Effect of three-dimensional modeling on behavior of plane strain or plane stress around crack tip in compact-tension (CT) specimen

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ABSTRACT

An analysis of the two concepts the failure and crack propagation in various materials has always been of interest to researchers. Thus, it is of necessity to investigate the failure of construction steel as one of the most widely used materials in the industry. Numerical modeling is always a complement to the analysis of laboratory samples. One important issue, particularly in failure problems, is to study the behavior of laboratory samples according to their dimensions. In the current research, the effect of sample thickness size on crack tip behavior is numerically examined. A standard CT specimen is commonly used to evaluate the failure of ductile materials. The crack tip behavior along the thicknesses of the laboratory samples is a combination of plane stress and plane strain behavior. Accordingly, in the present study, the effect of thickness on the numerical samples was investigated via the numerical result validation. The validated results then were used as a complement to the experimental results. Modeling and analysis of the numerical samples of varying thicknesses indicated that, with progression from the sample thickness center towards the free edges, the behavior shifts from plane strain to plane stress. In the case of the standard CT specimen with 25 mm crack length, the samples with greater than 15 mm thickness have an almost plane strain behavior, and the results are proved to be reliable. Then, with further analysis and taking into account the parameters dependent on sample size, loading value, and stress-strain values perpendicular to the equation plane, an equation was presented which can be used to realize to what extent the behavior in the free edge of the CT specimen operates in the form of plane stress or plane strain.

KEYWORDS

Crack, Ductile Material, J-Integral, Finite Element, Thickness

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1. Introduction

Subramany et al.[1] investigated the behavior of crack tip in the ductile material in three dimensions under the combination of first and second fracture modes[1]. Toshiyuki et al.[2] analyzed the effect of sample thickness on J integral value, and by analyzing finite element samples and calculating the Θ parameter, the authors concluded that by increasing Θ value and thickness of numerical samples, J-integral value decreases [2]. In the current research, after validation of steel yield surface and j integral method, the effect of sample thickness size on the results of numerical analyzes was investigated. Finally, an equation was presented considering the sample dimensions (B/W), the amount of load applied (P/P_0) and the stress-strain perpendicular to the plane. Using the equation, it would be feasible to realize what proportion of the sample thickness in the free edge operates as plane stress or plain strain.

2. Specifications of materials and sample dimensions

In the current study, CT specimen proposed by Simha[3] was used to analyze the effect of 3D modeling and the effect of thickness on crack tip behavior. The sample is made of German standard St37 steel[4]. Fig. 1 shows the dimensions and geometry of the pressure-strain sample according to ASTM-E833[5].

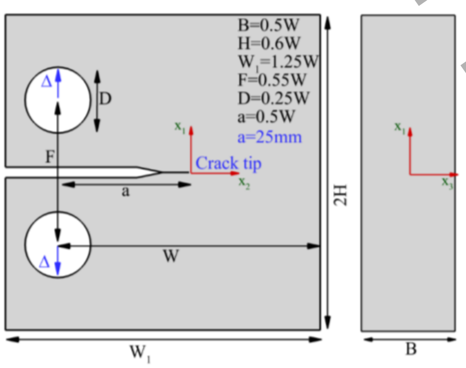

Fig. 1. Dimensions and geometry of model according to ASTM standard[5]

3. Numerical model validation

ANSYS v19 software was used for numerical analysis. Solid 186 20-node element and plane183 8-node element were applied for 3D and 2-D modeling, respectively.

3.1. Validation of nonlinear steel behavior

To analyze the nonlinear behavior of steel, the Von Mises yield level with Voce Law Nonlinear Isotropic Hardening was used.

3.2. Validation of extraction of crack tip parameters

Ensuring of the nonlinear steel behavior model, J integral method was used to calculate the crack tip parameters[6]. Shih[6] formulation was applied to perform the analysis in 2D and 3D space.

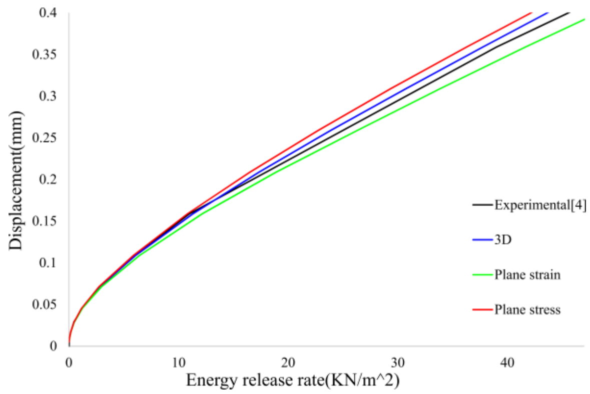

Fig. 2. Comparison of numerical and laboratory results Energy-displacement release rate

4. Investigate the effect of sample thickness on the results

In this part, the effect of the varying thicknesses of the sample on the numerical results of the CT specimen was investigated. The numerical sample thickness from 1 mm (plane stress) to 25 mm (plane strain) with a 1 mm increment was modeled and analyzed to take into account a wide range of responses ranging from plane stress to plane strain. At the center of the numerical sample thickness (X_3/B), as the sample thickness increases, the strain value decreases in the third direction. This strain reduction perpendicular to the plane provokes the sample behavior to approach flat strain behavior. Thus, considering the strain results in the direction perpendicular to the plate, if $(thk/25) \geq 0.6$, the strain value remains constant in the third direction. In other words, for the samples with a crack length of 25 mm, the thickness of the laboratory sample must be greater than 15 mm in order for the sample behavior to be approximately plane strain.

4.1. Plain stress or plain strain behavior or their combination along the thickness

In this part, the effect of stress in the direction exterior to the plane in different loading steps is investigated. In other words, with an increase in loading, what proportion of the sample thickness $(b/B) = ?$ operates as a plane stress or a plane strain?

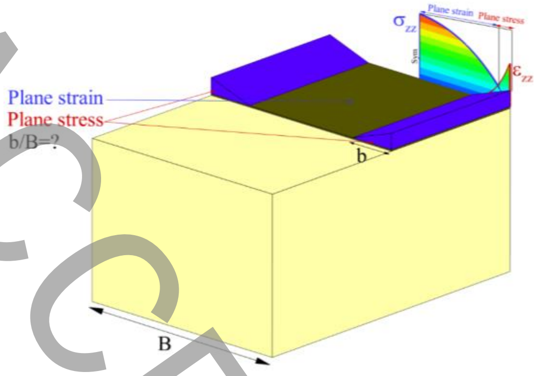

Fig. 3. Strain and stress values in the direction exterior to the plane along the thickness

To further investigate the effect of the numerical sample thickness on the sample behavior along the thickness, the numerical samples with a thickness of 5 to 100 mm were modeled $(0.1 \le B/W \le 2)$ to consider the wide range of the responses.

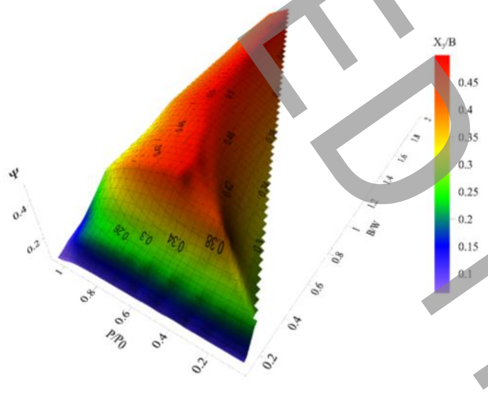

Fig. 4. Intersection of stress and strain values in the third direction surface Ψ

Given the three variables B/W, P/P_0, and X_3/B considering all the thicknesses of the numerical models from 5 mm to 100 mm, the boundary lines can be represented continuously with a single surface (Ψ). Given the B/W ratio, Ψ indicates the behavior of plane stress or plane strain along the thickness during loading time of numerical samples. By performing several nonlinear regression and surface Ψ sensitivity analysis, the optimal formula for this surface is a combination of exponents and powers (Eq. [1]).

$$\begin{cases} \Psi = a(\exp(b(\frac{B}{W})^c)(\exp(d(\frac{P}{P_0})^f), \left[\begin{array}{c|c|c|c|c|c} a & b & c & d & e & f \\ 0.77 & -0.269 & -1.006 & -0.466 & 3.477 & 0.031 \end{array}\right] \\ 0 \le \Psi \le 0.5, \ \frac{X_3}{B} \ge \Psi \rightarrow plane\ stress, \ \frac{X_3}{B} < \Psi \rightarrow plane\ strain \end{cases} \quad (1)$$

5. Conclusion

In the present article, nonlinear behavior of steel and extraction of crack tip parameters were validated by J integral method. The energy release rate of the crack tip in the 3D model was very close to the experimental results due to the consideration of all the stress components. Thus, it is recommended to enhance the accuracy of the results when analyzing ductile failure problems via increasing computational cost (3D modeling). By modeling the standard specimen (CT) in accordance with Fig. 1 with varying thicknesses ranging from 1 to 25 mm and 1 mm increment, it was observed that by increasing the sample thickness, the strain perpendicular to the plate (ε_{zz}) at the thickness center of the numerical samples tends to decrease. Thus, the behavior of the 3D numerical models inclines toward the plain strain behavior. In the next part of the article, taking into account the three variables including B/W, P/P_0 and X_3/B the intersection of the normalized stress and strain perpendicular to the plane, surface was obtained in the 3D space. By formulating surface Ψ, it would be feasible to realize what proportion of the sample thickness in the free edge operates as plane stress or plane strain.

6. References

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