Indian Journal of Engineering & Materials Sciences
Vol. 30, December 2023, pp. 757-765
DOI: 10.56042/ijems.v30i6.528

Progressive Deformation Analysis in Carbon and Glass Fiber Reinforced Hybrid Composites Using Finite Element Method

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Received: 13 April 2023; Accepted: 15 October 2023

Progressive deformation analysis is a method used to predict the behaviour of composite materials under loading with pre-existing matrix cracks or fiber breakage. It involves the estimation of the gradual deformation of the material, taking into account the material properties, the applied loads, and the associated defect. This paper investigates the fracture behaviour of a carbon-glass fiber-reinforced polymer composite with pre-existing delamination between the layers. Using the finite element technique, the location of delamination and the number of layers in the laminate are investigated to better understand composite material response under the progressive deformation loading. To comprehend the progressive deformation of examined composites under tensile loading, the finite element-based programme Ansys is used. The analytical findings are used to validate the finite element models. For the studied composites with pre-existing cracks, the deformations, forces, equivalent stress, stress intensity factor, and strain energy release rate are given. In this work, the sensitivity of the delamination position on the laminate under progressive deformation loading is found. The current work is used for the effective design of the composite laminate with pre-existing delamination under service loading conditions.

Keywords: Ansys, Crack, Carbon and glass fiber reinforced composite, Progressive displacement analysis, Stress intensity factor, Strain energy release rate

1 Introduction

In a variety of applications, from giant wind turbine blades to microelectronics, polymer matrix composites are used because of their high specific strength and stiffness[1]. Composite materials made of fiber-reinforced polymers are quickly taking over as the material of choice for building aircraft and spacecraft[2]

The remarkable qualities of carbon fiber reinforced polymer composites (CFRP) include superior chemical resistance, exceptional mechanical properties at low density, and strength characteristics that may be specifically tailored for a given load[3,4] A very distinctive composite material is carbon fiber reinforced polymer (CFRP). The aircraft industry has employed CFRP extensively. Its introduction into the automotive industry has occurred slowly but surely as a result of cost reduction[5] Glass fibers exceptional qualities, including their high strength, flexibility, stiffness, and resistance to chemical damage, enable these composites to be used in a variety of industries, including electronics, aircraft, and automobiles[6] . Glass and carbon fiber reinforced composites are extensively used in the building industry as well. Glass-fiber reinforced polymer (GFRP) composite bridge decks are significantly more affordable than steel or concrete bridge decks since they are initially lighter to construct and have a longer lifespan[7]. Without transverse reinforcing steel, reinforced concrete columns lack the

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essential flexibility to disperse seismic energy during a significant earthquake. Utilizing a carbon fiber reinforced polymer composite is one of the options in this scenario[8]. On the other hand, research is being drawn to the hybridization of carbon and glass fibers. The development of the carbon/glass hybrid composite and evaluation of its mechanical properties are necessary to achieve both design versatility and cost savings[9]. The addition of glass fibers to carbon fiber reinforced composites appears to enhance their impact characteristics and raise the carbon fibers strain limit in tension. By adding carbon fibers, the flexural modulus of polymer beams made of glass fibers is greatly increased[10].

Due to their higher specific stiffness, strength, and damping capacity compared to typical metallic materials, glass fiber reinforced plastic (GFRP) and carbon fiber reinforced plastic (CFRP) composites have attracted a lot of attention for automobile structures[11]. Understanding the progressive degradation behaviour is crucial for improving the performance of these hybrid composites. With the help of a two-inclusion model, the effect of local stress redistribution due to fiber interaction on the progress of debonding was studied. The simulation of increasing debonding in fiber reinforced composites was carried out using composite many-fiber models12. A three-dimensional finite element based progressive damage model for unidirectional carbon fiber reinforced polymer (CFRP) laminates with two holes in various configurations subjected to tensile loading is also provided[13]. The effect of fiber position on the progressive damage characteristics was also identified for carbon fiber reinforced composites using experimental and simulation studies[14] . To capture the onset and initial propagation of damage within a three-dimensional woven composite in a single-bolt, double-shear joint, a three-dimensional progressive damage model was created[15]. The crack band theory is used in the framework to record damage propagation within composite material constituents. The maximum principal stress state is used to decide the initiation and orientation of the crack band in the matrix, and the traction separation law governing crack band growth is linked to the matrix's fracture toughness[16]. To investigate the damage and failure behaviours of 2D plain weave composites under different uniaxial and biaxial loadings, a two-step, multi-scale progressive damage analysis is used[17]. Development of nano and CNT associate material has proven good mechanical behaviour[28-31][28-31]. Development of artificial and machine learning, internet of things approaches has given good scope in the research domain of materials, many real-time problems[32-39]

However, the effect of carbon fiber and glass fiber reinforced epoxy hybrid composite response by considering the number of layers, crack position effect on stress intensity factor and strain energy release rate in mode one and mode two is not explored yet. This study is required for the effective design of the carbon/glass hybrid composite with the presence of cracks at different positions. Considering all this, the present work is planned to explore the carbon/glass fiber reinforced hybrid composite laminate stress intensity factor in mode 1 (K_1), mode 2 (K_2), and strain energy release rate in modes one and two (G_1 and G_2) with different crack positions using the Ansys programme.

2 Materials and Methods

Finite element numerical analysis can be used to figure out how the whole structure works and how it breaks down, from the first steps of the process to the point where the structure fails. Using the finite element-based programme Ansys, a composite plate with varying numbers of layers that is progressively subjected to deflection at one end is examined. Without altering the laminate's thickness, the number of layers varies from 2, 4, 8, and 16 layers. The material properties considered for the present work are presented in Table 1.

Table 1 — Material Properties of carbon/epoxy and E-glass/epoxy composites

Property	E-Glass Epoxy	Carbon/ Epoxy
Density[kg/mm^3]	2e-06	1.49e-06
Young's Modulus X direction[MPa]	45000	1.21e+05
Young's Modulus Y direction[MPa]	10000	8600
Young's Modulus Z direction[MPa]	10000	8600
Poisson's Ratio XY	0.3	0.27
Poisson's Ratio YZ	0.4	0.4
Poisson's Ratio XZ	0.3	0.27
Shear Modulus XY[MPa]	5000	4700
Shear Modulus YZ[MPa]	3846.2	3100
Shear Modulus XZ[MPa]	5000	4700
Tensile X direction[MPa]	1100	2231
Tensile Y direction[MPa]	35	29
Tensile Z direction[MPa]	35	29
Compressive X direction[MPa]	-675	-1082
Compressive Y direction[MPa]	-120	-100
Compressive Z direction [MPa]	-120	-100
Shear XY [MPa]	80	60
Shear YZ [MPa]	46.154	32
Shear XZ [MPa]	80	60

2.1 Finite Element Model

Materials for the current investigation included unidirectional carbon fiber reinforced epoxy composite and unidirectional glass fiber reinforced epoxy composite. The properties of the carbon/epoxy and glass/epoxy composites are presented in Table.1. The composite plate's length is assumed to be 100 mm. The plate has a 5 mm thickness. For every laminate with a layer configuration, the composite plate thickness remains constant. For composite laminates with two layers, each layer is 2.5mm thick. However, each layer is 1.25mm thick for composite laminates with four layers. In the current investigation, an accurate and time-efficient finite mesh was created using elements with a size of 0.05 mm.

PLANE 182, a two-dimensional continuum finite element, was used to mesh the model. The element is defined by four nodes. Each node has two degrees of freedom, or translations, in the x and y dimensions. It should be noted that in order to make sure the mesh was fine enough to produce trustworthy findings, a mesh sensitivity study was carried out with respect to the number of elements before carrying out additional computations. The composite laminate and the number of layers are presented in Fig. 1(a). According to Figure 1a, the fiber direction is parallel to the global X-axis, and the transverse direction is parallel to the global Y-axis.

15% of the length of the composite plate is fixed at the bottom left end. The pre-meshed crack is located at the center of the composite laminate. The top 15% of the length of the composite plate is subjected to progressive deformation as a load. For the prediction of lamina number and crack position effect, the FE model was subjected to progressive deformation of a maximum of 5mm, with the increment being 1mm for each model.

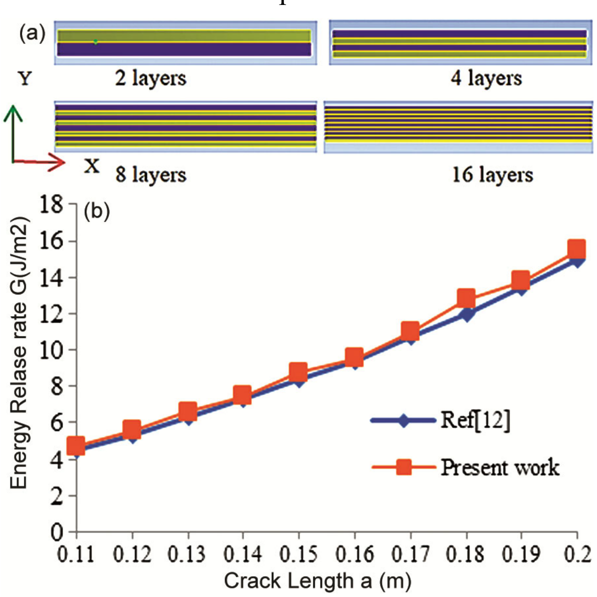

Fig. 1 — (a) Composite with different number of layers, and (b) validation of present work.

2.2 Validation

A double cantilever beam of a finite element model has been modelled and assigned glass fiber reinforced polymer laminate properties, and by varying the crack size, the energy release rate GI is predicted and compared with the present work. The geometry, loading, and boundary conditions of the model are the same as those considered for the reference[24] , and closeness in the results is observed between the published and present work (Fig. 1b).

3 Result and Discussion

Progressive damage analysis (PDA) is a technique used to model and predict the failure behavior of composite materials under various loading conditions. In the context of composite materials, PDA is an important tool for designing and optimizing composite structures for maximum performance and safety. In this work, the carbon and glass fiber reinforced epoxy composites are studied under progressive deformation loading to predict the position of the delamination effect and the number of layers on the fracture behaviour of the respective composite materials. The following results are shown in Fig. 2-5, which shows the magnitude of forces generated during the progressive deformation of carbon/glass fiber reinforced composite. The crack is initiated at the left end and located at the center of the laminate (Position A) as shown in the Fig. 6. The deformation applied to the laminate progresses from

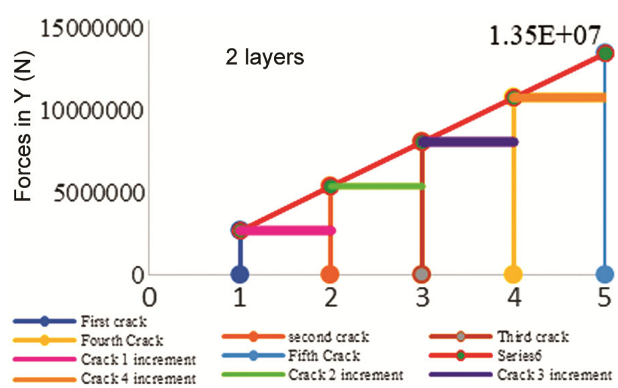

Fig. 2 — Forces in 2 layers laminate.

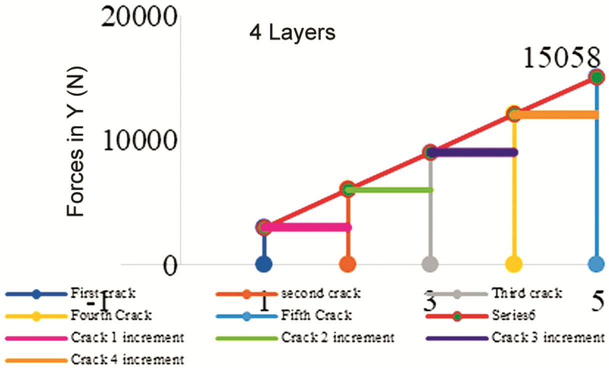

Fig. 3— Forces in 4 layer laminate.

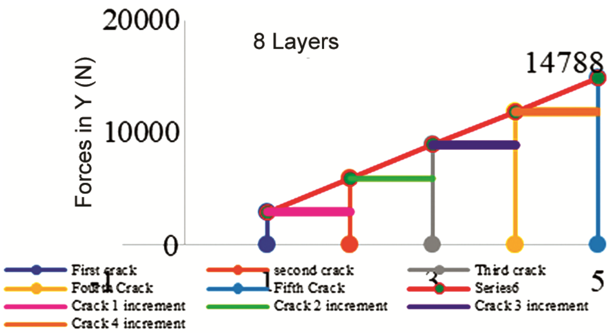

Fig. 4 — Forces in 8 layers laminate.

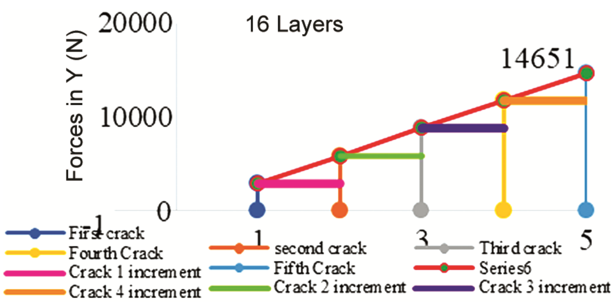

Fig. 5 — Forces in 16 layer laminate.

1 mm to 5 mm in 5 steps. Increasing the number of laminas in the laminate decreases the forces generated during crack propagation. (Fig .2-5). In the 2-layer laminate, the forces generated during the progressive deformation on the laminate are very high. These forces will be decreased by increasing the number of layers. The progressive deformation applied to the 2 layer laminate has generated high forces in the deformation loading direction compared to the 4, 8, and 16 layer composites. This is because each layer in the laminate will contribute to sharing the load and distributing the stress. With more layers, there are more fibers and interlayer interfaces to distribute the load, reducing the overall stress on each individual layer.

Therefore, it is also true that a 2-layer laminate will generally experience higher forces during progressive deformation than a 4, 8, or 16 layers composite, all other factors being equal. The greater number of layers in the latter composites allows for better load distribution and thus lower forces on individual layers.

The laminas in the laminate support the load applied to the composite laminate[25].The forces in the 2 layer composite at maximum deformation are 13485000N (Fig. 2). These forces are reduced to 14651N by increasing the number of layers from 2 to 16 (Fig. 5). Compared to the 2 layered laminate, the 4 layered laminate decreased the same directional forces to 15058N (Fig. 3) and the 8 layered laminate showed 14788 N forces under similar loading and boundary conditions (Fig. 4). Increasing the number of laminas can increase the fracture toughness of the laminate, making it more difficult for the crack to propagate. This can reduce the speed of crack growth and increase the amount of energy required for crack propagation, which can reduce the forces generated during crack propagation.

Stress intensity factor (SIF) is a critical parameter used to characterize the susceptibility of a material to fracture under applied load[18]. The considered composites are made up of 2 different materials with varying properties.

3.1 The effect of crack position on fracture response

In this work, the crack is made in different places, and this section shows how the crack responds differently depending on crack position.

The SIF describes the magnitude of the stress at the crack tip and is directly related to the crack propagation rate[18]. In composites, the SIF depends on various factors such as the crack orientation, fiber orientation, and the interface between the fibers and matrix.

Understanding the SIF is critical for the design and analysis of composite structures. Engineers use SIF calculations to predict the life of composite materials and determine the stress levels at which a material may fail. By analyzing the SIF, designers can optimize the design of composite materials to improve their resistance to failure and reduce the likelihood of catastrophic failure.

As presented in Fig. 6-9, the position of the crack at different locations is identified and named as positions A, B, C, and D. The stress intensity factor in mode-1, 2 and the strain energy release rate in mode 1,2 are presented in Fig. 10-13. k_1 refers to the stress

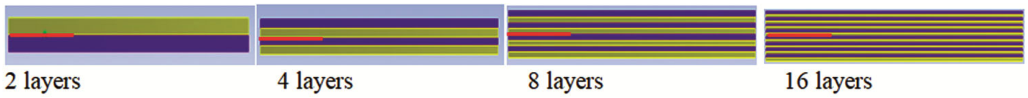

Fig. 6 — Position of the crack at the center of the laminate at the left end (Position A).

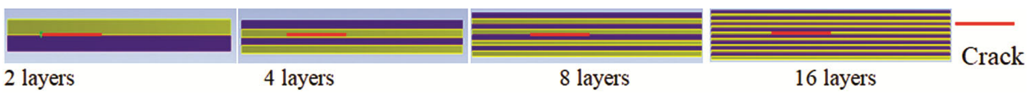

Fig. 7 — Position of the crack at 15mm away from left end of center layer of the laminate (Position B).

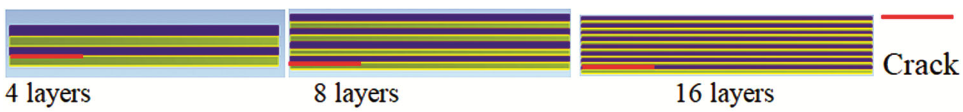

Fig. 8 — Position of the crack at bottom layer of the laminate at the left end (Position C).

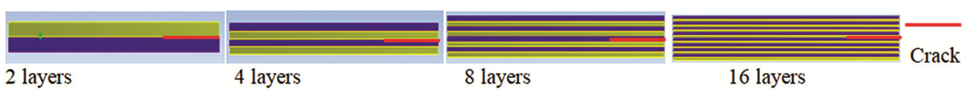

Fig. 9 — Position of the crack at the center of the laminate at the right end (Position D).

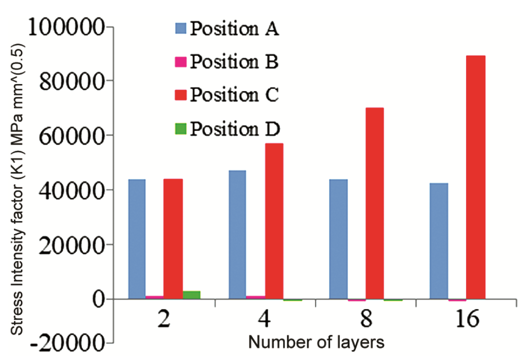

Fig. 10 — K_1 with respect to no of layers.

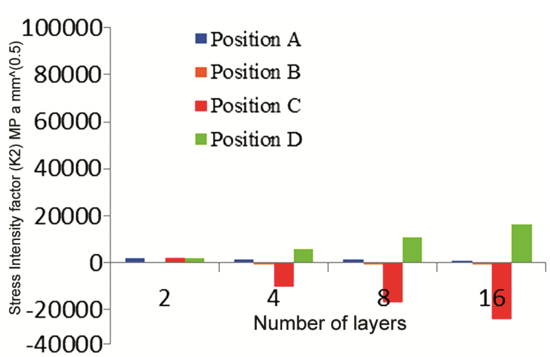

Fig. 11 — K_2 with respect to no of layers.

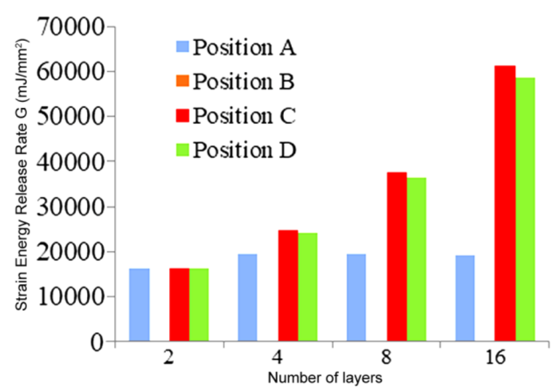

Fig. 12 — G_1 with respect to no of layers.

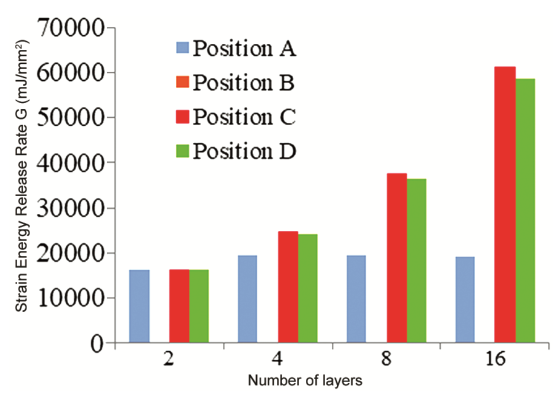

Fig. 13 — G_2 with respect to no of layers.

intensity factor in the direction perpendicular to the layers of the composite, while k_2 refers to the stress intensity factor in the direction parallel layers of the laminate.

The stress intensity factor in mode 1 (K_1) is high due to the crack location at position C and position A. Increasing the number of layers in the laminate also increases the magnitude of K_1 for the same position of the crack[19].

In laminates, the layers can interact with each other and affect the stress distribution around the crack tip.

When more layers are added to the laminate, the stress distribution around the crack tip can become more complex, leading to increased magnitudes of K_1[20]. The reason for high K_1 is not same for crack position at C and A. In the case of crack at position C, the loading direction is perpendicular to the crack position as a results the displacement load applied on composite is further extending the crack tip displacement. In crack position C, the growth of the crack is more due to the associate of end effect and crack.

Crack in other positions, such as position B and D, has very little influence on the K_1. These positions of cracks are far away from the loading and the surrounding layers suppressed the crack extension[21]. (Fig. 10).

Figure 11. shows the stress intensity factor in mode 2 for different crack positions considered for the present study. When compared to K_1, the magnitude of K_2 is very small, with the highest magnitude observed for the laminate with the crack at position D due to laminate end effects[22].

In composite materials, the layers typically provide the majority of the resistance to crack growth, while the matrix material serves to hold the layers together and transfer stresses between them. The layers are usually much stronger and stiffer than the transverse direction. As a result, the stress intensity factor in the direction perpendicular to the layers (k_1) is usually higher than the stress intensity factor in the direction parallel to the layers (k_2). This is because crack growth perpendicular to the layers has to overcome the resistance of both the layers and the matrix material, while crack growth parallel to the fibers or layers mainly has to overcome the resistance of the matrix material[23].

The strain energy release rate in mode 1 (G_1) is maximum for crack positions C and D and increases with increasing the number of layers in the laminate.

The strain energy release rate (G) is a measure of the energy per unit area required to propagate a crack. The strain energy release rate in mode 1 (G_1) specifically relates to the opening mode of the crack. In a present laminate material, the strain energy release rate in mode 1 (G_1) is maximum at crack positions C and D due to the maximum interlaminar stresses that occur at these locations (C and D). These stresses are caused by the shear deformation that occurs at the interface between two adjacent layers of the laminate.

As the number of layers in the laminate increases, the bending stiffness of the laminate also increases. This leads to higher interlaminar stresses and consequently, an increase in the strain energy release rate in mode 1 (G_1). This is because the interlaminar stresses are directly related to the energy required to propagate the crack.End effects, on the other hand, refer to the influence of the free edges of the laminate on the strain energy release rate in mode 1 (G_1). At the free edges, the interlaminar stresses are not uniform and are affected by the presence of the edges. (Fig. 12).

Figure 13 shows the strain energy release rate in mode-2. The crack position at D has promoted more energy release in mode-2 due to the lack of support at this area and the end effects of the laminate.

In a considered laminate material, the crack position at D generated more energy release in mode 2 compared to other positions due to several reasons. Firstly, the crack position at D has a lack of support from neighboring plies. This means that the shear stresses that are generated at the interface between two adjacent plies are not effectively transmitted to adjacent plies, leading to a concentration of stresses at the crack tip. This concentration of stresses leads to a higher strain energy release rate in mode 2, which is associated with the sliding or in-plane shear of the crack surfaces. Secondly, the end effects of the laminate can also contribute to the promotion of energy release in mode 2 at the crack position at D. The end effects refer to the influence of the free edges of the laminate on the stress distribution and strain energy release rate in the material. At the free edges, the stress state is not uniform, and this can lead to stress concentrations and a higher strain energy release rate in mode 2.

Figures 14-17 shows the variation of equivalent stress of the composite laminate with cracks at different

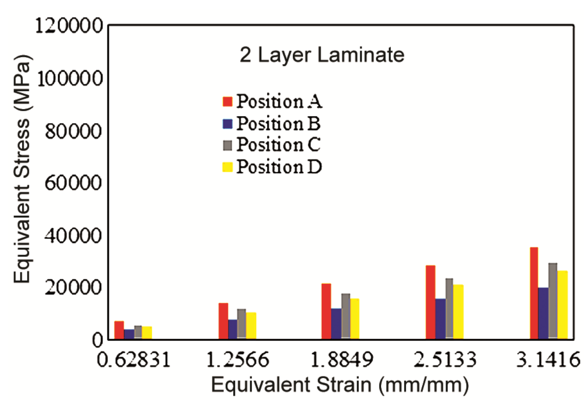

Fig. 14 — Stress v strain for 2 layer laminate.

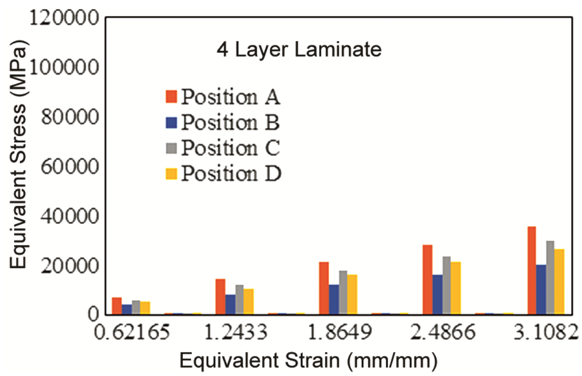

Fig. 15 — Stress v strain for 4 layer laminate.

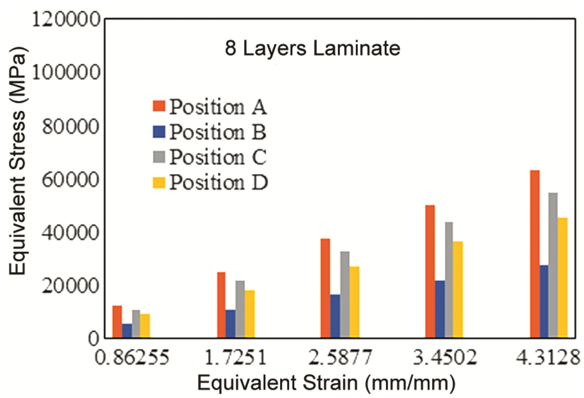

Fig. 16 — Stress v strain for 8 layer laminate.

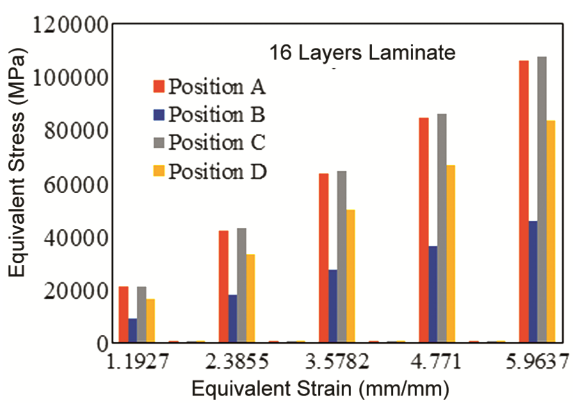

Fig. 17 — Stress v strain for 16 layer laminate.

positions. Figure 14 shows the equivalent stress vs equivalent strain curve for a 2-layer laminate. Of all the positions considered for the present study, cracks at the center layer and nearer to the load end generated more stresses than cracks at other positions. The same trend is continued for the 4- and 8-layered laminate (Fig. 15-16).

When a displacement load is applied at the top one end of a laminate, the laminate will experience bending, which leads to the development of tensile and compressive stresses. These stresses will be maximum at the top and bottom surfaces of the laminate and will decrease towards the neutral axis[26]. Cracks at the center layer of the laminate will experience the highest tensile stress at the top surface and the highest compressive stress at the bottom surface of the laminate. This is because the center layer is the farthest from the neutral axis, and thus it experiences the highest bending moment. As a result, the cracks at the center layer will generate more stresses compared to cracks at other positions. Cracks nearer to the load end will also experience higher stresses due to the concentration of the load at the top one end of the laminate. The concentration of the load will cause a stress concentration at the crack tip, which will lead to a higher stress intensity factor and a higher crack propagation rate. As a result, the cracks nearer to the load end will generate more stresses compared to cracks at other positions.

For the 16-layered composite, positions A and C give the same magnitude of equivalent stress. The increasing lamina numbers as well as the progressive deformation applied to the composite laminate are responsible for this behavior.

The fact that cracks positions A and C give the same magnitude of equivalent stress in a 16-layered composite is likely due to the symmetrical arrangement of the composite and the progressive deformation applied to the laminate. In a symmetrical laminate, the stress distribution is also symmetrical, meaning that the equivalent stresses will be the same for positions that are equidistant from the neutral axis of the composite. Additionally, the increasing number of laminae in the composite can also contribute to the similar magnitudes of equivalent stress at positions A and C. As the number of lamina increases, the composite becomes stiffer and stronger, which can lead to a more uniform stress distribution across the laminate. This can cause the equivalent stresses at positions A and C to converge to the same value. Finally, the progressive deformation applied to the composite laminate can also contribute to the similar magnitudes of equivalent stress at positions A and C. As the deformation is applied progressively, the stresses in the laminate are redistributed, and the stress concentration at any particular position is reduced. This can cause the equivalent stresses at positions A and C to converge to the same value as well.

Increasing the number of layers in the laminate means the lamina thickness is decreasing[27].and cracking with this thin lamina shows more distortion due to crack as well as the load acting on the laminate (Fig. 17).

4 Conclusion

The effect of the position of the crack in the carbon/glass fiber reinforced epoxy composite beam along with the number of layers is studied from the perspective of forces generated, equivalent stress, strain, stress intensity factor in mode 1,2, and strain energy release rate in mode 1,2. The following conclusions are drawn from the present results.

- The forces generated in the progressive deformation direction are decreasing with increasing the number of layers in the unidirectional carbon/glass fiber reinforced epoxy hybrid composite.
- The stress intensity factor in mode-1 and 2 and the strain energy release rate in mode-1 and mode-2 are dependent on the position of the crack and the number of layers of carbon/glass fiber reinforced epoxy hybrid composite.
- The strain energy release rate in mode 1 (G_1) is maximum at crack positions C and D due to the maximum interlaminar stresses at these locations. The strain energy release rate in mode 1 (G_1) increases with increasing the number of layers in the laminate due to higher interlaminar stresses. End effects can affect the strain energy release rate in mode 1 (G_1) at the free edges of the laminate, causing a reduction in value compared to the maximum value at crack positions C and D.
- Maintain the same size of the laminate and increase the number of layers of the laminate from 2 to 16, generates more K_1, K_2 and G_1 and G_2
- For the same position of crack, the response of the K_1 and G_1 is not same. The K_1 is high for the crack positions of C and A, whereas the G_1 is high for the crack positions of C and D. The position of crack at position D may not be serious in terms of K_1, but it should be considered in terms of G_1.
- The combination of the lack of support at the crack position at D and the end effects of the laminate can promote a higher energy release rate in mode 2 compared to other crack positions. This is because the lack of support and the end effects can cause a concentration of stresses and stress gradients, leading to a higher strain energy release rate in mode 2 associated with sliding or in-plane shear of the crack surfaces.
- Cracks at the center layer and nearer to the load end of a laminate material can generate more stresses compared to cracks at other positions under displacement load at the top one end due to the higher bending moment and stress concentrations at these positions.

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