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Fracture study in notched ductile polymeric plates subjected to mixed mode I/II loading: Application of equivalent material concept

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ABSTRACT

Fracture of a ductile polymeric material containing U-notches is studied both experimentally and theoretically under mixed mode I/II loading conditions. Rectangular plates containing a central bean-shaped slit with two U-shaped ends are utilized for conducting fracture tests. Specimens with different notch inclination angles and various notch tip radii are loaded under remote tension to measure their load-carrying capacities (LCCs) experimentally. The Equivalent Material Concept (EMC) is reformulated to be utilized for theoretically predicting the obtained experimental results. For this purpose, the maximum tangential stress (MTS) and the mean stress (MS) criteria are combined with EMC. As the main novelty of this research, it is revealed that both the EMC-MTS and EMC-MS criteria, which have been more recently used for studying only pure mode I fracture behavior of U-notched epoxy resin, can provide very good predictions to the experimental results obtained under mixed mode I/II loading conditions.

1. Introduction

As a category within the thermosetting polymers, epoxy resins are widely utilized in various engineering fields such as automotive, marine, electronics and wind energy etc. Once cured by using appropriate curing agents, they can exhibit excellent mechanical and chemical properties (Li et al., 2013; Jin et al., 2015). Mechanical properties, including fracture properties, of these polymeric materials depend significantly on the choice of curing agents (Kanchanomaia et al., 2005; Rodriguez et al., 2015). Understanding the fracture behavior of polymeric materials is necessary for reliable design of polymer components. It should be noted that the fracture behavior of epoxy resins is often affected by temperature, strain rate, additive concentration and environmental variables (Kanchanomaia et al., 2005; Rodriguez et al., 2015; Park et al., 2000).

Various types of defects can be found in polymeric components, that most of them, e.g. cracks, voids, inclusions, scratches etc. are not desirable. However, there is a group of defects or discontinuities, called notches, which are intentionally introduced by designers in the components. Due to the stress concentration, crack(s) may initiate from the notch border in polymeric components. Depending on the brittleness or ductility of the polymeric materials, cracks may nucleate from the notch border and extend suddenly or slowly. Therefore, developing appropriate fracture criteria is essential for reliably designing each notched component according to its fracture behavior (Garg and Mai, 1988). For polymeric materials, high yield strength can typically be achieved at low temperatures, low hardener contents, and high strain rate loading. At low yield strengths, the fracture energy is high, which affects the failure behavior of material and changes the mode of failure from brittle fracture to ductile rupture (Kinloch and Williams, 1980).

While brittle fracture behavior of epoxy materials containing cracks has been studied in several researches (Kinloch and Williams, 1980; Razavi et al., 2017; Fiedler et al., 2001; Bowden and Jukes, 1972; Asp et al., 1996), there are few papers in which the ductile rupture of epoxy materials are studied in the presence of cracks (Allaer et al., 2015; Low and Mai, 1989; Craword and Lesser, 1999; Trappe et al., 2012). Due to their wide applications in the engineering structures, brittle failure of V-, U-, and O-notches introduced in polymeric materials has been frequently studied by researchers (Torabi et al., 2015; Gomez, and Elices, 2003; Ayatollahi and Torabi, 2010; Gomez et al., 2000; Berto et al., 2013; Aliha et al., 2016; Kanchanomaia et al., 2005; Rodriguez et al., 2015; Allaer et al., 2015; Dehnavi et al., 2013).

For predicting the mechanical failure in defective components exhibiting elastic-plastic behavior, the elastic-plastic fracture mechanics (EPFM) is usually utilized whose analyses are rather time-consuming and complicated. Torabi (2012) has proposed the Equivalent Material

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Nomenclature

E	Young's modulus
ρ	Notch radius
K_{Ic}	Plane-strain fracture toughness
σ_u	Ultimate tensile strength
$\sigma_{\theta\theta}$	Tangential stress
σ_c	Critical stress
$\overline{\sigma_{\theta\theta}}$	Mean value of tangential stress
MTS	Maximum tangential stress
MS	Mean stress
d_c	Critical distance of the MS criterion measured from the-border
r_c	Critical distance of the MTS criterion measured from the notch border

Concept (EMC) by which the EPFM analyses are avoided in predicting ductile failure of notched components. In this new concept, the real ductile material is equated with a virtual brittle material. Torabi et al. (2017a) have also shown that EMC could be successfully combined with energy-based brittle fracture models, e.g. the Averaged Strain Energy Density (ASED) criterion, for predicting ductile failure of notched specimens.

Some epoxy materials have elastic-plastic behavior in which cracks propagate in a stable manner. Hence, the use of ductile epoxy resins is normally preferred in engineering components and structures over the brittle ones. To the best of authors' knowledge, just one paper is available in the literature in which the ductile fracture of an epoxy material has been evaluated in the presence of notches. Torabi et al. (2017b) have more recently studied the fracture behavior of a ductile epoxy resin weakened by U-shaped notches of various tip radii under pure mode I loading. They have linked EMC to the maximum tangential stress (MTS) and the mean stress (MS) brittle fracture criteria and proposed the EMC-MS and EMC-MTS criteria for predicting the experimentally obtained fracture results.

In the present research, the effectiveness of EMC-MS and EMC-MTS criteria, which have been more recently proposed for predicting the fracture behavior of some U-notched ductile polymeric specimens only under mode I loading conditions (Torabi et al., 2017b), is evaluated by predicting the experimentally obtained fracture results of some inclined U-notched specimens made of the same ductile polymeric material under mixed mode I/II loading conditions. It is shown that both combined criteria can predict the experimental results well.

2. Experiments

2.1. Characterizing the epoxy material

In this study, the main issue is to have an epoxy resin with a considerable nonlinear portion in its stress-strain curve in order to investigate the ductile fracture in polymeric materials. Therefore, the material selected for this study is the epoxy resin Araldite LY 5052 with wide engineering applications. For curing this epoxy resin, Aradur 5052 is used as a hardener. There are two important parameters affecting the stress-strain curve of polymers; the hardener concentration and the strain rate. Hence, different tests are designed and performed in this work to study these effects on the selected epoxy material.

Tensile specimens are fabricated and tested (see Fig. 1) according to the well-known standard test method ASTM D638 (1994). There are several researches in the literature reporting these effects (Rodriguez et al., 2015; Gensler et al., 2000; D'Almeida and Monteiro, 1996).

At first, for determining the effects of the hardener concentration on the stress-strain curve of the selected epoxy material, tensile specimens with deferent hardener contents are prepared and tested. Specimens are prepared according to the resin supplier recommendations (2007). Based on the obtained stress-strain curves of the tested specimens (Torabi et al., 2017b), the epoxy resin with 50 wt% hardener concentration is selected because of the highest ductility.

In the next step, the effect of strain rate on the stress-strain curve of the epoxy material is evaluated. For this purpose, the tensile tests are performed on the epoxy resin with 50 wt% hardener concentration for four different strain rates as 0.2, 1, 5 and 10 mm/min. By considering the results reported in Torabi et al. (2017b), it is evident that the maximum ductility is obtained for the strain rate of 1 mm/min. Therefore, the strain rate of 1 mm/min is selected in this study for conducting the fracture experiments.

Tensile properties and fracture toughness of the epoxy resin are presented in Table 1 (Torabi et al., 2017b). These properties are obtained experimentally based on the standard codes ASTM D638 (1994) and ASTM-D5045 (1999), respectively.

2.2. Fracture testing of the epoxy material weakened by U-notches

In the previous subsection, the epoxy material was characterized. Therefore, some U-notched specimens made of this epoxy material are prepared for performing the fracture tests. As shown in Fig. 2, the test specimen is a rectangular plate of 4 mm thick containing a central bean-shaped slit with two U-shaped ends. Three different notch tip radii of $\rho = 1$, 2 and 4 mm are considered in the experiments. To have mixed mode I/II loading conditions at the vicinity of U-notches, different values are selected for the rotation angle β. Pure mode I loading is trivially achieved by $\beta = 0$ (deg.) and by increasing this angle, the contribution of mode II loading increases. The values of the rotation angle β in the experiments are considered to be equal to 0, 30 and 60 (deg.). Note that pure mode II loading is obtained when $\beta_{II} = 71$ (deg.). The whole notched specimens are tested under uni-axial monotonic tension. Some of the U-notched specimens tested are shown in Fig. 3.

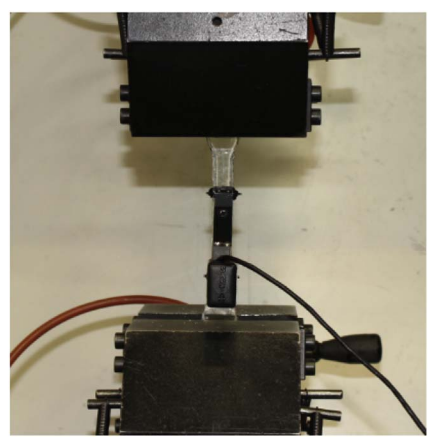

Fig. 1. The standard tensile test specimen inside the test machine.

Table 1
The mechanical properties of the tested epoxy resin (Torabi et al., 2017b).

Material property	Value
Elastic modulus (GPa), E	1 2.41
Poisson's ratio, ν	2 0.33
Ultimate tensile strength (MPa), σ_u	3 71.2
Yield strength (MPa), σ_Y.	4 .1
Fracture toughness (MPa.m$^{0.5}$), K_{Ic}	5 1.34
Elongation at ultimate tensile strength (%)	6 12.2