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Numerical simulation of crack growth in a welded joint with defects

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Abstract

Research presented in this paper involves the numerical simulation of crack growth in a welded joint made of common structural steel S235JR2, but with the presence of a number of different welding defects, which represents a scenario that is not covered by relevant standards, in this case EN ISO 5817. After analysing several defect combinations, which could occur in reality, the one with the least favourable combination of stress concentration and plastic strain was selected as the relevant model. A crack was then introduced in the location where the stresses, caused by tensile loading of the welded joint model, were above the yield stress. The numerical analysis performed in this case involved different combinations of load magnitudes and crack length, in order to determine at which point the initial crack will start propagating.

Keywords: welded joint; defects; finite element method; crack growth; steel S235JR2

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1. Introduction

Defects in welded joint are inevitable, due to structural, metallurgical and other reasons, and their occurrence can significantly decrease the work life of a welded joint/structure, and in the worst case, it could lead to failure [Aranđelović (2020), Tanasković (2018)]. The frequency and size of these defects can be decreased to an acceptable minimum by using proper welding procedures, materials and heat treatment. Standard EN ISO 5817 (2015), which defines the acceptability criteria for welded joint defects only considers one type of defect in a welded joint, and does not fully take into account the integrity of the welded joint. Particular problems occur due to residual stresses which can cause stress concentration and result in crack initiation in the cases of inadequate welded joint geometry, as can be seen in the works of R. Jovičić (2015) and S. Sedmak (2018).

In this particular case, a number of different defect combinations were simulated on welded plates, and numerical models were later developed in order to determine the stress distribution of such welded joints under tensile loads. All of the defects which were intentionally introduced to the welded joints were defined and selected in accordance

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with standard SRPS EN ISO 6520-1 (2008). Particular focus was on the vertical misalignment of plates, as it was expected that this defect would have to most adverse effect on welded joint integrity. The next step in this research is to experimentally verify these results and obtain relevant data about the behaviour of welded joints with multiple defects in exploitation conditions.

2. Materials and welding technology

Parent material was S235JR steel, widely used in all industry fields, mainly due to its availability and low cost, while also having good weldability. These were the reasons why this material was selected for the first stage of the research, for the purpose of creating welded joints with specific defect combinations S. Sedmak (2018). Tables 1 and 2 give the chemical composition and mechanical properties of the aforementioned steel. VAC 60 wire was used as filler material. This wire is typically used for welding of non-alloyed and low-alloyed steels with yield stress up to 530 N/mm2. Chemical composition and mechanical properties of this material are shown tables 3 and 4.

Table 1. Chemical composition of steel S235JR

Element	C	Mn	P	S	N	Cu
Percentage	0,17	1,4	0,035	0,035	0,12	0,55

Table 2. Mechanical properties of steel S235JR

Material	Yield stress ReH/MPa	Tensile strength Rm/MPa	Thickness/mm
S235JR	235	360-510	12

Table 3. Chemical composition of VAC 60

Element	C	Si	Mn	P	S
Percentage	0.08	0.9	1.5	<0.025	<0.025

Tabela 4. Mechanical properties of VAC 60

Material	Yield stress R_{eH}/MPa	Tensile strength R_m/MPa	Elongation %	Toughness at -40° J
VAC 60	>410	510-590	>22	>47

MAG procedure was used in order to weld the plates, with the M21 gas mixture (82% argon and 18% carbon-dioxide). Welding parameters (amperage and voltage) were deliberately varied during the welding in order to obtain the required welding defects, and their values ranged from 110-141A and 18.8-23.9V. Welding speed was also varied between 4.1 mm/s and 1.6 mm/s. Groove edges were ground to an angle of 60°, and the groove width was 2 mm. Welded plates had the dimensions of 500 and 300 mm.

The first plate was welded without the misalignment. The first half of the welded joint was made with the following defects – incomplete root penetration, excess weld metal and undercut, whereas the second half of the welded joint was made with weld face sagging and incomplete root penetration. The second plate had a 2 mm misalignment, which was combined with the following defects: in the first half, there were also incomplete root penetration and an undercut, whereas in the second half included excess root penetration along with the aforementioned incompletely filled groove and misalignment. Figure 1 shows the various stages of welding performed on one pair of plates, including the preparations.

The same procedure was used for both plates, including the one in the above figure, which shows the prepared groove on both plates and two fill passes. The second one is particularly important, since this is the pass during which the defects were introduced. The figure also shows some of the defects on the weld face, including the insufficiently filled groove, and an undercut made by grinding.

Table 1. An example of a table.

2.1. Construction of references

Figure 1: Welding of the plate with a misalignment

3. Numerical simulations

Second part of the research presented here involved the development of two-dimensional numerical models, using ABAQUS 2017 software. The goal was to simulate the behaviour of welded joint with geometries corresponding to the ones obtained after welding, in order to determine the stress magnitudes and distribution along the weld. Numerical methods, particularly the finite element method (FEM), are frequently used for these purposes, as they provide a reliable and relatively simple approach to solving structural integrity problem [Jovičić (2015), Hemer, Aranđelović (2020), Mijatović (2019). Additionaly, models developed in this manner ensure the repeatability of calculations, as input parameters, such as geometry, material properties, boundary conditions and loads can be varied easily, without the need to create new models from scratch.

Before the two-dimensional models, representing the cross-sections of each welded plate and its joint were made, the actual plates needed to be carefully measured, in order to obtain the dimensions of each imperfection/defect present in the welds. Once these dimensions were determined for all four cases, the models were drawn to resemble the real welded joints as closely as possible. In terms of material properties, two different regions were defined – the parent material region and the welded joint region. The former used the mechanical properties – yield stress and tensile strength – of steel S235JR, whereas the welded joint used the properties of the filler material, VAC 60. The properties used for the calculations are given in table 5 below. It should be noted that these values are slightly different from the real ones, due to ABAQUS requirements when plastic behaviour is simulated. More on this can be found at and Hemer, S. Sedmak (2020).

Table 5. Material properties used for the numerical simulations, for S235JR and VAC 60 materials.

Material	Yield stress R_{eH}/MPa	Tensile strength R_m/MPa	Strain -
S235JR	236	415.7	0.185
VAC 60	461.25	720	0.199

Boundary conditions and loads were defined in the same way for all four models. An example can be seen in figure 2, along with the finite element mesh. One side of the model was fixed, and the other was subjected to a tensile load, with a magnitude of 100 MPa, following the logic from the similar models found in [4]. Mesh was made using hex elements (CPS4R elements - 4-node bilinear plane stress quadrilateral, reduced integration, hourglass control elements), whose size was varied for each model, until sufficient convergence of results was achieved. In other words, the element size was iteratively increased/decreased until the results of two successive iterations started showing almost identical values, as is common practice when working with finite element models, Jovičić (2015, Hemer, A. Sedmak (2020).

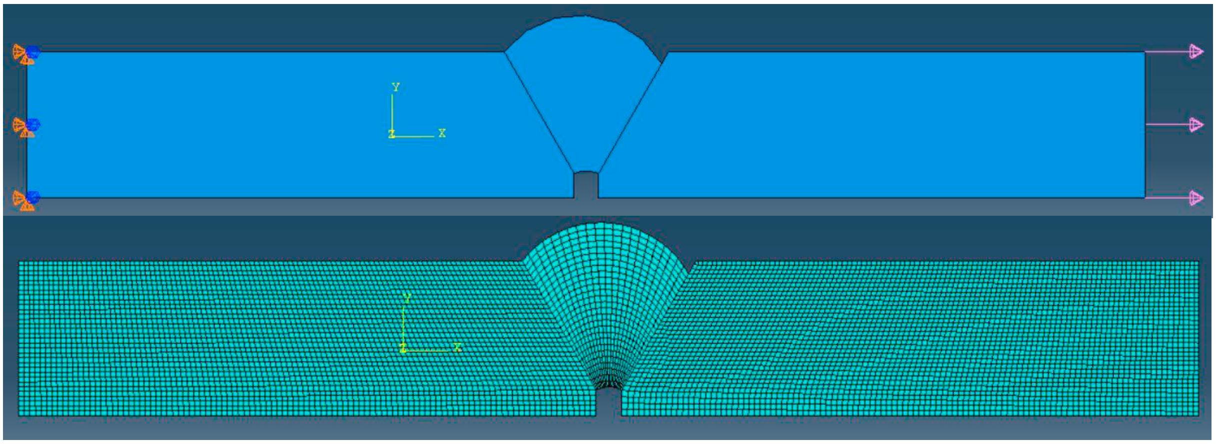

Figure 2. Boundary conditions (fixed), top right image and the load, top left image; finite element mesh, bottom image

4. Numerical results and discussion

The results of the previously described numerical analyses are presented in this section of the paper. These results include the equivalent (Von Misses) stress distribution and magnitudes for all four variants of the welded joint. Obtained results are shown in figures 3-6, wherein:

- Figure 3 represents the welded joint with excess weld metal, incomplete root penetration and continuous undercut
- Figure 4 represents the welded joint with an undercut, incomplete root penetration and a 2 mm linear misalignment.
- Figure 5 represents the welded joint, with excess root penetration, insufficiently filled groove and 2 mm linear misalignment.
- Figure 6 represents the welded joint with incomplete root penetration and weld face sagging.

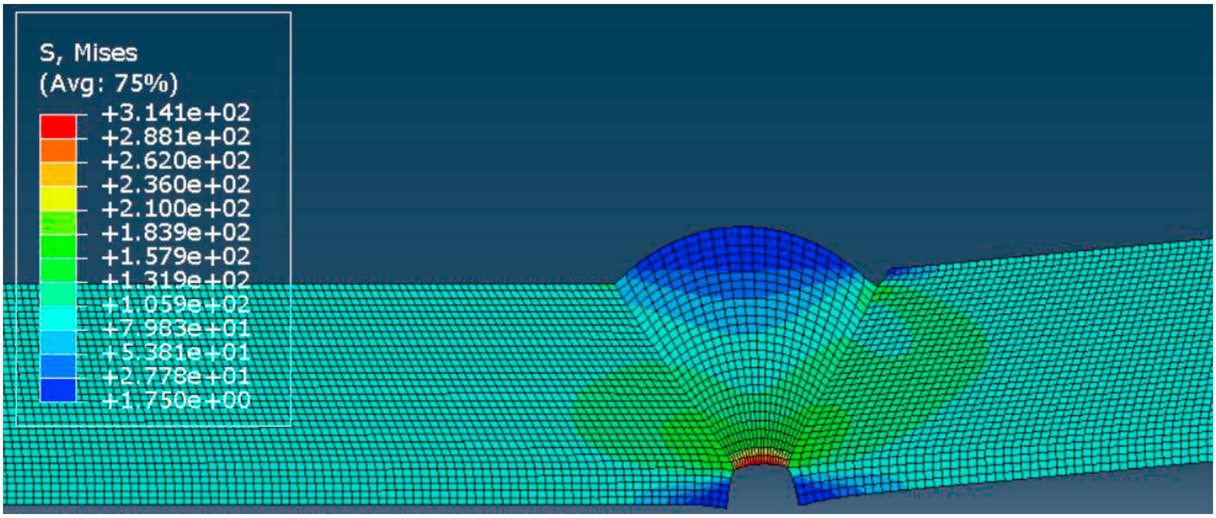

Figure 3. Model with excess weld metal, undercut and incomplete root penetration.

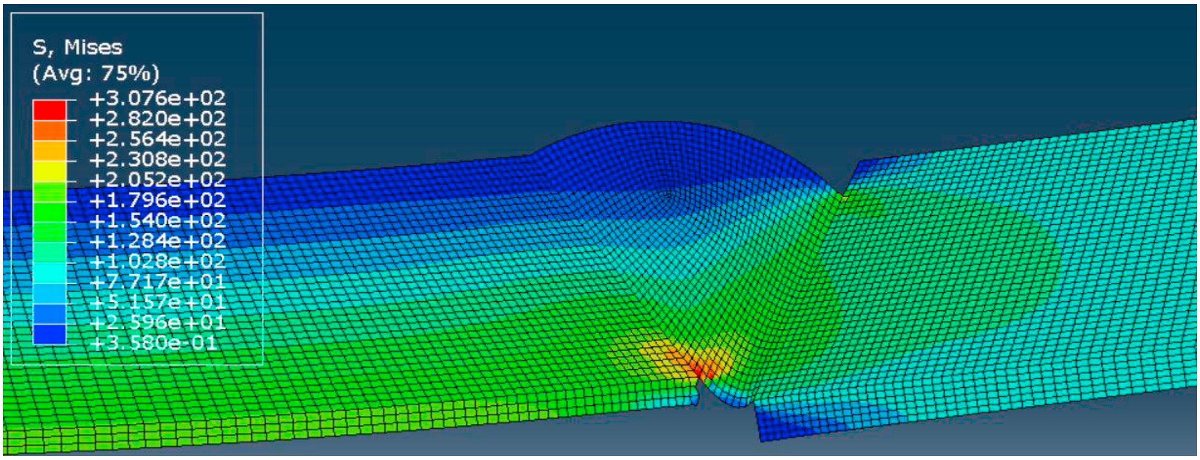

Figure 4. Model with an undercut, linear misalignment and incomplete root penetration.

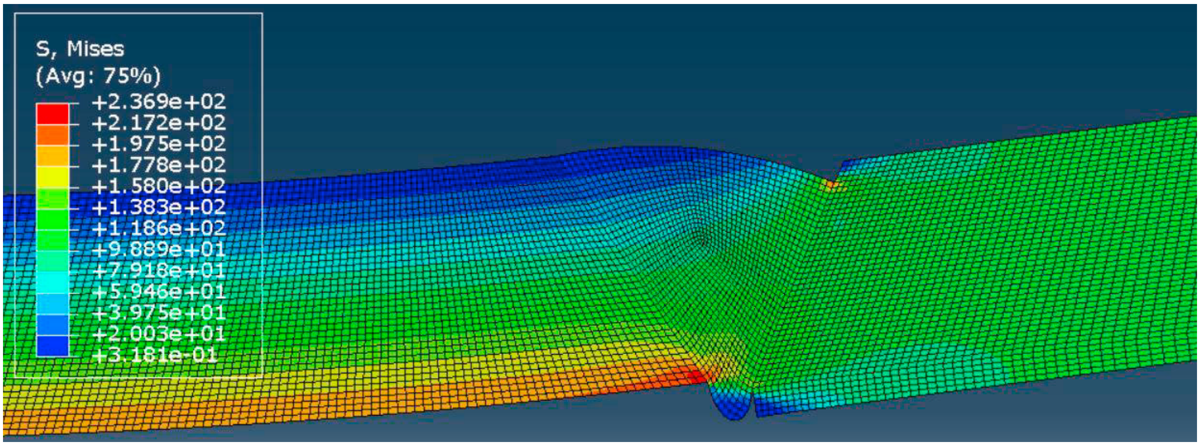

Figure 5. Model with an undercut, linear misalignment and excess root penetration

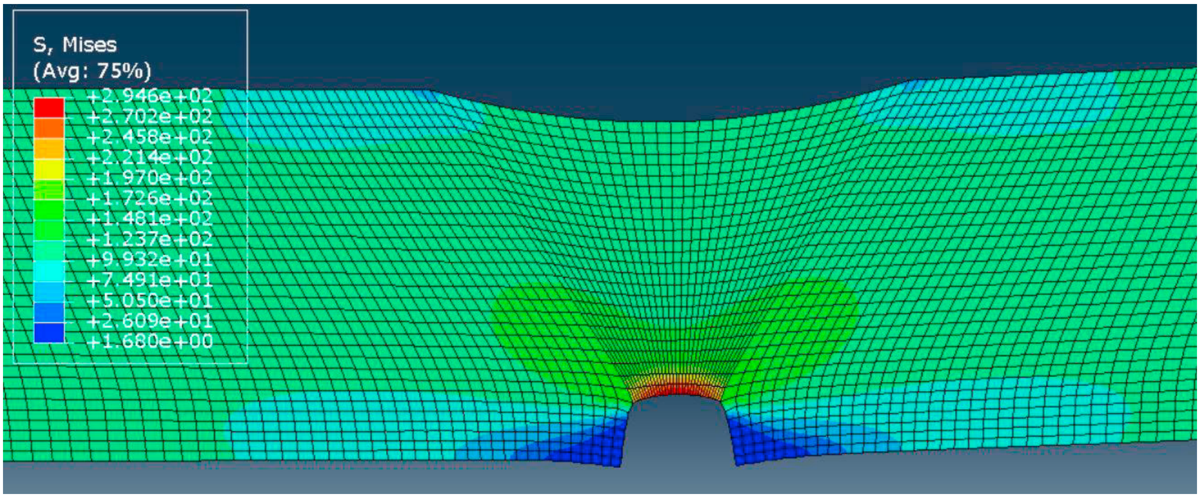

Figure 6. Model with sagging and incomplete root penetration.

Maximum values of stress determined for each model are given in table 6. It can be seen that, in terms of stress magnitude alone, the first case (figure 3) is the least favourable, since this is where the highest stresses had occurred. By contrast, the case shown in figure 5 would be the best, since the maximum stress values were considerably lower than in other cases.

Table 6. Stress magnitudes for all four models

Model	Maximum equivalent stress MPa
Excess WM + incomplete penetration + undercut (fig. 3)	314.1
Undercut + incomplete penetration + linear misalignment (fig. 4)	307.6
Undercut + excess penetration + linear misalignment (fig. 5)	236.9
Weld face sagging + incomplete penetration (fig. 6)	294.6

However, there is another important factor to take into account here – the distribution of these stresses. Since there are significant differences in the mechanical properties of the parent material and weld metal, due to noticeable overmatching (the filler material is considerably stronger in terms of yield stress and tensile strength), the location of stress concentrations affects the integrity of the welded joint up to a point where models with lower magnitudes are actually worse. This is due to the fact that in the models shown in figures 3 and 6, highest stresses were located within the weld metal, whose yield stress is above 400 MPa, hence their magnitudes of around 300 MPa are still in the safe zone, from the structural integrity point of view. In the other two models, shown in figures 4 and 5, critical stress magnitudes „shifted“ from the weld metal to the parent material, whose yield stress is much lower. In this case, even the value of ~237 MPa from figure 5 was sufficient to cause small plastic strain in the model. Of course, no plastic strain was present in the fig. 3 and 6 models.

Based on the above results, it can be concluded that various combinations of welding defects can affect the behaviour of the welded joint in more ways than one. Significant differences in stress concentration were observed, more often than not in entirely different locations, as the consequence of prominent differences in geometry of the welded joints. Whether the integrity of the welded joint was compromised or not depended mostly on which of its regions had highest stress values.

As was expected, welded joints with misalignments were confirmed as the less favourable scenarios, since stress concentrations were mainly within the parent material, in the areas with sharpest angles and most prominent changes in plate thickness, both of which were direct consequences of asymmetry caused by the misalignment. Additionally, the case with two defects (weld face sagging and incomplete root penetration) had actually shown the best behaviour, since stresses were concentrated in the middle of the weld metal, the „safer“ region in this case. This case simply involved the decrease in the load bearing cross-section, without other stress concentrators (such as sharp angles in other cases), which did not affect its integrity in any noticeable manner.

5. Conclusions

This paper presented the first stage of an extensive research on the influence of the presence of multiple different defects on the integrity of welded joints. Plates were welded with intentionally caused defect combinations and these welded joints were used as the base for numerical simulations, for the purpose of determining which combination was the most dangerous in terms of structural integrity. This was achieved by variation of welding parameters and deliberately inadequate geometry.

Obtained results provided some interesting insight into the behaviour of welded joints in the presence of various defects, suggesting that the geometry itself plays a very important role, and that the maximum values of stresses did not necessarily correlate with the integrity – it was determined that the case with the lowest magnitudes was one of the worst scenarios, whereas the one with the highest values was the most favourable. This was due to the stress concentration locations, depending on whether they were in the weld metal (the stronger material in this case) or the weaker parent material.

The next stage of this research will involve experimental verification of these finding, via tensile tests and other destructive test methods, which will be performed on the welded joint specimens with preserved defects and inadequate geometries.

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References

Aranđelović M., Milovanović N., Đorđević B., Sedmak S., Martić I.: Reparation, inspection and damage analysis of steam boiler, Welding & Material Testing, 3/2020, 2020, 9-12.

Tanasković D., Đorđević B., Gajin M., Aranđelović M., Gostović N.: Damages of Burner Pipes due the Working Conditions and its Repairing Welding, Procedia Structural Integrity Procedia 13, 2018, 404 – 409, https://doi.org/10.1016/j.prostr.2018.12.067

SRPS EN ISO 5817:2015 – Welding - Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded) - Quality levels for imperfections - Institut za standardizaciju Srbije, 2015

SRPS EN ISO 6520-1 - Welding and allied processes — Classification of geometric imperfections in metallic materials — Part 1: Fusion welding – Institut za standardizaciju Srbije, 2008

Jovičić R., Sedmak S., Tatić, U., Lukić, U., Walid M. Stress state around imperfections in welded joints - Structural Integrity and Life, 15(1), 2015, 27–29

Sedmak S., Jovičić R., Sedmak A., Aranđelović M., Đorđević B.: Influence of Multiple Defects in Welded Joints Subjected to Fatigue Loading According to SIST EN ISO 5817:2014, Structural Integrity and Life, 18(1), 2018, 77–81

Hemer, A, Arandjelović, M, Milović, Lj, Kljajin, M, Lozanović Šajić, J. Analytical vs Numerical Calculation of Fatigue Life for Different Welded Joint Regions, Technical Gazette, 27(6), 2020, 1931-1937, https://doi.org/10.17559/TV-202009211 52557

Mijatović, T, Milovanović, A, Sedmak, A, Milović, Lj, Čolić, K. Integrity assessment of reverse engineered Ti-6Al-4V Eli total hip replacement implant, Structural Integrity and Life, 19(3), 2019, 237-242

Hemer, A, Sedmak, S, Milović, Lj, Grbović, A, Sedmak. A. FEM simulation of welded joint geometry influence on fatigue crack growth resistance, Procedia Structural Integrity, 28, 2020, 1827-1832, https://doi.org/10.1016/j.prostr.2020.11.005