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Using the Point Method to estimate failure loads in 3D printed graphene-reinforced PLA notched plates

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Abstract. This work estimates failure loads in Fused Filament Fabrication (FFF) printed graphene-reinforced PLA (polylactic acid) plates containing different types of stress risers. With this aim, firstly, several notched plates are tested and conducted to fracture. Then, linear elastic Finite Element (FE) analyses are completed to define the corresponding stress profiles and, finally, the Point Method (PM) is applied to establish the failure criterion. This approach asserts that fracture conditions are achieved when the stress level equates the inherent strength (σ_0) at a distance from the notch tip equal to L/2, so both parameters (related to each other through the material fracture toughness, K_{mat}) have been defined beforehand. The estimations of fracture loads obtained following this approach agree with the experimental results. Thus, the present work demonstrates the accuracy of the PM to estimate failure loads in this 3D printed material.

1. Introduction

Fused Filament Fabrication (FFF), enclosed within additive manufacturing (AM), is a technology that allows intricate geometries to be fabricated. FFF is applicable to a wide variety of materials, covering polymers, ceramics, metals and composites. It involves extruding a melted filament through a sufficiently heated nozzle, and depositing the extruded material on a build platform layer by layer until the final part is completely built [1]. So far, FFF has been fundamentally used for prototyping, but not for parts with structural purposes, the main reason being that the obtained mechanical performance is commonly lower than that attained when using more conventional fabrication methods, such as injection or extrusion. Nevertheless, aiming to improve the mechanical performance of FFF components, there has been noteworthy research activity to gain a better understanding about this technique and the resulting printed materials (e.g., [1-6]).

On the other hand, structural parts usually contain stress risers, and those generated by FFF are not an exception. In fact, FFF parts may have defects generated during the manufacturing process (e.g., pores), geometric features defined in the proper design (e.g., drilled or printed holes), or defects caused by operational damage, as some examples that are usually found in practice. Obviously, all such defects (here, generally referred to as notches) are not crack-like defects, so evaluating them and their effect on the corresponding structural integrity necessitates the application of specific approaches beyond traditional fracture mechanics criteria. In other words, if they were assessed as cracks, following conventional fracture mechanics principles, the results could result overly conservative. There are different approaches that may be applied to analyze notches, with the Point Method (PM) [7] providing an exceptional balance between the simplicity of the analysis and the precision of the evaluations.

With all this, the present paper analyses the fracture loads in FFF graphene-reinforced PLA plates that contain different types of U- and V-shaped notches. Firstly, the experimental critical loads are obtained on the notched plates; secondly, the estimations of the critical loads are derived by using the Point Method. The obtained results demonstrate that the PM generates good predictions of the experimental fracture conditions on this particular 3D printed material.

2. Materials and methods

The material analyzed in this work is FFF graphene-reinforced (1 wt%) PLA, supplied by FiloAlfa3D (Italy) as filaments. All the specimens were printed with raster orientation 45/-45. The material tensile and fracture properties are analyzed in a previous work (see [8] for details), with the main mechanical properties being collected in Table 1.

Table 1. Tensile and fracture properties for graphene-reinforced PLA, raster orientation 45/-45: E is Young's modulus; σ_y is the yield stress; σ_u is the ultimate tensile strength; ε_u is the strain under maximum load. TCD parameters: L is the critical distance; σ_0 is the inherent strength.

E (MPa)	σ_y (MPa)	σ_u (MPa)	ε_u (%)	L (mm)	σ_0 (MPa)
3972	47.5	49.0	1.5	0.48	185.4

The plates analyzed in this work were all printed by FFF using a Prusa i3 printer with the following printing parameters: nozzle diameter 0.4 mm; nozzle temperature 200 ºC; bed temperature 75 ºC; infill level 100%; printing rate 30mm/s; layer height 0.3 mm. The process was identical to the one followed for the tensile and fracture specimens printed to complete the basic characterization of the material [8]. The notches were all machined after the printing process.

The total amount of printed and tested plates for this work was 21, with 7 different geometries and 3 specimens per geometry:

- 15 U-notched specimens with two possible nominal notch radii (0.9 mm or 1.3 mm), defect length to specimen width radio (a/W) of 0.25 in all cases, and 3 possible thicknesses (5 mm, 10 mm and 20 mm). The notch radius of 0.9 mm covers the 3 thicknesses, whereas the 1.3 mm notch radius was only performed on 5 mm and 10 mm thick plates.
- 6 V-notched plates: V-notch with fixed opening angle of 60°, nominal notch radius 0.90 mm and a/W=0.25 (see Figure 1). 2 different thicknesses (5 mm and 10 mm).

In all the different tests the loading rate was fixed at 1 mm/min. The load-displacement curve was recorded for each individual test, also determining the corresponding critical (i.e., maximum) load.

After testing, the PM was applied to estimate the corresponding critical loads. This approach is actually one of the methodologies composing the Theory of Critical Distances (TCD), and it is (thus) characterized by the use of a material length parameter (the critical distance, L), which follows equation (1):

$$L=\frac{1}{\pi}\left(\frac{K_{mat}}{\sigma_0}\right)^2 \quad (1)$$

K_{mat} being the fracture toughness and σ_0 being the material inherent strength. σ_0 matches the material ultimate tensile strength (σ_u) in those materials with linear-elastic behavior at both the micro and the macro fracture mechanisms, whereas in materials with non-fully linear behavior, σ_0 requires calibration.

As shown in Table 1, for the 3D graphene-reinforced PLA analyzed in this work, σ_0 (185.4 MPa) is much larger than σ_u (49.0 MPa).

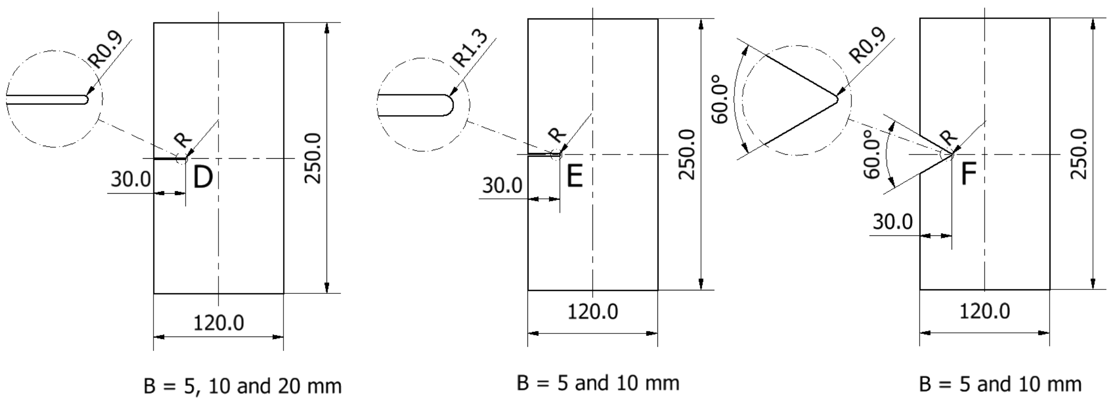

Figure 1. Different dimensions of the tested plates and notches. B: thickness. R: notch radius.

The PM is actually the simplest version of the TCD, requiring the definition of the stress field at the defect tip being analyzed. It states that fracture takes place when the stress reaches the inherent stress, at a distance of L/2 from the defect tip (Figure 2). In other words:

$$\sigma\left(\frac{L}{2}\right) = \sigma_0 \quad (2)$$

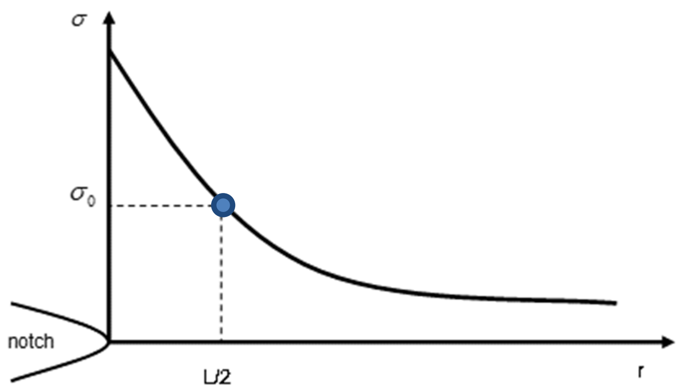

Figure 2. Graphical explanation of the PM.

The different geometries of the specimens were modelled through finite element (FE) software (Ansys) by using 20-node hexahedron elements and assuming fully linear-elastic behaviour. Then, for an arbitrary external tensile load (1N in this case), the stress field was defined in the mid plane of the fracture section, together with the corresponding stress value at a distance of L/2. Then, finally, the estimation of the critical load was obtained applying proportionality conditions, as that one generating a stress value equal to σ_0 at the same distance (L/2).

3. Results and discussion

Figures 3 and 4 show, correspondingly, cases of the experimental setup and the FE model, whereas Table 2 gathers the experimental critical loads and the estimations provided by the PM (P_{PM}). The table also includes the actual measured value of the notch radius of each individual specimen, which was used in the corresponding FE analysis. The experimental loads and the resulting predictions are also compared in Figure 5.

The results show how the PM provides good estimations of the fracture loads. Average fracture loads are predicted with an accuracy of ±10%, while the divergence between estimates and individual fracture loads is always less than 20%.

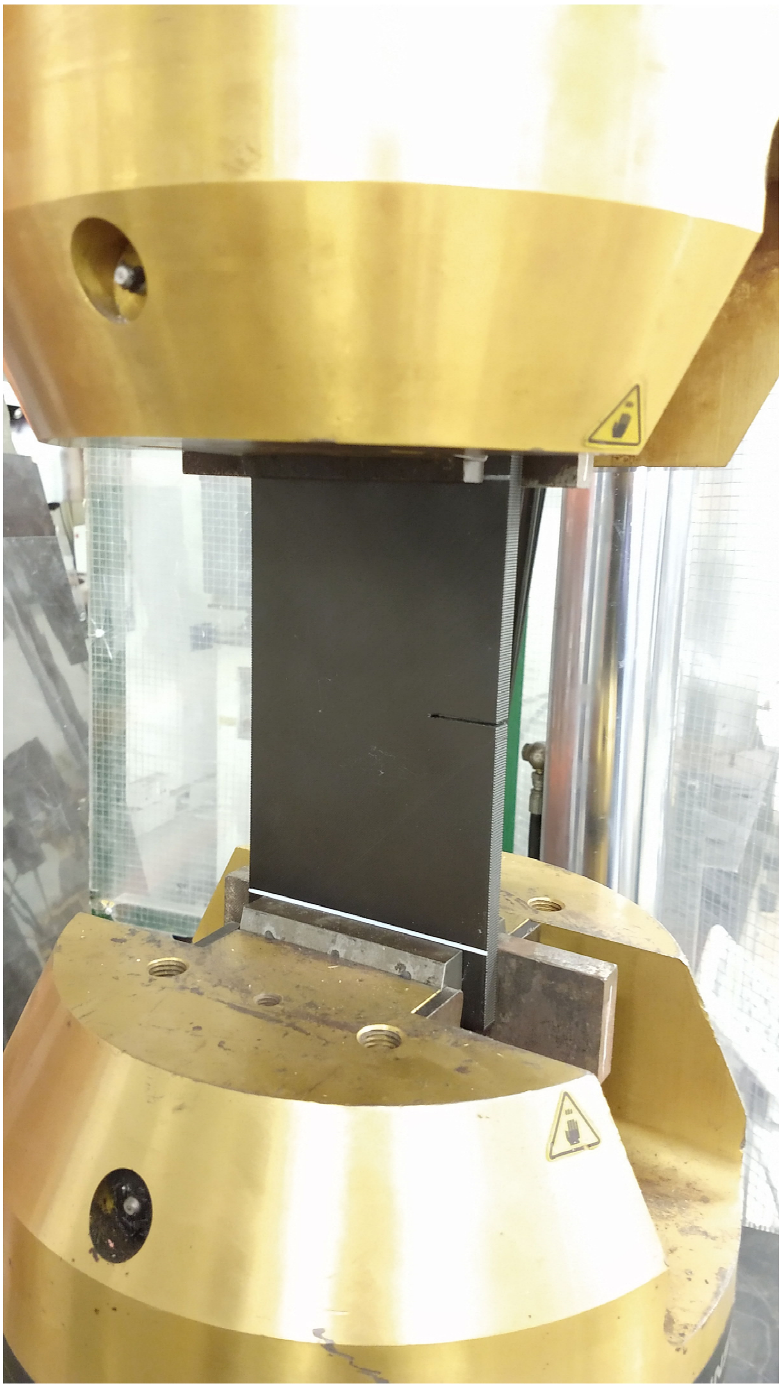

Figure 3. Example of experimental setup. U-notched specimen, notch radius 0.89 mm, thickness 10 mm, a/W = 0.25

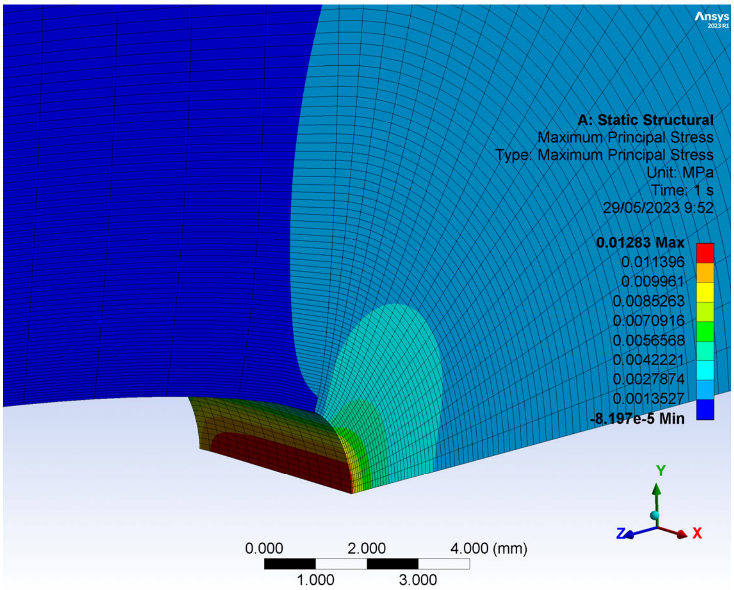

Figure 4. Case of FE model. U-notched specimen, notch radius 0.89 mm, thickness 10 mm. Applied load = 1 N.

Table 2. Experimental results and PM results. i=1,2,3 refers to the three specimens (test) per geometry. $P_{exp,i}$: critical load for test i; $P_{exp,average}$: mean value for each geometry; P_{PM}: PM prediction.

Specimen	Defect	Thickness (mm)	Notch radius ρ (mm)	$P_{exp,i.}$ (kN)	$P_{exp,average}$ (kN)	P_{PM} (kN)
U5-09-1 Gr	U-notch	5	0.81	10.56		
U5-09-2 Gr	U-notch	5	0.83	13.15	11.37	11.20
U5-09-3 Gr	U-notch	5	0.89	10.15		
U10-09-1 Gr	U-notch	10	0.89	24.44		
U10-09-2 Gr	U-notch	10	0.84	26.41	24.64	22.34
U10-09-3 Gr	U-notch	10	0.88	23.01		
U20-09-1 Gr	U-notch	20	0.88	39.91		
U20-09-2 Gr	U-notch	20	0.89	42.56	43.29	45.06
U20-09-3 Gr	U-notch	20	0.87	47.30		
U5-13-1 Gr	U-notch	5	1.26	11.52		
U5-13-2 Gr	U-notch	5	1.27	11.22	11.401	11.96
U5-13-3 Gr	U-notch	5	1.26	11.47		
U10-13-1 Gr	U-notch	10	1.27	25.37		
U10-13-2 Gr	U-notch	10	1.26	22.38	24.69	23.79
U10-13-3 Gr	U-notch	10	1.26	26.32		
V5-09-1 Gr	V-notch	5	1.07	10.65		
V5-09-2 Gr	V-notch	5	1.15	10.30	11.00	11.74
V5-09-3 Gr	V-notch	5	1.01	12.05		
V10-09-1 Gr	V-notch	10	0.97	24.25		
V10-09-2 Gr	V-notch	10	0.89	25.32	24.56	23.52
V10-09-3 Gr	V-notch	10	1.05	24.10		

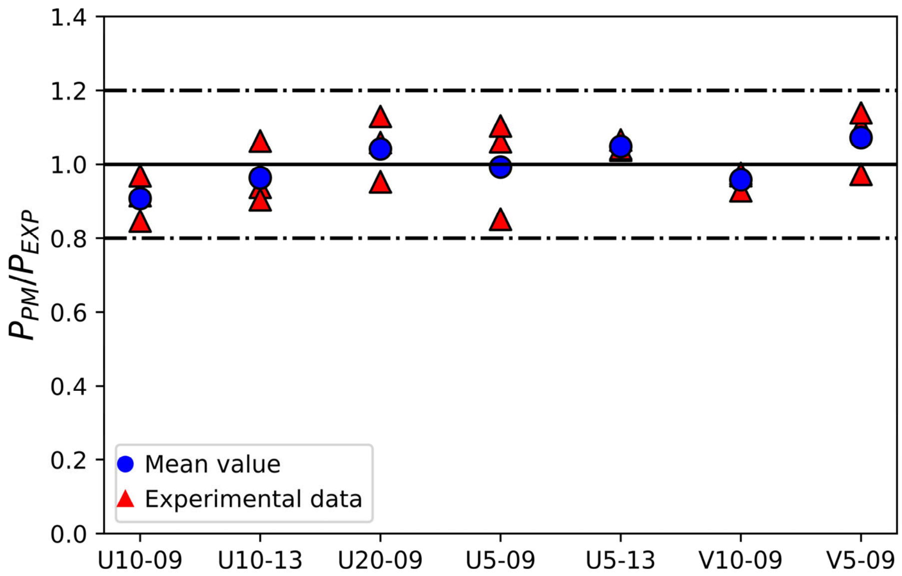

Figure 5. Comparison between fracture load estimations and experimental fracture loads.

4. Conclusions

This work provides an evaluation of the fracture loads in FFF graphene-reinforced PLA plates containing U- and V-shaped notches and subjected to tensile loads. The raster orientation is fixed at 45/-45 in all cases. The estimation of the fracture loads is performed by using the Point Method, and the results are compared to the corresponding experimental values. The PM, supported by linear-elastic FE modeling, provides good predictions of the average experimental critical loads, within deviation in the range of ±10%.

Acknowledgments

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