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出版情報：Proceedings of the ASME 2022 41st International Conference on Ocean, Offshore and Arctic Engineering: OMAE2022. 3, 2022-10-13. The American Society of Mechanical Engineers : ASME
バージョン：

Proceedings of the ASME 2022 41st International Conference on Ocean, Offshore and Arctic Engineering
OMAE2022
June 5-10, 2022, Hamburg, Germany

OMAE2022-87473

BENCHMARK STUDY OF WELDING DEFORMATIONS IN STIFFENED PLATE

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ABSTRACT

The fabrication of ship hulls involves welding operations, one typical operation is fillet welding of stiffeners to plates (panels) a so-called T-joint. The residual stresses from the welding process will influence the fatigue life of the structure, and residual deformations will increase the risk for buckling of the panel and give poor fabrication tolerances which may complicate the assembly of a built-up structure.

Though this weld geometry has been frequently studied in the literature both experimentally and numerically, the focus has been on the residual stress field and if residual deformations are studied, the angular distortion and the typical V-shape seen in the welded plate (panel) are reported. This benchmark focusses on the residual shape after two-pass fillet welding of a stiffener to a plate (T-joint and the influence of the constraints used during welding. The information of the full welding residual deformations may be useful for the fabrication of larger complex welded structures.

The benchmark study clearly shows that careful consideration is needed when defining a reference plane for comparison of resulting deformations from FE-simulations and from experiments as well as good documentation of the actual boundary conditions and steps carried after the completion of the welding and before measuring residual deformations. The FE-simulations have shown that it is difficult to obtain the full antisymmetric, twisted shape of the plate as measured in the experiments, although a trend similar to the experiments can be seen as the plate tends to move upwards at the end of each weld pass, i.e *a slight influence of the weld pass direction,*

Keywords: Welding; Benchmark; Residual deformation; Residual stress; Finite element analysis

1. INTRODUCTION

The fabrication of ship hulls involves welding operations, one typical operation is fillet welding of stiffeners to plates (panels) a so-called T-joint. When constructing the panels, the GMAW (Gas Metal Arc Welding) process is often used. Molten material is then deposited at a joint thus heating up and melting the edges of the plates to be joined. This local heating followed by a rapid cooling of the supplied metal and the plate edges will lead to local yielding and development of plastic strains which, in turn, will lead to residual deformations and residual stresses in the welded panel. The residual stresses will influence the fatigue life of the structure, and residual deformations will:

- Increase the risk for buckling of the panel, as the deformations (or distortions) reduce the buckling load for panels subject to compressive loads.
- Give poor fabrication tolerances which may complicate the assembly of a built-up structure.
- Give aesthetic problems and low perceived quality.

Fillet welding of a stiffener to a plate (panel) has been frequently studied experimentally and numerically, using non-linear FE-analyses, in the literature. The ISSC 2015 V.3 Committee carried out a benchmark [1] where both residual welding distortions and residual stresses were determined experimentally and numerically (using FEA) for a common “T” welded assembly used in the shipbuilding industry. The same weld geometry has also been studied in a similar way, with a focus on the influence of the boundary conditions [2,3], of the material model [4], of the weld sequence [5] and of the plate geometry [6]. In [7] this weld geometry was studied using the inherent strain method with a focus on weld deformations. However, for residual deformations, these references focus on the angular distortion, and the typical V-shape seen in the welded plate (panel).

It was therefore decided to carry out a benchmark exercise with a two-pass fillet welding of a stiffener to a plate (T-joint) using results from a different experiment and focus on residual deformations, determined using nonlinear FEA, including the full shape of the welded plate (and stiffener) and the influence of the constraints used during welding. With the focus on welding residual deformations, information useful for the fabrication of larger complex welded structures may be obtained.

The welding experiments were carried out at the Facility for Intelligent Fabrication at the University of Wollongong (Australia) where residual deformations were recorded for a fillet welded T-joint using a weld pass on each side of the stiffener.

Five participants carried out the FE-simulations, Chalmers University of Technology (Sweden), P1, Shanghai Ocean University (China), P2, CENTEC-IST Lisbon Portugal, P3, Kyushu University (Japan), P4, and Jiangsu University of Science and Technology (China), P5. All the benchmark participants used the same technical specification about welding experiments, thermal and mechanical material data for the plate and stiffener, boundary constraints during welding and method of removing rigid body motion from the analysis. In the finite element (FE) simulations, the participants could choose FE software, type of elements used, mesh size, the model for moving heat source and (in one case) a different model of the weld heat source.

2. WELDING EXPERIMENT

A stiffener (1000 x 80 x 5 mm) was tacked on a plate (1000 x 400 x 5 mm) with the rolling direction parallel to the highest length. The stiffener has a small bulb at the top. The size of the bulb was estimated in the FE-simulations as the exact dimensions were not available at the start of the benchmark. Both the base plate and the stiffener were made of the low carbon grade DH36 ferric steel plate. Figure 1 show a view of the set-up (Above) and a cross-section of the fillet welds from the experiments (Below). All parts were ground smooth with a grind disk (grain 40) on a 40 mm width at the centre of the plate and a 20 mm height at the bottom of the stiffener. The planarity of the plate was controlled.

The stiffener was tacked only on one side (opposite side of the bulb) using 5 tacks of 15-20 mm spaced by 200 mm starting from the centre (the locations indicated in Figure 2 (Above)). The spacing between the stiffener and the plate is aimed at being zero (0 mm) all along the weld line. In the benchmark, the tack welds are not modelled (or the stresses and deformations in the plate after tack welding). The plate and stiffener are assumed to be fully joined at the right angle.

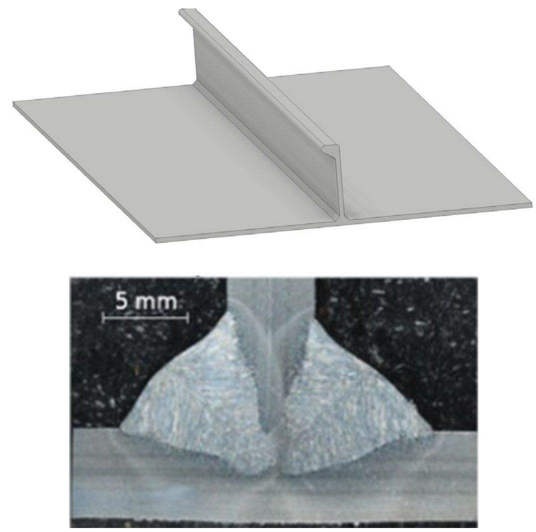

FIGURE 1: ABOVE: VIEW OF NOMINAL WELD GEOMETRY, BELOW: CROSS-SECTION OF FILLET WELDS

During the welding, the plate was tacked to a table at 6 positions as illustrated in Figure 2 (Above), note at the opposite side of the bulb. The first weld pass is deposited on the side where tacks are located. The second weld pass is then deposited on the other side of the stiffener in the other direction. The tack welds were removed after the second weld reached ambient temperature. The sequence of removal of the tack welds is unknown. Note also, that run on and run off tabs were used during the welding.

For both weld passes pulsed GMAW (Gas Metal Arc Welding) was used with the weld parameters:

- Welding speed: 0.59 m/min, Wire feed rate: 9.0 m/min
- Current: 250 A, Voltage mean: 29 V, Arc efficiency: estimated value 0.7

This gives a heat input for the simulations: 0.74 kJ/mm, though the arc efficiency is uncertain, it may be somewhat higher.

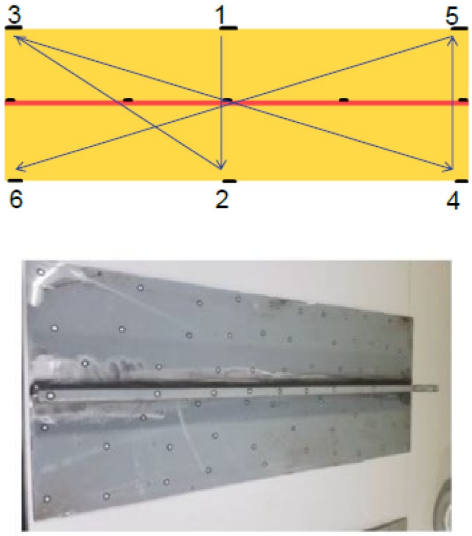

FIGURE 2: ABOVE: ILLUSTRATION OF THE CLAMPING CONDITIONS BY TACKING THE PLATE TO THE GROUND AT 6 POSITIONS, BELOW: USE OF OPTICAL SPOTS FOR THE 3D SCANNING FOR A FILLET WELD

2.1 Measurements

The residual deformation of the welded plate was measured after the six tack welds, and the run on and run off tabs had been removed. A 3D laser scanner apparatus, Creaform Handyscan 300, was used for this metrology control, see Figure 2 (Below). This device has a specified maximum resolution of 0.1 mm and a maximum accuracy of 0.04 mm. The 3D scanning was done using some markers put randomly on all external surfaces of the welded plates. The laser scanning was performed from all sides in order to get a volumetric representation of the welded assemblies and compare these surfaces (plate deviation) with a reference non-distorted CAD model of the fillet weld. The software program Geomagic Control X was used for this purpose. This software aligns the reference CAD model to the distorted scan and uses a least-squares fit to find a reference point and orientation. The reference point chosen for the measured deformations is at the intersection between the plate and the stiffener at the D – C edge, placed in the middle of the stiffener centreline but at the base of the underlying plate, see Figure 3.

Figure 3 shows the measured residual deformations in the plate and stiffener. The plate has a twisted shape which can be seen also in Figure 2 (Below). The maximum vertical displacement in the corners A, B, C and D are 3.6, -2.1, 2.7 and -1.7 mm respectively. This twisted shape may be caused by the use of different directions of the two weld passes. The first weld pass was deposited in the direction B to C in Figure 3, and the second weld pass was deposited in the direction D to A. One finds that the plate tends upwards at the end of each weld pass. In the literature, this shape for a fillet welded stiffener to a plate is sometimes called a buckling mode.

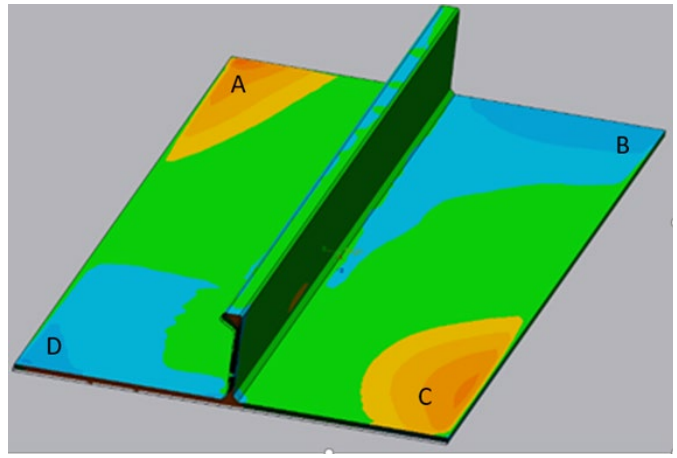

FIGURE 3: MEASURED RESIDUAL DEFORMATIONS IN PLATE AND STIFFENER. ORANG/RED COLOURS INDICATE VERTICAL DISPLACEMENTS UPWARDS AND BLUE DOWNWARDS.

3. MATERIALS AND FE-MODELS

3.1 Material data

The plate and stiffener material used is DH36 steel, a steel used for the construction of ships. The nominal room temperature yield stress is 360 MPa, and the main components are C 0.18 % and Mn (up to) 1.6 %. The filler metal used was 1.2 mm Lincoln Ultramag ER70S-6, with the room temperature yield stress of 450 MPa. The main components are: C 0.09 %, Mn (up to) 1.6 % and Si 0.90 %. As the primary interest for the benchmark was residual deformations it was decided to use the temperature variation of material parameters for the similar steel S355JR, [8], and to omit effects of the final phase transformation from austenite to pearlite / bainite /martensite. Note also that isotropic hardening was used, which was found to be appropriate for the S355JR steel, see [8] and that creep strains at higher temperatures were not considered. One participant, P4, used temperature-dependent data for S355 available in the FE software. Figure 4 shows the temperature variation for the thermal and mechanical parameters used. Included in Figure 4 (Below) is the estimated temperature variation for the yield stress and hardening modulus for the weld metal. This different temperature variation (for the weld metal) was used by some of the participants.

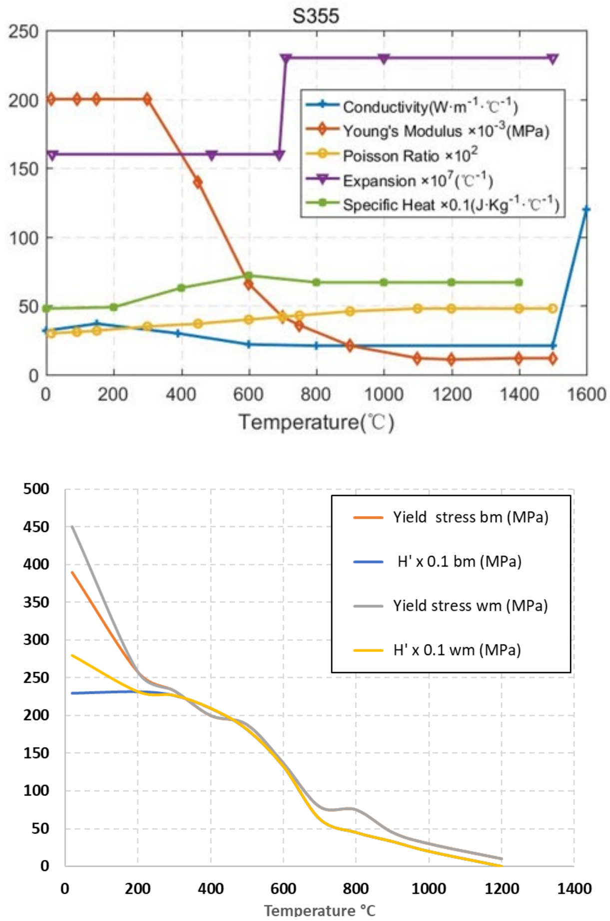

FIGURE 4: ABOVE: TEMPERATURE VARIATION OF THERMAL AND SOME MECHANICAL MATERIAL PARAMETERS FOR DH36 STEEL, BELOW: TEMPERATURE VARIATION OF YIELD STRESS AND HARDENING MODULUS FOR DH36 STEEL (BM) AND FILLER METAL (WM).

3.2 FE-Models

The participants chose the FE software to use for the simulations and were also free to choose element type, element mesh and grading of elements at the weld, though all participants used linear hexahedral (brick) elements, with possibly some linear tetrahedral elements to model the weld metal. The same FE-mesh was used for the thermal and mechanical analysis. One participant, P1, included run on / off tabs in the FE models. All participants carried out the simulations as a sequential 3D thermomechanical analysis, where the calculated temperature field from the transient non-linear thermal analysis is used as input, "load" for the subsequent non-linear mechanical analysis. A large displacement, large strain formulation was also employed by all participants in the FE simulations. Though the plate is strongly restrained during the welding there may be a considerable springback when the plate is released (tack welds are removed).

Thermal analysis: Surfaces of the plate and stiffener are subject to natural convection, modelled with a heat transfer coefficient. Possible radiation from the surfaces at higher temperatures was not considered, as this occurs in a very short time. Natural convection to the surrounding air is modelled with a low value for the heat transfer coefficient. As the plate is placed on a 25 mm thick steel table during the welding, the bottom surface may have a boundary condition simulating conduction to the table. Some of the participants have used an increased heat transfer coefficient h for the bottom surface of the plate to simulate heat transfer to the table. Initial mechanical FE-simulations show that parts may lift from the table when the weld passes are deposited. By experience, the effect of the table on the temperature field in the plate and thus the subsequent mechanical analysis is also believed to be minor.

Mechanical analysis: In the experiment, the plate is sitting on a table. During the welding, there will be mechanical contact between the plate and the table, which may also influence the mechanical analysis. It was decided to not include the mechanical effects of the table in the FE analyses, as this seems to be the case in the literature for a fillet welded stiffener to a plate. However, one participant, P1, has included possible contact with the table (in parts of the table close to the stiffener) in the mechanical analysis to see the possible effect of the table on the residual deformations, see below. One may also note that one participant, P4, included the self-weight of the plate and stiffener in the mechanical analysis.

Neglecting the mechanical influence of the table, the plate is fixed at the tack welds and taken as free otherwise during the welding. The nodes representing the six tack welds are fixed in three directions. Note, that the precise locations of the nodes with fixed degrees of freedom, dof:s, varied somewhat between the participants. When the tacks are removed the FE-model is free to move in space. This possible rigid body motion needs to be restrained, i.e. six dof:s need to be constrained, to find the residual displacements from the FE-analysis after the removal of the tack welds. In the benchmark, a 3-2-1 scheme was used to prevent rigid body motion, with nodes selected to match the observed experimentally found residual deformations. Figure 5 (Left) shows the six dof:s which were fixed to remove rigid body modes. This 3-2-1 scheme differs somewhat from the scheme, Figure 5 (Right), that has often been used in the literature, see for example [1,3]. Most participants used the same scheme shown in Figure 5 (Left).

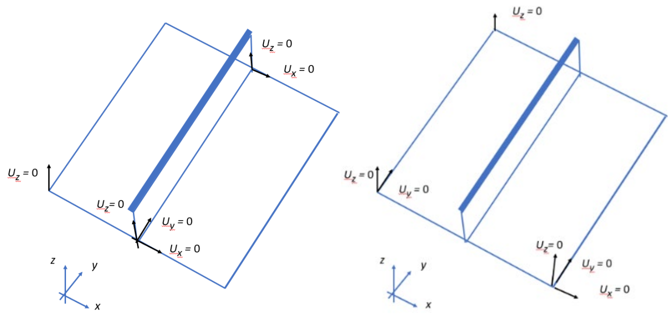

FIGURE 5: SCHEMES TO REMOVE RIGID BODY MODES FROM THE MECHANICAL FE-ANALYSIS, LEFT: USED IN THE BENCHMARK, RIGHT: USED IN [1,3].

3.3 Heat source and activation of elements

There are several alternative approaches available for the modelling of a moving heat source in arc welding. Four participants chose the double ellipsoidal model, the Goldak heat source [9] with entering parameters adjusted for the heat input given above and the extend of the melted weld metal as seen in Figure 1 (Below). Moreover, to model the joining effect of the moving heat source, the participants used an element Birth technique, by using “thermally and mechanically soft” elements with very low values for conductivity and Young’s modulus ahead of the head source. These elements are included in the FE-models and activated, i.e. given the values for material parameters shown above when the heat source reaches their position.

One participant, P1, chose a simplified approach for the moving heat source, where a block of elements was given a prescribed temperature during a short time interval. The time interval and progression of the heating block of elements were adjusted to match the actual speed of the heat source. The prescribed temperature was adjusted to give a cooling rate, Δt8/5, in the weld elements that matched experiments. The same technique as above was used to model inactive weld elements. Table 1 summarizes the different choices made by the participants.

Table 1: DIFFERENT INPUT AND MODELLING AMONG PARTICIPANTS

Parti-cipant	FE-software	Min mesh (mm)	Heat source	*h* table $W/m^2 °C$
P1	Abaqus	1.0	Block with temp	300
P2	Abaqus	2 .0	Goldak	no
P3	ANSYS	1.5	Goldak	15
P4	Simufact Welding	2.0	Goldak	700
P5	ANSYS	0.5	Goldak	no

4 FE-SIMULATION RESULTS

As discussed above, residual deformations are of primary interest. Figure 6 shows the calculated residual deformation field from two participants, P3 and P4. In Figure 6, the maximum vertical displacement is 2 mm for P3 and 4 mm for P4. Note, that P3 and P4 treated the rigid body modes somewhat differently.

This shape of the welded plate can be compared with the experimentally determined shape from Figure 4. It is seen that the FE-simulations will give a slightly twisted shape, though they don’t seem to fully capture the twisted shape found from the experiments. A direct comparison of the residual shape of the plate is not possible as the FE-simulations show the residual deformation field relative to the rigid body mode restraint, whereas the experimentally determined residual deformation field is determined with another reference point. Moreover, the participants have chosen to place the corner node with the vertical displacement zero in the 3-2-1 scheme in Figure 5 left at different corners, and one participant, P5, chose the 3-2-1 scheme shown in Figure 5 right. Note also, that the influence of the table below the plate (in the mechanical analysis) is not included in the results shown in Figure 6.

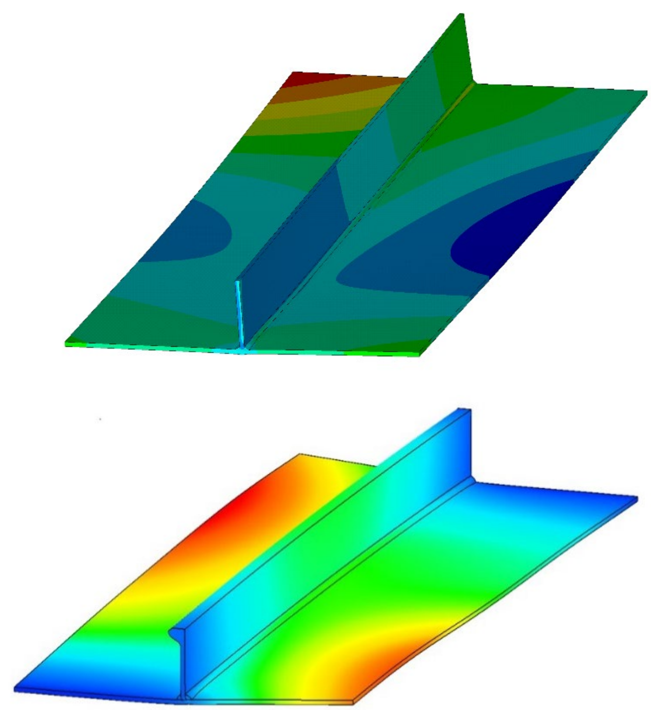

FIGURE 6: CALCULATED SHAPE OF WELDED PLATE AND STIFFENER FOR PARTICIPANTS P3, ABOVE, AND P4, BELOW. RED COLOUR INDICATES DISPLACEMENTS UPWARDS AND BLUE DISPLACEMENTS DOWNWARDS.

One attempt to compare the relative shape of the residual deformations from the FE-simulations with the experimentally determined shape is shown in Figure 7 where the residual vertical displacements along longitudinal lines B to C and D to A relative to the vertical displacement along a longitudinal line under the

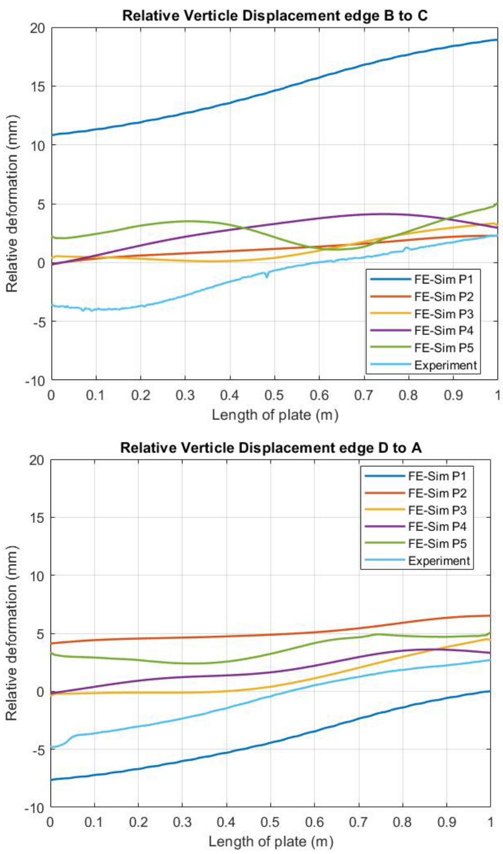

FIGURE 7: CALCULATED RESIDUAL VERTICAL DISPLACEMENTS ALONG LONGITUDINAL EDGES WITH EXPERIMENTS.

stiffener are plotted. This longitudinal line forms a part of the 3-2-1 scheme used in the FE-simulations to eliminate rigid body motion, and it includes the reference point used in the experimental measurements. It is also found to be reasonably undeformed, although a small upward vertical deformation is seen at the mid-plate compared to the edges.

One finds a similar trend in the FE simulations and in the experiments, that the plate tends to move upwards at the end of a weld pass, though the anti-symmetry found in the experiments is less pronounced in the FE simulations, and magnitudes of the vertical displacements can not be compared. The largest relative displacements in Figure 7 are found for Participant P1, who also used a simplified approach for the moving heat source where the correct heat energy (as used in the experiments) was not supplied to the plate. The bulb on the stiffener was small enough not to have a noticeable influence on the residual deformations in the plate. Note, that some participants did not model the bulb, see Figure 6 (Above).

It is difficult to compare with results from the literature for residual welding deformations for a fillet welded stiffener to a plate as the deformed shape for the full plate and stiffener is normally not reported and several factors in these references differ from the current benchmark. These different factors are the boundary conditions including type of restraint and a possible table under the plate, the direction of the two weld passes, the welding method (and thus heat input) and the dimensions of the plate and stiffener (including flange / bulb). In most references the two weld passes seem to have been deposited in the same direction, resulting in a more symmetric deflection of the welded plate. In several references it is also unclear if the plate was restrained when the deformations, or rather the angular distortion, were measured. Though a twisted, antisymmetric shape has been reported [7].

The angular distortion at the longitudinal midplate, the distance 500 mm, can be estimated from Figure 7 to be in the range of 0.5°, to 1.5° (using the plate half-width 200 mm). This can be compared with the experimental estimations 0.3°, and the analytical estimation of 0.6° for the given plate dimensions and heat input [10]. These values are in agreement with the angular distortion reported in the literature for similar weld setups.

The residual stress field in the plate is also obtained from the FE simulations. For this weld geometry, the most interesting stress component is the longitudinal stress. Figure 8 shows the transverse variation of the residual longitudinal stress at the mid-section of the plate. The other two stress components have lower magnitudes than the longitudinal component. The residual longitudinal stress variation transverse the weld direction compares well with results from the literature, see for example [1]. Although two participants differ in the magnitude of the residual longitudinal stress at the centre, the variation in the width of the tensile zone for the residual longitudinal stress seems to be a bit high. The maximum value for the longitudinal residual stress also compares well with the yield stress in the weld metal.

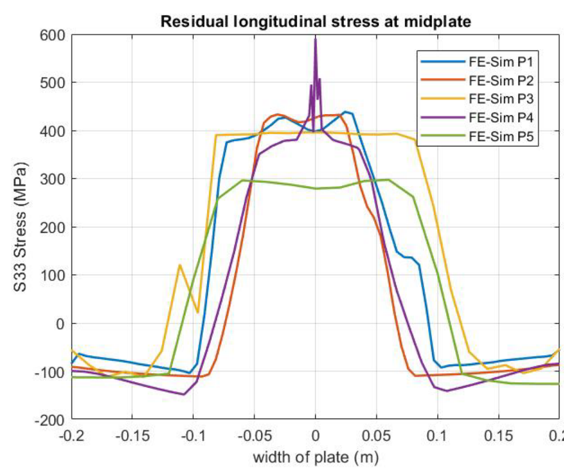

FIGURE 8: CALCULATED LONGITUDINAL RESIDUAL STRESSES AT MID-SECTION OF THE BASE PLATE

4.1 Influence of mechanical contact between table and plate

During the welding operations, the plate was positioned on a table that may affect both the thermal and mechanical analyses. As mentioned above, the influence of the table is believed to be small on the thermal analysis and has been neglected in the thermal simulations. However, the influence of the table on the mechanical may be higher, as the table will prevent vertical displacements of the plate during the welding and cooling phases of the welding. This influence has to be modelled with mechanical contact conditions, which is computationally intensive. One participant, P1, modelled contact in an area of the plate under the stiffener (and at a certain distance away from stiffener in the transverse direction) using hard contact i.e. a Lagrange multiplicator method (with zero vertical penetration and assuming no friction in the plane of the plate) as initial simulations indicated that parts of the plate, outside the six tack welds, lift during the welding and cooling. Figure 9 shows the residual deformations from P1 where mechanical contact was included. When comparing with results for participant P1 in Figure 7 above, the calculated relative residual vertical displacements at edges B to C and D to A will be similar in shape though the displacement magnitudes are lower, and some waviness in the edge displacements was also observed. The calculated twist, though, does not fully capture the twist measured at the experiments as also noted in Figure 7.

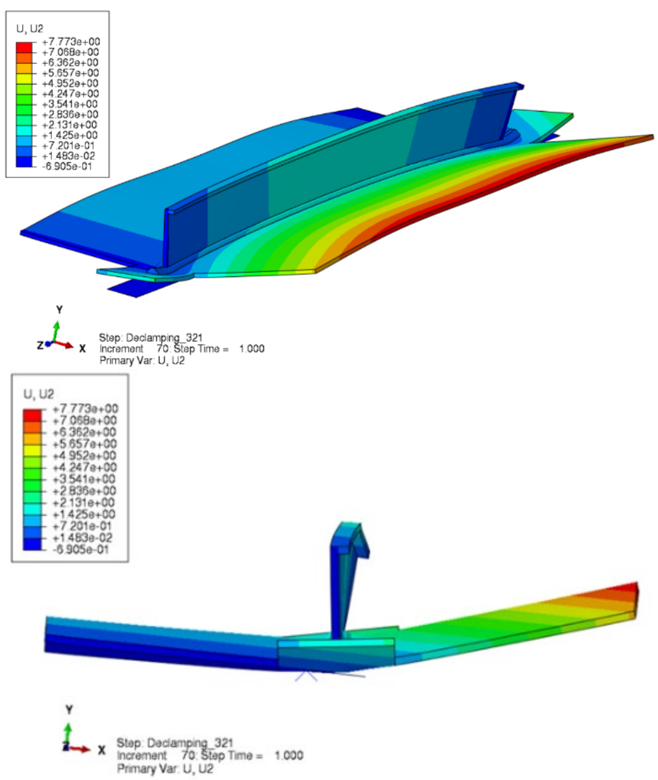

FIGURE 9: CALCULATED SHAPE OF WELDED PLATE AND STIFFENER WITH INFLUENCE OF MECHANICAL CONTACT WITH TABLE, FROM P1.

1. DISCUSSION

The benchmark clearly shows that careful consideration is needed when defining a reference plane for comparative measurement of resultant distortion for varying conditions. FE-simulations have to introduce restraints to eliminate rigid body motion from the results, which is normally done by constraining six degrees of freedom in three points as shown in Figure 5, though alternatives exist like inertia relief (in the FE-software Abaqus) or supporting the FE-models in weak springs. For the measurements, special consideration was given to determining the magnitude of deformation (or distortion) relative to original CAD geometry with one reference point chosen. The resulting measured deformation (or distortion) will be relative to this point. An attempt was made to manually align the FE-simulated deformed shape of the plate to the reference point chosen in the measurements.

The FE-simulations have shown that it is difficult to obtain the twisted shape of the plate as measured in the experiments, although a trend similar to the experiments can be seen with a slight influence of the weld pass direction, as the plate tends to move upwards at the end of each weld pass. This is more clearly indicated in the measurements. Both experiments and FE simulations show that the deformations resulting from welding one stiffener to the plate may cause further fabrication issues if the welded plate is released before subsequent fabrication operations. In production, this may not be an issue, because the deformed structures are usually referenced to constrained attachment points during the manufacturing.

There are several possible causes for uncertainties in the FE-simulated results, related to modelling of the weld-setup and also values for process parameters and values for parameters in the material models:

- The welding set-up with the plate placed on a table (that may have a finite stiffness compared to the plate). The table will, as discussed above, influence the thermal and mechanical analysis, with the influence on the mechanical analysis being higher. The possible contact between parts of the plate and the table will influence the deformation field, and in parts reduce the deformation magnitudes. The influence of the thermal FE calculations is, as discussed above, believed to be lower, though the table will act as a thermal sink, and alter the temperature gradient through the plate thickness.
- The welding set-up also involves welding five tack welds to position the stiffener to the plate. Their position at the centre of the plate, also as an initial operation, indicate that their influence on the residual deformations is low. Also, the use of run-on / run-off tabs is believed to have a minor effect.
- The order of the release of the tack welds was not recorded at the experiments. Initial FE simulations showed that this order had a marginal influence on the residual deformations, indicating that this release is elastic. Therefore, most of the participants re-leased all tack welds in one step. However, there could be some effects of large deformations (rotations) when the final tack welds are removed and the plate restraint is very low.
- The choice of actual points for the 3-2-1 scheme for the removal of rigid body modes can be chosen arbitrarily as long as the rigid body modes are eliminated properly. Here a scheme was used, see Figure 5 left, that should promote anti-symmetric deformations. Initial FE-simulations indicate that the resulting deformation field will differ somewhat if the 3-2-1 scheme, Figure 5 right, (often used in the literature), was used.

• There are uncertainties in the material data, mainly in the mechanical data, used in the FE simulations. High temperature data for Young's modulus and the thermal expansion coefficient, of particular interest for deformations, are scarce, thus uncertain. These parameters may be of more interest when residual deformations are of importance. Moreover, the effects of volume changes during solid-state phase transformations were not included in FE simulations.

• One participant, P1, used a simplified method of describing the heat input, which will give shorter computational times than with the use of the more accurate modelling with the Goldak heat source [9]. With the simplified method, the cooling rates in the weld metal are captured, but the correct heat energy supplied by the heat source is not deposited. The calculated results with this approach are similar to the results using the Goldak heat source, though the magnitudes in the relative residual edge displacements field are higher as seen in Figure 7 (for the default case without considering the table below the plate). Thus, one may obtain similar results in the deformation field using a simplified heat source model, without losing much in accuracy. More investigations are needed to be able to recommend the use of simplified heat source modelling. One may also note that though parameters in the Goldak heat source could be matched to welding conditions, like the actual welded zone, the FE mesh used by the other four participants are maybe too coarse to give an accurate modelling of the temperature gradients present during the early cooling phase.

2. CONCLUSIONS

The FE simulations have shown that it is difficult to accurately calculate the shape of the plate after a two-pass fillet welding of a stiffener to the plate. Though different reference systems have been chosen for the FE-simulations and the experimentally determined distortions, some trends can be seen, like an antisymmetric shape of the plate and that the plate tends upwards at the end of each weld pass. This benchmark complements the benchmark reported in [1] where the angular distortion and the residual stresses were determined and compared with experiments. In addition to the recommendations made in [1], to FE-simulate the deformations / distortions in the plate with one stiffener fillet welded by two passes one needs to:

• Have good documentation of the experimentation, besides welding process parameters and geometrical dimensions of the material also the actual boundary conditions and steps carried after the completion of the welding and before measuring residual deformations and stresses.

• Carefully select reference systems for measuring the deformations in the welded plate, ideally have this similar to the restraints imposed in the FE-models to remove rigid body motion in the FE-simulations.

• Have a good knowledge of values for parameters in the constitutive models, mainly mechanical parameters (over a large temperature interval).

ACKNOWLEDGEMENTS

Parts of this work were carried out in a benchmark study in the Specialist Technical Committee V.3 Materials and Fabrication Technology of the International Ship and Offshore Structures Congress 2022. Numerical simulations by participant P1 were performed on resources provided by Chalmers e-Commons (C3SE). Participant P1 also acknowledges the assistance in the FE-simulations by Shivaprasad Gurram, MSc.

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