ECF22 - Loading and Environmental effects on Structural Integrity

Numerical simulation of crack propagation in high-strength low-alloyed welded steel

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Abstract

The industrial application of high-strength low-alloyed steel (HSLA) in welded structures has increased the demand for understanding fracture behavior and structural integrity assessment of this type of steel and produced welded joints. The aim of this paper is to simulate the experimental evaluation of the fracture mechanics specimens by using the micromechanical model. The investigation is performed on two standard single edge notch bend (SENB) specimens with imposed crack in the central region. Numerical analysis was carried out by using Simulia Abaqus software package on 2D models used to simulate the damage development on the local level. The comparison between numerical and experimental results is presented through measured values of J-integral, load-line displacement v_{LL} and crack growth resistance (J-Δa) curves. This paper shows that numerical simulations are promising in respect to their accuracy. The application of this model enables to decrease the amount of expensive experiments for determination of the load level that causes crack propagation.

Keywords: high strength steels; welded joints; strength mismatching; finite element method; crack propagation; fracture mechanics

1. Introduction

The application of HSLA steel in modern design of welded structures exposed to high pressure (such as pressure vessels, storage tanks, penstock, pipes) requires the evidence of operational safety under real loading conditions. Industrial assessment of welded joints is necessary to provide safety, having in mind heterogeneity and the constraint effect on fracture behavior that rise from micro-structural differences in the heat affected zone and the weld metal that usually have low toughness. Structural integrity issues of welding HSLA steels are associated with different problems among which the occurrence of crack-like defects in welded joints is the most common, Jindal et al. (2012). These

defects, regardless of their nature and origin of occurrence (in production or operation), must be determined by the appropriate parameters and features for a realistic assessment of the remaining load capacity of the welded structure.

J-integral and CTOD are widely used as elastic-plastic fracture parameters for characterization of the material state around crack tip. It is, however, noted that they posses certain limitations. Since there is no standard procedure for fracture mechanics testing of specimens with welds, and the mechanical heterogeneity of welded joints makes the determination of the CTOD from the measurement of the crack mouth opening displacement more difficult, therefore it is preferable that the J-integral analysis is used instead of CTOD, Shi et al. (1998). There are also some theoretical limitations of J-integral, like the fact that the HRR singular field may not be valid in the case of certain amount of crack extension where J ceases to act as amplifier for this singular field, Shi et al. (1998), Rice and Rosengren (1968), Hutchinson (1968). 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 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.

It is very difficult to provide solid estimation of mechanical properties and ductile fracture behavior in heterogeneous and homogeneous regions (such as heat affected zone, weld metal and base metal) of a welded joint with the conventional methods. Therefore, the numerical simulations that are developed based on elastic-plastic finite element method (FEM) for nonlinear stress analysis can be a significant tool for investigation. FEM is widely used in computer programs for easier and quicker numerical calculations for various parameters, among which are the fracture parameters for determination of crack behavior. There are many procedures developed and implemented in computer programs, so the application of standard finite elements is possible without significant adaptation of the mesh. The J integral calculation is also implemented as a standard option that can be calculated for the specific problem.

The aim of this work is to simulate the experimental evaluation of fracture resistance properties of single edge notch bend (SENB) with crack located in the central section of weld and basic metal. There are different methods of numerical simulation and analysis of the initiation and propagation of crack. 2D micromechanical models are used to simulate the local fracture. The objective of this study is determination of the effect of mechanical heterogeneity on ductile crack initiation and propagation in welds using micromechanical approach.

2. FEM computational methods

In this study, an elastic–plastic finite element method has been used to investigate the effects of weld strength mismatching on the J-integral, Force - load-line displacement v_{LL} and J-Δa curves. Two SENB specimens were examined, one that is pre-cracked in the middle of the weld metal and one made only from the base metal with a pre-crack in the middle, Fig. 1.
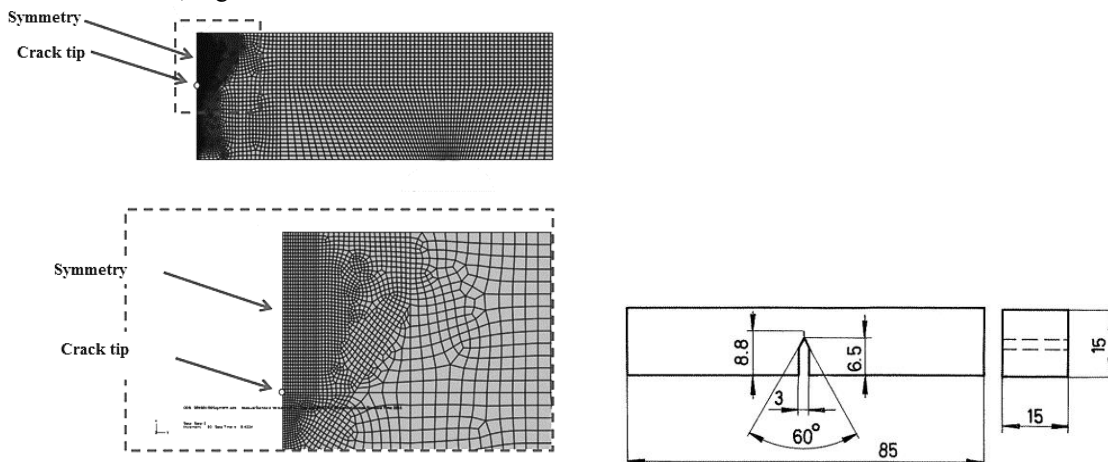

Fig. 1. Geometry and mesh configuration of center-cracked SENB specimen

Numerical computation was performed using two-dimensional elastic–plastic analysis mode, Abaqus (2017). These SENB specimens are analyzed in conditions of plane strain state. The isoparametric square finite elements are used to simulate the propagation of the crack. At the top of the crack, square elements with a size of 0.2 x 0.2 mm are used for the pre-cracked SENB specimen in the metal of the weld and the base metal. The size of both SENB specimens with length of pre-cracks in the center are given in Table 1. The base material is a HSLA steel Sumiten 80P, Petrovski et al. (1991). The mechanical properties of base material (BM) and weld metal (WM) are given in Table 2.

Table 1. Pre-crack lengths for the tested SENB specimens.

Specimen designation	B(mm)	W(mm)	a_0 (mm)	a_0/W
SENB-BM	15	15	8.8	0.587
SENB-WM	15	15	8.6	0.573

Table 2. Mechanical properties of material.

Specimen designation	σ_Y(MPa)	σ_m (MPa)	E (MPa)
SENB-BM	797.9	842	206843
SENB-WM	595	770	200000

Generally, there are six possible methods to simulate crack propagation in finite element analysis: element splitting, node releasing, element deleting, stiffness decreasing, remeshing and extended finite element method X-FEM. Stiffness decreasing technique has been used in this work. In the models, the tearing zone is a single layer in front of the prospective crack plane to simulate ductile tearing. Crack propagation in both SENB specimens is numerically modeled with application of Gurson yield criterion, through the complete Gurson model (CGM), Zhang et al. (2000). This model includes the void coalescence criterion, Thomason (1990), and critical damage parameter value used as the failure criterion is not a material constant, but depends on the stress/strain state and constraint level, Rakin et al. (2013). The crack growth simulation is performed by tracking the deterioration of elements in front of the crack tip. Unlike the Gurson-Tvergaard-Needleman (GTN) model, Gurson (1977) and Tvergaard (1981), the critical value of damage parameter f_c is not used as an input for calculating in CGM, but a variable that is calculated with the analysis. This value corresponds to the initiation of the ductile fracture and is taken as a criterion for fracture in this work. CGM is used through the UMAT subroutine created by Z.L. Zhang. The parameters of the Gurson model are given in Table 3.

Table 3. Gurson model parameters.

	f_0	f_N	q_1	q_2	q_3
Base metal	0.005	0	1.5	1	2.25
Weld metal	0.005	0	1.5	1	2.25

Symmetry conditions enable the modeling of one-half of the specimen; 4-noded full integration elements were used. The crack tip is simulated using refined FE mesh without singular elements; such an arrangement enables the modeling of the crack growth. External loading is defined by prescribing vertical displacement of the rigid body (pin), which is in contact with the model. All other motions of the pin are restrained and contact is also used for defining the boundary conditions for supports. The supports were also modeled as rigid bodies. Surface-to-surface contact with a finite-sliding formulation is defined between the contact surfaces in all cases.

The mesh is refined in the region ahead of the tip of the crack, since propagation is expected in the same area. The crack growth Δa has been simulated by tracing the path of completely damaged elements, which appear in different color in front of the crack. In other words, the crack growth has been estimated by multiplying the original length of an element with the number of completely damaged elements. The element is assumed to be failed when void volume fraction at the final failure f_F is reached according to expression: $f_F = 0.15 + f_0$, Z.L. Zhang et al. (2000).Then the corresponding value J-integral is obtained. The crack growth resistance curves were obtained for both models and compared with the results obtained from experiments.

3. Results and discussions

The comparison between numerical and experimental results is presented through measured values of J-integral, load, load-line displacement v_{LL} and J-Δa curves. The deformed mesh after some amount of the crack growth is given in Fig. 2. The dark color shown on Fig. 2 indicates that the values of the variables are high and the elements in the ligaments completely lost their carrying capacity. This loss of capacity can also be noticed in Fig. 3, where the values of the calculated stress by the von Mises method in the ligament are equal to zero.

Based on a series of computations, the relationship between the F-v_{LL} and J-v_{LL} are shown in Fig. 4 and 5 for specimen with fatigue pre-crack in the base metal and in weld metal. It is clear that the J-integral values are increased with the load line displacement values when the load is increased for both cases. However, the rate of increase in the J-integral values is higher for specimen with crack in base metal in comparison to the specimen with crack in weld metal. When compared with experimental results, the relationship between both curves is not linear but curvilinear. With further increases in load, the curves tend to separate. The results have shown almost the same trend as given by relationships between J and crack growth increment. The computations have indicated that the weld strength mismatching may have a weak influence on the relationship between the J-integral and values at low load levels. Strong effects of strength mismatching exist at high load levels, where the local deformation of welds may play an important role. Thus, it is expected that the relationship between J-integral and Δa can vary significantly depending on the mismatch properties in yield strength between weld and base materials, and the load conditions.
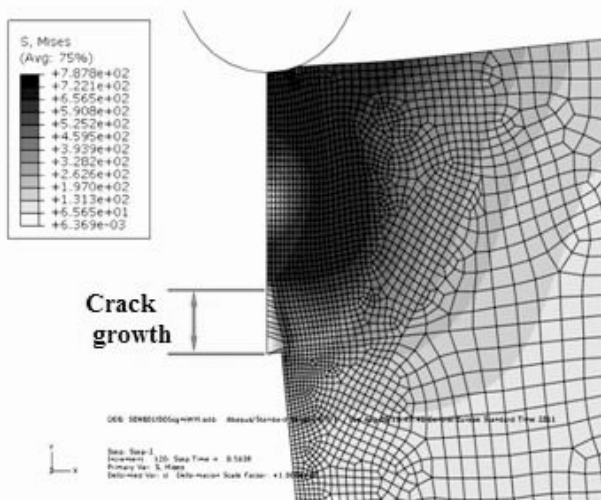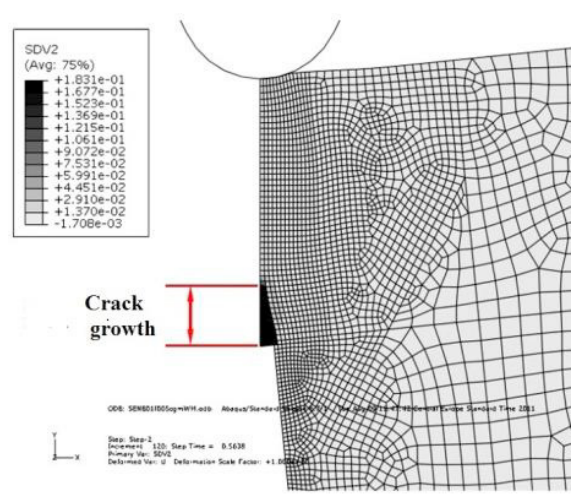

Fig. 2. Crack growth with CGM

Fig. 3. von Mises stress in elements near crack tip

The CGM predicts the loss of the load of the material through the mechanism of damage ductile fracture. Also, the influence of the finite element size at the tip of the crack and the initial void volume fraction is evident.

With reducing the size of the elements and increasing the void volume fraction, there is a loss of load bearing capacity, which also affects the lower crack resistance. Numerical results show a good correlation with experimental results if dimensions of finite elements used in the ligament in front of the crack tip are approximately 0,1 mm and the initial void volume fraction is 0,005. Resistance curves for SENB specimen with fatigue pre-crack located in the middle of the base metal and weld metal are shown on Fig. 6. The numerical model of SENB specimen with crack in base metal provides somewhat less resistance to crack in comparison with the experimentally obtained results.
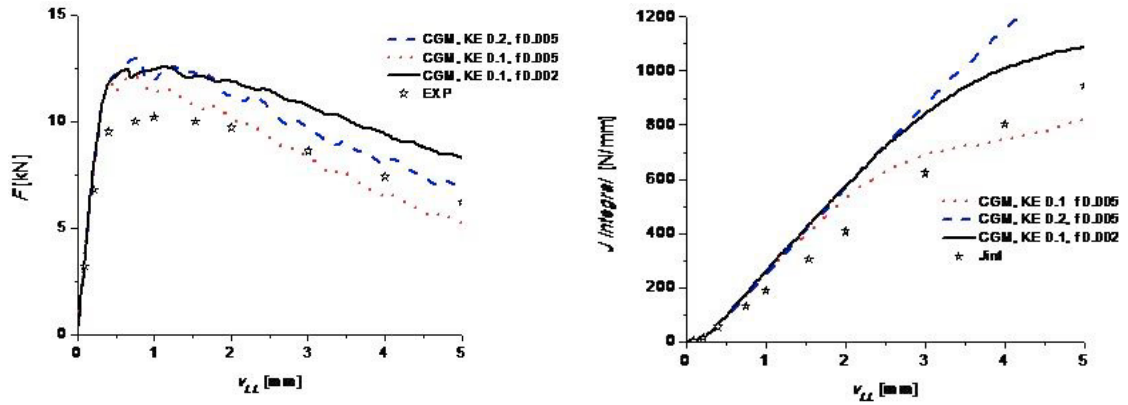
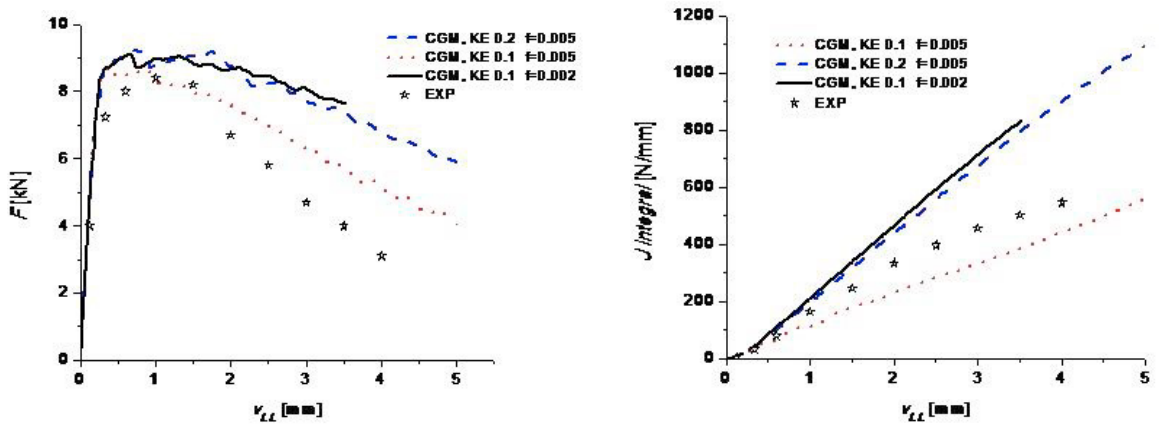Fig. 4. *F-v_{LL}* and *J- v_{LL}* curves for specimen SENB-BM (base metal)

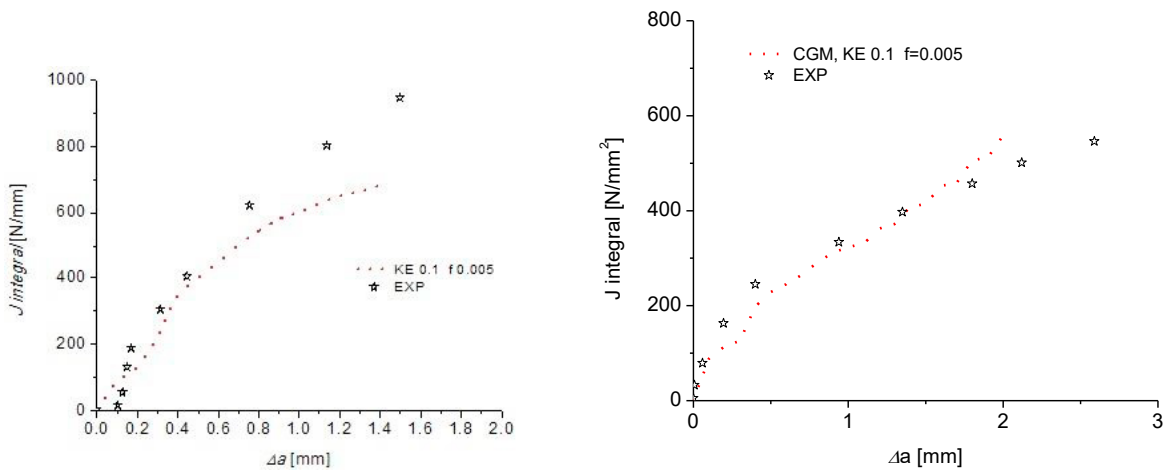Fig. 5. *F-v_{LL}* and *J-v_{LL}* curve for specimen SENB-WM (weld metal)

Fig. 6. *J-Δa* curve for specimens SENB-BM and SENB-WM

4. Conclusions

Based on the results obtained during the initial stage of the investigation, it is determined that the estimate of structural integrity of the examined specimens requires a detailed experimental and numerical analysis. It is understood that mechanical properties used for the presented numerical computations provide satisfactory results. Based on the presented numerical investigation the following can be concluded:

- The shape and size of the finite elements near the crack affects the results, which is a common property of micromechanical models for ductile fracture assessment. It turns out that the same element size is appropriate for both base and weld metal. Actually, integration order influences ductile fracture initiation, hence the distance between integration points is also relevant for ductile fracture.
- At low load levels, before the plastic zone has reached the weld-base material's interface, no effects are observed due to the inhomogeneity of the yield properties in both cases (numerical and experimental). However, at high load levels, once the plastic zone in the crack tip start to interact and is affected by the yield behavior of the basic material outside the weld the development of the plastic zone, and hence crack tip constraint starts to be affected by difference between the flow properties of the mismatched materials in the weld.
- The curves obtained with numerical investigation differ from the experiments with variation of the volume fraction of porosity, and the value 0.005 is shown to be appropriate for both base and weld metal. The agreement of the experimental and numerical results is quite good when considering dependence of F on v_{LL}.
- Stress distributions obtained numerically make it possible to approximately determine the direction of crack propagation.
- Comparison of experimental and numerical results provides verification of the numerical model, and suggests directions for future improvements. The use of the presented procedure could: reduce the high costs of experimental investigations, help to understand the material behavior and provide the directions for experiment planning.

Acknowledgements

References

[1] Jindal, S., Chhibber, R., Mehta, N.P., 2012. Issues in welding of HSLA Steels. Advanced Materials Research 365, 44–49.
[2] Shi, Y., Sun, S., Murakawa, H., Uedab, Y., 1998. Finite element analysis on relationships between the J-integral and CTOD for stationary cracks in welded tensile specimens. International Journal of Pressure Vessels and Piping 75, 197–202.
[3] Rice, J.R., Rosengren, G.F., 1968. Plane strain deformation near a crack-tip in a power-law hardening material. Journal of Mechanics and Physics of Solids 16, 1–12.
[4] Hutchinson, J.W., 1968, Singular behavior at the end of a tensile crack in a hardening material. Journal of Mechanics and Physics of Solids 16, 13–31.
[5] Simulia Abaqus documentation, 2017. www.simulia.com.
[6] Petrovski, B., Kocak, M., Sedmak, S., 1991. Fracture behavior of under-matched weld joint with short surface crack. Proceedings of the 10th International conference on Offshore Mechanics and Arctic Engineering, Stavanger, Norway, 101-107.
[7] Thomason, P.F., 1990. Ductile fracture of metals. Pergamon Press, Oxford.
[8] Rakin, M., Medjo, B., Gubeljak, N., Sedmak, A., 2013. Micromechanical assessment of mismatch effects on fracture of high-strength low alloyed steel welded joints. Engineering Fracture Mechanics 109, 221–235.
[9] Gurson, A.L., 1977. Continuum theory of ductile rupture by void nucleation and growth: Part I - yield criteria and flow rules for porous ductile media. Journal of Engineering Materials and Technology - Transactions ASME 99, 2–15.
[10] Tvergaard, V., 1981. Influence of voids on shear band instabilities under plane strain conditions. International Journal of Fracture 17, 389–407.
[11] Zhang, Z.L., Thaulow, C., Odegard, J., 2000. A complete Gurson model approach for ductile fracture. Engineering Fracture Mechanics 67, 155–168.