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Sensitivity analysis of fracture behavior in carbon-epoxy composite at different displacement rates under mode I tensile loading by regression analysis

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ABSTRACT: In this article, the sensitivity analysis of the displacement rate effect under tensile loading on the crack growth behavior in the carbon-epoxy composite has been investigated. For this objective, the tensile test was performed on double cantilever beam samples, according to the ASTM-D5528 standard under displacement-controlled loading and under displacement rates of 0.05, 0.5, 5 and 50 mm/min. Then, the regression analysis was done on outputs of experimental data by the Minitab software. For this objective, the sensitivity analysis was performed on three fracture characteristics of composite specimens. These fracture mechanics parameters were the critical energy release rate (with three different fracture energy methods), the maximum failure force and the initial crack tip opening displacement by the use of the digital image correlation technique. Results showed that the variation of the displacement rate affected the maximum failure force and the energy release rate and therefore, these values were sensitive to changes in the displacement rate. However, the maximum value of the initial crack tip opening displacement of the composite was dependent on the logarithmic displacement rate under tensile loading. Finally, the changing trend of fracture mechanics characteristics in the composite was increasing by increasing the displacement rate.

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1- Introduction

Today, fiber-reinforced polymer composites are increasingly used in aircraft and spacecraft structures due to their high rigidity and strength and also due to their relatively low density [1]. Therefore, identifying the failure behavior of materials is one of the most important issues for designers and engineers. Since the structure may be under different loading rates, in such conditions, different damage mechanisms occur, especially in structures made of composites [2].

Rajan et al. [3] investigated the effect of the loading rate on the fracture behavior and the relationship of the tension-separation law using a double-edged head beam sample in the control mode and the first mode, under loading rates of 0.03, 0.3, 3 mm/min. Their results showed that values of tensile-separation parameters, such as the maximum viscous stress and the strain energy release rate were highly dependent on different loading rates and were known as a function of the loading rate. Thorson et al. [4] studied the fracture behavior in a composite sample of a double-edged beam under different quasi-static loading rates, using the modified wedge method. They performed this test under load rates of 0.01 to 3600 mm/s, using the ASTM-D5528 standard. They observed that the failure behavior at higher rates was different from that at lower rates.

2- Methodology

The studied material was a composite with a total thickness of about 5.3 mm. The dimension of the standard test sample was 125×25 mm. Such specimens were considered based on the ASTM-D5528 standard [5], entitled Double Cantilever Beam (DCB) samples. Fig. 1 shows the image of the DCB specimen, including the schematic image and the prepared geometry. Therefore, all fracture toughness experiments were performed under the cross-head displacement-control condition and the loading rate of 0.05, 0.5, 5 and 50 mm/min. Fig. 2 depicts the DCB sample under tensile loading for mode I.

As suggested in the ASTM-D5528 standard, three data reduction methods could be utilized to determine fracture properties, including the energy release rate and its critical value. These approaches are the Modified Beam Theory (MBT), the Compliance Calibration method (CC) and the Modified Compliance Calibration method (MCC). The modified fracture toughness was calculated in mode I, as follows [5], where P and δ are the load and the load line deflection.

$$G_{Ic} = \frac{3p_c\delta_c}{2b\left(\left|a+\Delta\right|\right)} \tag{1}$$

Compliance specimen values in this CC method were written as follows, where n is the slope of the curve of log c versus log a [5]:

$$G_{Ic} = \frac{n\,p_c\delta_c}{2b\,a} \tag{2}$$

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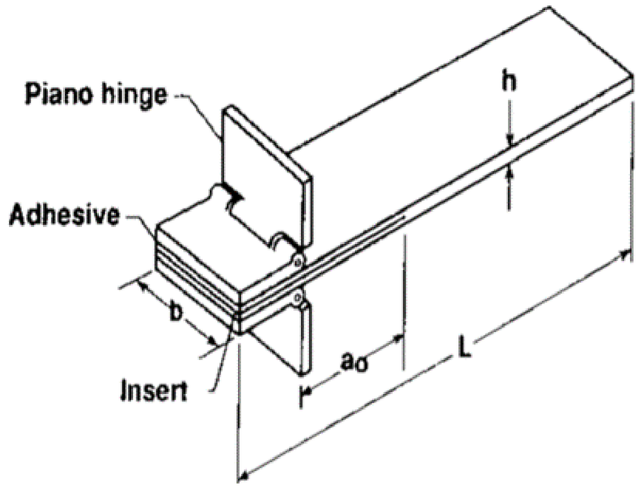

Fig. 1. Schematic of the geometry of double cantilever beam specimens [5]

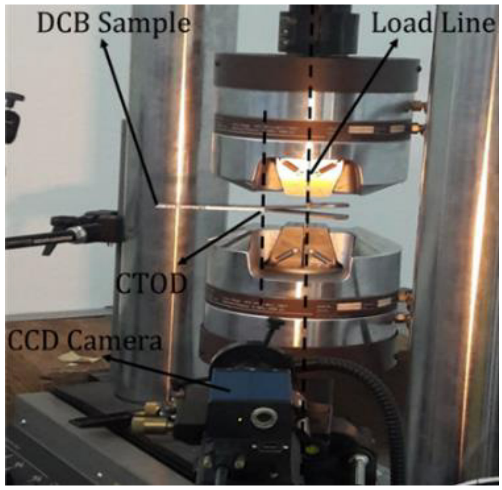

Fig. 2. The device for tensile testing on DCB samples

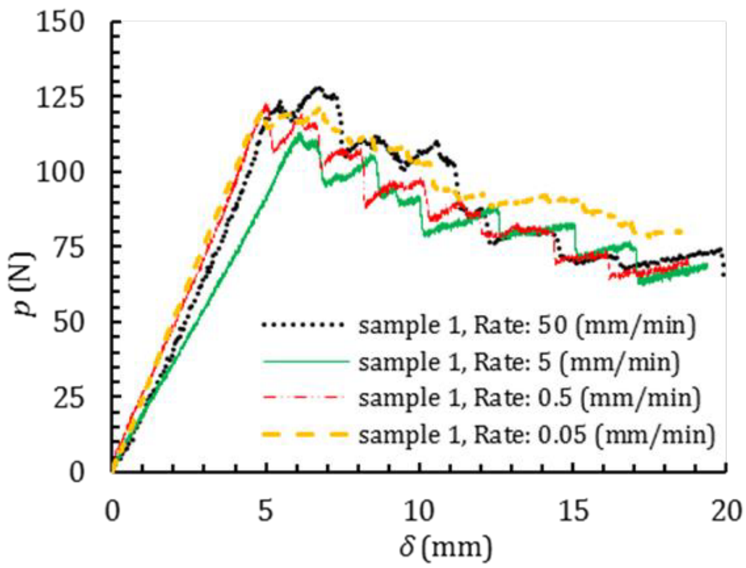

Fig. 3. The force-displacement curve under different displacement rates

Then, the fracture toughness for the MCC method was obtained, as follows [5]:

$$G_{IC} = \frac{3P_c^2 C^{2/3}}{2A_1 b\, H} \quad (3)$$

To determine the effect of the displacement rate change on each of data obtained from the tensile test (the maximum fracture force, the strain energy release rate and the maximum initial crack opening displacement), the sensitivity analysis could be used by the regression analysis. Test outputs were statistically analyzed in the Minitab software [6].

3- Results and Discussion

Obtained results including force-displacement curves are shown in Fig. 3. It should be noted that the displacement was measured through the load line. It was found that the increase in the loading rate had no significant effect on the maximum force. Of course, this result was a qualitative conclusion and to confirm this conclusion and more accurate analysis, the sensitivity analysis was performed using the regression analysis by the Minitab software. Fig. 3 also shows that curves were linear in the initial stage of the test and were then followed by a nonlinear behavior for the displacement, larger than 5 mm. All specimens exhibited a zigzag shape extension, beyond 5 mm. Due to the loading condition, which was the displacement-controlled state, loading caused the crack to grow in a constant displacement. In addition, the maximum amount of force under low loading rates was much lower than that under high loading rates, which was also shown in the literature [3]. The reason for this observation could be the very low speed of loading, which caused a change in the fracture behavior of the material. Loading at very low speeds also changed the effect of the joint length on the fracture toughness [4].

Table. 1. Results of the regression analysis for the objective function of the maximum force

Parameters	F-Value	P-Value
Regression analysis of the first model	99.04	0.000
First power of the displacement rate	10.97	0.030
Second power of the displacement rate	6.36	0.067
Third power of the displacement rate	5.81	0.074
Coefficient of determination	$R^2 = 98.67$ %	

Table 1 shows the results of the sensitivity analysis, obtained for the maximum force. According to the results of Table 1, the P-value for the displacement rate was less than 0.05 and also the value of R^2 was 98.67%, which indicated that the regression analysis was meaningful and correct. Moreover, according to the P-Value in Table 1, it could be said that the change in the displacement rate affected the maximum failure force. In other words, the maximum failure force was sensitive to changes in the displacement rate.

4- Conclusions

In this research, the sensitivity analysis of the fracture behavior in the carbon-epoxy composite was done under different displacement rates and mode I tensile loading by the regression analysis. Obtained results could be listed as follows,

· Based on the third-degree regression model of the displacement rate, the sensitivity analysis showed that displacement rate changes affected the maximum fracture force, due to the tensile test on composite specimens.

· The amount of the strain energy release rate in the carbon-epoxy composite, with all three failure methods (including MBT, CC and MCC approaches), based on the third-degree regression model, was sensitive to the loading rate.

· The maximum amount of the initial crack opening displacement in the composite, based on the regression logarithmic model, was sensitive to the logarithmic displacement rate, under tensile loading.

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