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Numerical and Experimental Investigations on Fatigue Behavior of Carbon/Epoxy Laminates Toughened by Nanofibers

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ABSTRACT: Composite laminates are advanced engineering materials that are widely used in various industries due to their unique properties. The aim of this paper is to assess the effect of electrospun nanofibers on the fracture and fatigue behavior of composite laminates and also to investigate the performance of the Finite Element Method based on the Cohesive Zone Model, in predicting the fatigue behavior of the laminates. For this purpose, standard specimens were fabricated from carbon/epoxy Prepregs interleaved with nylon 6,6 nanofibers. The specimens were then subjected to mode I static and fatigue loading conditions. The results showed that fracture toughness was doubled by adding nanofibers between composite layers. Under fatigue loading, the crack growth rate of the nanomodified specimens was less than the virgin specimens. So, the crack growth rate decreased by 8 times with interleaving the nanofibers at $\frac{\Delta G}{G_C}=0.9$. The Cohesive zone model method was used to evaluate the efficiency of finite element in modeling the fatigue crack growth rate in virgin and nanomodified specimens. The progressive failure model was used to simulate the fatigue behavior. Consistency of finite element results with the experimental results showed that the Cohesive zone model method is a suitable tool to model the fatigue behavior of interleaved composite laminates.

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1- Introduction

Carbon Fiber-Reinforced Polymers (CFRPs) are among the most applicable composite materials applied in various industries, especially in aerospace. Despite their advantages, such as high specific strength, they are easily damaged under fatigue loadings. The main damage modes of composite laminates are matrix cracking, fiber breakage, matrix/fiber deboning, and finally delamination. Up to now, many studies have focused on the latest one to remove, or at least decrease, its influence on the final failure of composite structures. Various techniques have been presented, but applying thermoplastic nanofibers as additives in thermoset-based CFRPs is one of the attractive methods for this aim [1]. Researchers have applied different types of polymeric nanofibers, such as nylon 6,6 and Polycaprolactone, and showed experimentally their excellent effects on toughening CFRPs [1].

Another technique for considering the behavior of nanofiber-toughened laminates is numerical methods, like Finite Element (FE). Although the number of experimental studies in this field is so high, but very limited publications focused on numerical studies. For instance, Saghafi et. al [1] considered the influence of nanofibrous mat position on damage size during impact loading and in another study, they considered the effect of nanofibers on cohesive parameters [2] during fracture loading.

Fatigue is a very important mechanical loading that many composite structures experience during their service. Experimental studies proved that nanofibers are very effective during fatigue and can increase the life cycle of the structure. However, there is no study, which considered this phenomenon numerically. In this paper, Nylon 6,6 are applied between carbon/epoxy laminates to consider its effect on crack growth rate. The investigations were conducted experimentally and simulated in ABAQUS (FE method) and the results were compared.

2- Methodology

2- 1- Experiments

To produce nanofiber, electrospinning is employed as the most common method. For this aim, nylon 6,6 polymer (provided by Solvay) was used and Formic acid and Trifluoroethanol (purchased from Merck company) were applied for preparing the solution. The thickness of produced nanofibrous mat was 50 mm (Fig. 1).

To manufacture the composite laminates, 24 layers of AS4/8552 prepreg were used. A thin Teflon (with a thickness of 13 mm) was applied for producing the initial crack, and a nylon 6,6 nanofibrous mat as a toughener part were placed in the middle of the sample (between the 12^{th} and 13^{th} layers).

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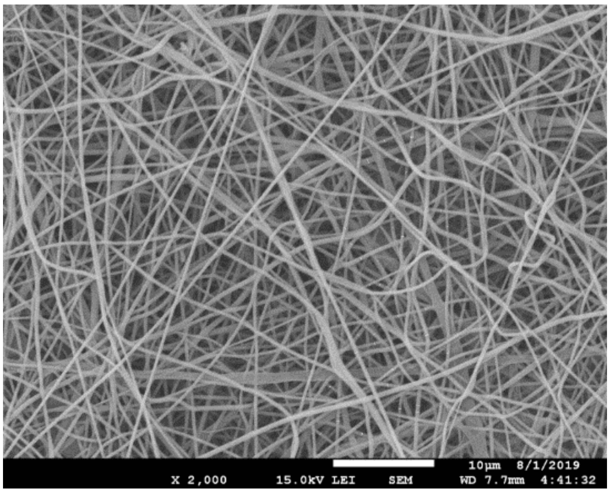


Fig. 1. Scanning electron microscopy image of the produced electrospun Nylon 6,6 nanofibers.

After preparing the samples, two test types were conducted: 1- mode-I quasi-static tests and 2- mode-I fatigue tests. They were conducted according to ASTM D5528 [3] and ASTM D6115 [4] standards, respectively. Both tests were loaded under displacement control. Quasi-static static were done under the rate of 1 mm/min while the second one was tested under cyclic loading at a frequency of 5 Hz and a displacement ratio of $R = \delta_{min}/\delta_{max} = 0.3$.

2- 2- Finite element method

In this study, ABAQUS software and cohesive element were used for simulating fatigue crack growth. This method was presented for the first time by Dugdale [5] in which a cohesive zone is considered in front of the crack tip. The behavior of the cohesive model is shown by a bilinear shape which is shown in Fig. 2.

A 2-D model was generated in the software and CPE4 and COH2D4 elements were used for modeling the composite and cohesive parts, respectively. The utilized cohesive parameters are presented in Table 1.

In order to model the fatigue behavior of laminates, progressive damage equations presented by Turon [6] was used. For this aim, a USDELD subroutine was written and introduced to the software.

Table 1. The cohesive element parameters used in the FE simulation

Parameters	Units	Virgin samples	Nanomodified samples
σ_I^{max}	MPa	60	60
G_{IC}	N/mm	0.18	0.40
k	N/mm^3	20000	20000

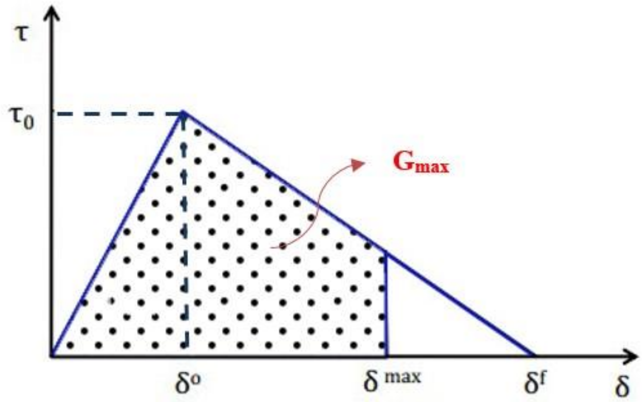


Fig. 2. Calculation of the variation of the strain energy release rate according to the constituent curve of the cohesive element.

3- Results and Discussion

3- 1- Quasi-static test results

The numerical and experimental results of the reference and nanomodified samples under quasi-static loading are illustrated in Fig. 3.

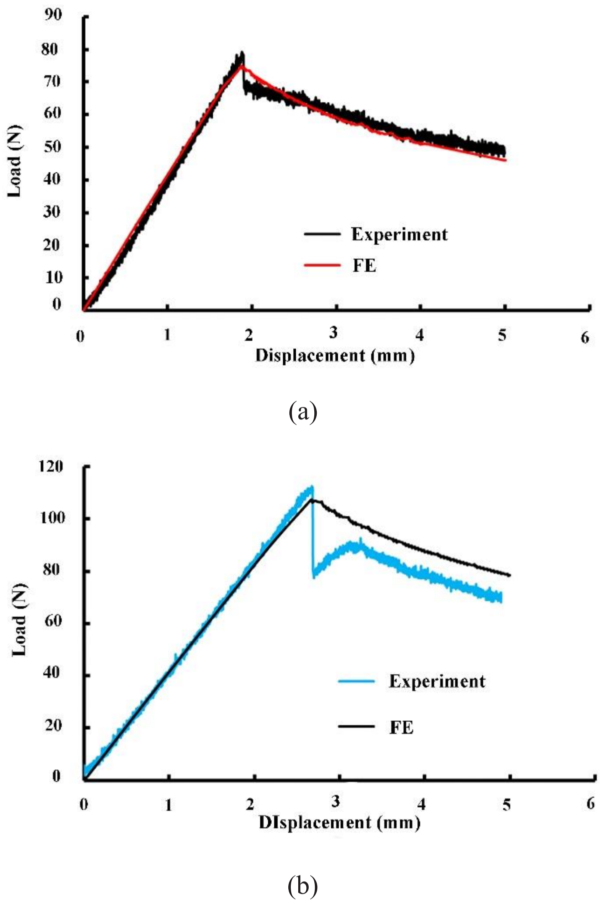
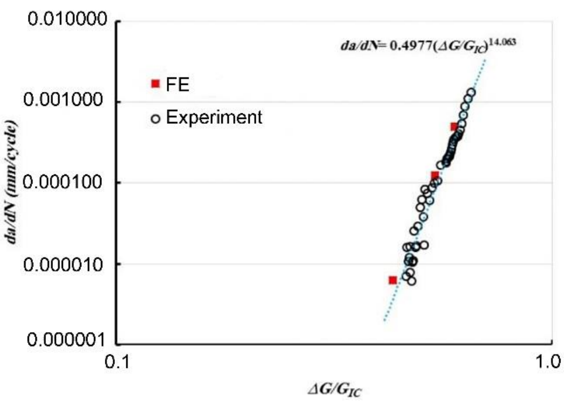
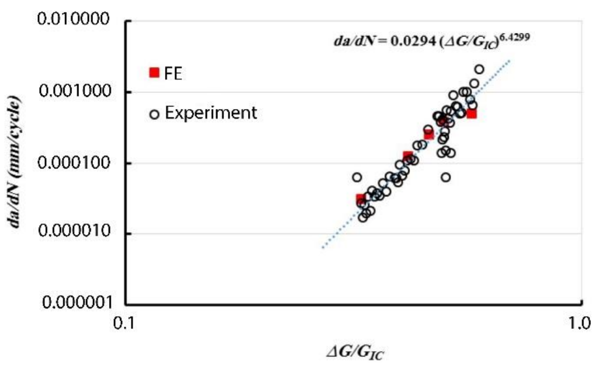


Fig. 3. Load-displacement curve of the quasi-static mode I loading, a) the FE results for the virgin specimen, and b) the FE results for the modified specimen



(a)



(b)

Fig. 4. The fatigue results of mode I loading, a) the FE results for the virgin specimen, and b) the FE results for the modified specimen.

As seen, there is good agreement between the numerical and experimental results. The results also show that the fracture toughness increased from 0.18 kJ/m2 to 0.4 kJ/m2, which shows more than double enhancement.

3- 2- Fatigue test results

Fig. 4 shows the effect of nanofibers on crack growth rate under fatigue loading. The comparison between experimental and numerical outcomes are also presented. Results showed that adding nanofibers between composite layers could decrease the rate of crack growth. For instance, when , the crack growth rate decreased from 0.113 mm/cycle in the reference laminate to 0.014 mm/cycle in the nanomodified one. As seen in the figure, the numerical simulation effectively could anticipate the experiments.

4- Conclusion

Inserting nanofibrous mats between composite layers led to more than double the enhancement in fracture toughness.

Under the fatigue test, the crack growth rate decreased about eight times by adding nanofibers.

The FE modeling using Cohesive Zone Model (CZM) showed that the numerical methods have capable to anticipate the fracture and fatigue behavior of the reference and nanomodified samples.

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