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Fracture assessment of U-notched graphite specimens by means of cohesive zone model

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Abstract

Various types of graphite have gained interest in many industrial applications due to their high strength and excellent heat tolerance. However, due to the brittle nature of this material, presence of stress concentrators such as notches and geometrical discontinuities considerably re-duces the overall loading bearing of the graphite components. Here we evaluate the applicability of the Cohesive Zone Model (CZM) for the assessment of the fracture strength of experimentally tested U-notched specimens subject to mode I loading. The fracture loads of U-notched components with different notch tip radii can be predicted with an average discrepancy of ±7%.

Keywords: Brittle fracture; Cohesive zone model; Graphite; U-notch.

1. Introduction

Due to great applications of notched components in engineering brittle components, it is essential to develop proper brittle fracture models for designing notched members under different modes of loading conditions. Up to now, some well-stablished brittle fracture models on the basis of stress, energy, and combined both energy and stress evaluations, have been suggested in the topic of notch fracture mechanics (NFM) in order to investigate the

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fracture behavior of various notched components under different loading conditions. Up to now, a large number of experimental results dealing with brittle fracture and ductile rupture of various notched components have been assessed by several fracture models like J-integral (Matvienko 1994; Majidi et al., 2019a) and the averaged strain energy density (SED) (Aliha et al., 2017; Marsavina et al., 2017; Razavi et al., 2017, 2018; Majidi et al., 2019b) as energy-based models, the Theory of critical distances (Torabi et al. 2019) as stress-based models, and also the cohesive zone model (CZM) (Lewicki et al., 2000; Gomez et al., 2006, 2008; Ham and Hong, 2018; Bahrami et al., 2018; Torabi et al., 2020), and the finite fracture mechanics (FFM) (Carpinteri et al., 2008) can be classified as combined energy-stress based brittle fracture prediction models. A combination of the mentioned researches with the equivalent material concept was then used by Torabi et al. (2018a,b) for failure prediction of notched components made of ductile materials. In the present research, brittle fracture of U-notched isostatic polycrystalline graphite under mode I loading is studied theoretically by using the XFEM based on linear cohesive zone model approach. In the present research, brittle fracture of U-notched isostatic polycrystalline graphite under pure mode I loading is studied theoretically by using the XFEM based on linear cohesive zone model approach.

2. Experimental results reported in literature

Berto et al. (2012) have recently published a research paper in which a series of experiments on the U- notched rectangular specimens have been conducted to assess experimentally the brittle fracture in U- notches under tension loading. The test specimen is shown in Fig. 1. The material used is commercial isostatic graphite particularly used in mechanical applications for its high performances. Details of their experimental program can be found in the published research by Berto et al. (2012). The mechanical properties of the tested graphite are listed in Table 1. The experimentally obtained fracture loads for the tested U- notched graphite plates are presented in Table 2.

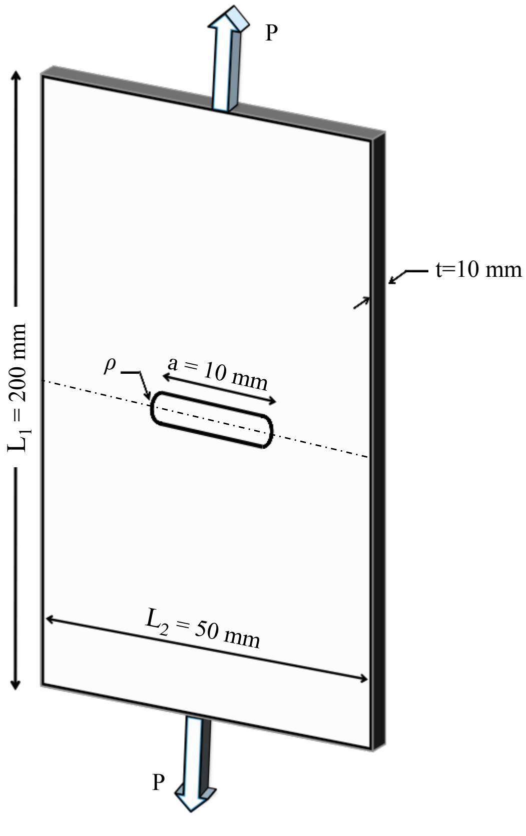

Fig. 1. Geometry of the tested specimens by Berto et al., (2012).

Table 1. Some of the properties of the tested graphite material (Berto et al., 2012).

Material property	Graphite
Elastic modulus (MPa)	8050
Poisson's ratio	0.2
Ultimate tensile strength (MPa)	46
Plane strain fracture toughness (MPa.m$^{0.5}$)	1.06

Table 2. Summary of the experimental results reported by Berto et al. (2012) for the key-hole notched graphite specimens.

ρ (mm)	P_1 (N)	P_2 (N)	P_3 (N)	$P_{av.}$ (N)
0.25	4115	4708	4455	4426
0.5	4592	4495	4429	4505
1	4461	5152	4830	4814
2	5182	5824	5541	5516
4	7083	6406	6879	6789

3. A brief description of cohesive zone model

According to CZM, failure initiates when the cohesive traction in the material reaches the critical tensile stress which is normally considered equal to the ultimate tensile strength of material. In CZM, the relationship between the cohesive traction and the crack opening displacement is as follows:

$$T = f(\delta) \tag{1}$$

In Eq. (1), T, δ and f(δ) are the cohesive traction, the crack opening displacement and the softening function, respectively. In fact, the softening function determines how the cohesive traction decreases as the crack opening displacement increases. Two material properties, namely the tensile strength σ_u and the specific fracture energy G_f, have great roles in the softening function. Thus, for applying CZM, these two parameters should be given to the FE software. The specific fracture energy for brittle materials can be calculated through the Irwin's equation as follows (Irwin 1957):

$$G_f = \frac{K_{IC}^2}{E/(1-\nu^2)} \tag{2}$$

Therefore, the value of G_f for the tested graphite material is obtained from Eq. (2) to be equal to 0.134 N/mm. Unlike the CZM in combination with the embedded crack approach in which the crack propagation does not have a considerable dependency on the finite element meshing algorithm, the crack propagation in the notched components is almost dependent upon the element size at the notch border in the CZM approach without any embedded crack. For solving this dependency, Majidi et al. (2018) have proposed a new mesh algorithm to achieve representative simulations for fracture prediction of all of the tested notched specimens. Details of the mesh algorithm utilized in this research were previously presented by Majidi et al. (2018). The scheme of the crack initiation process for the specimen with ρ = 2 mm obtained from CZM is shown in Fig. 2.

4. Results and discussion

In the present research, the fracture behaviour of some tested U-notched rectangular specimens was investigated theoretically. This work shows the capability of the CZM approach in predicting the fracture load of U-notched brittle specimens loaded under pure tension loading condition. To this aim, five different geometries of notched rectangular

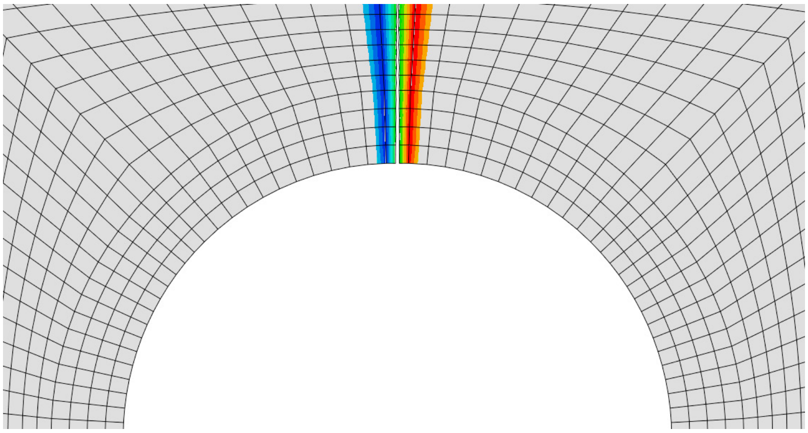

Fig. 2. The scheme of the crack initiation process for the specimen with ρ = 2 mm obtained from CZM.

samples weakened by U-notches, made of graphite were analysed. The experimental fracture loads of tested U-notched samples were predicted by CZM calculations. Also, the experimental results of the tested samples were previously predicted by ASED criterion was reported again in this research to find the superiority of each two criteria investigated in this research. The theoretical results showed that both CZM and ASED criteria can predict well the fracture load. Thus, either CZM or ASED can be utilized to study the fracture behaviour of U-notched brittle specimens under pure tension loading condition.

Table 3. The theoretical prediction for the U-notched graphite specimens subjected to pure mode I loading.

ρ (mm)	$P_{av.}$ (N)	P_{ASED}	Dis (%)	$P_{XFEM-CZM}$ (N)	Dis (%)
0.25	3967	4128	6.7	4204	5.0
0.5	4060	4313	4.3	4470	0.8
1	3998	4919	2.2	5102	6.0
2	4967	5914	7.2	6132	11.2
4	4910	7223	6.4	7611	12.1
Average discrepancies			**5.4 %**		**7.01 %**

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