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Optimisation of numerical models of welded joints with multiple defect combinations

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Abstract

This paper presents the continued efforts in investigating behaviour of low-alloyed low-carbon steel welded joints in the presence of different combinations of multiple welding defects, (undercuts, incomplete root penetration, misalignments). Since these defect combinations can greatly affect the integrity of welded joints, due to significant changes in geometry which are induced by their presence. For this reason, a total of 8 numerical models were made, including four different defect combinations (2 models for each group). This number of models was equal to the number of actual test specimens that were used for tensile test experiments, which also provided the necessary input data (mechanical properties) for each model. The goal was to determine if the two models from each group were sufficiently similar to each other, so that in the future research, they could be replaced by a single, unified model for each defect combination. Comparison was made in terms of stress and strain distribution, and it was determined that three out of four models have nearly identical values, whereas the first group specimens had shown slightly bigger differences, which were still acceptable. Thus, it was concluded that a single representative model could be made for each defect combination group.

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Keywords: Welded joint defects; Finite element method; Steel S275

1. Introduction

Welded structures often require a lot of attention in terms of structural integrity, due to welded joint heterogeneity, as well as geometry, [1-5]. Geometry of welded joints plays a particularly important role in the case where defects are present in welded joints. Due to the very nature of welding processes, defects will always appear in joints, to a certain

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extent. In many cases, they are within acceptable limits, in accordance with relevant standards, such as EN ISO 6520 series. However, these standards tend to focus on one defect at a time, without considering the possibility of multiple different types of defects occurring in welded joints.

The goal of research which inspired the work that will be presented here was to determine the effects of several different combinations of welded joint defects on the integrity of a welded joints (mainly in terms of how stress and strain magnitudes and distributions change depending on which defects were present). After initial analyses with specimens made of S235 steel [6-8], a methodology was developed for the testing of specimens made of higher quality steel, S275 [9]. This methodology included the welding of plates, cutting of specimens, tensile and hardness tests, measuring of strains using digital image correlation [10-14] method (DIC) and the making of numerical models which would simulate real specimen behaviour as accurately as possible.

Based on the previous experience with steel S235, a number of improvements were made in order to optimise the whole process and eliminate/minimise the problems which were encountered initially. This paper will focus of the optimisation of numerical models for steel S275, where the goal was to obtain a representative model for each of the existing four groups of defects, and use those models for all of the simulations that would follow.

Since there were two models of specimens for each group (8 in total) initially, the idea was to compare each pair and determine if the stress/strain distributions are sufficiently close. This, if proven true, would allow each group to be represented by a single specimen, whose dimensions would be adopted as the average between the two initial values (dimensions in question being related to the size of weld metal and heat affected zones, which varied with each group). Obtained results have shown sufficient similarity for each pair, and thus it was concluded that a single, representative numerical model could be adopted for each specimen group.

2. Experimental basis

Before explaining the development of mechanical models, a short overview of the experimental part of the research will be shown, in order to better understand how the geometries for each model were adopted. For this purpose, the dimensions of real specimens for all four groups are shown in figures 1-4. Each group had its unique combination of welded joint defects, mostly including those which are typically expected for the adopted welding procedure (metal active gas welding – MAG) and the welded structure application, which in this case was related to piping. Welded joint specimen groups were defined as follows:

- First group – excess weld metal, weld face undercut, incomplete root penetration
- Second group – weld metal sagging, incomplete root penetration
- Third group – vertical misalignment, weld face undercut, excess weld metal
- Fourth group - vertical misalignment, weld face undercut, incomplete root penetration and excess weld metal.

Tensile tests of the aforementioned specimens were performed, and stress-strain diagrams were then made, based on force-displacement diagrams. These would be later used as the input data for the numerical simulations. Each individual specimen had its own yield stress/tensile strength combination, in accordance with the relevant stress-strain diagrams, although these differences were rather small between specimens from the same defect group.

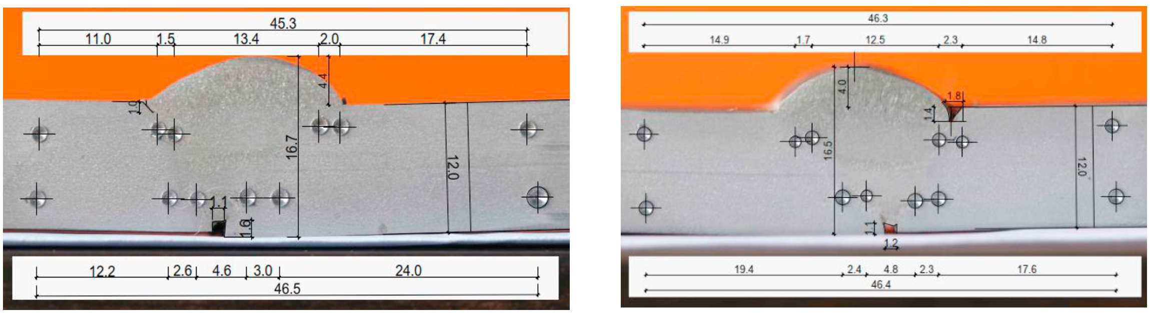


Figure 1. Dimensions for the first group of specimens.

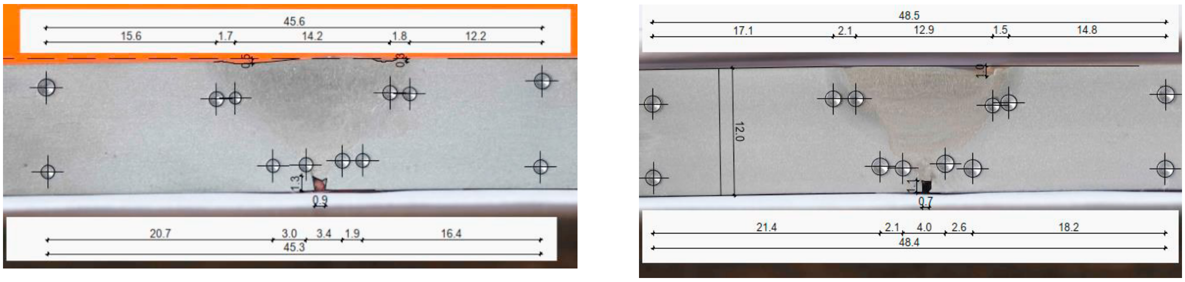


Figure 2. Dimensions for the second group of specimens.

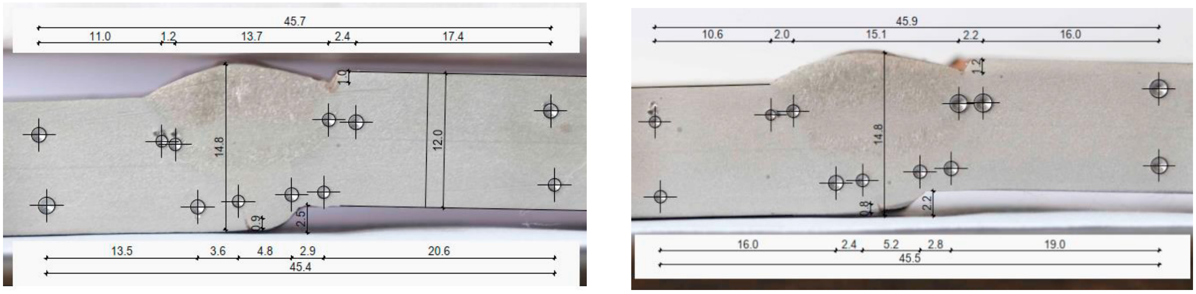


Figure 3. Dimensions for the third group of specimens.

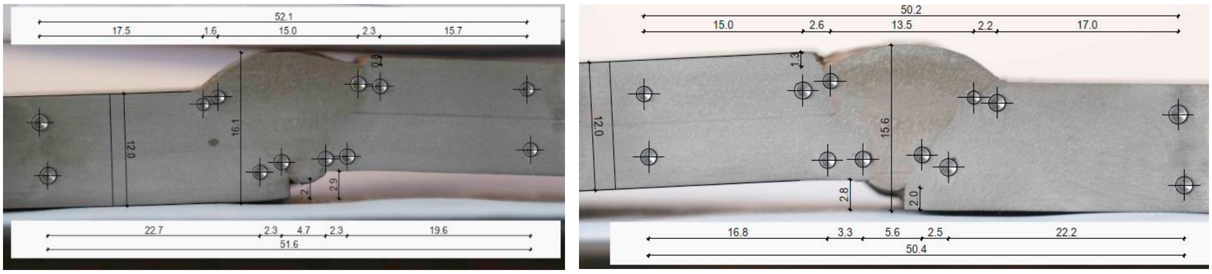


Figure 4. Dimensions for the fourth group of specimens.

Dimensions of defects in the numerical model, as well as the position of welded plates, were based on the figures shown above, which include detailed measures for each specimen. This was actually the first step towards improving the models – in the previous case involving S235 specimens and models, dimensions were not measured this accurately, since the goal then was to obtain functional models in term of behavior, without focusing too much on actual stress/strain values [6-8].

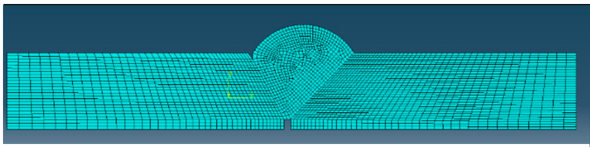
3. Finite element method approach

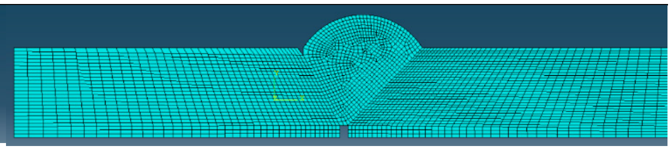
This chapter will describe the development of numerical models, using the finite element method, as the common and most efficient way to analyze stress and strain state in a welded joint, [2-4, 6-8, 15-22]. This method is based on discretization of physical models into finite elements, while defining the adequate boundary conditions and loads. Results are obtained by determining the displacement of each finite element under the predefined conditions, and deformation and stresses are then calculated based on these results. This is, in short, how numerical simulations which will be presented here work, and more detail about it can be found in the references.

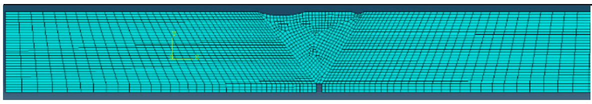
The models, with their corresponding finite element meshes, are shown in table 1 below. These meshes were a result of a number of iterations, which were performed in order to ensure result convergence, i.e. the proper accuracy of the obtained stress/strain states. Once the adequate finite element meshes were defined, the results could be reliably compared to each other, in order to determine if there are any significant differences between the models for each pair of specimens.

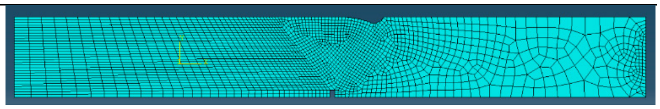
Unlike typical simulations involving butt welded joints, this one had some very specific problems related to geometry – some of the specimens were so asymmetrical that there was a significant difference in behavior depending on which side the load was applied to. In other words, when defining the locations of boundary conditions and loads in the numerical models, additional attention had to be paid to which side of the model will be fixed, and which will be subjected to tension. This was particularly prominent in the case of models representing third and fourth groups (ones with vertical misalignment).

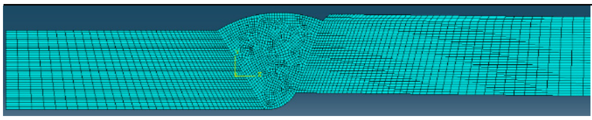
Table 1. Finite element meshes for all four groups of numerical models of specimens

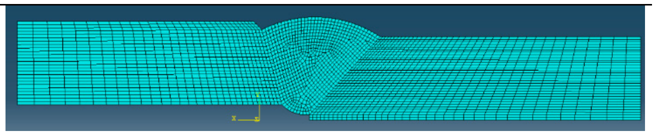

First specimen group (specimen 1.1)

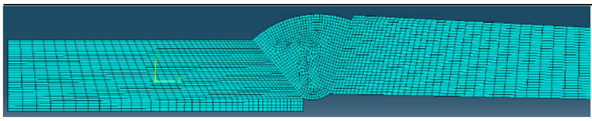

First specimen group (specimen 1.2)

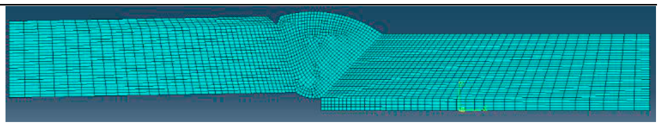

Second specimen group (specimen 2.1)


Second specimen group (specimen 2.2)


Third specimen group (specimen 3.1)


Third specimen group (specimen 3.2)


Fourth specimen group (specimen 4.1)


Fourth specimen group (specimen 4.1)

As can be seen from the table, the meshes were very similar between each pair of specimens from the same group. The only notable expection is the second group, but that part of the finite element mesh is located further away from the areas subjected to highest stresses, i.e. areas of interest for this analysis, so there was no need to further refine that part of the mesh. This was confirmed by the results that were obtained.

As for the definition of loads, they were adopted according to the tensile forces (from the actual experiments) which corresponded to the yield stress levels for each specimen, and ranged from 187 MPa to 247 MPa. To avoid confusion, loads were defined in the form of pressure (relative to the actual force), since applying a concentrated force as load in ABAQUS software is unnecessarily complicated and impractical.

4. Results of numerical simulations

This section of the paper contains the comparison between the results obtained by numerical simulations of specimen pairs for all four groups of defects, in terms of stress magnitudes and distribution. The goal was to determine the differences in maximum stress values, to see if they are sufficiently close to each other. If this was proven correct, future simulations of this kind would be much easier and faster, since every defect combination group could be represented by a single specimen.

Figure 5 shows the comparison of results obtained for group 1 specimens (excess weld metal, undercut, incomplete root penetration. In this case, a difference of around 10% in maximum stress values can be observed, which is still within acceptable limits, especially when considering that the stress distribution is very similar in all critical locations, i.e. where the defects were located. In both cases, incomplete root penetration was the location of highest stresses, followed by the undercut, which was not so prominent (with stresses of around 305 MPa for specimen 1.1 and 270 MPa for 1.2). In both cases, the excess weld metalhad the lowest stresses, of similar values.

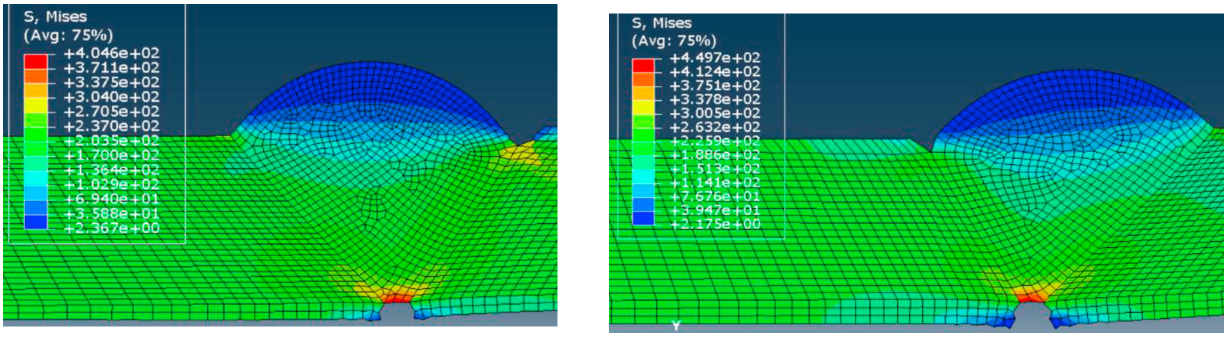


Figure 5. Stress analysis results for specimens from the first group of defects (specimen 1.1 – left, specimen 1.2 – right)

Figure 6 shows the results for the pair of second group specimens, including weld metal sagging and incomplete root penetration. As can be seen, there is not much to discuss in terms of stress values – their maximum values were identical. The only noticeable difference was in the weld face, where specimen 2.2 had stresses of around 423 MPa, compared to specimen 2.1 and its 350 MPa. Still, the distribution of stresses was once again very similar.

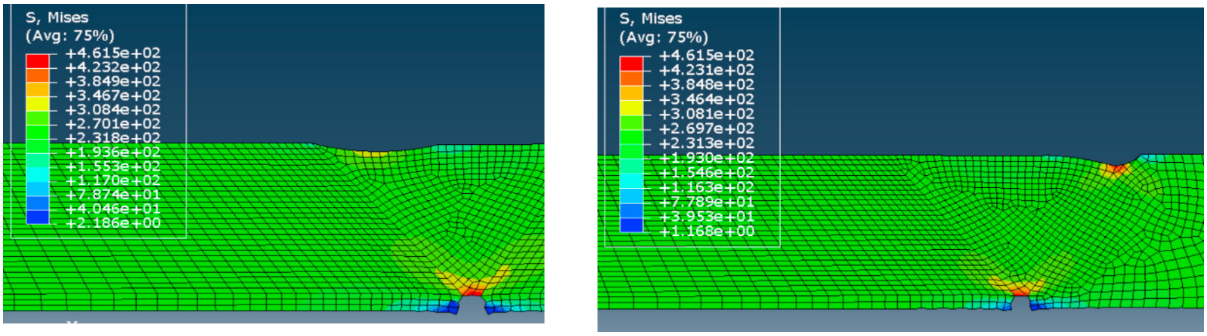


Figure 6. Stress analysis results for specimens from the second group of defects (specimen 2.1 – left, specimen 2.2 – right)

Figure 7 represents the comparison of results for specimens 3.1 and 3.2, from the defect combination of undercuts, excess weld metal and vertical misalignment. This model had shown the biggest difference in results, 12.1%, which can still be considered acceptable, considering that the usual differences in results that can occur in case of numerical simulations (both when compared to each other or to experimental results) can be up to 20% and still be considered valid. Stress distribution in this case was mostly the same, with the exception of the weld root. This is not surprising, considering that this region of the welded joint had the most prominent difference in geometry between the two models.

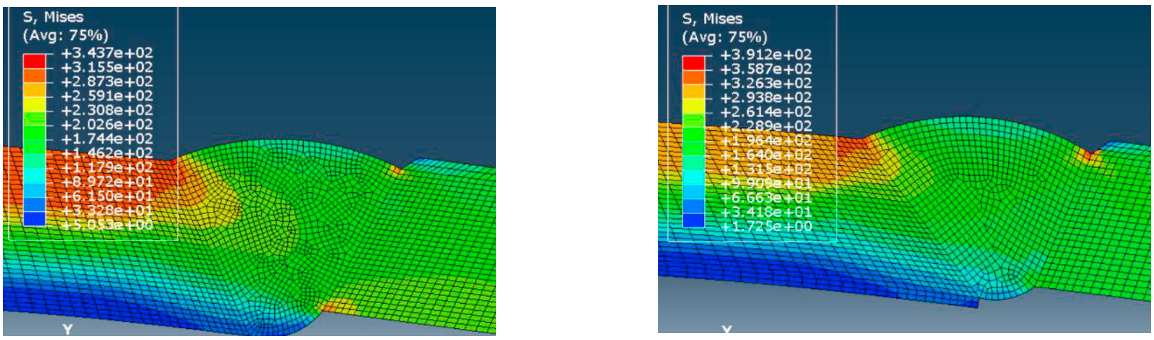


Figure 7. Stress analysis results for specimens from the third group of defects (specimen 3.1 – left, specimen 3.2 – right)

Finally, figure 8 shows the models from the last group of specimens, ones with undercut, vertical misalignment and incomplete root penetration. Maximum stress in model 4.1 was 301 MPa, whereas in the case of model 4.2, it was slightly higher – 322 MPa, suggesting an acceptable 6.5% difference. Stress distribution was also quite similar, with critical locations in the higher side of the weld root, and the part of the weld face opposite of it. Most of the differences in this case were the consequence of vertical misalignment, like in the previous case.

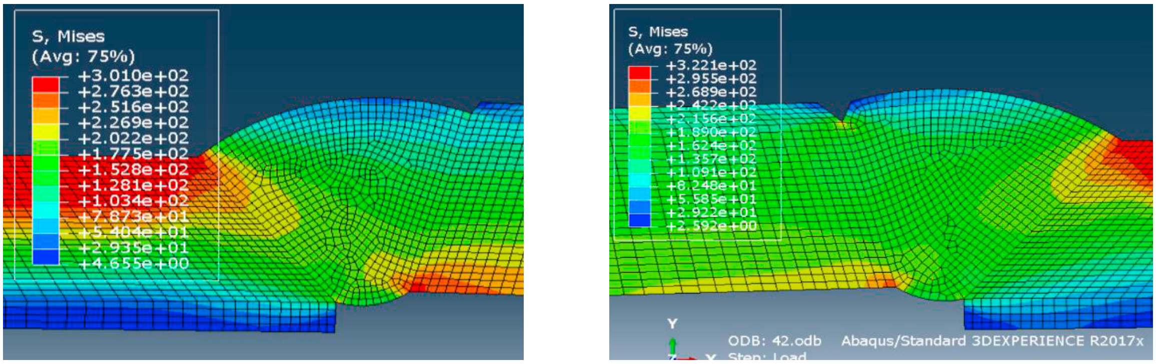


Figure 8. Stress analysis results for specimens from the fourth group of defects (specimen 4.1 – left, specimen 4.2 – right)

5. Discussion and conclusions

The comparison between two models of specimens for each of the four groups had confirmed the initial assumption of the author that each group can be approximated by a single, representative specimen. As indicated in figures 5-8, the differences between each pair were sufficiently small to ensure a good level of accuracy, despite certain differences in geometry. Specimens from the second group had shown the best compliance, having identical values of maximum stress, which makes sense considering that the differences between their geometries were minimal, compared to others. In fact, they came as close to being symmetrical as possible under the assumed circumstances (presence of multiple different defects in each welded joint). This was also the only case where stress distribution differed more significantly than the magnitudes themselves. The rest of the groups were similar in terms of differences – ranging from 6.5 to 12.1%. All of these can be considered valid, thus justifying the future approach of approximating all specimens from each group with a single one.

Still, there are some things to consider here – the results indicate that some differences are noticeably bigger than others and the reasons for this should also be discussed. Based on the geometries of each pair, it can be seen that bigger differences in geometry lead to bigger differences in stress values. It might not be obvious for the first group, but the excess weld metal for specimen 1.1 was 0.4 mm higher than the one in 1.2, giving the first one a greater load-bearing cross-section, thus decreasing the overall stresses. On the other hand, the stresses in the undercut are higher in 1.2, since higher excess weld metal also results in sharper angle of transition between it and the undercut.

The third group has the biggest differences in geometry and also the biggest differences in stresses and their distribution. Finally, the specimens in the fourth group are not that much different when it comes to dimensions of defects, but still show some difference in results, suggesting that the presence of vertical misalignment in itself affects the accuracy of results.

Of course, all of the results still remain in acceptable limits of each other in this case, so the ultimate goal of this research was achieved. The above discussion, on the other hand, indicates that there is still a limit to how much geometries of same group specimens can differ before a point is reached where the accuracy of their models is no longer at a satisfying level. This is a question that should be answered by a more detailed analysis, which could include larger groups of specimens, as well as welded joints made of other materials (such as high-alloyed steels), wherein combinations of defects could have a much more noticeable effect on both geometry and integrity of welds.

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