ELASTIC-PLASTIC NUMERICAL ANALYSIS OF TENSILE SPECIMENS WITH SURFACE CENTER-CRACKED ASYMMETRIC WELDED X-JOINTS

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Abstract

The aim of this work is to determine appropriate numerical model to simulate the experimental evaluation of fracture resistance properties of tensile panels with surface crack located in the central section of asymmetric X-joint. The investigation is performed on high-strength low alloyed (HSLA) steel with undermetched weld configuration. Numerical analysis was carried out by ABAQUS three dimensional elastic plastic analysis mode. The work was performed on centre-cracked welded specimens, with two different sized cracks in order to examine the geometry impact on fracture resistance parameters. Comparison between experimental and numerically obtained results is done with attention focused on J-integral, crack mouth opening displacement (CMOD) and J-R resistant curves. Results are discussed in terms of further development on modeling procedure and technique. Approaching to real fracture behavior in similar welded structures with numerical investigation, can be far more economical solution instead of performing experiments. This paper, shows that simulations are promising in respect to their accuracy and can be used as a toll for further development of numerical models that have more complex nature.

Keywords:

welded joint, surface crack, heterogeneity, mismatch

1. Introduction

In engineering structures, particularly in produced welded joints, cracks are likely to arise from weld defects, inclusions, surface damage etc., and it is necessary to design structures with the knowledge that cracks are already present and capable of propagation at stresses below the macroscopic yield stress as measured in a tensile test. The service safety of welded structures is strongly dependent on the integrity and fracture resistance of the welded joints. A proper integrity assessment of a welded structure is more complex than that of the constituent materials because the welded joint may consist of two or more regions of different materials, each region having its own tensile and fracture properties. Considering this, it is necessary to develop an adequate evaluation procedure and systematization of fracture resistance properties of each region of the welded joint. It is commonly accepted to distinguish between three major regions: the base metal (BM), the heat-affected zone (HAZ) and the fusion zone or weld metal (WM). Mechanical properties (such as strength, toughness and ultimate tensile strength) as well as micro-structural properties are significantly different and change as distanced away from the fusion region. At a certain distance from the fusion zone the material is not affected by the welding process and has the properties of the original BM. The WM and BM are considered as different but homogeneous materials. The HAZ material is inhomogeneous in respect to both mechanical and micro structural properties and its located between the BM and WM without any sharp interface. Structural performance, deformation, stress and fracture behavior of welded joints can be distinctly affected by these region differences [1-2]. Crack propagation is strongly influenced by difference in fracture toughness and yield strength of WM, BM and HAZ. If the strength of the WM is lower compared to BM, this generally leads to an undermatched weld configuration ($M<1$) which is suitable for HSLA steel structures in order to avoid cold cracks [1-2]. In this case plastic strains are localized in weld metal until strain hardening is fully exhausted and then the BM starts to yield. But even this is the ductile type of failure, HAZ is still considered to be a weak point for crack initiation since its straining could be constrained during deformation [2]. When examining the effects of WM undermatching on structural integrity it is essential to determine the materials resistance to crack extension [1]. Many analytical and experimental studies on elastic-plastic fracture mechanics (EPFM) suggest that J-integral and crack mouth opening displacement

(CMOD) are the most viable parameters for characterizing initiation of crack growth, the stable crack growth and the subsequent instability that occur in ductile materials [3-4]. This clearly indicates that the fracture parameters like J-integral and CMOD can be conveniently used to assess structural integrity for both leak-before-break and in-service flaw acceptance criteria in degraded welded structures. J-integral is a suitable parameter for characterization of plastic deformation around crack tip, however, it should be noted that this parameter still possesses some theoretical limitations [4-5]. Nevertheless, possible error is considered tolerable if the relative amount of crack extension stays within a certain limit and if elastic unloading and non-proportional plastic loading zones around a crack tip are surrounded by a much larger zone of nearly proportional loading controlled by the HRR field. Under this condition of J-dominance, both the onset and limited amount of crack growth can be correlated to the critical values of J and J-resistance curve, respectively.The comparison of crack driving force, expressed by J-integral and materials J-R curve provides the critical crack extension. The method of resisting curves is based on elastic-plastic analysis and can provide an adequate assessment in terms of plane state of stress [6]. In this paper, the reader will find basic concepts for numerical investigation of tensile panels made of HSLA steel with assymetric X welded joint in the central section. In order to study the ductile fracture behaviour of undermetched weld metal, two surface cracks are introduced in the weld metal, refered as long and short. The geometry of the tensile panel and the shape of the surface cracks are given in Fig. 1.

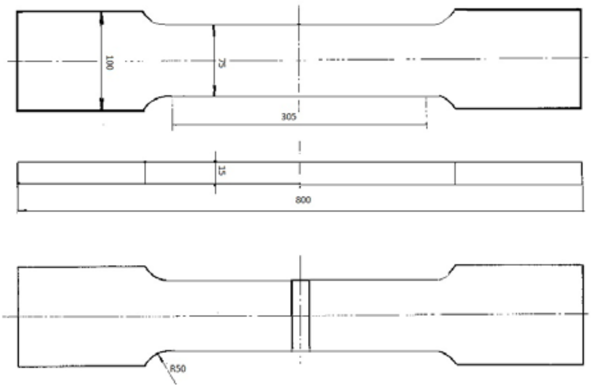

Figure 1. Geometry of tensile panels

The considered problem has an important role in further development of numerical models that will provide solid estimation of mechanical properties and ductile fracture behavior in heterogeneous regions such as HAZ or homogeneous WM with complex asymmetric X groove. The tensile panels are simulated in Abaqus 6.13-1 using the three-dimensional finite element method. The combination of numerical simulation and experimental data obtained from previous investigations, can easily provide accurate results for the fracture response.The comparison between the obtained results is given graphically and several conclusions are drawn from the here elaborated numerical analysis.

2. Experimental procedure and data

In order to get a closer insight in the stress-strain distribution and fracture resistance capability in undermatched butt welded joints, several tensile tests were made on tensile panels. The material used for this investigation is high-strength low-alloyed steel Suminten 80P, commonly used for pressure vessels and pipelines. The modulus of elasticity according to obtained results is E=206845 MPa and hence the yield stress R_{eh}=796MPa and poason ratio ν= 0.3, are used as an input data. The welded specimens are produces with submerged arc welding process using consumables of US 80B wire and MF38 flux [6]. Results from tension testing of welded metal show that R_{eh} and R_m are smaller than the one obtained for basic metal, so this is a clear case of undermatched weld configuration. The mismatch factor determined from yield strengths of base and weld metal is 0.74. Three tensile panels are made of base metal (without weld), one without crack and the other two are with introduced surface crack (long surface crack and short surface crack respectively) in the middle of the tensile panel. Tensile tests were also made on six other welded panels (with asymmetric X groove weld), with short crack and long cracks introduced in WM and in HAZ region respectively. In this study, only panels made of basic metal with introduced semi-elliptical short surface crack (2c=26mm, a=2,5mm) and long surface crack (2c=25mm, a=5mm) are analysed. An illustrated preview of a semi-elliptical crack is shown in Fig.2.

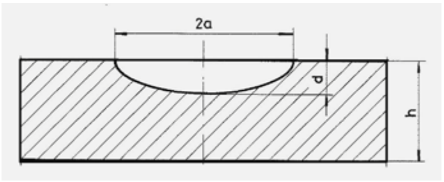

Figure 2. Geometry of tensile panels

3. Numerical simulation

Three-dimensional models are developed for determining fracture and ductile behaviour of cracks through basic elastic-plastic fracture mechanics parameters. The effect of the restrictions around the crack tip, heterogeneity and mechanical load conditions were carefully studied and with the help of Abaqus and finite element method two tensile specimens are modelled with surface cracks with different geometries. For facilitating the calculation process of the parameters, the analysis is made on 1/4 of the specimens with assigned limitations arising from the presence of the material in the surrounding area of the cut. This type of modelling is already used by several researchers in terms of computational economy [7]. In the models the zone ahead of the crack front is modelled with minimum of two layers of elements with a highly refined mesh stretch out across the ligament, because of expected damage and crack propagation in this region. Coarse meshes are applied beyond this region where no significant material degradation is expected. In current models is assumed that the materials of weld metal and base metal are isotropic in order to simplify the finite analysis. It is considered that the coarse grained and fined grained zones are very small and have small effect on stress and strain distributions along the tensile panel and on the overall load capacity of the specimens. Both models have all of the geometrical attributes of the welded joints, but the materials assigned in each zone are the one obtained from the numerical calculations made in the beginning of the investigation for material calibrations with very small variation. The focus of the numerical investigation is analysis of different crack geometries in under-match welded asymmetric joints. The materials of both base and weld metals have been modelled by using conventional von Mises plasticity with large displacement analysis. The mesh size near the cracks was chosen to approximate the mean free path between non-metallic inclusions, that is 0,2 x 0,2 mm quadratic elements. Layers along crack front which are distanced are not influential or significant and so coarser mesh is applied. This is also the case in the areas away from the welded joint, so the smooth transition from very small mesh elements to large ones is applied as indicated in Fig.3.

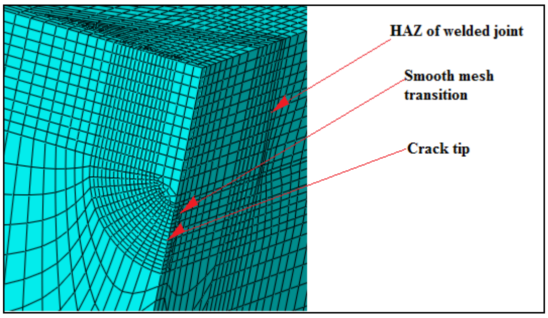

Figure 3. Geometry of tensile panels

The numerical computations were performed using ABAQUS 6.13-1 three-dimensional elastic–plastic analysis mode. The different weld zones (BM, HAZ and WM) are assumed to have isotropic elastic-plastic behaviour. Symmetry conditions are applied, that enabled modeling of one-quarter of the specimen. The elements in both models are 20-node quadratic isoparametric. The crack tip is surrounded by finer mesh for obtaining more punctual calculations.The finite element mesh details are given in table 1 and displayed in figure 4.

Table 1.Model details

Model designation		Element type	Elements	Nodes
WMSC	Tensile panel with small crack in WM	C3D20R	26932	118063
WMLC	Tensile panel with large crack in WM	C3D20R	19176	85290

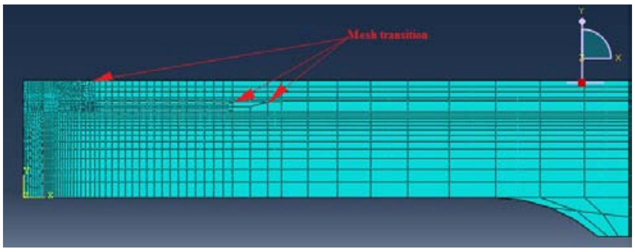

Figure 4. Details showing mesh transition

Details concerning the geometries of tensile panels with semi-elliptical surface cracks in the central region of the asymmetric welded joint are given in table 5.

Table 5.Geometries of center cracked tensile panels in welded joint

Specimen	t	2W	2c	ao	ao/t	ao/c	c/W
MSC	15	75	16	2.5	0.33	0.313	0.21
WMLC	15	75	26	5.0	0.17	0.384	0.35

4. Results

Based on a series of computations, the relationship between the J-integral and CMOD is obtained for WMSC and WMLC. The specimens have the same weld strength mismatching assigned and have different crack geometries. Results show that the values for J-integral and CMOD change significantly when the loading is increased. When the load becomes significant the effect of the strength mismatching becomes strong. The reason for this may be related to the change in plastic constraint level. In general, under-metching increases constraint.The constraint level produced in specimens containing strength mismatched joints are dependent on the size of the plastic zone in the crack tip [8-11].Figure 5 and 7 display results obtained from model WMSC. Figure 6 and 8 show results obtained from model WMLC. Figure 9 and 10 represents the F-CMOD relationship between results from numerical and experimental investigation for both small and large crack cases.

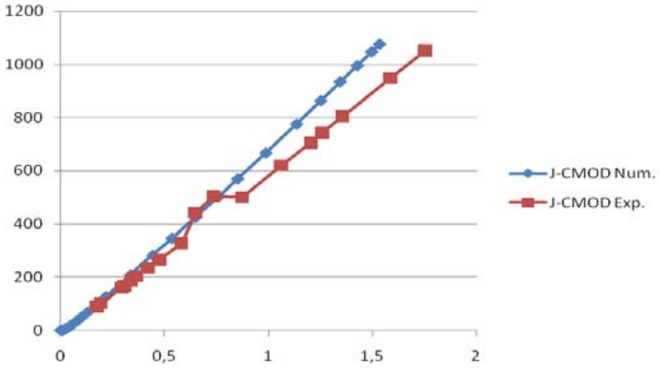

Figure 5. J-CMOD results for 3D model WMSC compared with experiments

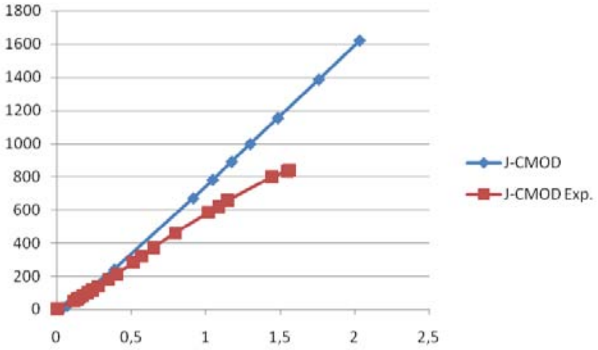

Figure 6. J-CMOD results for 3D model WMLC compared with experiments

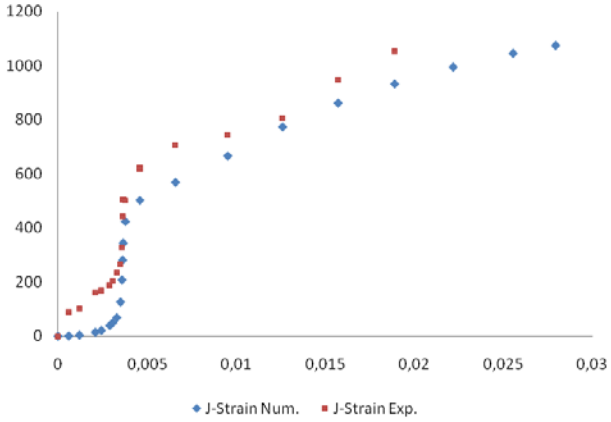

Figure 7. J-Strain results for 3D model WMSC compared with experiments

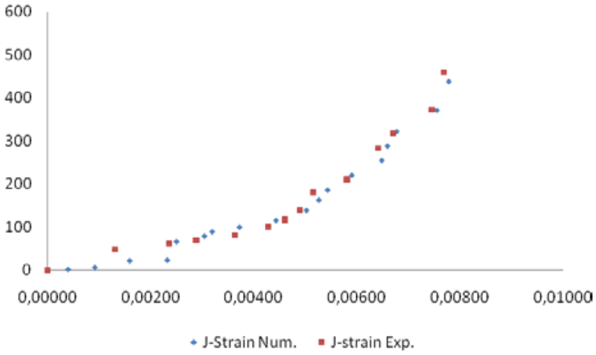

Figure 8. J-Strain results for 3D model WMLC compared with experiments

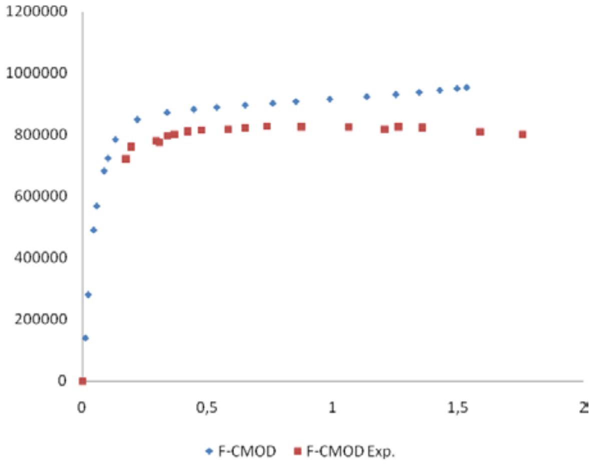

Figure 9. F-CMOD results for 3D model WMSC compared with experiments

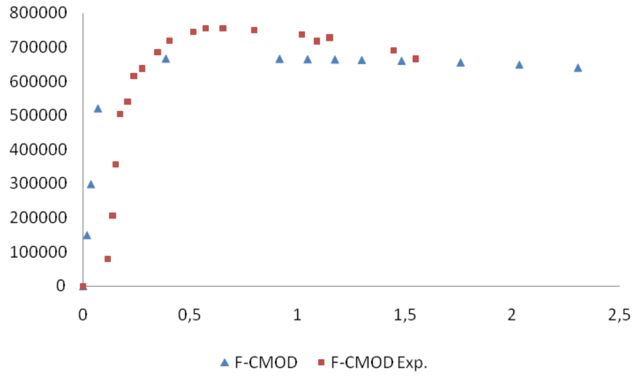

Figure 10. F-CMOD results for 3D model WMLC compared with experiments

5. Conclusion

Based on the results obtained, it is expected that the mismatching effect becomes significant at greater load levels. Moreover, the computation showed that crack size is related to plastic constraint of the crack tip and therefore must have an important influence on the relationship between the J-integral and CMOD. The effect of weld strength mismatching and crack size and geometry on the evolution of the equivalent plastic strain field can be clearly demonstrated. Although some recent results show that the crack length appears to have very little effect on the plastic constraint factor [11], in this investigation it has been shown that crack length have a strong influence on the relationship between the J-integral and CMOD. Figure 6 shows the results for under-matched welded joints in which the rate of increase of the J-integral values with an increase in CMOD values is highest for specimens with large crack.

From the above discussion, it is indicated that the relationship between J-integral and CMOD is affected by loading conditions, flow properties of the base and weld metals, crack size and weld width. This means that if the onset of crack growth occurs when CMOD attains a critical value, the value of the J-integral associated with the onset of the crack growth is not unique. It depends on the weld strength mismatching and geometry factors. It is very difficult to maintain a simple relationship between J-integral and CMOD for the welded joints and other factors must be considered. The results of this work gives future possibilities for calculating the quantification of the change between the J-integral and CMOD occurring in welded specimens.

The numerical analysis proved to be sufficiently reliable in order to serve as a basis for further development and improvement, since they can not cover precisely all the factors and mechanisms that influence the behavior of the material in the non-linear elastic-plastic regime. But, considering the fact that experimental research can not fully anticipate all situations that might affect, further ideas and thoughts should turn towards solutions that will unite several methods. The successful combination of theoretical, numerical and experimental research can be the key for getting results that will bring us closer to the real behavior of cracks.

6. References

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