Amirkabir Journal of Mechanical Engineering

Amirkabir J. Mech. Eng., 51(5) (2019) 341-344
DOI: 10.22060/mej.2018.14020.5776

Experimental and Numerical Investigation on Mixed Mode Fracture of PMMA

P. Hosseini and N. Choupani

Mechanical Engineering Department, Sahand University of Technology, Tabriz, Iran

ABSTRACT: Existence a crack in structural parts is the main problem of predicting failure especially in mixed mode loading conditions. In most applications, fracture is happened under mode-I (tensile), mode-II (shear) or the combination of shear and tensile modes. Arcan test specimen was originally designed for use with composite materials, but in recent years has been adapted by many researchers for use with isotropic materials. In this paper, in an attempt to study the fracture toughness, test specimens were prepared in the form of butterfly from Polymethylmethacrylate polymer in specimen thickness of 10 mm. Experimental fracture tests were performed in three different crack lengths and first mode, mixed-mode and the pure second mode by changing the loading angle, using a specially developed fixture, based on Arcan. Load versus displacement curves were obtained. Furthermore, the fixture and specimen were modeled in ABAQUS/CAE, and stress intensity factors were derived. Using critical loads of the tests and the dimensionless stress intensity factors, obtained from the finite element analysis, fracture toughness of the polymer was determined. As the result, it can be seen that the shearing mode fracture toughness is larger than opening mode toughness. This means that cracked specimen is weaker in tensile loading. Finite element analysis was performed using elastic properties of the Poly methyl methacrylate polymer.

Review History:

Received: 2018-01-28
Revised: 2018-04-29
Accepted: 2018-04-30
Available Online: 2018-05-05

Keywords:

Polymethylmethacrylate polymeric material
Fracture
Mixed mode
Arcan modified fixture
ABAQUS

1. Introduction

Polymethylmethacrylate (PMMA) has been recognized as a favorite material for fracture tests. PMMA is a relatively homogeneous and isotropic material which often fractures in a brittle manner at room temperature. Determination of material resistance before the failure is the most important issue in fracture mechanics related investigations.

This paper seeks to determine critical stress intensity factors (K_C) and critical strain energy release rate (G_C) for mode-I, mixed mode, and mode-II loading conditions through experimental and numerical attempts. All experimental studies are performed using a modified Arcan fixture. One of the main advantages of Arcan fixture is the special geometry that makes it possible to determine mode-I (α=0°), mixed mode (α=45°) and mode-II (α =90°) critical load and fracture properties [1].

2. An Overview of Mixed-Mode Fracture Mechanics

The purpose of fracture toughness testing is to determine the value of plane strain fracture toughness. This material property is used to characterize the resistance to fracture in the design of structural members. The critical stress intensity factors at the tip of the crack were calculated by using the following equations:

$$K_C = \frac{P_C}{wt}\sqrt{\pi a}\, f\left(a/w\right) \quad (1)$$

where P_C is the fracture load, a is the crack length, w is the specimen width, t is the specimen thickness and $f\,(a/w)$ is a geometrical factor, that is obtained by numerical analysis. Linear elastic fracture mechanics and plane strain conditions are the primary requirements. Also, strain energy release rate for isotropic material with edge crack can be calculated from the following relationships:

$$G_I = \frac{{K_I}^2}{E'} \qquad G_{II} = \frac{{K_{II}}^2}{E'} \quad (2)$$

where $E' = E/(1-\nu^2)$ for plane strain conditions, E is the modulus of elasticity, ν Poisson's ratio [2].

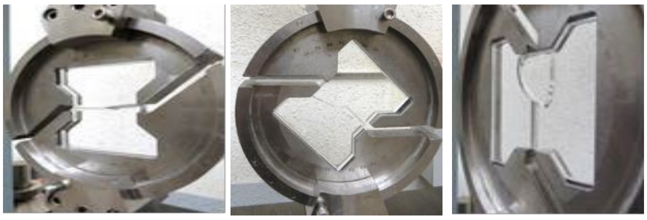
3. Experimental Procedure

In this study, fracture mechanics experiments were carried out for two series of different specimens. At first step uniaxial tensile test, with the dog-bone tensile sample, was carried out to obtain PMMA mechanical properties, Table 1. The dog-bone specimen dimensions were chosen according to standard ASTM D638 [3].

Table 1: Mechanical properties of polymethylmethacrylate specimens

Test	Elasticity Modulus E (MPa)	Yield Stress σ_{ys} (MPa)
1	2044	46.37
2	2089	51.47
3	1935	44.84
Average	2022.6	47.56

*Corresponding author E-mail: parva.hsy@gmail.com



(a) (b) (c)

Fig. 1. Loading device and test setup (a) pure mode-I, (b) mixed mode and (c) pure mode-II

Table 2: Average critical fracture loads (N)

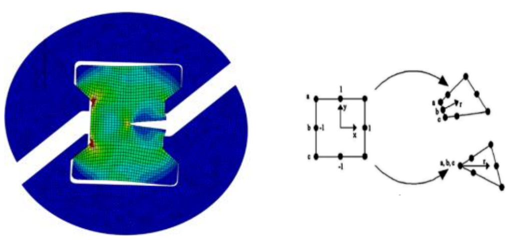
Loading Angle ϑ (degree)	Crack Length a (mm)	Critical Load F (N)
0	25.2	1430
45	28	1440
90	30.8	3105
0	25.2	1375
45	28	1380
90	30.8	2845
0	25.2	1231
45	28	1310
90	30.8	2615

In order to determine fracture parameters of PMMA at the second step, Butterfly specimens were developed. By using a loading fixture in the loading range from 0˚ to 90˚, Stress intensity factor were derived. Fig. 1 depicts the specimen loading in mode-I, mixed mode and mode-II conditions, respectively.

Fracture loads were determined in this research by placing the butterfly specimens inside modified Arcan fixture and loading them by a test machine up to final fracture. The average results of critical loads are presented in Table 2.

4. Finite Element Implementation

The Finite Element Method (FEM) implementation was carried out by simulation of the butterfly specimen and related apparatus using ABAQUS software. A two dimensional FE analysis was performed under plane strain condition. Fig. 2 indicates the mesh pattern of the apparatus and butterfly-shaped specimen.



(a) (b)

Fig. 2: (a) Meshing of the modified Arcan fixture and butterfly specimen (b) collapsed 2-dimensional element

All of the effective parameters in the simulation, such as the specimen geometry, loading rate, and operating temperature were applied according to the experimental tests. The main purpose of finite element simulation is to determine non-dimensional stress intensity factors at the crack tip from mode-I to mode-II.

5. Experimental and Numerical Results

By studying the numerical and experimental fracture results of PMMA polymer specimens, average critical stress intensity factors of pure mode-I, mixed mode and pure mode-II of the modified Arcan fixture were found. Therefore, in light of Eqs. (1) and (2) and also according to the sample dimensions, the critical stress intensity factors and strain energy release rates obtained. These values are gathered in Table 3 and 4.

6. Conclusion

In this paper mixed mode brittle fracture was studied using butterfly specimens made of PMMA. The fracture load was determined from experiments from pure mode-I to pure mode-II. A modified version of Arcan specimen was employed to conduct a mixed mode test using the special test loading device and recording the critical loads. As a numerical part, modified Arcan fixture and specimen were modeled in ABAQUS software in order to determine the non-

Table 3: Critical stress intensity factors (K_C) for PMMA

Loading Angle θ (degree)	Crack Length a (mm)	Fracture Toughness K_{IC} ($\mathrm{MPa}\sqrt{\mathrm{m}}$)	Fracture Toughness K_{IIC} ($\mathrm{MPa}\sqrt{\mathrm{m}}$)
0	25.2	0.7643	----
45	28	0.5702	0.6211
90	30.8	----	1.7701
0	25.2	0.7601	----
45	28	0.5819	0.6328
90	30.8	----	1.7498
0	25.2	0.7101	----
45	28	0.5892	0.6389
90	30.8	----	1.7454

Table 4: Critical strain energy release (G_C) for PMMA

Loading Angle θ (degree)	Crack Length a (mm)	Fracture Toughness, G_{IC} (J/m^2)	Fracture Toughness, G_{IIC} (J/m^2)
0	25.2	253.43	----
45	28	141.05	167.30
90	30.8	----	1359.60
0	25.2	250.65	----
45	28	146.90	173.72
90	30.8	----	1328.62
0	25.2	218.70	----
45	28	150.61	177.09
90	30.8	----	1321.04

dimensional stress intensity factors under a constant load of 1000 N and plane strain condition. The uniaxial tensile tests were performed to evaluate the mechanical properties of PMMA by dog bone specimens.

The fracture toughness determined for the butterfly-shaped specimen in mode-I, mixed mode and mode-II loading conditions. The average values summarized in Table 3 and 4. These values are in good agreement with the reported ones [4]. It is shown that K_{IC} decreases by changing the loading angle from 0 ˚ to 90˚ and its maximum value was about 0.7643 $\mathbf{MPa\sqrt{m}}$ in 0˚. But on the opposite side, K_{IIC} increases from 0˚ to 90 ˚ and its maximum value was about 1.7454 $\mathbf{MPa\sqrt{m}}$ in 90˚. The shearing mode fracture toughness (α=90°) was larger than the opening-mode fracture toughness (α=0°). This means that the cracked specimen is tougher in shear loading conditions and weaker in tensile loading conditions.

For loading angles 0˚ to 42.76˚ opening mode non-dimensional stress intensity factor, f_I (a/w) was larger than f_{II} (a/w) and mode-I was the dominant fracture mode. By changing the loading angle from 42.76˚ to 90˚, shearing non-dimensional stress intensity factor behaved as a dominant.

Due to fracture toughness independency from butterfly-specimen geometry in-plane strain condition; it could be seen that as the length of crack increases the fracture toughness for in-plane modes remains almost constant.

References

[1] Oskui, A.E.h., N. Choupani, and E. Haddadi, Experimental and numerical investigation of fracture of ABS polymeric material for different sample's thickness using a new loading device. Polymer Engineering & Science, 2014. 54(9): p. 2086-2096.

[2] Chong, A.C., et al., Fracture toughness and fatigue crack propagation rate of short fiber reinforced epoxy composites for analogue cortical bone. Journal of biomechanical engineering, 2007. 129(4): p. 487-493.

[3] Shameli, M., N. Choupani, and M.K. Razavi, Measurement of Mixed-mode Fracture Toughness of Polypropylene using Multi-specimen J-integral Method. Modares Mechanical Engineering, 2016. 16(4): p. 333-344.

[4] Howard, S., Materials Data Book 2003 Edition. 2003, Cambridge University Engineering Department, Cambridge, UK.