Tensile Fracture Analysis of V-Notches with End Holes by Means of the Local Energy
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Abstract—This paper deals with investigating brittle fracture in V-notches with end holes under mode I loading. Thirty-six fracture test results, reported most recently in the literature on a new notched disk-type specimen, namely the Brazilian disk containing central VO-shaped notch made of polymethyl-metacrylate, were theoretically predicted by means of the well-known brittle fracture criterion, namely the strain energy density over a critical control volume which embraces the notch edge. A very good agreement was shown to exist between the experimental and theoretical results.

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Keywords: V-notch with end hole (VO-notch), brittle fracture, strain energy density (SED), Brazilian disk, mode I loading

1. INTRODUCTION

In practical engineering applications, cracks and damages normally appear at the notch vicinity because of the stress concentration resulted from mechanical and/or thermal loadings. Such cracks may grow and lead to fracture of the notched component. Generally, two approaches exist to overcome this problem. The first one is to replace the notched component containing damage and the second one is to repair the component. The first approach is normally utilized when the component is cheap; however, the second one is employed for expensive components.

For very large cracks initiated from the notch border, the common repairing method is to drill a stop hole on the crack tip and to prevent the crack growth. For small cracks (most cases), however, the traditional repairing method is to drill a circular hole with the center/radius normally equal to the notch tip/crack length and to remove the crack. As seen in Fig. 1, for V-shaped notches, such a hole changes the initial V-notch to a V-notch with end hole (VO-notch) resulting in different stress concentration and thus, different fracture behavior. Therefore, from the viewpoint of structural safety, the fracture toughness of the newly born VO-notch should be investigated in order to demonstrate the safety of the VO-notched component. Unlike ductile components for which stable crack growth is seen, crack propagation in brittle and quasi-brittle members usually takes place with very high speed resulting in sudden fracture of the members. Hence, most of the fracture investigations have been focused on brittle and quasi-brittle materials under static loading (see for example [1–5]). In the presence of a notch, for example a VO-notch, brittle fracture can become much more serious because of the stress concentration. Consequently, brittle fracture in notched components should be studied both theoretically and experimentally.

In the notch fracture mechanics, different loading modes can be defined like those in the classic fracture mechanics. They are mode I (opening mode), mode II (in-plane sliding), mode III (out-of-plane sliding), and mixed mode loadings. The simplest loading mode is certainly the mode I loading under which brittle fracture has been widely investigated. Mode I brittle fracture studies on notched domains reported in the open literature are briefly quoted herein.

Fracture toughness of ceramics and ceramic composites has been studied by Gogotsi [1] under three-point and four-point bending. Knesl [2] published a paper in which a criterion has been proposed for V-notch stabi-
lity. Nui et al. [3] obtained the stress distribution around a large round-tip V-notch and used it for investigating the fracture toughness of brittle materials by means of the critical notch stress intensity factor. A brittle fracture criterion has been suggested and experimentally verified by Seweryn [4] for sharp V-notches. Strandberg [6] studied successfully the fracture in V-notched samples made of soft annealed tool steel at $-50^\circ C$ by considering plastic deformations at the notch neighborhood. A combined stress-energy based criterion has been proposed by Leguillen [7, 8] for crack onset at a notch. Comparisons with the experimental results conducted on homogeneous notched materials and on bimaterial structures showed a good agreement [7, 8].

Gomez et al. [9] proposed the cohesive zone model for estimating successfully the maximum load that U-notched specimens made of polymethyl-metacrylate (PMMA) can sustain under three-point bending. To investigate theoretically the brittle fracture in sharp V-notches, the cohesive zone model has also been utilized [10]. Gomez and Elices [10] verified the cohesive zone model estimations by means of experimental results obtained from sharp V-notched PMMA specimens. In Ref. [11], the cohesive zone model has been successfully utilized to predict mode I brittle fracture in blunt V-notched PMMA samples. Gomez et al. [12] made use of the cohesive zone model for predicting fracture in notched PMMA samples tested at $-60^\circ C$.

Sih [13] suggested a point-wise strain energy density criterion for predicting brittle fracture in cracked domains by considering both the strain energy density and the critical distance measured from the crack tip. Lazzarin and Zambardi [14] extended the strain energy density concept to sharp and blunt notches (sharp and blunt V-notches, U-notches etc.) by averaging the strain energy density over a specified control volume which embraces the notch edge in order to estimate the static [14–19] and the fatigue [20, 21] behavior of notched components. The strain energy density has been utilized in Ref. [22] to estimate the crack onset at a V-notch having very small tip radius. A few fracture criteria including the strain energy density criterion have also been proposed by Yosibash et al. [23] for brittle elastic materials and verified successfully by means of experimental results. In Ref. [24], the strain energy density criterion has been employed to predict well the fracture test results reported in the literature on different V-notched polycrystalline graphite specimens. The U-notched Brazilian disk specimen has been utilized in Refs. [25, 26] to measure experimentally the maximum load that coarse-grain polycrystalline graphite weakened by a U-shaped notch can sustain under pure mode II [25] and mixed mode [26] loading conditions. The experimentally measured fracture loads have been very well predicted by means of the averaged strain energy density criterion.

As a well-known approach in the context of fracture mechanics, J-integral has been formulated in recent years for sharp and blunt notches with the aim to predict brittle fracture in notched members (see for instance [27–33]). Carpinteri et al. [34] proposed the finite fracture mechanics approach for predicting successfully the load-carrying capacity of V-notched rectangular PMMA beams loaded under three-point bending. Minor et al. [35] investigated the fracture toughness of high-strength steel using the notch stress intensity factor and the volumetric approach.

A bulk of mode I brittle fracture assessments have been performed by Torabi and his co-researchers on notched domains both theoretically and experimentally. Ayatollahi and Torabi [36] proposed two closed-form expressions for the mode I fracture toughness of blunt V-shaped notches on the basis of the point-stress and the mean-stress criteria. They verified successfully the point-stress and the mean-stress predictions by using extensive experimental results on V-notched samples made of PMMA and ceramic materials [36]. In Ref. [37], they also made use of the mean-stress criterion for predicting fracture in blunt V-notched polycrystalline graphite specimens. Torabi [38] made use of the point-stress and the mean-stress criteria to estimate the load-carrying capacity of U-notched Brazilian disk specimens made of coarse-grain polycrystalline graphite.

A few papers have been recently published on brittle fracture of V-notches with end holes. Berto and Zappa-

![Fig. 1. The scheme of forming a V-notch with end hole by hole drilling method.](image-url)
Table 1. Mechanical properties of the tested PMMA [40]

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young's modulus $E$, GPa</td>
<td>2.96</td>
</tr>
<tr>
<td>Poisson’s ratio $v$</td>
<td>0.38</td>
</tr>
<tr>
<td>Tensile strength $\sigma_t$, MPa</td>
<td>70.5</td>
</tr>
<tr>
<td>Plane-strain fracture toughness $K_{IC}$, MPa$\cdot$m$^{0.5}$</td>
<td>1.96</td>
</tr>
</tbody>
</table>

lorto [39] made use of the fictitious notch radius concept for fracture assessment of VO-notches. Torabi and Amininejad [40] extended the point-stress and the mean-stress failure concepts to VO-notched domains and predicted accurately the experimentally measured notch fracture toughness (NFT) values for VO-notched Brazilian disk (VO-BD) specimens made of PMMA. As a reduced VO-notch (zero notch angle), key-hole notch has also been analyzed in the literature against brittle fracture. Under mode I loading, two closed-form NFT expressions have been proposed by Torabi [41, 42] on the basis of the point-stress and the mean-stress criteria and verified by means of experimental results on isostatic graphite [43] and PMMA [42] plates weakened by key-hole notches of various tip radii. The brittle fracture of graphite [44] as well as PMMA [45] notched members has been also analyzed by means of the maximum tangential stress. A comparison between strain energy density and maximum tangential stress criteria can be found in [46].

In this work, it was attempted to check the suitability of the averaged strain energy density criterion over a specified control volume which embraces the notch edge in predicting the fracture loads of VO-notched brittle components. For this purpose, the strain energy density criterion was applied to the VO-BD specimens made of PMMA [40] and it was found that very good correlation exist between the theoretical and the experimental results.

2. EXPERIMENTAL RESULTS REPORTED IN THE LITERATURE

Thirty-six new experimental results have recently been published in the literature on brittle fracture of VO-notches under mode I loading [40]. Details of the experiments carried out by Torabi and Amininejad [40] are presented in the next subsections.

2.1. Material

Polymethyl-metacrylate with the mechanical properties presented in Table 1 has been utilized in Ref. [40] for performing the fracture experiments.

2.2. Specimen

The well-known Brazilian disk (BD) specimen containing central VO-notches (VO-BD specimen) has been tested in Ref. [40] to measure experimentally the static strength of VO-notches against brittle fracture. Figure 2 depicts the VO-BD specimen. As can be seen in Fig. 2, the VO-ends of the central slit are subjected to pure mode I loading conditions because the direction of the compressive load is aligned with the notch bisector line [40].

The disk diameter $D$, the overall slit length $d$ and the disk thickness have been equal to 80, 40 and 10 mm, re-

Table 2. The experimental fracture loads of the VO-BD PMMA specimens [40]

<table>
<thead>
<tr>
<th>$\rho$, mm</th>
<th>$P_1$, N</th>
<th>$P_2$, N</th>
<th>$P_3$, N</th>
<th>$P_{\text{mean}}$, N</th>
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<td>0.5</td>
<td>5635</td>
<td>5277</td>
<td>5724</td>
<td>5545.3</td>
</tr>
<tr>
<td>1.0</td>
<td>5203</td>
<td>5612</td>
<td>5128</td>
<td>5314.3</td>
</tr>
<tr>
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<td>6497</td>
<td>6081</td>
<td>6389</td>
<td>6322.3</td>
</tr>
<tr>
<td>4.0</td>
<td>6997</td>
<td>6530</td>
<td>6730</td>
<td>6752.3</td>
</tr>
<tr>
<td>2$\alpha = 60^\circ$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>3857</td>
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<td>3566</td>
<td>3737.6</td>
</tr>
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<td>5325</td>
<td>5440</td>
<td>4754</td>
<td>5173</td>
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<tr>
<td>4.0</td>
<td>5793</td>
<td>5866</td>
<td>5939</td>
<td>5866</td>
</tr>
<tr>
<td>2$\alpha = 90^\circ$</td>
<td></td>
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<td>0.5</td>
<td>2290</td>
<td>2481</td>
<td>2360</td>
<td>2377</td>
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<tr>
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<td>2473</td>
<td>2385</td>
<td>2476</td>
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<td>2951</td>
</tr>
<tr>
<td>4.0</td>
<td>3779</td>
<td>3947</td>
<td>3971</td>
<td>3899</td>
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</table>
spective[40]. Three notch angles of 30°, 60° and 90° and four notch radii of 0.5, 1.0, 2.0 and 4.0 mm have been considered in the experiments[40]. Each test has been repeated three times in order to check the repeatability of the fracture tests. All fracture test results have been reported in Ref.[40]. The experimental fracture loads of the VO-BD PMMA specimens reported in Ref.[40] are presented in Table 2 for different notch angles and various notch radii. Figure 3 also represents the VO-BD specimens during and after the mode I fracture tests[40].

It has been stated in Ref.[40] that the load-displacement curves recorded in the tests were all linear up to final fracture demonstrating brittle fracture. Moreover, experimental observations have confirmed that fracture has taken place suddenly without a visible phase tied to crack initiation. Therefore, it is fundamentally allowable to use the strain energy density criterion for predicting the experimental results presented in Table 2.

In the next section, the strain energy density criterion is utilized to predict the fracture loads of the VO-BD PMMA specimens presented in Table 2.

3. FRACTURE CRITERION BASED ON THE STRAIN ENERGY DENSITY AVERAGED OVER A CONTROL VOLUME

In order to estimate the fracture load of notched PMMA components, engineers need a suitable fracture criterion based on the mechanical behavior of material around the notch tip. A strain energy density based criterion is described in this section by which the fracture loads obtained from the experiments can be estimated with a sound accuracy.

As described in the introduction, dealing with cracked components, the strain energy density factor $S$ was defined first in [13] as the product of the strain energy density by a critical distance from the point of stress singularity. Failure was thought of as controlled by a critical value of $S_c$, whereas the direction of crack propagation was determined by imposing a minimum condition on $S$. Furthermore, this theory was used to study three problems of structural failure, namely the problem of stable growth of an inclined crack in a plate subjected to uniaxial tension, the problem of fracture instability of a plate with a central crack and two notches, and the problem of unstable crack growth in a circular disc subjected to two equal and opposite forces. The study of crack initiation and propagation is still an active research topic as demonstrated by some recent papers in the field [47–51]. This is particularly true when complex loading modes are taken into account [52, 53].

Different from Sih’s criterion, which is a point-wise criterion, the averaged strain energy density criterion as presented in Ref. [14] states that brittle failure occurs when the mean value of the strain energy density over a given control volume is equal to a critical value $W_c$ This critical value varies from material to material but it does not depend on the notch geometry and sharpness. The control volume is thought of as dependent on the ultimate tensile strength and the fracture toughness $K_{IC}$ in the case of brittle or quasi-brittle materials subjected to static loads.

Such a method was formalized and applied first to sharp, zero radius, V-notches under mode I and mixed I/II loading[14] and later extended to blunt U- and V-notches[54]. Some recent developments and applications are summarized in Refs. [55, 56] with some considerations also to three-dimensional effects [57–61], which have been widely discussed in Refs. [62–64].

When dealing with cracks, the critical volume is a circle of radius $R_c$ centered at the tip [14]. Under plane strain conditions, the critical length $R_c$ can be evaluated according to the following expression [14, 54]:

\[ R_c = \frac{1}{K_{IC}} \]

where $K_{IC}$ is the fracture toughness of the material.


\[ R_c = \frac{(1 + \nu)(5 - 8\nu)}{4\pi} \left( \frac{K_{lc}}{\sigma_t} \right)^2, \]

where \( K_{lc} \) is the fracture toughness, \( \nu \) is the Poisson’s ratio, and \( \sigma_t \) is the ultimate tensile strength of a plain specimen that obeys a linear elastic behavior.

For a V-notched specimen with end holes, the volume assumes the crescent shape shown in Fig. 4 where \( R_c \) is the depth measured along the notch bisector line. The outer radius of the crescent shape is equal to \( R_c + r_0 \) (Fig. 4). Value \( r_0 \) depends on the notch opening angle according to the following expression:

\[ r_0 = \frac{q - 1}{q} \theta \]

with \( q \) defined as

\[ q = \frac{2\pi - 2\alpha}{\pi}. \]

Under mixed mode loading, the control volume is no longer centered on the notch tip, but rather on the point where the principal stress reaches its maximum value along the edge of the notch. It was assumed that the crescent shape volume rotates rigidly under mixed mode, with no change in shape and size. This is the governing idea of the “equivalent local mode I” approach, as proposed and applied to U- and V-notches [15, 54].

Avoiding any simplified assumption, the strain energy density values can be directly derived from finite element models. The advantage of the direct evaluation of the strain energy density from a finite element model is that the value of this parameter is mesh-independent as described in Ref. [56]. A very coarse mesh can be adopted for the strain energy density evaluation contrary to the mesh required to evaluate the notch stress intensity factors or other stress-based parameters. An example is shown in Fig. 5 depicting a typical mesh (Fig. 5a) together with the principal stress (Fig. 5b) and strain energy density (Fig. 5c) contour lines.

4. STRAIN ENERGY DENSITY APPROACH IN FRACTURE ANALYSIS OF THE TESTED PMMA SPECIMENS

The fracture criterion described in the previous section is employed here to estimate the fracture loads obtained from the experiments conducted on the PMMA specimens weakened by V-notches with end holes. In order to determine the strain energy density values, a fi-
nite element model of the specimen was generated. The averaged strain energy density criterion states that failure occurs when the mean value of the strain energy density over a control volume \( W \) is equal to a critical value \( W_c \), which depends on the material but not on notch geometry [14]. This critical value can be determined from the ultimate tensile strength \( \sigma_t \) according to Beltrami’s expression:

\[
W_c = \frac{\sigma_t^2}{2E}.
\] (4)

In parallel, the control volume definition via the control radius \( R_c \) needs the knowledge of the fracture toughness \( K_{ic} \) and the Poisson’s ratio \( \nu \), see Eq. 1. The critical load that a notched component is able to sustain can be estimated by imposing \( W \) equal to the critical value \( W_c \). This value is considered constant under mode I, mode II and in-plane mixed-mode conditions while it is generally different under mode III loading. This assumption has been extensively verified for a number of different brittle and quasi-brittle materials [15, 54].

As mentioned earlier, the properties of the PMMA considered in the present investigation are: \( \sigma_t = 70.5 \) MPa, \( K_{ic} = 1.96 \) MPa \( \times \) m \( \frac{1}{2} \), Poisson’s ratio \( \nu = 0.38 \). As a result, the critical strain energy density for the considered PMMA is \( W_c = 0.839 \) MJ/m\(^3\) whereas the radius of the control volume is \( R_c = 0.166 \) mm, considering realistic plane strain conditions.

The strain energy density occurring inside the control volume embracing the edge of the notch was calculated numerically by using the finite element code ANSYS. For each geometry, a model was created defining the control volume where the strain energy density should be averaged (see Fig. 5c). All the analyses were carried out by using eight-node finite elements under the hypothesis of plane-strain conditions. Only negligible differences (less than 1%) occur by using fine or coarse meshes. This point has been accurately discussed in previous works [54, 56].

Table 3 summarizes the results of the experimental, numerical and theoretical findings for the tested PMMA.

Table 3. Experimental fracture loads compared with theoretical loads evaluated by means of strain energy density (SED) approach. The strain energy density in the table has been evaluated applying to the numerical models \( P = \langle P \rangle \)

<table>
<thead>
<tr>
<th>2( \alpha )</th>
<th>2( \alpha )</th>
<th>( \rho ), mm</th>
<th>( \langle P \rangle ), N</th>
<th>SED, MJ/m(^3)</th>
<th>( P_{th} ), N</th>
<th>( P_1 ), N</th>
<th>( P_2 ), N</th>
<th>( P_3 ), N</th>
<th>( \Delta_1 ), %</th>
<th>( \Delta_2 ), %</th>
<th>( \Delta_3 ), %</th>
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<tbody>
<tr>
<td>30°</td>
<td>0.5</td>
<td>5545</td>
<td>0.86</td>
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<td>5277</td>
<td>5724</td>
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<td>5612</td>
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<td>9.0</td>
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<td></td>
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<td>0.72</td>
<td>7305</td>
<td>6997</td>
<td>6530</td>
<td>6730</td>
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<td>10.6</td>
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<tr>
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<td>0.83</td>
<td>3767</td>
<td>3857</td>
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<td>21.9</td>
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Fig. 6. Comparison between theoretical fracture loads obtained by strain energy density and experimental data for 2\( \alpha = 30° \) (a), 60° (b) and 90° (c); \( R_e = 0.166 \) mm, \( W_c = 0.839 \) MJ/m\(^3\), \( d/D = 0.5 \).
specimens, analyzed here by means of strain energy density. In particular, the table summarizes the experimental loads to failure \( P \) for every notch radius \( \rho \) compared with the theoretical values \( P_{th} \) based on the strain energy density evaluation. The table also gives the strain energy density value as obtained directly from the finite element models of the PMMA specimens by applying to the model the average experimental load \( \langle P \rangle \).

The last columns of the table report the relative deviations between experimental and theoretical loads. As widely discussed in Ref. [54], acceptable engineering values range between \(-20\%\) and \(+20\\%\). As visible from the table, this range is satisfied for all the summarized test data apart one single point.

The results are given also in graphical form in Fig. 6 where the experimental values of the critical loads (open dots) have been compared with the theoretical predictions based on the constancy of the strain energy density in the control volume (solid line). The plots are given for the notched PMMA specimens as a function of the notch tip radius \( \rho \). The trend of the theoretically predicted loads is in good agreement with the experimental ones.

A synthesis in terms of the square root value of the local strain energy density averaged over the control volume (of radius \( R_c \)), normalized with respect to the critical energy of the material as a function of the notch tip radius is shown in Fig. 7. The plotted parameter is proportional to the fracture load. The data are plotted together independent of the notch geometries and specimens shape. The aim is to investigate the influence of the notch tip radius on the fracture assessment based on strain energy density. From the figure, it is clear that the scatter of the data is very limited and almost independent of the notch radius. All the values fall inside a scatter ranging from 0.8 to 1.2 with the majority of the data inside 0.9 to 1.1. The synthesis confirms also the choice of the control volume which seems to be suitable to characterize the material behaviour under pure mode I loading independent of the notch opening angle. The scatter of the experimental data presented here is in good agreement with the recent database in terms of strain energy density reported in Ref. [54].

5. CONCLUSION

A set of experimental results regarding tensile brittle fracture in V-notches with end holes was provided and analyzed in the paper. The fracture loads of PMMA specimens weakened by VO-notches were theoretically predicted here by means of the well-established brittle fracture criterion, namely the strain energy density over a specified control volume which embraces the notch edge. Different notched test specimens with three different notch opening angles were considered in the predictions. All the theoretical results fall inside a scatter band of \( \pm 20\% \) with the majority of which inside a scatter band of \( \pm 10\% \) demonstrating the effectiveness and the repeatability of the strain energy density criterion. The choice of the control volume size seems to be suitable for the considered material.

REFERENCES


