

## COMBINED APPROACH FOR INTEGRITY ASSESSMENT OF WELDED JOINTS WITH MULTIPLE DEFECTS

## KOMBINOVAN PRISTUP OCENI INTEGRITETA ZAVARENIH SPOJEVA SA VIŠESTRUKIM GREŠKAMA

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### Keywords

- welding defects
- finite element method
- digital image correlation
- crack growth

### Abstract

*Presence of defects in welded joints is inevitable, and more often than not, presence of a specific defect is accompanied by other types. This research represents the development of a combined method for analysing the structural integrity of welded joints with multiple defects - relying on experimental testing, deformation monitoring using digital image correlation, and numerical simulations via finite element method. It all started a long time ago, with simple 2D models, and continued over time, introducing new improvements to the existing models, taking into account various factors, such as welded joint material heterogeneity, the presence of cracks initiated from the most critical defects, and stresses which act in directions outside of the model specimen's main axis.*

### INTRODUCTION

So far, defects in welded joints have been observed individually, without taking into account their potential cumulative effect on the integrity of welded joints. Presence of several different types of defects can result in significant geometric irregularities, which in turn cause stress concentrations, which could significantly decrease the load-bearing capacity of these welds.

This issue was first considered by the authors on an example of a welded joint made of P460NL1 steel, which had a combination of excess weld metal and an undercut /1/. In this case, the finite element model was very simple, only considering the weld metal and parent material as separate welded joint regions.

At a later point, it was decided to expand this research, by considering different combinations of multiple defects, in order to determine which of these are the most critical. For this purpose, a new methodology, based on a combined approach that would use experiments, digital image correlation and numerical simulations, was developed. In this case, different types of structural steels were used, namely S235 and S275 steels.

### Ključne reči

- greške u zavarenim spojevima
- metoda konačnih elemenata
- korelacija digitalnih slika
- rast prslina

### Izvod

*Prisustvo grešaka u zavarenim spojevima je neizbežno, i često se dešava da postojanje određenih grešaka podrazumeva još grešaka druge vrste. Ovo istraživanje obuhvata razvoj kombinovane metode analiziranja integriteta zavarenih spojeva sa višestrukim greškama i zasniva se na eksperimentalnim ispitivanjima, praćenjem deformacija primenom korelacije digitalnih slika, kao i na numeričkim simulacijama primenom metode konačnih elemenata. Sve je počelo pre mnogo vremena, u vidu jednostavnih 2D modela, i tokom vremena su postojeći modeli postepeno unapređivani, uzimajući u obzir brojne faktore poput heterogenosti zavarenog spoja, prisustva prslina koje su inicirane na mestima kritičnih grešaka, kao i napona koji deluju van pravca glavne ose modela zavarene epruvete.*

This paper presents a detailed overview of each step in the development of the aforementioned methodology, from simpler 2D models with two different regions, to more detailed and geometrically accurate models, which also include the heat affected zone as an individual welded joint region.

### THE INITIAL STAGE

The first numerical model is based on an existing welded plate, made of P460NL1 steel /1/. In this case, the defects in the weld include a small crack on the weld face side, and vertical misalignment of plates, /2/. Typically, standards such as the EN ISO 5817 series /3/ would consider only one of these defects at a time, but the initial idea here is to observe the combined effect of these two defects on the integrity of the welded joint by determining the stress concentration factor in the most critical areas, which is done by comparing the stress magnitudes in the model with defects to their corresponding values in a weld without any defects. In this particular case, it is determined that the presence of defect increases these stresses by a factor of 2.43, with the critical location around the crack.

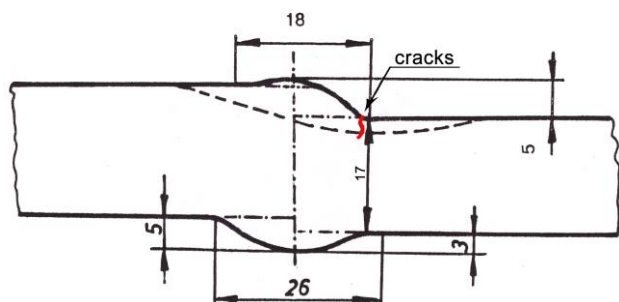


Figure 1. Weld geometry and defects, /2/.

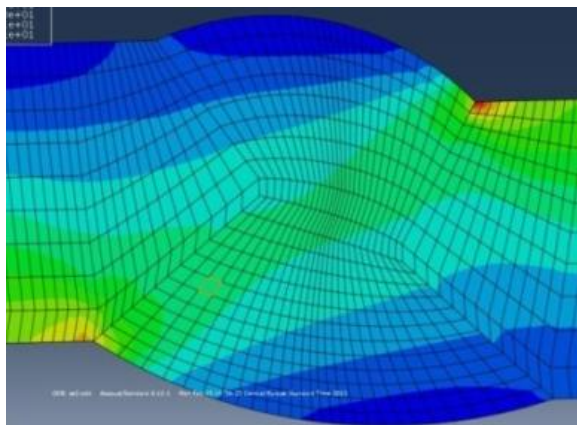


Figure 2. The initial, very simple model of a welded joint specimen with multiple defects, /3/.

This model allows the authors to obtain a base for future simulations which would introduce various improvements - for example, in this case the crack is represented by a small undercut, instead of using the actual XFEM option, which became standard practice in the later stages of this extensive research.

#### NEXT STAGE - MULTIPLE DEFECT COMBINATIONS

Later stages of analysis of welded joints with multiple defects include several different combinations, /4/:

1. excess weld metal, weld face undercut, incomplete root penetration;
2. incomplete root penetration, weld face sagging;
3. vertical misalignment, excess WM, weld face undercut;
4. vertical misalignment, weld face undercut, incomplete root penetration.

Numerical models are made before the experiments are performed in order to determine where the critical locations are, i.e., in order to determine where the failure of the real specimens is expected. An example of one of these numerical models is shown in Fig. 3. It can be seen that, while more detailed than the initial models, these models are still heavily approximated. These models are also used to determine the appropriate FE size in order to ensure proper convergence of results, /4/. In accordance with the usual practice, finite element size is refined around the critical areas where highest stresses/strain are expected, in order to ensure high level of accuracy, without sacrificing too much calculation time.

In order to simulate the conditions during the experiment, boundary conditions are defined as fixed on one end, and the load is applied as tension on the opposite (Fig. 3), /4/.

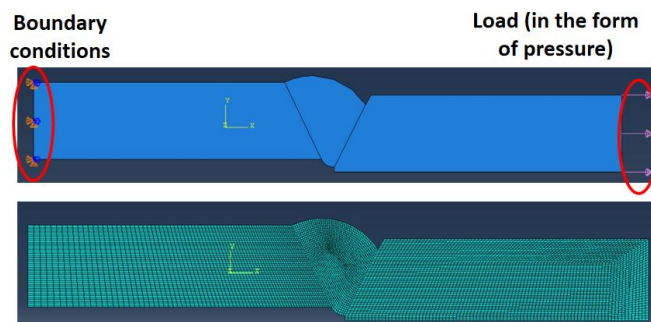
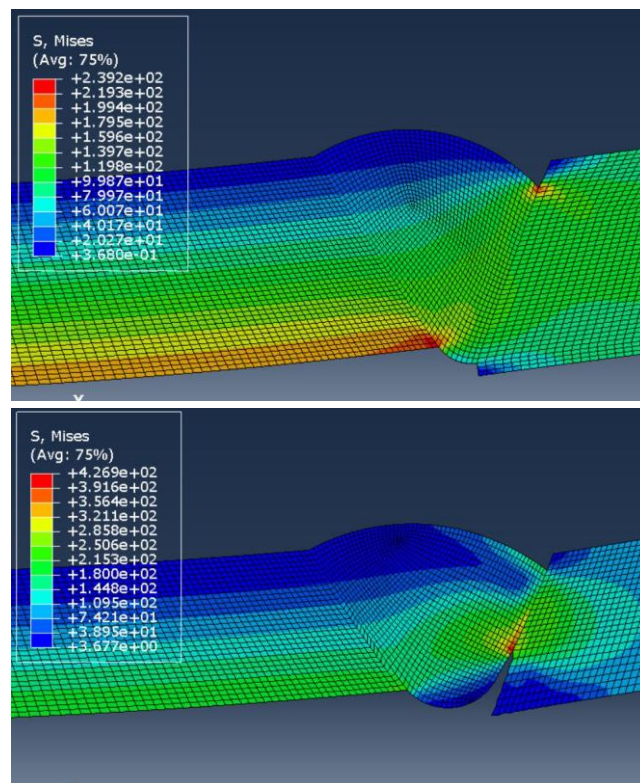


Figure 3. Loads, boundary conditions and FE mesh for the new models.

Experimentally obtained results validate all of the models except one - the 3<sup>rd</sup> defect combination model, where the locations of cracks are on the opposite sides of the weld root, which raises questions about the presence of additional defects which could not be detected visually. In other words, it is suspected that the irregular heat input during welding, which is necessary to ensure the forming of required defects, results in volumetric defects, namely lack of fusion. By analysing the fracture surface of the specimen in question /5/, these suspicions are confirmed. After introducing the 4 mm lack of fusion to the numerical model, its fracture matches with the experiment.

Figure 4 shows the results of numerical simulations for the initial model (a) and the corrected model (b), after the presence of 4 mm lack of fusion in the weld root was detected. Due to this, future experiments also take into account the possibility of lack of fusion occurring in the vertically misaligned models, although this did not cause significant issues in the new models.

Figure 4. 'Before' and 'after' results of the 3<sup>rd</sup> defect combination simulations, /4/.

## INTRODUCTION OF DIC TO THE METHODOLOGY

In order to improve the process of validation of numerical models and experiments, digital image correlation /6-9/ is also combined with these two approaches, with the purpose of providing detailed insight into how the specimens with different defect combinations deform during the loading. By comparing the strain field obtained by DIC during different stages of loading with the behaviour of numerical models, it is possible to further improve the accuracy of these models, especially in terms of strain/stress distribution in various regions of the welded joint and in its vicinity.

Figure 5 shows the comparison of DIC results with the ones obtained by numerical simulations /10, 11/. During this

stage of development, the DIC images are used as the basis for iteratively determining the mechanical properties of the heat affected zone, since these are unknown, and previously used methods for empirically determining their values are not sufficiently accurate, /12/. The logic behind the decision to represent each welded joint region individually is described in detail in /10/. This example provides a reliable and comprehensive basis for the research that follows, ultimately resulting in the iterative methodology for determining tensile mechanical properties of the HAZ. It demonstrates how using different mechanical properties for the welded joint and the parent material affects the accuracy of results on a simple example of a welded pipe.

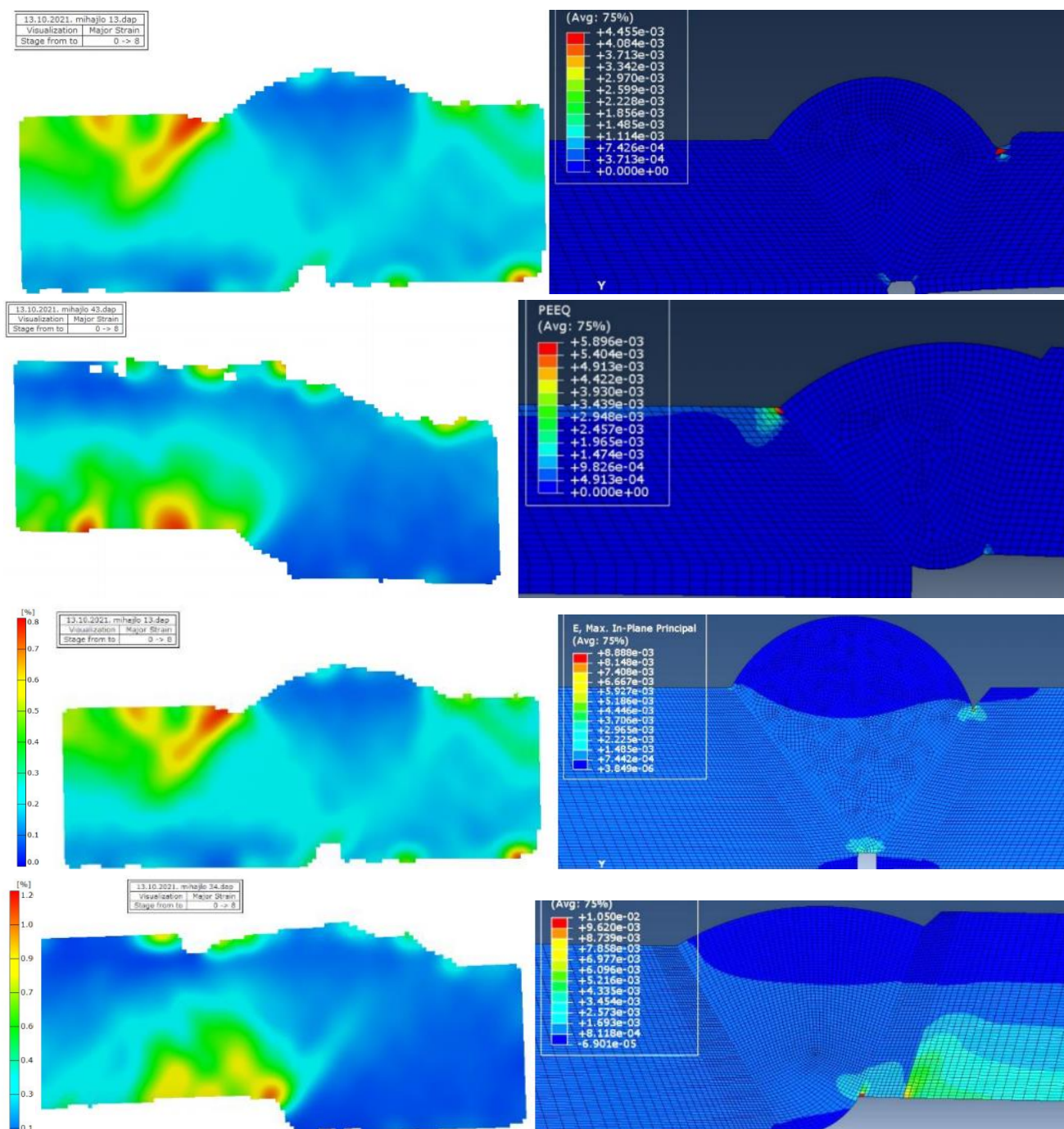


Figure 5. Comparison of numerical and DIC results /10, 11/.

As can be seen from the above figure, some models had shown better agreement with the DIC results in comparison to others, which is one of the main reasons why a more detailed approach to development of numerical models is eventually adopted, /11/. In short, this method involves varying of input mechanical properties (yield stress, tensile strength, deformation) in the HAZ until the distribution of stresses/strain in it matches the results obtained by DIC, with sufficient levels of accuracy.

#### CRACK GROWTH SIMULATIONS VIA XFEM

The next step in improving of the existing models is to introduce initial cracks in the most critical locations in each defect group (as determined by both numerical and experimental means) and analyse the behaviour of these models in terms of crack growth. Cracks are assumed to have an initial

length of 1-3 mm, for different defect combinations, and the extended finite element method is used /12-17/, since unlike the classic FEM, it has the ability to simulate crack growth.

Paper by Arandelović et al. /18/ involves the development of models with cracks, based on the experimental work from previous stages of this research. The experimental base, that has shown the critical locations of crack initiation, which coincide with the numerically determined locations in the models (locations of highest tensile stresses), are shown in Fig. 6.

Figure 7 shows the numerical models, with crack locations denoted by yellow lines. Three different initial crack lengths are used - 1, 2 and 3 mm, in order to obtain a more detailed insight in the behaviour of these welded joints in the presence of cracks, /18/.

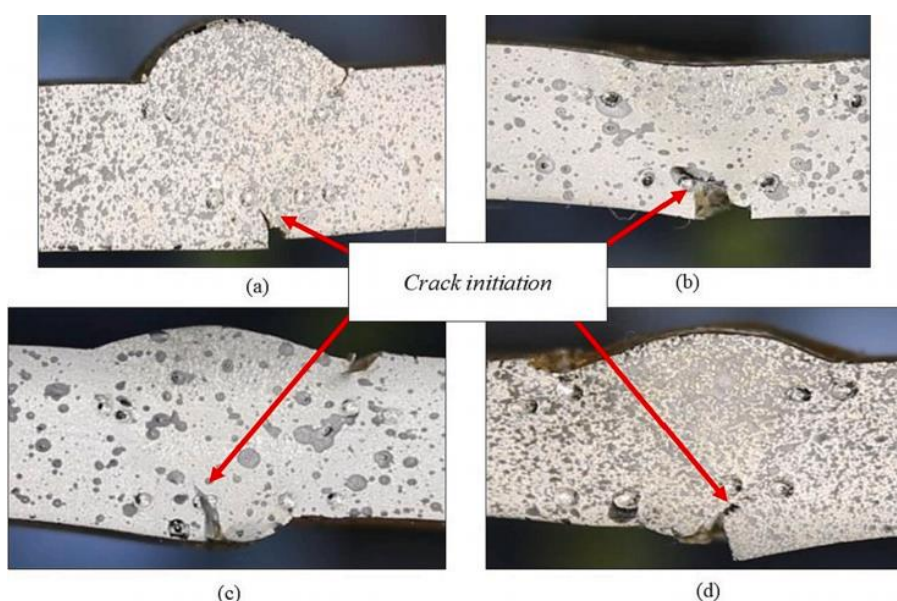


Figure 6. Crack initiation locations in each group specimen /18/.

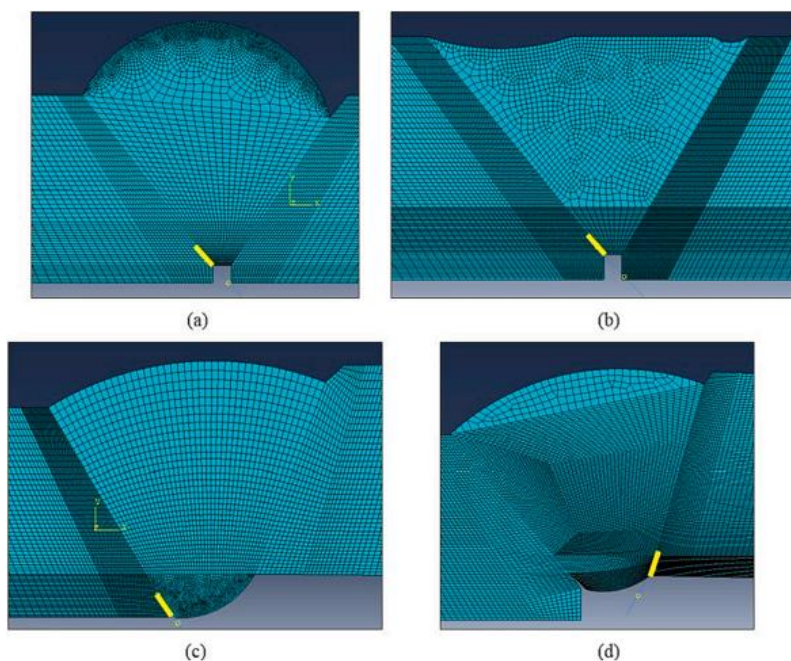


Figure 7. Initial crack locations, as determined by numerical simulations on models without cracks, /18/.

Some of the results from numerical analysis presented in /18/ are shown in Fig. 8. Results for the first two groups of defects (excess WM/undercut/incomplete root penetration and WM sagging/incomplete root penetration), as well as for the third group (excess WM/undercut/misalignment) include 3 mm initial crack lengths, whereas the 4<sup>th</sup> group (undercut/misalignment/incomplete root penetration) includes the 2 mm initial crack, since the 3 mm model could not be completed - this initial crack length actually corresponds to

the crack length for which the actual specimen would fail. These results have been selected since they illustrate the tendency of cracks - that initiated in the HAZ/fusion line - to propagate towards the WM. Additionally, the shape of the crack in the second group model corresponds to the experiment - in both cases, there is obvious crack tip blunting /18/. In the real test specimen, the cracks behave in a very similar manner, typically propagating towards/along the fusion line.

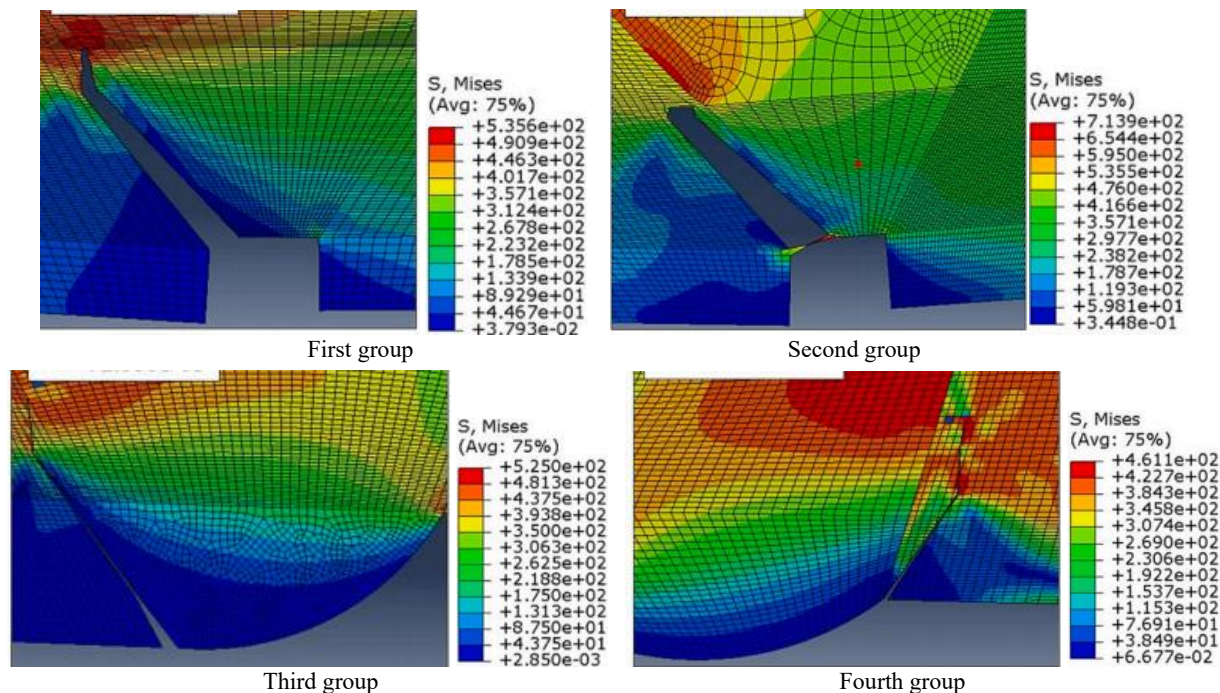


Figure 8. Numerical results for crack growth and stress distribution in specimens with multiple defects, /18/.

The next step in numerical analysis of the behaviour of such welded joints is to develop a prototype fatigue model which would simulate crack growth under cyclic loading. Initial results are obtained, and a base for future models is created, /19/. In this case, SMART crack, a more modern option for crack growth simulation is used instead of XFEM /20-23/. In order to fully analyse fatigue crack growth resistance of welded joints with multiple defect combinations, extensive experimental work needs to be conducted. Based on the results shown in Fig. 9 and in Table 1, it can be concluded that multiple defects significantly decrease the fatigue life of such welds. Next steps, once experimental results are obtained, will involve the accurate determining of the extent of fatigue life decrease for each group of defects. As for Fig. 9 and Table 1, results are given for third and fourth-group specimens and compared to a specimen produced without defects.

Table 1. Total fatigue crack length and number of cycles, /19/.

| Specimen        | Crack length | Number of cycles |
|-----------------|--------------|------------------|
| Third group     | 4.03 mm      | 17,300           |
| Fourth group    | 4.14 mm      | 30,000           |
| Without defects | 4.15 mm      | 900,000          |

Similar to the static crack growth simulations, the cracks propagate towards the fusion line, even though these models do not have different material properties for each welded

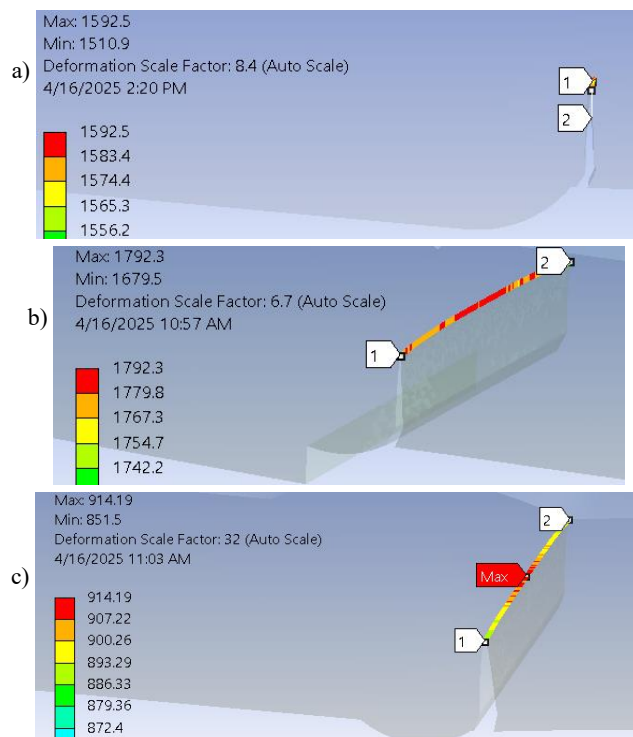


Figure 9. Stress intensity factors at the crack tip for: a) 4<sup>th</sup> group specimen; b) 3<sup>rd</sup> group specimen; c) defectless specimen, /19/.

joint region, which suggests that the geometry of the specimens, caused by the presence of the defects, plays a more significant role than what was initially assumed.

An interesting difference in the results can be observed in this case, when compared to the results of static crack growth simulations - the 3<sup>rd</sup> group of fatigue models is 'weaker' than the 4<sup>th</sup>, whereas in the static simulations, the 4<sup>th</sup> group is always the worst in terms of structural integrity, being the first to fail, due to higher stress concentration.

#### TRANSITION TO THREE-DIMENSIONAL MODELS

As can be seen from the last example, a 3D model is made. This is done for the purpose of more realistic fatigue crack growth simulation. Additional 3D models are then made, but with different goals. The first one is made in order to analyse the magnitude of stresses in directions other than the axial, i.e., along the  $y$  and  $z$  axes. This is necessary because of the way the specimens deform during the tensile tests. Due to their asymmetric geometry caused by defects, some specimens would deform along more directions which suggests that the stresses in these directions could not be neglected, which is typically the case during tensile tests.

The main focus is on the axis perpendicular to the welded joint ( $y$  axis), as noticeable deformation is observed along it. The goal of this research is to determine the ratio of stresses along this axis to the equivalent stresses. Typically, equivalent stresses in tensile test models are much higher

than stresses in the two perpendicular directions since the stress along the model axis is the dominant one.

Results shown in Fig. 10 confirm that stresses outside of the main axis do have a significant effect on overall stresses, reaching up to 40 % of equivalent stress for the third group and -65 % of equivalent stress for the fourth group. Another interesting aspect of these results is that some of the S22 ( $y$  axis) are negative (compressive). These stresses decrease the equivalent stress and explain why in certain cases some defects (vertical misalignment) actually negate the effects of other defects (e.g., undercut in the third group). This is observed in earlier, 2D models as well [4, 10, 12]. In this way, a more detailed insight into the influence of various defects in terms of geometry, is obtained.

The second example includes the preliminary results of the ongoing research which involves welded joints with defects, but in this case, two materials are welded, from different steel groups - one of S355 low-alloyed structural steel, and the other is S304L, an austenitic stainless steel.

The goal of this research is to confirm that the established methodology is applicable to other materials and defect combinations, and for this reason, a more specific combination of materials is selected - two steels with very different mechanical properties and different heat conductivity. As before, a specimen without defects is made, along with four different defect combinations. Figure 11 shows the first numerical model that is developed - the one without defects. Boundary conditions and loads are defined in the same way

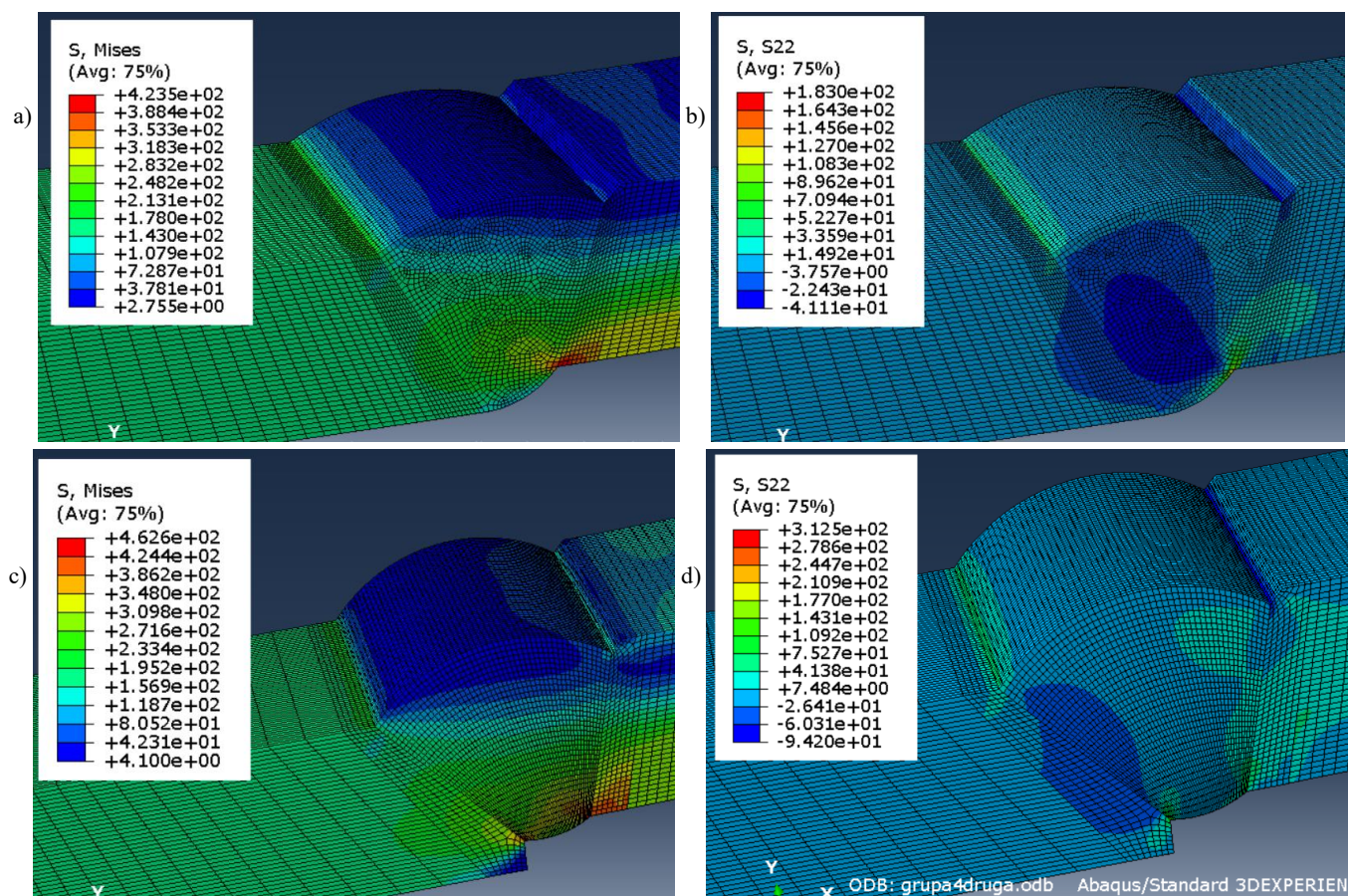


Figure 10. Comparison of equivalent stresses and  $y$  axis stresses for the third and fourth group specimens: a) equivalent stresses for the third group; b) S22 stresses for third group; c) equivalent stresses for the fourth group; d) S22 stresses for fourth group.

as in the previous models - one end is fixed, and the load (in the form of tension) is applied to the opposite end.

The approach to numerical modelling in this case is slightly different from before. The load is not predefined, instead calculations are performed iteratively with increases to stresses until the maximal stress at failure is obtained in the model, which is equal to the maximal stress from the experimental stress-strain curve. Load magnitude in the model which results in the stress distribution that corresponds to the experiment is almost the same as the force used during the experiment, showing good agreement between model and real specimen.

Figure 12 shows the stress distribution in this initial model. Grey areas represent stresses of 527 MPa and higher since this is the stress at which failure occurs in the parent material. Both the weld metal and the other material (S304L) had significantly higher tensile strength, which explains the extreme stress values in these regions without failure.

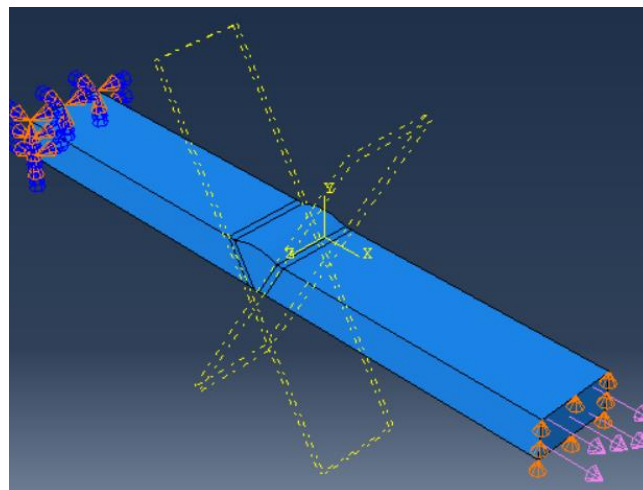


Figure 11. Geometry, loads and boundary conditions in the heterogeneous welded joint model.

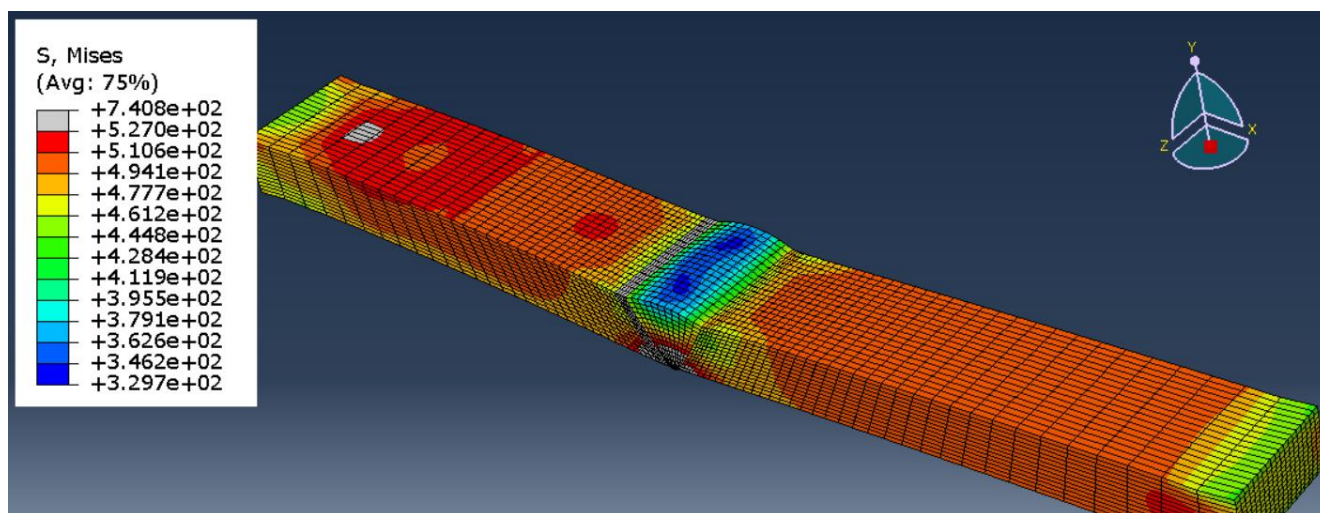


Figure 12. Geometry, loads and boundary conditions in the heterogeneous welded joint model.

It is worth noting that the plastic strain distribution in the numerical model corresponds to the experiment as well, with the former reaching around 19 % and the latter having maximal plastic strain of 18 %. During the experiment, the neck forms in the parent material, further away from the welded joint (as expected), and similar behaviour can be observed in the numerical model, where the critical location for failure is also in the PM, denoted by the small grey area on the left hand side of the image in Fig. 12.

## CONCLUSIONS AND FUTURE WORK

Work presented in this paper shows the evolution of numerical models based on experimental results and the use of DIC, from simple 2D models with numerous approximations to more complex and detailed calculations that take into account a number of factors that influence the behaviour of welded joints - presence of multiple defects, material heterogeneity and geometry on their integrity. With each new iteration of models, more insight into this behaviour is obtained, and the accuracy of obtained results improved. Another important contribution of these models is the determining of numerous issues which could occur during both numerical and experimental investigation of welded joints

with multiple defects, especially issues which may not be obvious, such as the presence of lack of fusion due to the combined effect of other, deliberately caused welded joint defects.

More recent efforts in this study have shifted towards using different materials, including a combination of structural steel and stainless steel, which also implies additional defect combinations, due to more complex issues with heat input. In addition, fatigue behaviour analysis will be another focus of future research. Finally, future work will also apply the newly developed iterative methodology for determining the mechanical tensile properties of the heat affected zone by using DIC results as the basis. The biggest advantage of this methodology lies in the fact that it is applicable to a wide range of issues, not necessarily related to welded joints with defects, but to the structural integrity of welded joints in general.

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