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Investigations on the material behaviour of weld seams for the use in finite element analyses

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Abstract

The design of complex structural steel connections by finite element analysis is common practice nowadays. However, for welded joints there are no normative regulations for the static finite-element-analysis. To analyse the specific material behaviour in the weld area and derive a geometry and material model for the finite element analysis, tensile tests on specimens with different weld geometries are made at the Technical University of Darmstadt. During the tests an optical measuring method, called Digital Image Correlation, is used. It records the deformations on the surface of the specimen and assigns the recorded analogue test load to the images. By this way, the load-deformation-behaviour in all areas of the weld can be determined. In addition to the tensile tests, microsection examinations are carried out. The applied colour etching makes the microstructure of the weld zones visible so they can be geometrically superimposed with the strain images of the tensile tests. In welded connections the stress state is very complex. Therefore, numerical investigation must be performed to derive the final stress-strain-curves of the weld area. These curves can then be implemented as a material model for the finite element analysis of welded connections.

Keywords

Structural steel connections, DHY-weld, fillet weld, weld zones, material behaviour, finite element analysis, tensile test, microsection examination

1 Introduction

For the design of structural steel connections apart from the classic manual calculation according to EN 1993-1-8 [1], finite element analysis is increasingly being used for the various connection verifications. The focus of the structural dimensioning shifts to an individual process of geometry modelling, definition of the material parameters and evaluation of the numerical results. In addition, there are no normative documents providing rules for the finite element modelling or analysis of welded connections.

For this purpose, in practice, welded joints are usually designed in a very simplified way in the finite element analysis. Very often fully welded seams are set at all plate joints. This simplification is justified, as the strength of welds in normal-strength steels is higher than that of the base material. At the same time, the load-bearing capacity of the weld is greatly underestimated, which leads to uneconomical weld thicknesses. In another method, the elastic stress distribution along the edges of the plates is taken from finite element analysis and inserted into the manual weld verifications according to EN 1993-1-8. Here, the challenge is to correctly determine the stress distribution with its local and model-dependent stress peaks and to convert them into a decisive load without knowing the actual material behaviour of the weld (Fig 1).

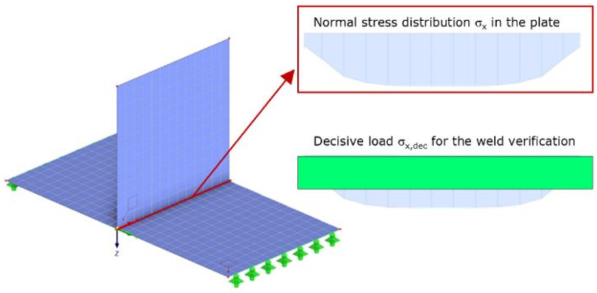

Figure 1 Finite-element-modelling of a connection without the weld

By modelling the weld geometry with its elastic-plastic material model, local stress peaks in the weld could be relocated within the finite element analysis. Thereby an increased load-bearing capacity of the weld is calculated, and smaller weld thicknesses can be set.

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To determine the material model of welded connections, experimental investigations on the material behaviour of welds with different geometries are carried out in the research laboratory of the Institute for Steel Construction and Materials Mechanics at the Technical University of Darmstadt. The results can then be used for further numerical studies to derive the final stress-strain-curves of the weld area, which then can be implemented as a material model for the finite element analysis.

2 State of standardisation and research

2.1 State of standardisation

EN 1993-1-8 [1]

In the European design standard for connections, the EN 1993-1-8, there are two verification procedures for the design of welds. In Fig. 2 the directional verification method is shown, which, in contrast to the simplified procedure, considers the individual stress components.

$$\sqrt{\sigma_\perp^2 + 3 \cdot (\tau_\perp^2 + \tau_\parallel^2)} \leq \frac{f_u}{\beta_w \cdot \gamma_{M2}}$$

$$\sigma_\perp \leq \frac{0.9 \cdot f_u}{\gamma_{M2}}$$

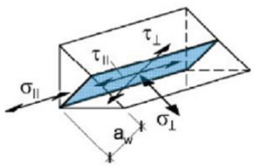


Figure 2 Directional verfication method for welds ([1], [2])

The acting stresses in the weld are determined by means of a design force and a design section, which differs depending on the geometry of the weld (Fig. 3).

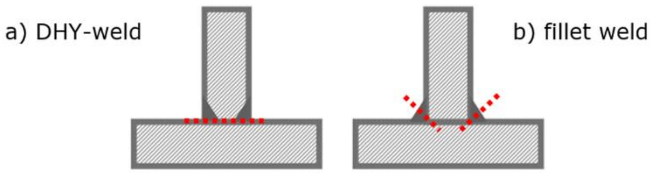


Figure 3 Design sections for DHY-welds and fillet welds [2]

The resistance side of the verification is based on component tests, which makes the design method of the EN 1993-1-8 a nominal stress concept. It does not provide any information concerning the local material behaviour in the welded connection and therefore is not suitable for the finite element analysis of welds.

prEN 1993-1-14 [3]

In the draft standard prEN 1993-1-14, the finite element modelling of plates and bolts is explained in detail. The material model of structural steel is therefore adopted from EN 1993-1-5 [4]. Welds are only dealt with in the chapters "Imperfections" and "Fatigue check". It is not regulated which geometry or material properties shall be assigned to the weld in the model and how the static verification can be done.

FKM-Guideline [5]

For the static weld verification by means of finite element analysis, the FKM guideline [3] provides some useful design approaches. However, it has not been introduced by the building authorities and therefore can only be applied in Germany in the form of approvals.

2.2 State of software development

Software – IDEA StatiCa

Most of the design software use the stresses in the connected plates (see Fig. 1) and verify the load-bearing capacity of the welds manually according to EN 1993-1-8. An exception is IDEA StatiCa from SCIA Software GmbH [6]. This software works with the Component Based Finite Element Method (CBFEM) [7]. The welds are represented in the model as shell-equivalent elements. These elements consider the thickness, position and orientation of the weld. The mesh nodes of the adjacent plates are connected by a multi-point constraint (Fig. 4).

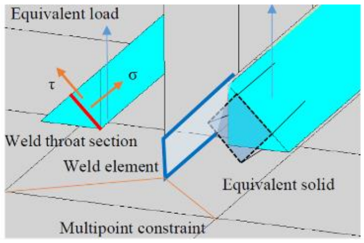


Figure 4 Weld model with multi-point constraint [7]

The weld stresses $\sigma_\perp$, $\tau_\perp$ and $\tau_\parallel$ are calculated from the stresses in the adjacent plates. The assigned material law of the weld element is elastic-plastic, analogous to the steel sheet, whereby the plastic strain limit is set to 5% [7]. This approach must be critically questioned as the welding process causes embrittlement of the weld area. Furthermore, the element properties of the weld are not explained in the technical background documents, which makes the software a kind of a "black box" for modelling.

2.3 State of research

Current research offers a wide range of experimental and numerical investigations on the material behaviour of welds. For example, in the work of Hölbling [8], the influence of the welding process on the load-bearing capacity of welds for normal strength steels is investigated by means of finite element analysis. Investigations concerning the material behaviour of fillet welds on high-strength steels are documented in detail by Rasche [9] und Stoetmann [10]. Hildebrand [11] instead studied the influences of temperature and residual stresses on the weld material properties by simulating the welding process with the finite element method.

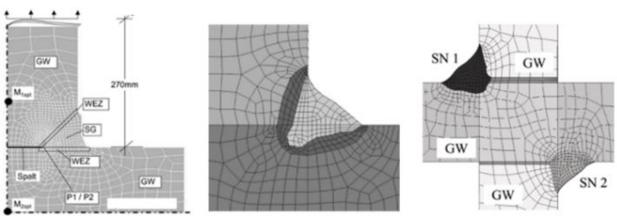


Figure 5 Finite-element-models by Hölbling [8], Rasche [9] and Hildebrand [11]

All these examinations use the finite element analysis primarily for basic research on very detailed weld areas (see Fig. 5). There are no investigations on a simple finite element model of welds for the use in a practical structural design.

3 Experimental Investigations

3.1 Experimental program

The experimental investigations in this paper are about the material behaviour of DHY-welds and fillet welds on normal strength structural steel (S355) under a tensile force. For this, tensile tests and microsection examinations are carried out in four test series (Fig. 6).

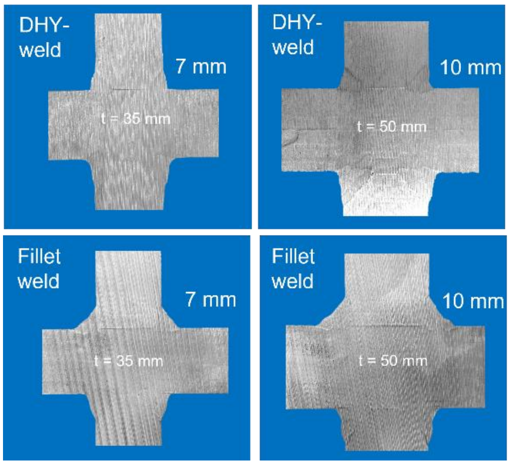


Figure 6 Four test series with different weld shapes and thicknesses

3.2 Preparation of the specimens

The shape of the specimens is a welded cross joint. To achieve approximately the same weld seam properties in all specimens of a test series, a large piece with a length of 90 cm was welded and later sawed in single specimens slices of each 25 mm (Fig. 7).

Figure 7 Production of the cross joint specimens

The optical deformation measurement used in the tensile tests requires a special speckle pattern on the specimen. For this purpose, first a white primer and then a black air-brush painting was applied on the surface (Fig. 8).

Figure 8 Prepared test specimens with a stochastic pattern

3.3 Tensile tests with Digital Correlation Image

At the beginning of the test, the cross-joint specimens were installed in the testing machine via the clamping jaws at the top and bottom. The tensile load during the test was applied shift-controlled at a test speed of 1 mm/min until the specimen breaks. The machine load was recorded via a stress-induced load cell. As the weld area is very small, an optical measuring method was used for the deformation measurement during the test. For this, two cameras were set up on a tripod in front of the test machine and the specimen was illuminated with a spotlight (Fig. 9). The cameras each took a picture series of the deformed state during the tensile test and passed on their image information to a special software called VIC-Snap.

Figure 9 Tensile tests on cross joint specimens - experimental setup

Parallel to the image data, the synchronised machine load data from the load cell was transmitted to VIC-Snap as analogue data. Each stored image file is thus assigned to a specific force, whereby the load-deformation-behaviour in any area of the weld at any time can be analysed. The evaluation of the image files recorded with VIC-Snap was carried out with the software VIC3d. This software uses the Digital image correlation (DIC) based on a grey value recognition. The first step in VIC3d is to define an Area Of Interest (AOI) on one image (Fig. 10, left) including the weld seam and the transition area to the steel plate.

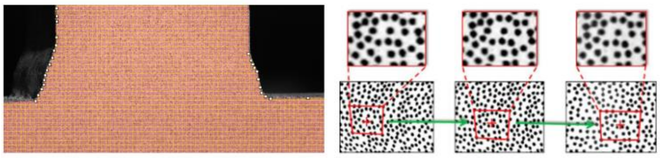


Figure 10 Area of Interest (AOI) / tracking of the subsets [12]

The AOI consists of many small subsets. Each subset contains a specific speckle pattern in the reference image, which can be tracked on all images of the deformed state (Fig 10, right). An algorithm recognises the greyscale distribution of the speckle pattern in each subset and assigns the corresponding coordinates to the image pixels. Using a correlation function, the subsets in the image of the deformed specimen are shifted until they match the subsets in the reference image as closely as possible. On the basis of the pixel coordinates of the deformed and undeformed state the relative displacement components u (horizontal) and v (vertical) can be calculated [13].

The deformations can be converted into technical strains. Figure 11 shows an example of the results of the DIC-measurement on the DHY-welds and the fillet welds.

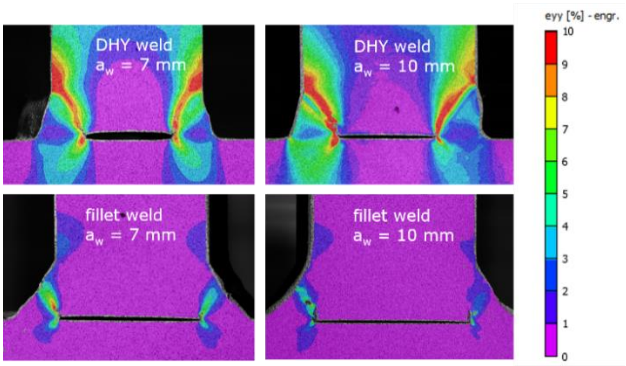


Figure 11 DIC images (strain e_{yy}) under maximum load of DHY-welds and fillet welds

The differences in the load transfer between a DHY-weld (top) and a fillet weld (bottom) can clearly be seen in these pictures. In contrast to the shape, the weld thickness has no significant influence on the strain distribution in the weld area. Thus, the results of the 10mm-welds are neglected in the following chapters. In addition to the DIC images, the fracture surfaces of the specimens with DHY-welds (Fig. 12a) and fillet welds (Fig. 12b) are considered in the evaluation of the material behaviour of the welds.

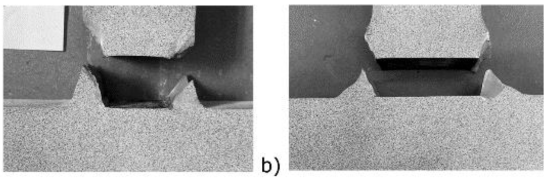
a) b)


Figure 12 Fracture surface of a DHY-weld and a fillet weld

3.4 Examination of the microstructure

The aim of the microsection examinations is to analyse the microstructures of the welded connection with its different weld zones (weld metal, heat-affected zones, base material). As each structural zone has a typical structural appearance, the exact geometry of the weld zones and their material properties can be determined. The investigations were realised at the Department of Physical Metallurgy at the Technical University of Darmstadt.

For the microsection examination a small piece of one specimens of each test series was sawed out and polished. Afterwards it was treated with a special colour etching (see Fig. 13). Under a microscope with objectives between 0.5 to 50x magnification the microstructure of the material gets visible (Fig. 14).

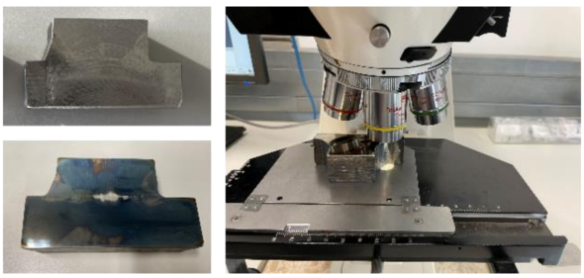


Figure 13 Microsection specimens under the microscope

With the help of a recording software either overviews (panorama function) or individual images (snap function) can be created. For the analysis of the different structural zones of the weld area, an overview is created for each weld geometry with a magnifying glass of 10. By means of a high zoom factor the boundaries of the different weld zones can be recognized and marked (Fig. 14).

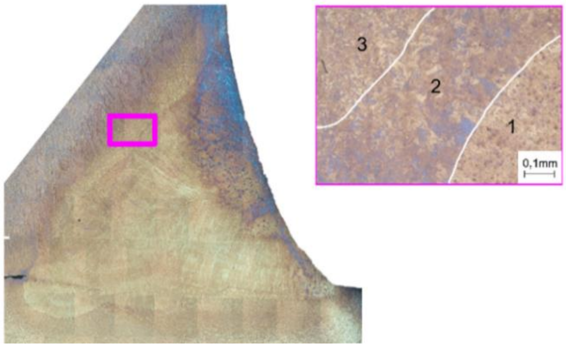


Figure 14 overview of the microstructure and marked weld zones

The overview microsections of the DHY-weld (Fig. 15a) and fillet weld (Fig. 15b) (each 7 mm) with the boundaries of the structural zones are shown below. For the fillet weld (Fig. 15b), only zone 1 – the weld metal - is marked since the other zones are not relevant for the further analysis.

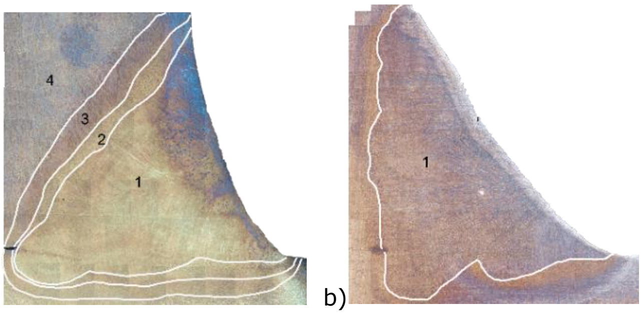
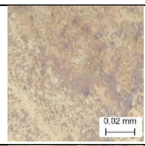
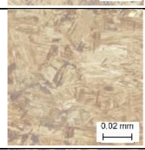
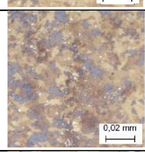
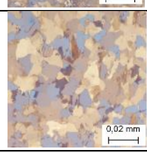
a) b)


Figure 15 Weld zone in a DHY-weld and in a fillet weld

The four main weld zones with their microsections and their structural description are listed in table 1. The first zone (weld metal) consists of the pure weld metal and the zone of partial melting.

Table 1 Microstructure of the four zones of the weld area

Designation	Microsection	Description
1 Weld metal (HL 46T-MC)		Fine grain Stem crystals oriented to the centre of the melt
2 Coarse grain zone		Strong grain growth Needle-like structure Widmanstätten's structure
3 Fine grain zone		Grain refinement Grainy structure of perlit and ferrit
4 Base material (S355)		Big grains of perlit and ferrit

4 Analysis of the material behaviour

4.1 Strain ranges and failure behaviour

To analyse the material behaviour of the welded connections, first the failure process must be considered. Therefore, the DIC images from the tensile tests under the maximum load are superimposed with the microsection images. By this, the strain distribution in y-direction can be assigned to the four weld zones.

<u>DHY-weld (7 mm)</u>

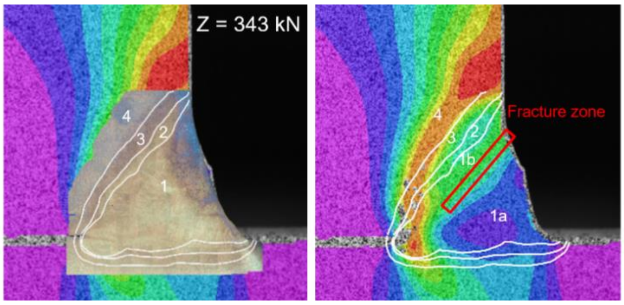


Figure 16 DHY-weld - microsection results over the DIC image – Strain distribution e_{yy} under maximum load (343 kN)

In the DHY weld (Fig. 16), the low-strain areas of the weld metal (1a) and the coarse grain (2) are clearly visible. In the weld metal, the strains are low due to the higher strength of the material. In the coarse grain zone, the rapid cooling results in a very brittle zone. The plastic zone runs along the boundary between the base material and the fine grain zone (3/4). At this point, the structure has the ductile properties of the S355. At the same time, the stresses due to the notch effect at the weld are significantly higher than in the undisturbed sheet area. When looking at the fracture surfaces, deformations due to a necking effect can already be seen in this area (Fig 17).

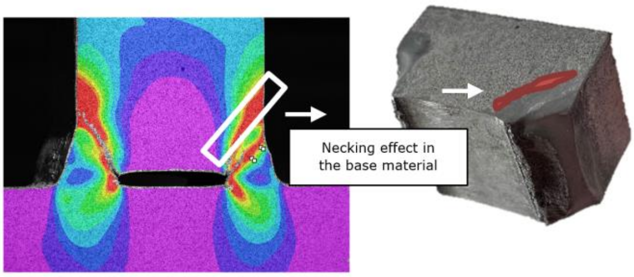


Figure 17 Plastic zone in the base material with necking effect – Strain distribution e_{yy} just before fracture (323 kN)

However, before the material fails in the base material, the lower fracture strain of the weld metal (1b) is reached.

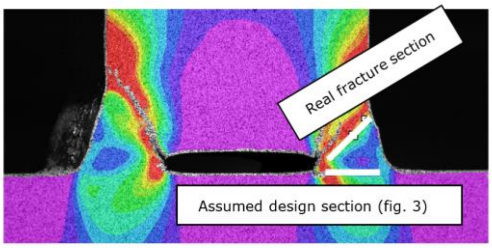


Figure 18 Assumed design section and real fracture section

The fracture line does not run along the bottom edge of the weld, as assumed, but along the border between the weld metal and the coarse grain zone (Fig. 18).

<u>Fillet weld (7 mm)</u>

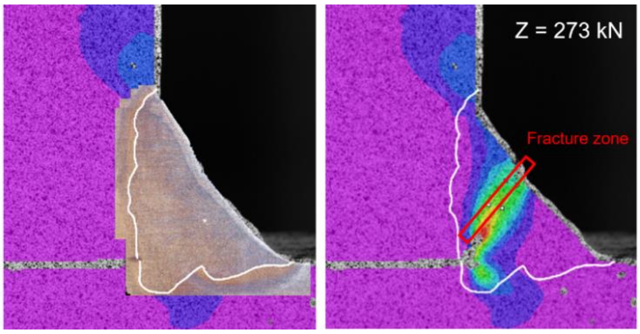


Figure 19 Fillet weld - microsection results over the DIC image – Strain distribution e_{yy} under maximum load (273 kN)

A simpler failure mode takes place in the fillet weld (see Fig. 19). The strains in the steel sheets remain constant at a relatively low level due to the same cross-section throughout. The weld fails in the weld metal zone (1) when the maximum strain is reached. The other weld zones have no influence on the failure. As expected, the fracture line runs 90° to the weld surface.

In figure 20 the load-strain-curves (y-direction) in the fracture zone of the DHY-weld and fillet weld (each 7 mm) are compared. The course is very similar in both test series. The shift of ≈ 80 kN results from the changed stress state in a fillet weld compared to the DHY-weld. Both test series show a very similar strain at break of $e_{yy} \approx 10\%$.

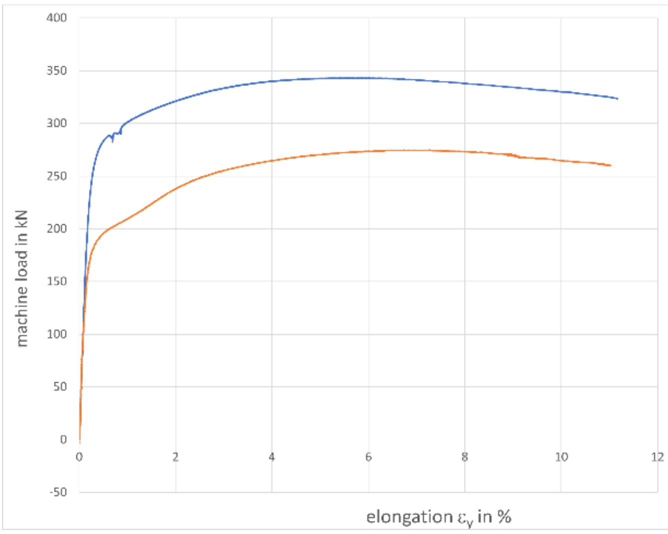


Figure 20 Load-strain-curves in y-direction of a DHY-weld (blue) and a fillet weld (orange) in the fracture zone

It should be noted that in this failure analysis only the strains in y-direction, i.e. in the load direction, are considered. Due to the complex stress state in the weld, additional deformation occur in the x- and also z-direction. An evaluation of the total strain state with a derivation of the plastic strain limit for the weld is currently still being investigated.

4.2 Derivation of the material curves

Due to the complex stress state in the weld area, which is influenced by both, the weld geometry, and the residual stresses from the welding process, it is not possible to determine simple stress-strain-curves, as for example in uniaxial tensile tests. Instead, the specific material behaviour of the weld must be determined iteratively via finite element analyses. For an initial finite element analysis, the weld is modelled with the material properties of the base material (see Fig. 21).

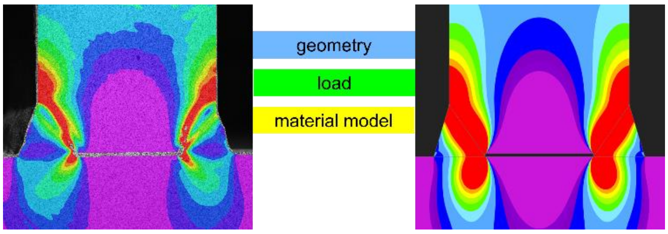


Figure 21 Transfer of the experimental results to a finite element model

In figure 21 there is a good agreement between the strain images from the DIC measurement and the finite element model. The investigations on the real welds in the tensile tests show a lower strain range than the welds in the finite element model with the assigned base material. This fact confirms the assumption of a more brittle weld area compared to the ductile base material. On the other hand, it shows, that the model approach is suitable for further material analyses.

5 Summary and outlook

For the economic calculation of welded connections by finite element analysis, there currently still is a lack of a weld-specific material model in practice.

For the analysis of the material behaviour of welds, various experimental investigations were carried out on welded cross-joint specimens. By tensile tests on four test series using an optical measuring method (DIC) the strain distribution in the weld area could be determined.

In addition, microsection images of the respective weld geometries were generated and analysed. It turned out, that there is a good agreement between the microstructural zone boundaries and the strain ranges from the DIC measurement. By this, the failure procedure could clearly be analysed.

As there is a very complex stress state in the weld area – due to the weld geometry and residual stresses of the welding process - it is not possible to derive simple stress-strain-curves or a plastic strain limit.

A finite element model of the cross-joint section with the experimental load is needed to determine the decisive parameters concerning the geometry and the material model. By variation of the parameters, it should be possible to map the strain pattern from the experiments. Instead of the base material, for example, the material parameters for the weld metal zone could be inserted in the material model.

Besides the geometry of the weld and its specific material behaviour, the residual stresses from the welding process have an important influence on the stress state and the load-bearing capacity of the weld area. For this purpose, further investigations are currently being carried out, which can then be included in the analysis.

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