Estimation of fracture loads in 3D printed PLA notched specimens using the ASED criterion

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Abstract

This paper provides estimations of the fracture loads in 3D printed PLA (polylactic acid) specimens containing U-notches. The estimations are obtained using the ASED criterion, which is based on the quantification of the Strain Energy Density averaged over a control volume located at the notch tip. The ASED criterion has been validated in a wide range of materials, mainly in polymers, but also in composites, structural steels, aluminum alloys, rocks, etc. It assumes that fracture occurs when the mean value of the elastic strain energy referred to a specific volume is equal to a critical value \( W_c \). The results obtained in this work demonstrate that the ASED criterion provides, in the presence of notch-type defects, good estimations of the fracture loads in 3D printed PLA.

Keywords: fracture; PLA; plate; additive manufacturing; notch; ASED

1. Introduction

Fused deposition modelling (FDM) is a fabrication technology that allows complex shapes to be generated, and it may be applied to a wide variety of materials (e.g., polymers, metals, ceramics, composites). It consists in extruding a melted filament through a heated nozzle, which is then deposited on a build platform layer by layer until the final component is fabricated Cantrell et al. (2017). Until now, FDM has been basically applied to prototyping of...
components, but not for structural components, given that the obtained mechanical properties are generally poorer than those achieved by other fabrication methods (e.g., injection, extrusion). However, there are currently remarkable research efforts to develop an improved knowledge about this 3D printing technique and the mechanical properties of the resulting printed materials (e.g., Ahn et al. (2002); Ameri, Taheri-Behrooz, and Aliha (2020); Bamiduro et al. (2019); Cantrell et al. (2017); Cicero et al. (2020); Ng and Susmel (2020)).

**Nomenclature**

- $a$: Notch length
- ASED: Average Strain Energy Density
- $B$: Thickness
- $E$: Young’s modulus
- FDM: Fused Deposition Modelling
- $K_I$: Stress intensity factor
- $K_{mat}$: Fracture toughness
- $L$: Critical distance
- $P_{exp}$: Applied load
- $P_{exp,avg}$: Average value of applied load
- $P_{ASED}$: Critical load prediction
- PLA: Polylactic acid
- $r$: Distance from the notch tip
- $R_c$: Critical radius
- SENB: Single edge notched bending specimens
- SENT: Single edge notched tensile panel
- TCD: Theory of Critical Distance
- $W$: Width
- $W_c$: Critical value of the elastic strain energy
- $\varepsilon_u$: Strain under maximum load
- $\Omega$: Critical area
- $\nu$: Poisson’s ratio
- $\rho$: Notch radius
- $\sigma_{max}$: Maximum elastic stress at notch tip
- $\sigma_y$: Yield stress
- $\sigma_u$: Tensile strength
- $\sigma_0$: Inherent strength

3D printed components usually contain stress risers, such as defects generated during the manufacturing process (e.g., pores), those caused by operational damage, or geometrical details included in the proper design (e.g., holes). Such defects are not generally crack-like defects (i.e., infinitely sharp) and require specific approaches when evaluating their effect on the structural integrity. If they are treated as cracks, following conventional fracture mechanics principles, the results are often overly conservative. Among the different approaches that may be applied to analyse notches, the Average Strain Energy Density (ASED) (Berto and Lazzarin (2009, 2014); Lazzarin and Zambardi (2001)) has been proven to provide accurate analyses in the past.

This paper presents the analysis of fracture loads in FDM printed PLA plates containing U-shaped notches. 27 plates are tested, obtaining the corresponding critical loads under tensile loading. Then, the ASED criterion is applied to obtain estimations of the critical loads. However, the ASED criterion is based on a linear-elastic assumptions, so it cannot be directly applied to non-linear materials such as 3D printed PLA. Thus, a calibration of the SED criterion is performed in order to accurately predict the load bearing capacity of 3D printed PLA specimens containing U-notches.

Finally, the experimental values and the ASED estimations are compared. The results reveal that the ASED criterion provides accurate predictions of the fracture loads on this particular material when containing U-shaped notches.
2. Materials and methods

The material analyzed in this work is FDM printed PLA, with raster orientation 45/-45. An earlier characterization program was performed by the authors in this same material, determining the material tensile and fracture properties. Details may be found in Cicero et al. (2021), whereas Table 1 gathers a summary of the main mechanical properties.

<table>
<thead>
<tr>
<th>Raster orientation</th>
<th>E (MPa)</th>
<th>( \sigma_0 ) (MPa)</th>
<th>( \sigma_u ) (MPa)</th>
<th>( \sigma_y ) (MPa)</th>
<th>( \sigma_{\text{ult}} ) (MPa)</th>
<th>( K_{\text{mat}} ) (MPa m(^{1/2}))</th>
<th>L (mm)</th>
<th>( \sigma_0 ) (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>45/-45</td>
<td>2751</td>
<td>35.3</td>
<td>41.1</td>
<td>2.6</td>
<td>4.59</td>
<td>0.12</td>
<td>236.4</td>
<td></td>
</tr>
</tbody>
</table>

The plates analyzed in this work were manufactured by FDM using the same printer and the same printing parameters used in Cicero et al. (2021): nozzle diameter 0.4 mm; nozzle temperature 200 °C; bed temperature 75 °C; printing rate 30 mm/s; infill level 100%; layer height 0.3 mm.

The total number of tested plates was 27, 3 specimens per geometry, with the following combination (see Fig. 1):

- 12 U-notched plates with \( W=60 \) mm, \( a=30 \) mm (\( a/W=0.50 \)), \( a \) being the notch length and \( W \) being the specimen width, 2 different thicknesses (5 mm and 10 mm) and 2 different notch radii (0.9 mm or 1.3 mm).
- 15 U-notched plates with \( W=120 \) mm, \( a=30 \) mm (\( a/W=0.25 \)), 2 different thicknesses (5 mm, 10 mm and 20 mm) and 2 different notch radii (0.9 mm or 1.3 mm).

The loading rate was 1 mm/min in all cases, and the load-displacement curve was recorded for each individual test until the corresponding critical (maximum) load.

Once the experimental critical loads were determined, the ASED criterion was applied with the aim of estimating the critical loads derived from this approach. The ASED criterion is based on the Strain Energy Density averaged over a control volume surrounding the notch tip. In plane problems, the control volume becomes a circle or a circular sector with a radius \( R_c \) in the case of U-notches Berto and Lazzarin (2014) (see Figure 2).

![Fig. 1. Geometry of the tested plates. \( \rho \): notch radius.](image1)

![Fig. 2. Control area. for blunt V-notch. The notch become U-notch when \( \alpha=0 \).](image2)
The SED approach assumes that fracture takes place when the mean value of the elastic strain energy referred to an area is equal to the critical value \( W_c \), which is a material property. According to Lazzarin and Zambardi (2001), if the material is ideally brittle, the value of the critical strain energy density follows:

\[
W_c = \frac{\sigma_u^2}{2E}
\]

where \( \sigma_u \) is the ultimate tensile strength and \( E \) is the Young’s Modulus. When the notch opening angle is zero \( (2\alpha=0) \), as it is the case in U-notches, the material critical radius \( R_c \) can be expressed in terms of the fracture toughness \( (K_{mat}) \), the ultimate tensile strength \( (\sigma_u) \), and Poisson’s ratio \( (\nu) \) Yosibash, Bussiba, and Gilad (2004):

\[
R_c = \frac{(1+\nu)(5-8\nu)}{4\pi} \left( \frac{K_{mat}}{\sigma_u} \right)^2 \quad \text{Plane strain}
\]

\[
R_c = \frac{(5-3\nu)}{4\pi} \left( \frac{K_{mat}}{\sigma_u} \right)^2 \quad \text{Plane stress}
\]

In the case of blunt notches, again the case analysed in this work, the total strain energy can be determined over the crescent shape volume (Fig. 2) and then the mean value of the SED can be expressed in terms of the elastic maximum notch stress \( (\sigma_{max}) \) (Berto and Lazzarin (2014); Seweryn (1994)). By applying this condition, the total strain energy can be obtained over the area \( \Omega \) (Fig. 1), and the corresponding mean value of the ASED follows equation (4) (Berto and Lazzarin (2014)):

\[
\bar{W} = F(2\alpha)H \left( 2\alpha, \frac{R_c}{\rho} \right) \frac{\sigma_{max}^2}{E}
\]

where \( F(2\alpha) \) depends on the notch opening angle \( (0.785 \text{ when } 2\alpha=0^\circ) \), \( H \) varies with the notch geometry \( (2\alpha, R_c/\rho) \) and \( \sigma_{max} \) is the maximum elastic stress at the notch tip. The values of the \( H \) function for U-shaped notches \( (2\alpha=0^\circ) \) may be found in Berto and Lazzarin (2014). Table 2 gathers different values of the \( H \) function for U-shaped notches (Berto and Lazzarin (2014)).

<table>
<thead>
<tr>
<th>( R_c/\rho )</th>
<th>( H(0.3) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>0.5638</td>
</tr>
<tr>
<td>0.05</td>
<td>0.5086</td>
</tr>
<tr>
<td>0.10</td>
<td>0.4518</td>
</tr>
<tr>
<td>1.00</td>
<td>0.1314</td>
</tr>
</tbody>
</table>

When the material being analysed does not have brittle behaviour, the application of the ASED criterion requires calibration of the material parameters, \( W_c* \) and \( R_c* \) (thus, \( H; \) Seibert et al. (2022)). In practice, the linear-elastic ASED criterion is applied to an equivalent linear-elastic material. The calibration performed in this work has been based on fracture tests performed on U-notched SENB specimens with notch radii of 0.25 mm \( (\rho_1) \) and 1.0 mm \( (\rho_2) \), whose details may be found in Cicero et al. (2021). With the fracture loads of these two conditions (and their corresponding maximum stresses, \( \sigma_{max1} \) and \( \sigma_{max2} \), respectively), the following conditions may be established:

\[
F(2\alpha = 0) \cdot H_1 \left( 2\alpha = 0, \frac{R_c}{\rho_1} \right) \cdot \frac{\sigma_{max1}^2}{E} = W_c
\]

\[
F(2\alpha = 0) \cdot H_2 \left( 2\alpha = 0, \frac{R_c}{\rho_2} \right) \cdot \frac{\sigma_{max2}^2}{E} = W_c
\]
The SED approach assumes that fracture takes place when the mean value of the elastic strain energy referred to an area is equal to the critical value \( W_c \), which is a material property. According to Lazzarin and Zambardi (2001), if the material is ideally brittle, the value of the critical strain energy density follows:

\[
\sigma_u E
\]

where \( \sigma_u \) is the ultimate tensile strength and \( E \) is the Young's Modulus. When the notch opening angle is zero \( (2\alpha = 0) \), as it is the case in U-notches, the material critical radius \( R_c \) can be expressed in terms of the fracture toughness \( K_{\text{mat}} \), the ultimate tensile strength \( \sigma_u \), and Poisson's ratio \( \nu \): Yosibash, Bussiba, and Gilad (2004):

\[
R_c = \frac{\sigma_u}{\sqrt{\frac{\nu}{E}}} (1)
\]

\( \text{Plane strain} \) \( (2) \)

\[
R_c = \frac{\sigma_u}{\nu} (2\alpha)^{\frac{1}{2}} \]  
\( \text{Plane stress} \) \( (3) \)

In the case of blunt notches, again the case analysed in this work, the total strain energy can be determined over the crescent shape volume (Fig. 2) and then the mean value of the SED can be expressed in terms of the elastic maximum notch stress \( \sigma_{\text{max}} \) (Berto and Lazzarin (2014); Seweryn (1994)). By applying this condition, the total strain energy can be obtained over the area \( \Omega \) (Fig. 1), and the corresponding mean value of the ASED follows equation (4) (Berto and Lazzarin (2014)):

\[
\bar{W} = F(2\alpha)H \left(2\alpha \frac{R_c}{\rho}\right) \sigma_{\text{max}}^2 = W_c^* \]

(4)

where \( F(2\alpha) \) depends on the notch opening angle \( (0.785 \text{ when } 2\alpha = 0^\circ) \), \( H \) varies with the notch geometry \( (2\alpha, R_c/\rho) \) and \( \sigma_{\text{max}} \) is the maximum elastic stress at the notch tip. The values of the \( H \) function for U-shaped notches \( (2\alpha = 0^\circ) \) may be found in Berto and Lazzarin (2014). Table 2 gathers different values of the \( H \) function for U-shaped notches (Berto and Lazzarin (2014)).

Table 2. Values of the function \( H \) when \( 2\alpha = 0^\circ \) for blunted V-shaped notches (coefficients determined numerically with \( \rho = 1 \text{ mm} \)).

<table>
<thead>
<tr>
<th>( R_c/\rho )</th>
<th>( H )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>0.01 0.5638</td>
</tr>
<tr>
<td>0.05</td>
<td>0.05 0.5086</td>
</tr>
<tr>
<td>0.10</td>
<td>0.05 0.4518</td>
</tr>
<tr>
<td>1.00</td>
<td>0.05 0.1314</td>
</tr>
</tbody>
</table>

When the material being analysed does not have brittle behaviour, the application of the ASED criterion requires calibration of the material parameters \( W_c^* \) and \( R_c^* \) (thus, \( H \)); Seibert et al. (2022)). In practice, the linear-elastic ASED criterion is applied to an equivalent linear-elastic material. The calibration performed in this work has been based on fracture tests performed on U-notched SENB specimens with notch radii of 0.25 mm \((\rho_1)\) and 1.0 mm \((\rho_2)\), whose details may be found in Cicero et al. (2021). With the fracture loads of these two conditions (and their corresponding maximum stresses, \( \sigma_{\text{max}}_1 \) and \( \sigma_{\text{max}}_2 \), respectively), the following conditions may be established:

\[
\bar{W} = F(2\alpha)H \left(2\alpha \frac{R_c}{\rho}\right) \sigma_{\text{max}}^2 = W_c^* \]

(5)

\[
\bar{W} = F(2\alpha)H \left(2\alpha \frac{R_c}{\rho}\right) \sigma_{\text{max}}^2 = W_c^* \]

(6)

By introducing different values of \( R_c \) in (5) and (6), two \( W_c \) vs \( R_c \) curves are generated (see Fig. 3). The crossing point of both curves provides the actual values of \( W_c^* \) and \( R_c^* \).

![Fig. 3. Calibration of \( W_c \) and \( R_c \) parameters with SENB specimens.](image)

From this calibration, the parameters are \( W_c^* = 4.34 \text{ MPa} \) and \( R_c^* = 0.60 \text{ mm} \). These parameters are used to calculate the critical load predictions.

3. Results and discussion

Fig. 4 shows an example of the experimental setup. Table 3 gathers the experimental critical loads \((P_{\text{exp}} \text{ for individual tests and } P_{\text{exp,avg}} \text{ for mean value of each geometry})\). As explained above, the calibration performed to obtain the ASED parameters provided values of \( W_c^* = 4.34 \text{ MPa} \) and \( R_c^* = 0.60 \text{ mm} \). Once \( W_c^* \) and \( R_c^* \) are known, fracture loads are derived from:

\[
\bar{W} = F(2\alpha)H \left(2\alpha \frac{R_c}{\rho}\right) \sigma_{\text{max}}^2 = W_c^* \]

(7)

Considering that \( F(2\alpha) \) is 0.785 for U-notches, the corresponding \( \sigma_{\text{max}} \) is easily derived from:

\[
\sigma_{\text{max}} = \sqrt\frac{E \cdot W_c^*}{0.785 \cdot H \left(2\alpha \frac{R_c}{\rho}\right)}
\]

(8)
Fig. 4. Experimental setup of one of the experiments. U-notch, notch radius 0.9 mm, thickness 10 mm.

Once $\sigma_{\text{max}}$ is obtained, the external load causing this maximum stress at the notch tip may be easily derived by using analytical expressions of the stress field, such as the Creager-Paris equation (Creager and Paris (1967)):

$$\sigma(r) = \frac{K_I}{\sqrt{r}} \cdot \frac{2(r+\rho)}{(2r+\rho)^{3/2}}$$

with $K_I$ being the applied stress intensity factor, $r$ being the distance from the notch tip and $\rho$ being the notch radius. Given that $\sigma_{\text{max}}$ takes place at $r=0$:

$$\sigma_{\text{max}} = \frac{2K_I}{\sqrt{\rho}}$$

Equation (10) provides the $K_I$ value at fracture conditions. Finally, using the recognized analytical solution of $K_I$ for single edge notched tensile (SENT) panel (equation (11), Anderson (2012)), the values of the predicted critical loads ($P_{\text{ASED}}$) can be derived:

$$K_I = \left(\frac{P_{\text{ASED}}}{B\sqrt{W}}\right) \cdot \sqrt{\frac{2\tan \frac{a}{2W}}{\cos \frac{aw}{2W}}} \left(0.752 + 2.02 \left(\frac{a}{w}\right) + 0.37 \left(1 - \sin \frac{aw}{2W}\right)^3\right)$$

where $a$, $B$, and $W$ denote the defect length, the specimen thickness and the specimen width, respectively.
Once $\sigma_{\text{max}}$ is obtained, the external load causing this maximum stress at the notch tip may be easily derived by using analytical expressions of the stress field, such as the Creager-Paris equation (Creager and Paris (1967)):

$$\sigma = \frac{K_I}{\sqrt{r}} \cdot \frac{1}{{\sigma_{\text{max}}}^2}$$

with $K_I$ being the applied stress intensity factor, $r$ being the distance from the notch tip and $\rho$ being the notch radius.

Given that $\sigma_{\text{max}}$ takes place at $r=0$:

$$\sigma_{\text{max}} = \frac{K_I}{\rho}$$

Equation (10) provides the $K_I$ value at fracture conditions. Finally, using the recognized analytical solution of $K_I$ for single edge notched tensile (SENT) panel (equation (11), Anderson (2012)), the values of the predicted critical loads ($P_{\text{ASED}}$) can be derived:

$$P_{\text{ASED}} = \frac{a}{W} \cdot \sigma_{\text{max}}$$

where $a$, $B$, and $W$ denote the defect length, the specimen thickness and the specimen width, respectively.

Table 3 also includes the corresponding estimation of the critical loads derived from the ASED criterion ($P_{\text{ASED}}$), which are also compared graphically with the experimental results in Fig. 5.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>B (mm)</th>
<th>W (mm)</th>
<th>a (mm)</th>
<th>Notch radius (mm)</th>
<th>$P_{\text{exp}}$ (N)</th>
<th>$P_{\text{exp, avg}}$ (N)</th>
<th>$P_{\text{ASED}}$ (N)</th>
<th>$P_{\text{ASED}}/P_{\exp}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>P201</td>
<td>5.38</td>
<td>60.67</td>
<td>30.65</td>
<td>0.85</td>
<td>3789.1</td>
<td>2241.9</td>
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<td>P202</td>
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<tr>
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<td>8014.6</td>
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<td>30.74</td>
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<td>30.57</td>
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<td>30.76</td>
<td>1.31</td>
<td>12803.7</td>
<td>8636.8</td>
<td>0.675</td>
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<td>120.65</td>
<td>30.78</td>
<td>1.32</td>
<td>13477.4</td>
<td>12837.7</td>
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<td>P309</td>
<td>4.93</td>
<td>120.74</td>
<td>30.85</td>
<td>1.31</td>
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<td>120.61</td>
<td>30.77</td>
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<td>120.40</td>
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<td>1.31</td>
<td>24363.4</td>
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<td>25023.1</td>
<td>17220.5</td>
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</table>

It can be observed how the predictions are actually conservative (safe) estimations of the physical critical loads for the different notch radii analysed here, with $P_{\text{ASED}}/P_{\exp}$ ratios ranging between 0.5 and 0.75. Additional research is required to justify such conservatism. One of the factors causing this could be the fact that the ASED parameters have been calibrated from fracture results in specimens subjected to bending loads (high constraint), whereas the plates are subjected to tensile loads (low constraint).
4. Conclusions

In this work, the Average Strain Energy Density (ASED) criterion, a has been applied to evaluate fracture loads in 3D printed PLA plates containing U-notches and subjected to tensile loads. Given that the material is not fully brittle, the ASED criterion has required a previous calibration process based on experimental fracture loads obtained in SENB specimens containing two different notch radii. The validation has been performed on one single raster orientation (45/-45), observing that the proposed approach has provided conservative safe estimation of critical loads in all cases, with $P_{\text{ASED}}/P_{\text{exp}}$ ratios ranging between 0.5 and 0.75.

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References

4. Conclusions
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