion

Longitudinal residual stresses determined from the strain gauge response at the upper (weld) and lower side of the chords are shown in Fig. 2 and Fig. 3. The closer the strain gauge was located relative to the weld the higher the stresses were. Up to 100 MPa were found adjacent to the weld independent from the material or the heat input. Away from the weld the stresses turned into compression. The mid and the outer position showed about -50 MPa. The back side of the chords was characterized by quite constant compressive residual stresses between approximately -50 MPa to -100 MPa. With higher heat input (Fig. 2, right and Fig. 3, right) the stresses tended to show slightly higher absolute values. In the following the stresses obtained at three fixed positons by strain gauges were added to the spatially resolved stresses obtained from XRD. Ranges were defined for each strain gauge - indicated in Fig. 2 and Fig. 3 by the dashed lines - in which the stresses from the strain gauges were assumed to be constant.

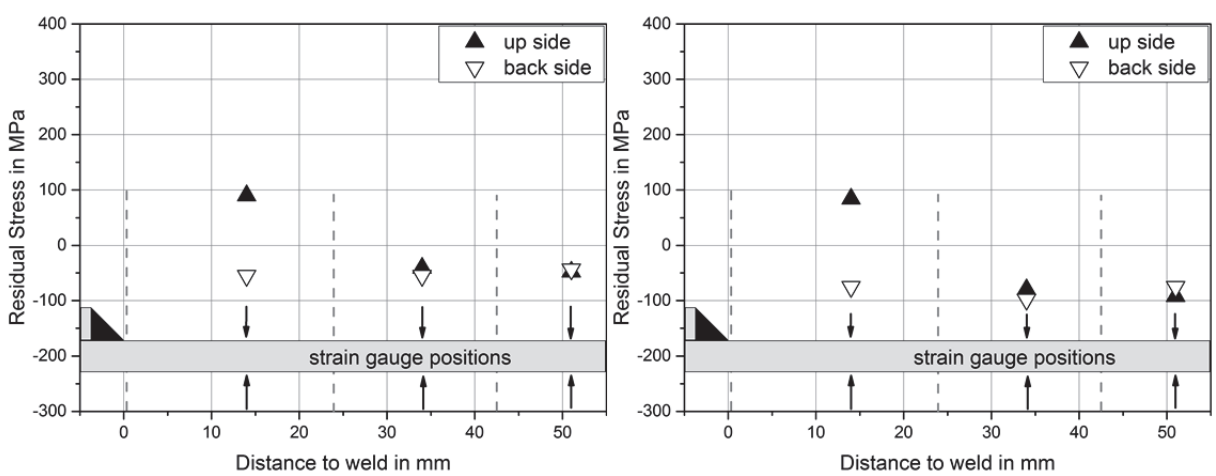

Figure 2: Longitudinal residual stresses determined by strain gauges during sectioning of samples 355L (left) and 355H (right)

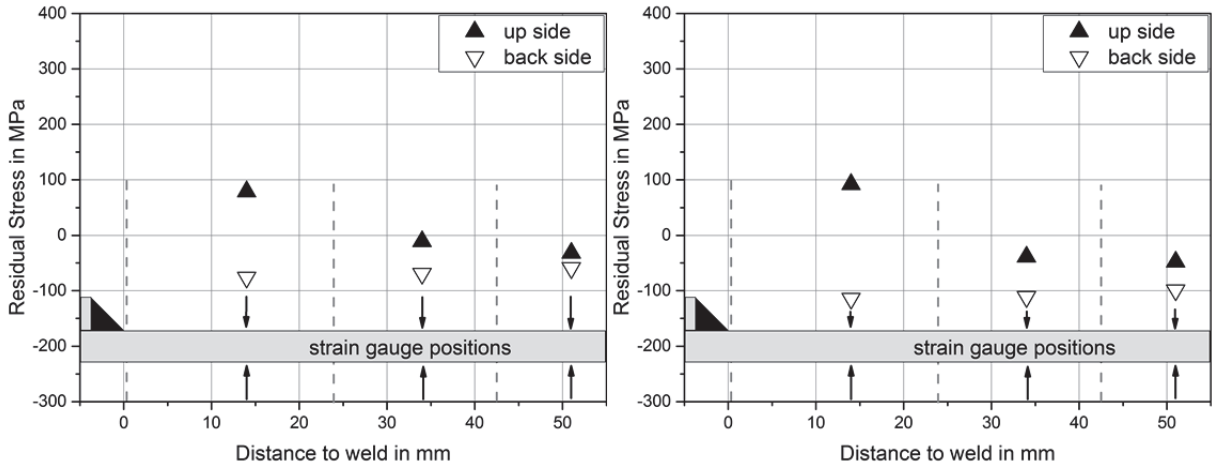

Figure 3: Longitudinal residual stresses determined by strain gauges during sectioning of samples 690L (left) and 690H (right)

Residual stresses determined from XRD after sectioning are shown for S355 in Fig. 4. The highest stresses were found close to the weld at the upper side of the chord. For the low heat input up to 300 MPa were registered. At high heat input up to 200 MPa remained after sectioning adjacent to the weld. Within the first 10 mm a gradient was present in the HAZ. Here the stresses turned into compression. Approximately -100 MPa were left in the base material. The back side of the chords showed stresses near 0 MPa in the range near the weld. The rest was characterized by stresses between 0 MPa and -100 MPa, which may stem from initial fabrication stresses present in the plates before welding. Note, that the plates were not subjected to stress relieve heat treatment prior to welding. No cutting influence is expected due to waterjet-cutting of the plates. The XRD results are always affected by the surface preparation which was critical at some points. This applied also in quality to the high strength steel S690 shown Fig. 5. The chord back side showed the same stress distribution also in quantity. Differences to S355 appeared at the upper side of the chord. Adjacent to the weld metal the tensile stress showed a dip. The stress was decreased here between 50 MPa and 150 MPa dependent on the heat input. Low heat input formed lower stresses at all. In the base material the stresses were around 0 MPa.

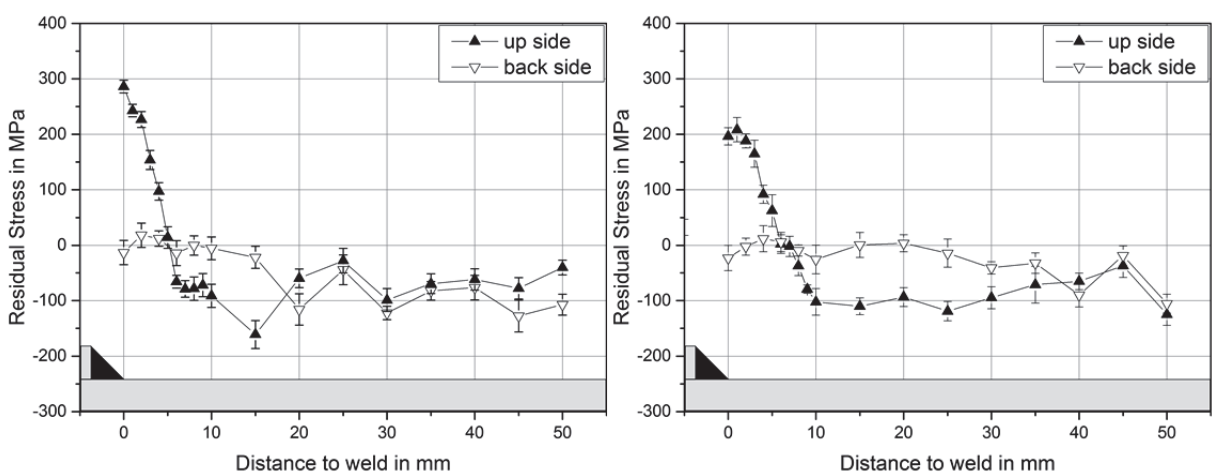

Figure 4: Longitudinal residual stresses determined by XRD after sectioning of samples 355L (left) and 355H (right)

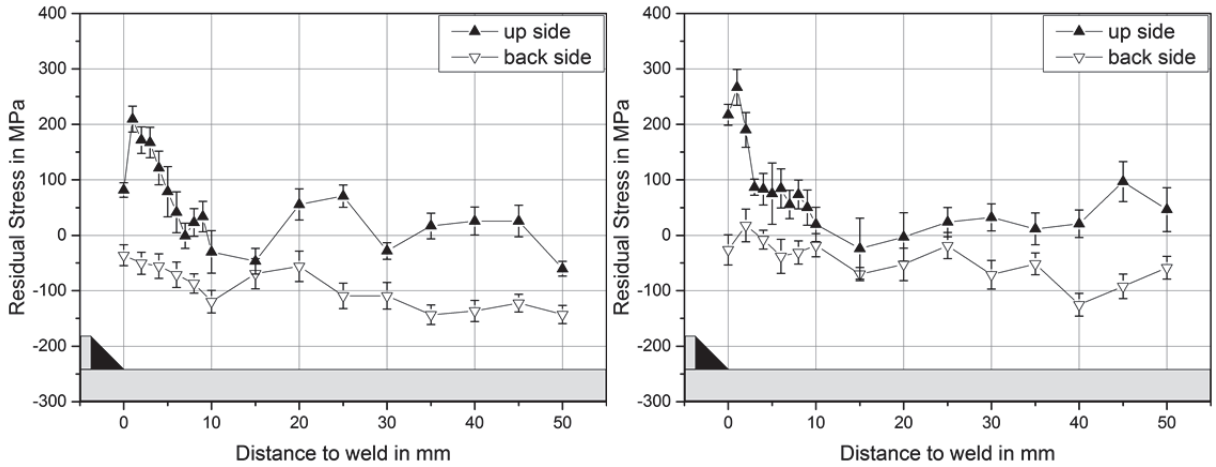

Figure 5: Longitudinal residual stresses determined by XRD after sectioning of samples 690L (left) and 690H (right)

After superposition of the stresses from sectioning and XRD the differences between HAZ and base material became higher. The highest tensile stresses up the yield strength were obtained for S355 welded with low heat input adjacent to the weld (see Fig. 6). The stresses remained tensile within a distance of 10 mm to the weld. With higher distance to the HAZ the stresses changed into compression up to -200 MPa. The stresses at the back side are in principle in compression showing the same absolute values as on the upper side. Also the back side of S690 was completely in compression up to -200 MPa (see Fig. 7). The upper side showed around 0 MPa far from the weld and HAZ. In the HAZ the highest tensile stresses were found around 2 mm away from the weld metal. In the transition to the weld the stresses were decreased from 300 MPa to about 150 MPa at low heat input. For the high heat input this decrease was less, from 360 MPa to 310 MPa. Related to the yield strength of the materials the higher stresses, up to the yield point, were present in the mild steel S355. The high strength steel S690 was stressed just to 52 % of the yield strength. As the geometry (restraint) of the samples was similar in each case the main reason was assumed to be the phase transformation behavior. Stress release by martensite formation is known to be effective in high strength steels [2-3].

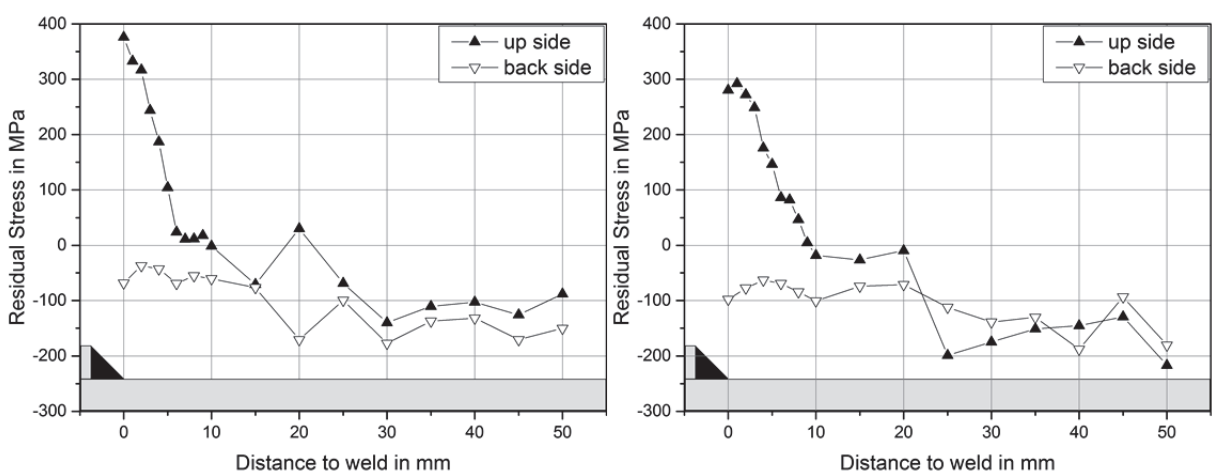

Figure 6: Longitudinal residual stresses determined from strain gauges and XRD of samples 355L (left) and 355H (right)

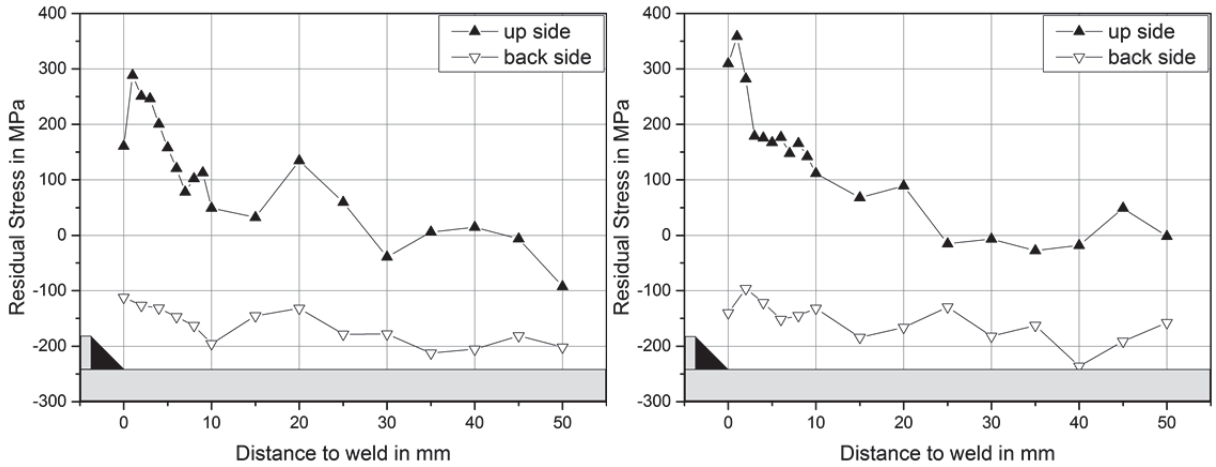

Figure 7: Longitudinal residual stresses determined from strain gauges and XRD of samples 690L (left) and 690H (right)

Summary

Residual stresses were determined on welded I-girders made of S355 mild and S690 high strength steel. A combination of the sectioning method and XRD was applied. The residual stresses released during sectioning showed a similar level independent from the material and the heat input applied. XRD has shown that the local residual stresses present in the HAZ are less affected by the heat input but were characteristic for the type of steel welded due to the impact of the solid state phase transformation. Residual stresses in the mild steel S355 reached the yield point, while the stresses in the high strength steel S690 just showed about half of that. Extensive use of strain gauges is just necessary to record the global stress relaxation by sectioning in order to have sufficient access by XRD. The latter can be applied then to ensure residual stress determination with high spatial resolution.

Acknowledgements

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