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Structural Integrity and Reliability of Advanced Materials obtained through Additive Manufacturing (SIRAMM23)

On the mixed mode fracture of DLP manufactured SCB specimens

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Abstract

The scope of this study is to investigate the mixed mode fracture of components manufactured from photo-polymerized resin using the Digital Light Processing (DLP) additive manufacturing technology.
The mixed mode tests were performed on Semi Circular Bend (SCB) specimens loaded under symmetric Mode I, asymmetric mixed mode and mode II loading, respectively. The specimens manufactured via DLP have a crack introduced during the manufacturing process. Tests were performed at room temperature using a universal testing machine with three point bending grips at a constant loading speed. Four tests were carried on for each supports position.
The experimental results expressed as K_{II}/K_{IC} versus K_I/K_{IC} are plotted by adopting four fracture criteria, namely the Maximum Tensile Stress (MTS), the Strain Energy Density (SED), the Maximum Energy Release Rate (G_{max}), and the Equivalent Stress Intensity Factor (ESIF). Most of the experimental results fall in the range of fracture envelope curves.

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Keywords: Semi Circular Bend specimens; fracture toughness; mixed mode

1. Introduction

Additive Manufacturing (AM) technologies start to be developed at the end of 20th Century and have had a great impact on the fabrication directly from a 3D model of objects with complex geometries, Wong and Hernandez (2012).

Digital Light Processing (DLP) is a 3D printing technology used to quickly manufacture polymeric components by photo-polymerization. It belongs to the family of additive manufacturing technologies known as vat photo-

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polymerization. They use a light source (laser beam or projector) to cure a liquid resin into a hardened plastic solid. Brighenti et al. (2021) presented a comprehensive review on processes and mechanical models on laser-based additively manufacturing of polymeric materials, while the influence of the manufacturing parameters on the obtained mechanical properties of additively manufactured photo-polymerized polymers is shown in Brighenti et al. (2022). The exposure time and the layer thickness have been considered as the main fabrication parameters to be used as design variables for controlling the mechanical characteristics of the obtained AM components. It has been shown that the exposure time represents the main parameter affecting the mechanical properties on tensile strength, while the influence of the layer thickness appeared to be less important.

The influence of the printing angle and load direction on flexure strength of two commercial resins obtained through Stereolithography (SLA) used for dental restorations is presented in Derban et al. (2000). The results show that the smallest flexural properties were obtained when the printing angle equals 45º. On the other hand, higher values of the flexural modulus and flexure strength were obtained when the applied load is parallel to the AM growing direction.

So far, a limited number of studies on the fracture toughness of vat photo-polymerization components is avaiable. Brighenti et al (2023) presented a study of the influence of curing and printing angle on the fracture toughness of DPL specimens. Single Notched Bend specimens loaded in three point bending were tested. Three printing angles (0^0, 45 and 90^0), and three curing treatments were considered: 1) 5 minutes maintained in Isopropyl Alcohol (IPA) and then cured for 5 minutes; 2) cleaned in hot water (60 -70 ºC) and 30 minutes ultrasonic curing; 3) cleaned for 5 minutes maintained in IPA and 30 minutes ultrasonic curing. The highest fracture toughness was obtained for 0^0 printing angle and 5 minutes maintained in Isopropyl Alcohol (IPA) and then cured for 5 minutes. For all the tested specimens, for which a plain strain condition was fulfilled, a brittle fracture was observed.

The present study investigates the mixed mode fracture of DLP manufactured specimens and compares this response with classical fracture criteria. The Semi Circular Bend (SCB) specimen loaded asymmetric was adopted for mixed mode loading. Previous studies on different materials showed that this specimen could produce different ranges of mixed modes, ranging from pure mode *I* to pure mode *II* only by changing the position of one support, Marsavina et al. (2023), Ayatollahi et al. (2011).

Nomenclature

a	crack length
K_I	mode I stress intensity factor
K_{II}	mode II stress intensity factor
K_{IC}	fracture toughness
R	specimen radius
S_1, S_2	spans
t	specimen thickness
θ_c	crack initiation angle

2. Experimental tests

Mixed mode fracture tests were performed using Semi-Circular Bend (SCB) specimens loaded asymmetric, Fig. 1.

The specimens were printed using a 3D LCD printer (Anycubic Photon®), based on DLP technology. The SCB specimens were manufactured using an UV-sensitive resin “translucent green” (curing UV light wavelength 405 nm) with the following parameters: light exposure time 20 s for each layer, layer thickness 0.05 mm, and printing orientation 0º. Post printing process consisted in 5 minutes in Isopropyl Alcohol (IPA) and then cured for 5 minutes in Anycubic® wash and post-cure machine 2.0. These manufacturing parameters were the optimal ones for obtaining the highest fracture toughness in our previous studies, Brighenti et al. (2023).

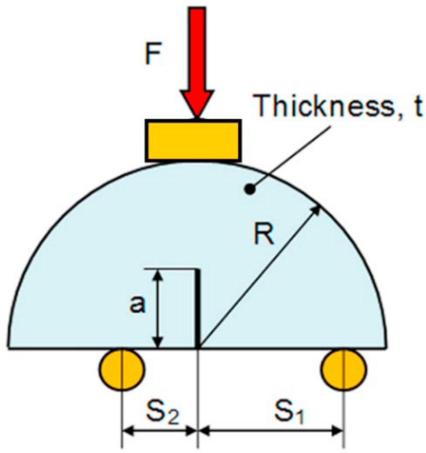

Fig. 1. The Semi-Circular Bend (SCB) specimen.

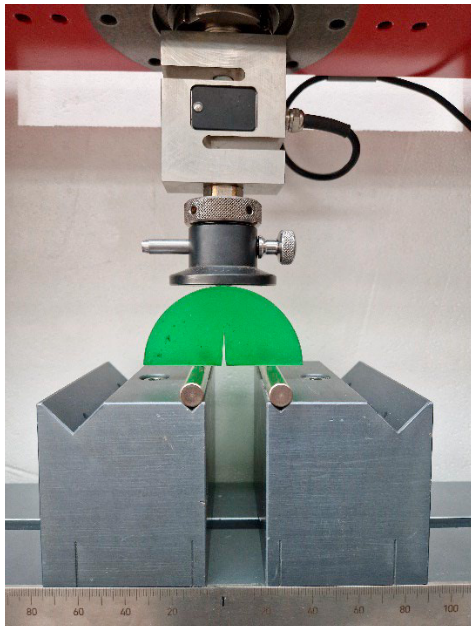

Fig. 2 The SCB specimen in three-point bending grips.

Mixed mode fracture tests were performed using Semi-Circular Bend (SCB) specimens loaded asymmetrically. The SCB specimens having radius R and thickness t have an edge crack of length a oriented normal to the specimen edge, inserted during the printing process, Fig. 1. The specimens were loaded in a three point bend fixture, which was proved to give a wide range of mixed modes, Fig. 2, from pure mode I ($S_1 = S_2$), mixed modes ($S_1 \neq S_2$) and to pure mode II, only by changing the position of one support, Lim et al. (1994), Ayatollahi et al (2011), Negru et al (2014). The specimen dimensions where: radius R =40 mm, thickness t =3 - 6 mm, crack length a≈18 mm, and spans S_1=30 mm, respectively S_2=30, 12, 8, 6, 4, 2.66 mm. The crack was introduced directly during the 3D printing process as a very sharp notch.

The Stress Intensity Factors (SIFs) solutions for the SCB specimen loaded asymmetric were provided in Marsavina et al. (2014):

$$K_i = \frac{P_{\max}}{2Rt}\sqrt{\pi a}\, f_i\left(a/R, S_1/R, S_2/R\right), \quad i = I, II \tag{1}$$

where, the non-dimensional SIFs, $f_i\ (a/R, S_1/R, S_2/R)$, were determined by finite element analysis using FRANC2D software, Marsavina et al. (2014):

$$\begin{aligned} f_I(S_2/R) &= 6.235(S_2/R)^3 - 15.069(S_2/R)^2 + 17.229(S_2/R) - 1.062 \\ f_{II}(S_2/R) &= 1.884(S_2/R)^5 - 7.309(S_2/R)^4 + 5.037(S_2/R)^3 + 2.77(S_2/R)^2 - 5.075(S_2/R) + 1.983 \end{aligned} \tag{2}$$

Four tests were performed, for each combination of S_1, S_2 positions, on a Zwick/Roell 5 kN testing machine at room temperature with a loading rate of 2 mm/min. Brittle fracture was observed for all tests and mode mixities, Fig. 3. The fracture load increases with decreasing the span S_2 from 30 (pure Mode I) mm to 2.66 mm (pure Mode II), respectively with increasing the mode II.

3. Results and discussions

Relations (1) and (2) were used to estimate the stress intensity factors K_I and K_{II}. The obtained experimental results are shown in Table 1. The average value of symmetric loading was considered the mode I fracture toughness of the additive manufactured resin, K_{IC} =1.012±0.057 MPa m$^{0.5}$.

Table 1. Experimental results

Specimen	R [mm]	t [mm]	a [mm]	S_1 [mm]	S_2 [mm]	P_{max} [N]	K_I [MPa m$^{0.5}$]	K_{II} [MPa m$^{0.5}$]
2.6-1	40.02	6.30	17.7	30	2.66	1160	0.000	0.904
2.6-2	40.10	6.24	17.3	30	2.66	1070	0.000	0.831
2.6-3	40.00	4.33	17.3	30	2.66	875	0.000	0.981
2.6-4	39.92	3.91	17.5	30	2.66	739	0.000	0.924
4.0-1	40.17	4.40	16.3	30	4	957	0.312	0.923
4.0-2	40.03	5.30	17	30	4	1000	0.280	0.820
4.0-3	40.00	5.89	16.5	30	4	1100	0.273	0.800
4.0-4	40.10	4.35	17.6	30	4	803	0.277	0.815
6.0-1	39.98	6.28	17.4	30	6	927	0.519	0.557
6.0-2	40.02	6.30	16.3	30	6	903	0.486	0.523
6.0-3	39.97	6.24	17.4	30	6	947	0.534	0.573
6.0-4	40.10	6.35	17.7	30	6	817	0.453	0.489
8.0-1	40.16	3.57	17.8	30	8	520	0.780	0.474
8.0-2	40.09	5.22	17	30	8	839	0.844	0.511
8.0-3	40.04	3.23	17.1	30	8	419	0.686	0.414
8.0-4	40.06	3.76	17.5	30	8	469	0.666	0.403
12.0-1	40.00	4.42	17.7	30	12	535	1.040	0.283
12.0-2	40.06	2.96	17.5	30	12	335	0.965	0.263
12.0-3	43.74	3.77	17.5	30	12	425	0.803	0.261
12.0-4	40.10	6.33	17.7	30	12	715	0.966	0.264
30-1	40.17	3.37	18	30	30	200	1.054	0.000
30-2	40.00	4.32	18	30	30	224	0.927	0.000
30-3	40.00	4.32	16.8	30	30	257	1.028	0.000
30-4	40.12	3.40	17.3	30	30	203	1.041	0.000

Generally, fracture criteria for mixed mode loadings provide:

- a combination of the stress intensity factors (K_I and K_{II}) and fracture toughness (K_{IC}), i.e.:

$$F\left(K_I, K_{II}, K_{IC}\right)=0 \tag{3}$$

- the crack initiation angle θ_c.

For comparison in the case of plane mixed mode fracture, four classical fracture criteria are considered, namely the Maximum circumferential Tensile Stress (MTS), the Minimum Strain Energy Density (SED), the Maximum energy release rate (G_{max}), and the Equivalent Stress Intensity Factor (ESIF); their mathematical formulation is provided in Table 2.

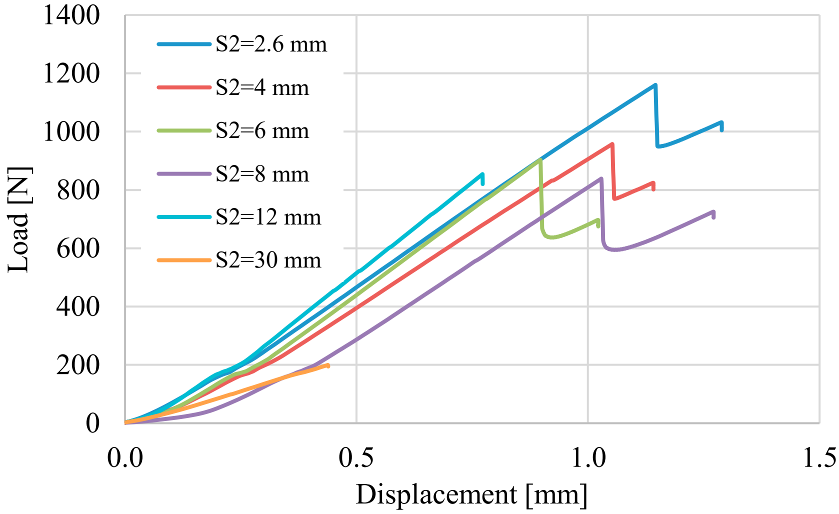

Fig. 3. Load – displacement curves for mixed mode loading.

Fig. 4 shows one cracked specimen for each of the tested modes. It could be observed a curvilinear crack trajectory for mixed mode and pure mode II loading. The crack initiation angle θ_c is increasing with increasing the mode II.

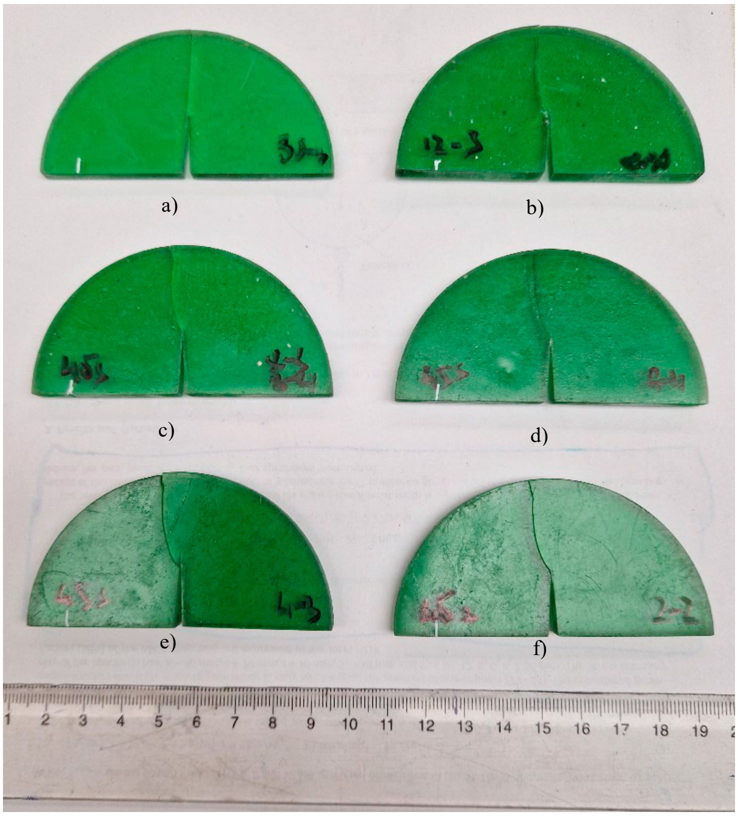

Fig. 4. Fractured specimens: a) S_1=S_2=30 mm; b) S_1 =30 mm, S_2=12 mm; c) S_1 =30 mm, S_2=8 mm; d) S_1 =30 mm, S_2=6 mm; e) S_1 =30 mm, S_2=6 mm; f) S_1 =30 mm, S_2=2.66 mm;

The experimental results expressed in terms of $\boldsymbol{K_{II}} / \boldsymbol{K_{IC}}$ versus $\boldsymbol{K_I} / \boldsymbol{K_{IC}}$ for the different fracture criteria reported in Table 2 are plotted in Fig. 5. It could be observed that the SED, MTS and ESIF criteria are in good agreement with the experimental results.

Table 2. Mixed mode fracture criteria

Fracture criterion	Formulation	Eq. (3)
MTS Erdogan – Sih (1963)	$\sigma_{\theta\theta,\max} = \sigma_{cr} = \frac{K_{IC}}{\sqrt{2\pi r}}$,	$F = \cos\frac{\theta_c}{2}\left(K_I\cos^2\frac{\theta_c}{2} - \frac{3}{2}K_{II}\sin\theta_c\right) - K_{IC}$
SED Sih (1974)	$S = S_{cr} = \frac{(\kappa-1)}{8\pi\mu}K_{IC}^2$	$F = \frac{1}{2(\kappa-1)}\left[(1+\cos\theta_c)(\kappa-\cos\theta_c)K_I^2 + 2\sin\theta_c(2\cos\theta_c-\kappa+1)K_IK_{II} + \right.$ $\left. + ((\kappa+1)(1-\cos\theta_c)+(1+\cos\theta_c)(3\cos\theta_c-1))K_{II}^2\right] - K_{IC}^2$
Gmax Hussain (1974)	$G(\theta_c) = G_{Ic} = \frac{K_{IC}^2}{E}$	$F = 4\left(\frac{1}{3+\cos^2\theta_c}\right)^2\left(\frac{1-\frac{\theta_c}{\pi}}{1+\frac{\theta_c}{\pi}}\right)^{\frac{\theta_c}{\pi}} \cdot \left[(1+3\cos^2\theta_c)K_I^2 + 8K_IK_{II}\sin\theta_c\cos\theta_c + \right.$ $\left. + (9-5\cos^2\theta_c)K_{II}^2\right] - K_{IC}^2$
ESIF Richard (1985)	$K_{eq} = K_{IC}$	$F = \frac{K_I}{2} + \frac{1}{2}\sqrt{K_I^2 + 4(\alpha K_{II})^2} - K_{IC}$

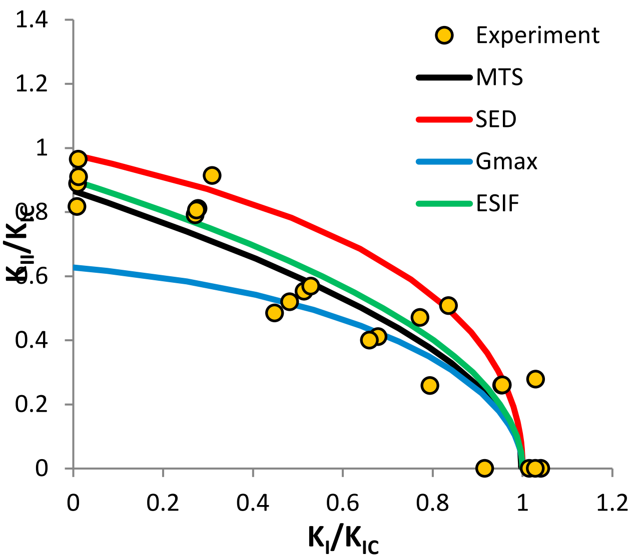

Fig. 5. The fracture criteria and experimental results.

4. Conclusions

The following conclusions of this study could be drawn:

- The semi-circular bend specimen loaded asymmetric was adopted to investigate mixed mode fracture of DLP additive manufactured specimens made of translucent green photo-polymerization resin. The advantages of this specimen are the simple geometry, the use of classic bending fixtures for loading the specimens and the ability to produce full range of mixed modes, from pure mode I to pure mode II, only by changing the position of one support.

- The obtained average value of the mode I fracture toughness is 1.021 MPa $m^{0.5}$ and is in agreement with those obtained on Single Edge Notched Bend specimens for different curing process 0.64 – 1.31 MPa $m^{0.5}$, Brighenti et al. (2023). The mode II fracture toughness has an average value of 0.895 MPa $m^{0.5}$.
- The four classical fracture criteria were assessed to characterize the failure of mixed mode loaded DLP resins. The experimental results proof that the SED, MTS and ESIF are the most suitable, Fig. 5. With the mention that the ESIF is the only criteria criterion which takes into account the ratio between mode I and mode II fracture toughness, $\alpha = K_{IC}/K_{IIC}$.

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