Fatigue Delamination Behavior of GFRP Composites under Mixed-Mode I/II Loading

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ABSTRACT*: Delamination is a severe threat to the wide use of composite laminates in primary structural applications. Delamination grows under fatigue loading and leads to structural failure. Very few studies exist on mixed-mode delamination on carbon fiber however glass fiber was not studied under mixed mode. The objective of this paper is to investigate fatigue delamination growth under mixed-mode loading in Glass Fiber Reinforced Polymer (GFRP). A mixed-mode bending fixture was developed and fabricated. Fatigue delamination growth tests were performed for different mixed-mode loading using that fixture. With the help of a Scanning Electron Microscope, micro examinations of the crack surface were carried out. The results showed a high growth rate for the case with more contribution of mode I. The Fractographic investigation performed on the different samples showed the existence of mode-I and mode-II features and broken fiber's confirming fiber bridging during delamination growth. The fractographic features varied systematically with mode shift.*

KEYWORDS: *Glass Fiber composite; Fatigue, Delamination; Mixed mode.*

INTRODUCTION

In the aircraft industry composite materials were used in lightweight assemblies, particularly in the marine, aeronautical, and sports sectors [1, 2]. However, composite materials have poor interlaminar strength, due to which delamination occurs in fiber-reinforced structures [3-7]. Therefore, the researcher was trying to investigate to improve the interlaminar properties of composite materials and there is a need to extend the scope of control delamination development to avoid failures, especially in aircraft structures [8-11].

Literature showed that different studies were presented on the delamination fracture under mode-I, and mode-II and where cases under combined mixed-mode I-II loading is limited. *Benanti et al.* suggested a developed beam theory for the Mixed-Mode Bending (MMB) test [12-14].

Szekrenyes et al. examined different tests in composite materials for cracks between different layers under mix mode loading. They reported that for unidirectional laminates, the MMB testing method separates the effects of mode I and mode II in an efficient way, however, this method was not applicable for multidirectional layers in laminates [15, 16]. Literature review reveals that fatigue investigations were still rare in combined under mixed-mode I-II loading conditions and the test procedures were different [17].

Blanco et al. applied Mixed Mode End Load Split (MMELS) test procedure to find out different ratios of mixed mode

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1021-9986/2023/10/3546-3554 9/$/5.09

by changing crack length start from mode-I to mode-II [18]. *Zhang et al.* advised quantitative methods for fatigue crack growth by changing mode mixity ratio [19]. *Ducept et al.* have examined the delamination of glass/epoxy composite utilizing mixed-mode failure criteria. They performed a test under mixed mode loading as per American Society of Testing Materials (ASTM) standard D5528-01 and utilized polypropylene film with 8 micrometers of thickness as a crack initiator. They change the lever length on various points and noticed the total fracture toughness and mode ratio [20, 21].

Rugg et al. examined the behavior of delamination fracture through-thickness reinforced carbon-epoxy laminates utilizing two distinctive test examples, a T-stiffener and MMB specimens. To improve the resistance to delamination small quantity of titanium or z-fiber was used in both specimens. Reinforcement improves the ultimate strength of MMB specimen. Delamination resistance improved due to crack bridging by the z-fiber [22]. *Naghipour et al.* investigated the delamination fracture behavior in multi-directional composite laminates under high cyclic fatigue loading by cyclic mixed-mode experiments and numerical simulation. It was seen that executing a repeated degradation variable in cohesive interface experimentally concluded that crack progression and degradation in stiffness could be noticed appropriately. Fracture surface after cyclic fatigue loading electron microscope proved that the weakening and degradation were due to the existence of crack bridging surface roughness [23]. *Shokrieh et al.* examined the behavior of fracture under both modes I-II using E-glass and E-glass epoxy, using the results from different tests such as Double Cantilever Beam (DCB), End Notched Flexure (ENF) and Mixed Mode Bending (MMB) to examine the delamination process of various composites at different mode mixity. It was noticed that the existence of hackle marking and roughness in the area where fracture occurs reflects the dependency on the loading in mode II state [24]. *De Moura et al.* did numerical and experimental investigations using the experiment of Single Leg Bending Test procedure to catch fracture under combined mode of carbon epoxy laminates. The results shows that the energy release is independent of the initial crack length. The simulated results were in compliance with the experimental test using Single Leg Bending (SLB) test thus validating the procedure [25]. *Fakoor* and *Khansari* considered that the available fracture failure models under mixed-mode for orthotropic materials had been proposed for the most part for crack along fiber [26].

Keanong et.al examined the displacement rate on mixed-mode I-II delamination in carbon epoxy composites. He suggested that during the experiment the mixed-mode ratio are not constant [27]. Many studies are dedicated for the investigation of the mixed mode fatigue delamination using different techniques in the previous decade [28-31].

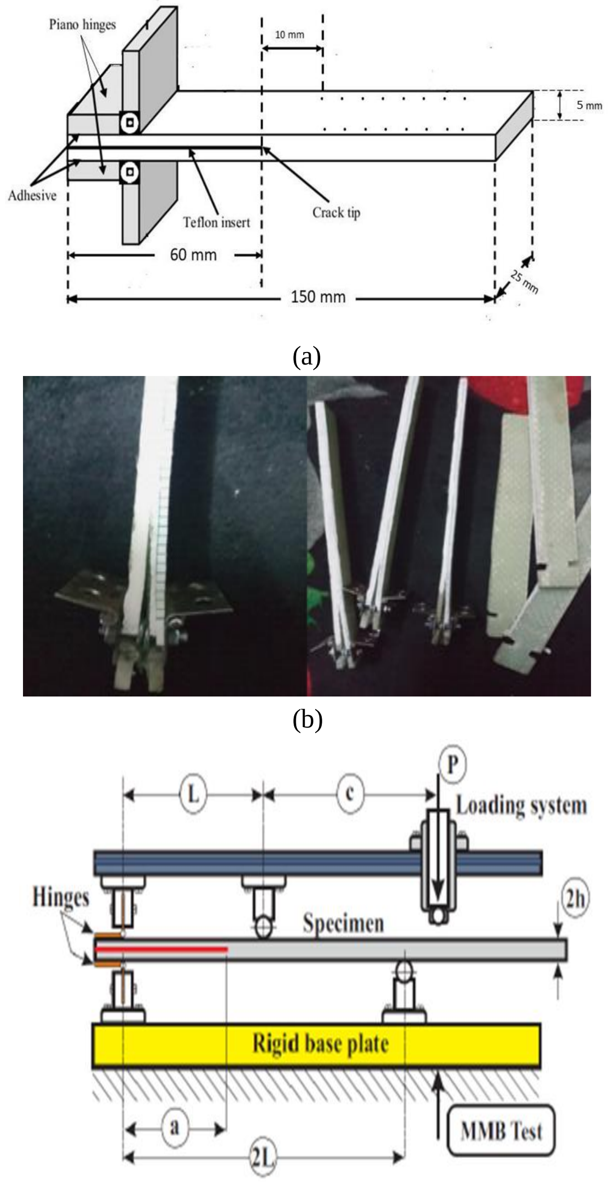
The literature review reveals that only few studies used MMB apparatus for the investigation of the delamination growth under mix mode loading. The delamination growth under mix mode loading can be only properly modelled if the effects of the individual modes are separated in both characterization of the growth and the fractured surfaces. In MMB apparatus the individual modes can be applied with different varying ratios for delamination growth intervals. The quantification of the fracture surface can lead to the contribution of the individual mode in mix mode and mechanistic model can be derived based on these observations.

The objective of this paper is to experimentally investigate mix mode delamination growth under mix mode fatigue loading in glass fiber reinforced epoxy laminates using mixed mode bending fixture. Mix mode delamination growth experiments were performed on glass fiber reinforce epoxy Glass Fiber Reinforced Polymers (GFRP) laminates using mixed mode bending apparatus. The delamination growth rate was characterized using strain energy release rate. The tested specimens were examined under Scanning Electron Microscope (SEM) for the surface morphology. Next section describes the experimental details which is followed by the results of the investigation.

EXPERIMENTAL SECTION

Sample and MMB apparatus preparation

In this investigation the sample were made from two materials, one was E-glass fabric mate-200 and other one was z-epoxy-300. In z-epoxy two material were used one was hardener and the other was base. These two materials were mixed in 1:2 ratio. A composite plate was made by stacking of 20 layers of E-Glass mate by hand layup. The layup is represented by $[90/0]_{20.}$ Twenty layers is an optimized number of layers for the double cantilever beam specimens to both avoid curvature effect and



(a)

(b)

(c)

***Fig. 1**: (a) Dimensions of specimen.(b) Sample which is attached with piano hinges for experiment (c)Test specimen of MMB [36]*

overdesigning for the fracture tests [32-34]. Before stacking, the layers were imbedded with z-epoxy-300. After stacking was completed, the plate was placed under pressure and left for curing at room temperature for 24 h. The samples were made having dimensions of 25mm width, 5mm thickness, 150mm length. Teflon inserts of 12.5 µm was used for finding MMB test procedure. Piano hinges also attached on one side of the sample which was used for fixing in the MMB apparatus as shown in Fig. 1(a). These sample are made as per ASTM standard D5528, displayed in Fig. 1(b) [35].

This test method was used to perform to find out the fracture toughness. In this test method a composite laminated sample having b was the width, 2h was thickness, a_0 was initial crack length and 2L was simply supported length. In between the middle layers non-adhesive Teflon of thickness 12.5µm was placed. Different mode mixity are achieved by changing the lever length c. The mixed-mode bending apparatus was designed as per standard procedure of ASTM standard method D-6671/D-6671M-06 to investigate fracture under mixed mode. The setup of the test is shown in Fig. 1(c) [21].

To envisage the crack growth during delamination both sides of the sample is whited with whitener and for measuring of crack length graph paper is also attached on one side of the sample.

Test procedure

The delamination growth fatigue test were performed on universal testing machine (Make: Zwick Roell Germany Model HC 25). According to the specification the maximum loading capacity of this machine is 25 KN, minimum strain rate of 0.005 mm/min and 500 mm/min is maximum one. The tests were performed on room temperature. Therefore, the crack growth was found out on room temperature. The rate of crack growth was found out with help of microscope using 100x magnification. During fatigue testing the loading was dynamic because the sample undergo continues vibration which was very difficult to find out the length of crack propagation. To carry out crack measurement after every 1000 cycles, the test was interrupted to stop and the sample was resumed to mean displacement location. The crack length was measured with the help of microscope and the crack growth rate was find out giving the progression speed with respect to fatigue cycles (da/dN). Finally, the rate of energy release after 1000 cycles, the maximum and minimum load values and crack length were taken. 4Hz Frequency was used to carry out all these tests [37]. Specimens were tested for two mixed mode (mode I and mode II) ratios by the lever arm distance C. These ratios were 24% and 50% of the mode I and mode II respectively.

After fatigue tests, the specimens fracture surfaces were examined for the surface morphology in Scanning Electron Microscope (SEM) having specification KYY EM6900

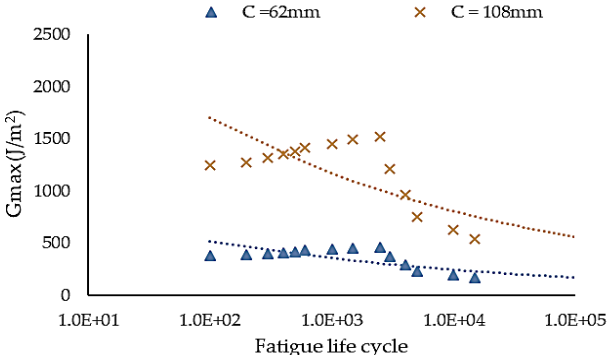


Fig. 2: Maximum energy release rate for two values of mixity ratio 0.50 (C = 62 mm) and 0.24 (C = 108 mm)

having minimum resolution power of 3nm at 30 KV electron beam and with the magnifying power of 6X to 300,000X.

Small samples were cut out from the original specimens for placing in the SEM holder. As the material of the sample was non-conducting, the surfaces were gold sputtered to avoid static charging. The voltage of the SEM was set at 15 kV during imaging.

Test data analysis

To find out energy rate of energy released G_I and G_{II}, the modified beam theory Equations (1) and (2) were used.

For fracture toughness, under mode-I and mode-II, test data was investigated, and strain energy and load components were [38]

$$G_I = \frac{12a^2P_I^2}{b^2h^3E} \tag{1}$$

$$G_{II} = \frac{9a^2P_{II}^2}{b^2h^3E} \tag{2}$$

$$P_I = \left(\frac{3C-L}{4L}\right)P \tag{3}$$

$$P_{II} = \left(\frac{C+L}{L}\right)P \tag{4}$$

$$G = G_I + G_{II} \tag{5}$$

Ratio of mixed-mode is labelled as

$$\frac{G_{II}}{G} = \frac{G_{II}}{G_I+G_{II}} \tag{6}$$

RESULTES AND DISCUSSION

Each test was performed for the constant value of displacement. The maximum rates of energy release were determined throughout the testing when crack was measured after 1000 cycle of interval using Equations (1) to (6). The results of maximum energy release rate verses fatigue life cycles were plotted and the micrographs of delaminated surface using Scanning Electron Microscope (SEM) results for different mode ratio were carried out. The required quantity of cycle to start delamination for a certain rate of energy release were found from graph ΔG-N under ratio R = 0.1.

The maximum energy release rate is plotted against the fatigue cycles under constant amplitude displacement is shown in Fig. 2. The two plots were for different mode mixity ratios. The upper plot is for mode ratio of 0.24. This mode ratio is achieved by keeping the C = 108 mm. The lower plot is for mode ratio of 0.5 keeping the C = 62 mm.

The energy release in the lower mode mixity ratio is higher than, the higher mode mixity ratio. The higher mode mixity ratio results in lower value of energy release due to higher contribution of mode II in the total release rate. The mode II failure is due to the shear stresses induced by the bending of specimen. Reaching to certain number of cycles the delamination stops in the specimen. The maximum rate of energy release for the higher mode-mixity is 160 J/m^2 at 10^4 cycles when delamination stops. Similarly, the maximum energy release rate find out from these curves for the lower mode mixity ratio is 500 J/m^2 at 10^4 cycles when delamination commenced. The slope of the curve for 0.24 mode ratio is steeper than 0.5 mode ratio as obvious from Fig. 2 which reveals a sharp decline in G_{max} as the fatigue tests progressed. This shows that a greater influence of the mode I on the fracture toughness.

Fig. 3 shows the behavior of fatigue for mode mixity ratio (0.24 and 0.50) using mixed mode test method. The graph presents the total rate of energy release $G_{Total} = (G_I + G_{II})$ versus number of cycles. The plots for both mode ratios show similar trend like Fig. 2. The total rate of energy release for the lower mode-mixity shows higher values as compared to the higher mixity ratios due to the greater contribution of tensile stresses in mode I. When the mixity ratio increases, the shear stress input rises, lowering the rate of energy release. The data points in Fig. 3 are extended to 5500 cycles however it does not significantly affect the delamination rate. Further increasing the number of cycles does not affect the energy release rate. Similar kind of trends for the energy release rates were observed as reported [9, 10].

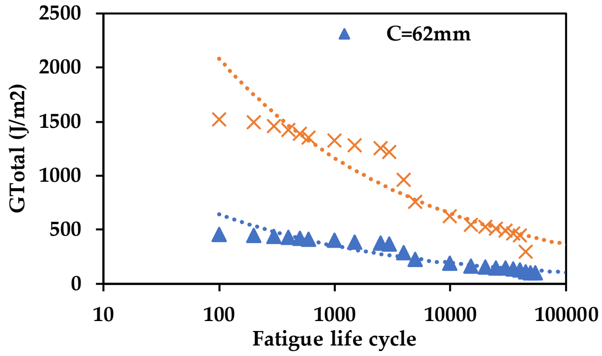


Fig. 3: Total energy release rate vs fatigue life cycles of specimen

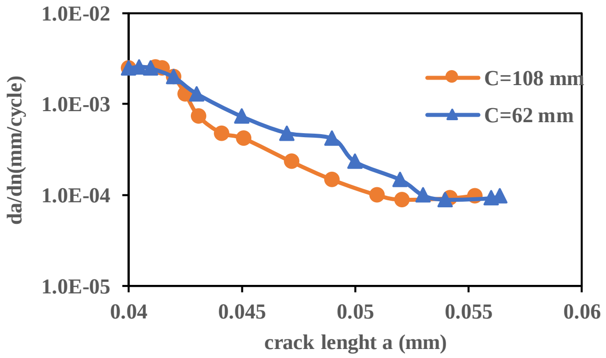


Fig. 4: Crack propagation rate vs crack length

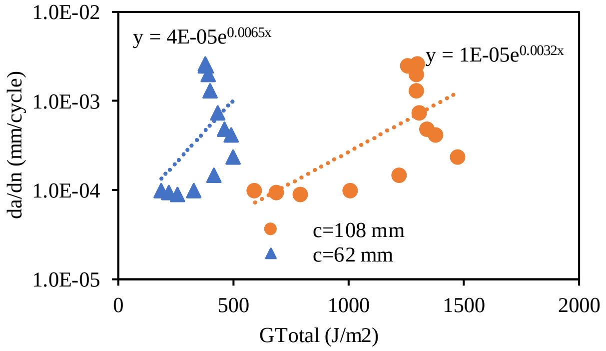


Fig. 5: Crack propagation rate vs total energy release rate (G_{total})

The strain energy release rate have some abrupt changes in the range 1000 to 10000 cycles during fatigue tests as observed from Fig. 2 and Fig. 3. These changes are common in composite fracture and caused by fiber bridging [39]. Fiber bridging increase the crack growth resistance in composites and act as crack arrest agents [40]. Although the bridging increase fracture toughness, still it makes the analysis of the crack growth more complicated.

The crack propagation rate during fatigue loading for the different mixity ratio is shown in Fig. 4. The delamination rate is observed to be constant at the beginning of loading cycles, however it decreases with the progressing delamination. The delamination rate for the 0.24 (|C=108 mm) mixity ratio is sharply decreasing as compared to the higher mixity ratio 0.5 (C=62 mm). The higher decreasing rate is due to the higher contribution of tensile loading. The tensile loading (Mode I) causes the delamination to progress more as compare to the shear loading (Mode II) [41]. The delamination rate become constant when the crack length reaches 0.051 mm and 0.053 mm for the mixity ratio of 0.24 and 0.5 respectively. The delamination stops when the delamination reaches 0.056 mm and 0.0564 mm for the mixity ratio of 0.24 and 0.5 respectively.

Delamination growth rate da/dN is plotted against G_{total} in Fig. 5. The growth rate is higher for higher mode ratio which confirms the greater contribution of mode I in the fatigue fracture process. The Paris equation exponents 0.0065 and 0.0032 respectively for both ratios as shown in Fig. 5. These values are typical in the range for fatigue in composites [42].

To observe the existence of several damaged mechanisms that impacted the material during experiment. Scanning Electron Microscope (SEM) was used to carry out Fractography study. The propagation regions of numerous samples tested under fatigue loading were examined.

Fig. 6 shows the area near the delamination initiates in specimen under fatigue for ration of mode mixity ratio 0.24. The presence of damaged fiber may be seen as confirmation of earlier presence of fiber bridges [18, 36, 43] and river markings [36, 44, 45] specific structure of mode I fracture together with cups [46, 47], which is typical of fracture of mode-II.

Fig. 6 shows fibers broken from the characteristic fiber-bridging of this mode of fracture. The formation of this fiber-bridging over a system coming about because of test geometry, which preciously rises the values of the material toughness.

For $\frac{G_{II}}{G} = 0.50$, as shown in Fig. 7. The formation of Hackle marking and cusps were related to crack of mode-II and River markings, shows normal for mode I fracture.

The fatigue lines of the crack growth can be seen in this situation.

The matrix between composite layer converts to matrix rollers in the higher mode II ratio tests as shown in SEM image in Fig. 8. The rollers are formed due to successive rolling of the matrix in the successive fatigue cycles [48].

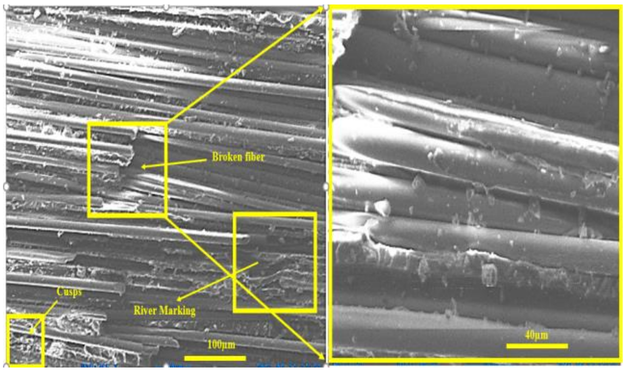


Fig. 6: SEM micrographs of fatigue sample under MMB test for mixed-mode ratio 0.24

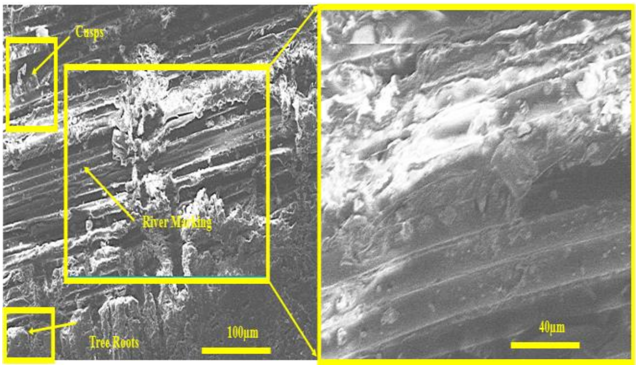


Fig. 7: SEM micrographs of fatigue sample under MMB test for mixed-mode ratio 0.50

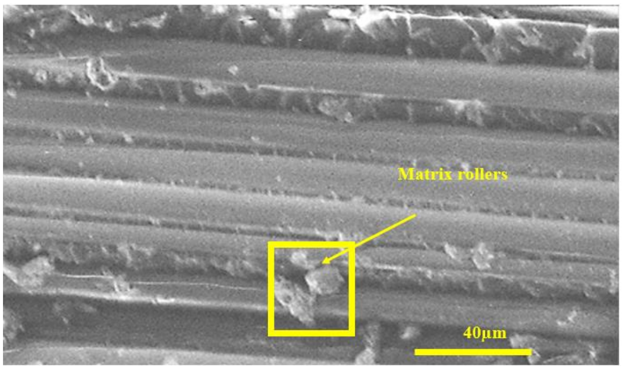


Fig. 8: Matrix rollers in the high mode II tests

The SEM analysis confirms that the contribution of the individual mode is reflected in the fractographic morphologies of the fractured specimens under mixed mode loading. The striation marking and hackles typical fracture features of mode I [48]. Hence in higher mode I ratios, these features are more obvious. But shifting to higher mode II in the mixed mode also brings a transition in the fracture features of the surfaces with more cusps and matrix rollers. This means that quantification of these surface features under controlled mode ratios can lead to mechanistically model the delamination growth under mode loading and may achieved using MMB test fixture. The current study was focused to explore possibility of the using fractographic features in the understanding of the mixed mode delamination growth. In order to develop a mechanistic model based on these fractographic observations, further delamination growth tests with close ranges of mix mode ratios are required with the fractographic feature quantification techniques like laser microscopy and Transmission Electron Microscopy (TEM).

CONCLUSIONS

In this paper the delamination growth in the glass fiber reinforced epoxy under mix mode I/II has investigated using the test method MMB. The mode ratio was varied by adjusting the lever arm distance. The post mortem SEM was performed for the morphology of the test specimens. From this investigation following conclusions are drawn.

The strain energy release rate for higher mode II is higher than mode I with the same applied load. The decrease in the strain energy with respect to fatigue cycles is however steep for greater mode II tests. Furthermore, the rate of crack growth decreases with expanding the length of delamination and fiber bridging. Abrupt variation in the strain energy release rate is caused by fiber bridging during fatigue tests. The delamination growth rates are higher for higher mode I ratio test. The Paris law exponents are typical for the composite material which shows less sensitivity to the variation in loading for higher mode I ratios as compared to metals crack growth. The Fractography reveals hacks and striation markings for higher mode I ratios which are transformed systematically to cusps and matrix rollers as the mode ratio approaches higher mode II. Further tests under mixed loading with advanced surface feature quantification are required for the development of mechanistic model for growth.

Limitations and way forward

The current study do not consider the environmental impact on the fatigue characteristics of glass fiber under mixed mode conditions. The environmental conditions may include thermal effect and humidity effect. Furthermore, the study can be extended to the mixed mode (Mode I/III and Mode II/III) conditions.

Nomenclature

MMELS	Mixed Mode End Load Split
MMB	Mixed Mode Bending
ASTM	American Society of Testing Materials
DCB	Double Cantilever Beam
ENF	End Notched Flexure
SEM	Scanning Electron Microscope

Received : Dec. 05, 2022 ; Accepted : Apr. 17, 2023

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