Analytical and numerical methods for estimating the probability of interlaminar fracture in Mode I of composite structures under the peel test

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Abstract:

Introduction/purpose: The present work utilizes a numerical and analytical approach to predict the likelihood of interlaminar fracture in Mode I of a composite structure under the peel test.

Methods:The finite element approach, which incorporates the Virtual Crack Closure (VCCT) method, is utilized to examine the delamination of the composite structure. The research investigated the effects of many aspects, including dimension, fiber alignment, and composite properties.

Results: The numerical results significantly concur with the analytical solution recorded in the current body of literature. The Monte Carlo technique predicts the distribution function of composite damage. As previously stated, the probability of structural failure is assessed by considering both the model's uncertainty and the statistical uncertainty linked to the essential variables.

Conclusion: The probability density function (pdf) is derived by fitting specific theoretical models to the histogram. The durability of composite structures is primarily dependent on their mechanical properties.

Keywords: composite, delamination, peel test, VCCT method, durability.

Introduction

Composite structures are frequently employed in the aerospace, construction, and automotive sectors to enhance the stiffness of various elements. The degradation process of composite laminates leads to their collapse over time. Load redistribution resulting from local failure leads to the accumulation of different failure modes, hence compromising the stiffness of the composite material, diminishing its load-bearing capacity, and ultimately resulting in overall failure (Kishore et al, 2021; Hatti et al, 2022). The primary constraint in advancing composite materials for aeronautical applications has consistently been the challenges associated with accurately forecasting damage events and understanding their interactions (Ibrahim et al, 2018; Mechab et al, 2016; Serier et al, 2016). The capacity of a design to mitigate damage and prevent severe structural failure during flight or ground loads is frequently constrained by the tendency for delamination in traditional laminated fiber-reinforced polymer (FRP) constructions (Das et al, 2021).

Delamination arises from elevated interlaminar stresses, typically caused by impact (De Carvalho et al, 2015), deviations in material and structure (Fotouhi et al, 2020), or the propagation of further types of harm. Within the aerospace industry, using design features like stiffener terminations and ply-drops to modify thickness can result in multiple regions of an aircraft that are subjected to elevated interlaminar stresses. (Jokinen & Kanerva, 2019; Krueger, 2015). Hence, delamination is frequently identified as the primary failure mode in composite airframe design (Rybicki & Kanninen, 1977). The load capacity of a structure is typically negatively impacted by delamination damage, especially when exposed to compressive stress circumstances. Delaminations result in reduced buckling loads (Madukauwa-David & Drissi-Habti, 2016). The visible detection of delaminations is frequently challenging, and in the majority of instances, internal delamination can only be identified by non-destructive inspection (NDI) techniques like ultrasound (Kaźmierczyk et al, 2022; Gliszczyński & Kubiak, 2017).

Several different approaches are used to predict and analyze composite delamination. Among these methods is the Virtual Crack Closure Technique (VCCT), which allows for the prediction of the delamination growth from the first crack and includes both the delamination initiation and growth (Rozylo, 2021; Yu et al, 2021). The VCCT technique requires mesh size improvements and measuring the critical strain energy release rate. Many authors have used the VCCT method to evaluate the delamination spread in composite structures subjected to different loading scenarios or impacts at low velocities (Rozylo, 2022; Debski et al, 2021). However, the limitations resulting from the discretization of the numerical model continue to impede the application of the VCCT-based computational methodologies for damage prediction and aircraft structure design (Aveiga & Ribeiro, 2018; Rozylo et al, 2021; Cepero et al, 2019; Turon et al, 2010). This work aims to predict when delamination will occur in Composite Structure Mode I under shear stress circumstances. This study aimed to analyse the mode I interlaminar fracture tests on unidirectional laminates under the peel test. The Virtual Crack Closure Technique (VCCT) uses the finite element method to assess a structure's delamination. The impact of fiber orientation, thickness, and properties of the composite beam is investigated in this work. The Monte Carlo method is used to predict the distribution function of the composite damage.

Material and geometric model

This study presents interlaminar fracture in Mode I of the composite structure under the peel test. The thickness of the composite beam ranges from 1 mm to 3 mm, and the length is L=120 mm. The pre-crack a=25 mm and Widthb=20mm.The diagram illustrates the geometric characteristics and the applied load on the composite beam. A single load cell was used for the test with displacement control at a 0.5 mm/min speed. The developed composite structure exhibited a symmetrical stacking sequence of laminate layers. [0/30/-30/0] s, [0/90/0/90] s, [0/45/-45/0] s, [90/0/90/0] s.

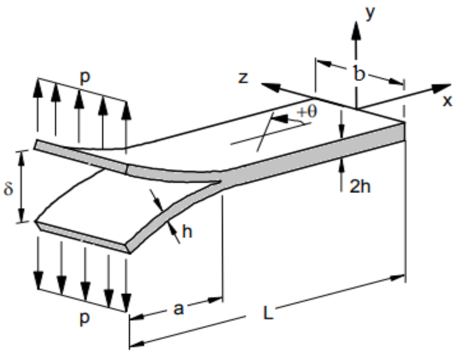

Figure 1 – Geometrical model

Tables 1 and 2 show the mechanical properties of the material used in this study.

Table 1 – Mechanical properties of different materials (Salem et al, 2015)

	E_1 (GPa)	E_2 (GPa)	E_3 (GPa)	ν_{12}	ν_{13}	ν_{23}	G_{12} (GPa)	G_{13} (GPa)	G_{23} (GPa)
Carbon/epoxy	120.0	10.5	10.5	0.3	0.3	0.5	5.25	5.25	3.48
Glass/epoxy	45.6	16.2	16.2	0.278	0.278	0.4	5.83	5.83	4.5

Table 2 – Mechanical interface properties of different composites (Turon et al, 2010)

	G_{Ic} (kj/m^2)	G_{IIc} (kj/m^2)	ŋ
Carbon/epoxy	0,260	1.002	2
Glass/epoxy	0.118	2.905	Two .6

FE Model

The numerical model using the VCCT was generated using ABAQUS (Dassault Systems, The 3D EXPERIENCE platform, 2014) in this investigation. The schematic depicted in Figure 2 illustrates the numerical model subjected to mechanical load. The study employed solid finite elements (C3D8R) with a regular hexagonal mesh. Every element consists of eight nodes, each having three degrees of freedom. The shape function is linear, and the integration is lowered. The discrete model consisted of 16.250 elements, specifically linear hexahedral elements of type C3D8R, and 35.620 nodes. The boundary conditions were applied to the upper (point A) item, allowing for movement only in the direction of the composite beam with respect to the Y-axis, and at (point B) given embedded. Figure 2 represents the boundary conditions and the discrete model.

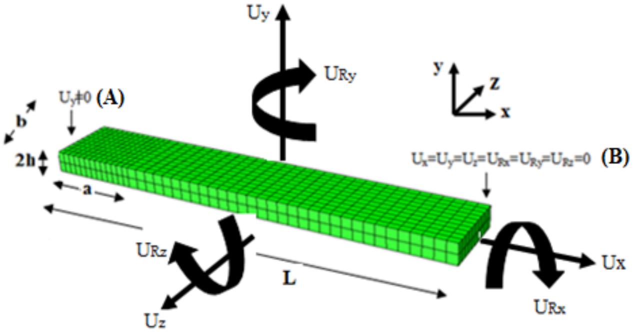

Figure 2 – Mesh and boundary conditions of the structure

Analytical formulation

The VCCT formulation

The VCCT employs an LEFM (Linear Elastic Fracture Mechanics) based method for forecasting the propagation of cracks in epoxy fiber-reinforced composites commonly used to construct aircraft structural elements. The VCCT, as introduced by Rybicki and Kanninen (1977) offers a notable reduction in the computational cost of the analysis compared to the previous method.

For sufficiently small values of (Δa), implying a finely meshed scenario where fracture propagation is anticipated, the extension of delamination from (a+Δa) (node l) to (a+2Δa) (node i) in the three-dimensional problem illustrated in Figure 3 (Rybicki & Kanninen, 1977) does not significantly impact the state at the crack tip. Consequently, the displacements behind the extended crack tip at node (i) are approximately equal to those behind the original crack tip at node (l). The strain energy release rate predictions will utilize equations (1, 2, and 3).

The components of Mode-I, Mode-II, and Mode-III strain energy release rates, denoted as GI, GII, and GIII, are determined as follows:

$$G_I = \frac{1}{2\Delta A} Y_{Li} \left(v_{Ll} - v_{Ll*} \right) \qquad (1)$$

$$G_{II} = \frac{1}{2\Delta A} X_{Li} \left(u_{Ll} - u_{Ll*} \right) \qquad (2)$$

$$G_{III} = \frac{1}{2\Delta A} Z_{Li}\left(w_{Ll} - w_{Ll*}\right) \tag{3}$$

where ($\Delta A = b.\Delta a$) represents the virtually closed area, with s being the width of the elements at the delamination front. In Figure 3, the columns are designated by capital letters, and the rows are identified by small letters. Thus, (X_{Li}), (Y_{Li}), and (Z_{Li}) denote the forces at the delamination front in the column L, row i.

The corresponding displacements behind the delamination at the top face in row l are denoted (u_{Ll}, v_{Ll}, and w_{Ll}), while at the lower face in row l*, they are denoted (u_{Ll*}), (v_{Ll*}), and (w_{Ll*})

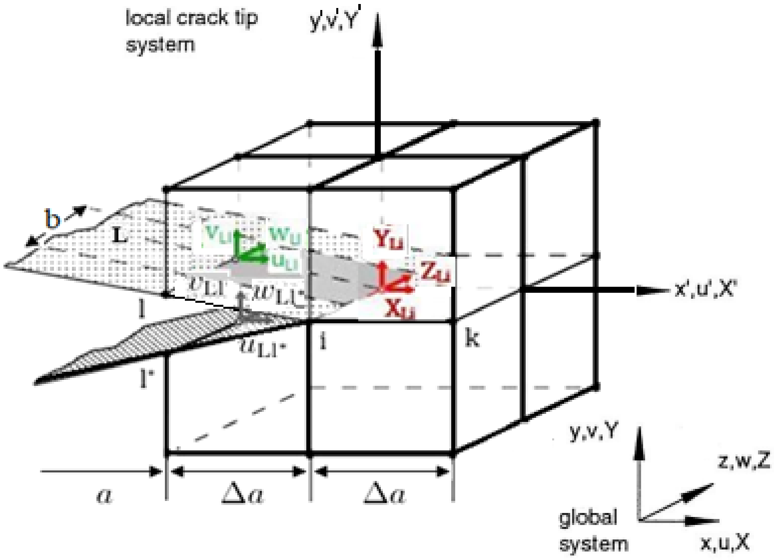

Figure 3 – The virtual crack closure technique (VCCT) for 3D solid elements (Rybicki & Kanninen, 1977)

Griffith's (1921) fracture theory obtained the fracture toughness values, KC, for a wide range of materials. Under the assumption of the plane stresses condition, the stress intensity factor K is related to the strain energy release rates G by the following expressions:

$$K_I = \sqrt{G_I E} \tag{4}$$

$$K_{II} = \sqrt{G_{II} E} \tag{5}$$

while the assumption of a plane strain condition yields

$$K_I = \sqrt{\frac{G_I E}{1-\upsilon^2}} \tag{6}$$

$$K_{II} = \sqrt{\frac{G_{II} E}{1-\upsilon^2}} \tag{7}$$

$$K_{III} = \sqrt{\frac{G_{III} E}{1-\upsilon^2}} \tag{8}$$

The total energy release rate (G_T), assessed at a specific point along the delamination front, attains a critical value denoted as (G_C), representing the material's mixed-mode fracture toughness.

$G_T \geq G_C \Rightarrow$ Delamination propagation

Various criteria are accessible for establishing a precise estimation of (G_C). Concerning (G_T), it can be computed as the summation of the nodal energy release rates for pure Mode I (opening), Mode II (sliding), and Mode III (scissoring).

$$f = \frac{G_T}{G_{I_C} + \left(G_{II_C} - G_{I_C}\right) * \left(\frac{G_{II} + G_{III}}{G_T}\right)^{\eta}} \geq 1.0 \tag{9}$$

$$G_T = G_I + G_{II} + G_{III} \tag{10}$$

where: G_I, G_{II}, and G_{III} are respectively the Mode I, II, and III energy release rates, respectively.

f: the effective energy release rate ratio

ŋ: the material constant

Analytical solution for the mode I DCB test

The analytical solution for the end-notched flexure specimens (ENF) test can be split into the three stages of the load-displacement curve. The load and displacement can be calculated with the following equations:

The necessary force P for crack propagation is given by

$$P = \sqrt{\frac{G_{IC} b^3 h^3 E_{11}}{12(a+\chi h)^2}} \tag{11}$$

χ can be calculated as

$$\chi = \sqrt{\frac{E_{11}}{11 G_{13}} \left\{ 3 - 2\left(\frac{\Gamma}{1+\Gamma} \right)^2 \right\}} \tag{12}$$

where Γ is the transverse modulus correction parameter and can be obtained using

$$\Gamma = 1.18 \sqrt{\frac{E_{11} E_{22}}{G_{13}}} \tag{13}$$

The corresponding displacement δ is given by

$$\delta = P \frac{8(a+\chi h)^3}{b h^3 E_{11}} \tag{14}$$

where (G_{IC}) is the critical mode I strain energy release rate, (B) is the width of the test sample, (h) is the half of the thickness of the sample, (E1) is the longitudinal Young’s modulus, (P) is the applied force, (a) is the crack length, and (L) is the half of the span.

Results and discussion

Validation of the model

Figure 5 demonstrates that the force-displacement curve of the FEM findings closely aligns with the analytical solution for all two types of materials. We note that the numerical results are in good agreement compared with the analytical solution found in the literature (equation (14)). The force exhibits a linear relationship with the applied displacement in the first loading phase. Upon achieving the maximum load, a sudden decrease in force suggests unstable delamination crack growth.

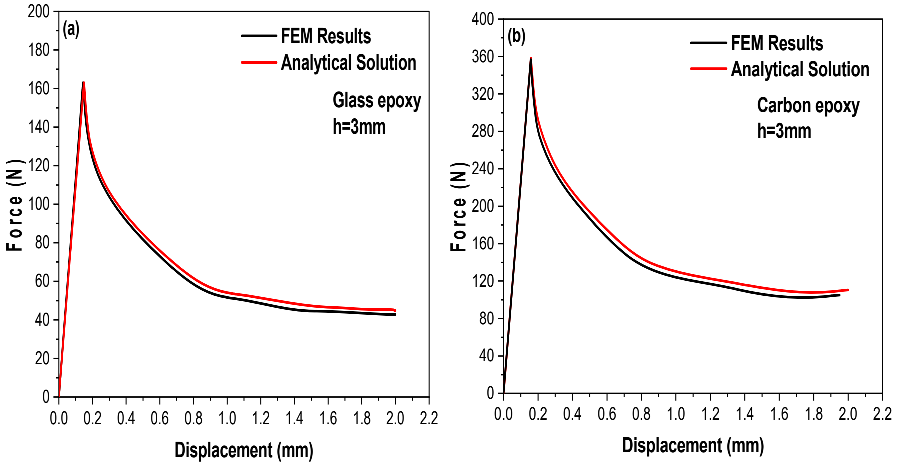

Figure 4 – Curve force displacement in Mode I of the FEM results compared with the analytical solution

Effect of the properties of the composite

The force-displacement curves for different materials, such as carbon/epoxy and glass/epoxy, are depicted in Figure 5. The force demonstrates a linear augmentation of the applied displacement during the initial loading period. After attaining the maximum load, a rapid decrease occurs, suggesting an unstable expansion of the delamination fracture.

The carbon/epoxy beam provides good fracture resistance compared to glass/epoxy beams and this composite increases the service life of the composite beam. Upon analyzing the energy distribution inside the delamination zone depicted in Figure 6, it is worth mentioning that the carbon/epoxy material demonstrates a lower energy value for (G_I) than the glass/epoxy. This characteristic contributes to an increased ability of the composite structure to withstand failure.

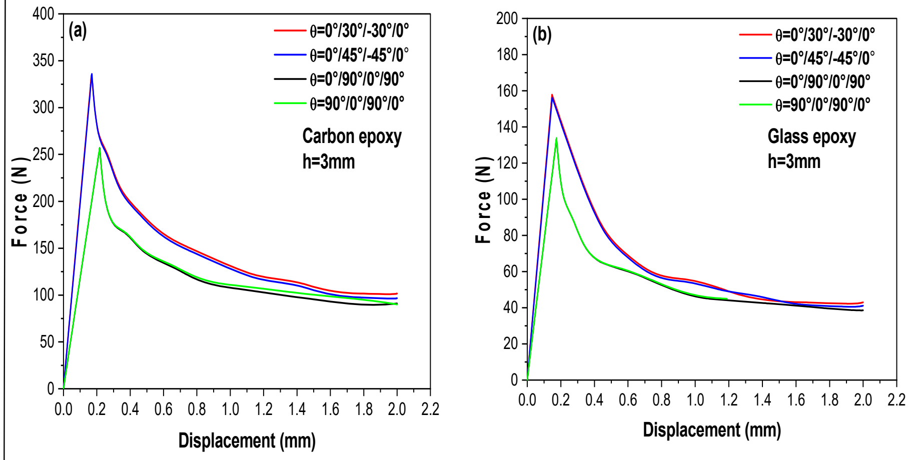

Figure 5 – Curve force-displacement in Mode I for different properties of the composite

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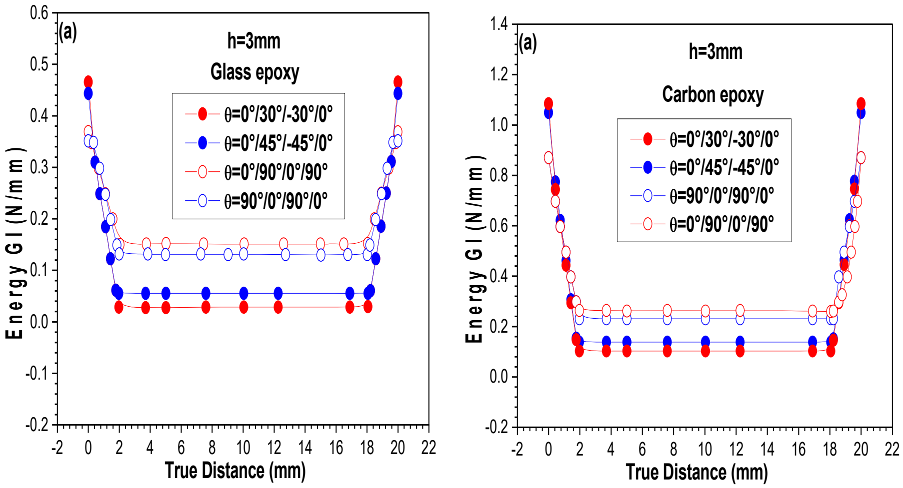

Figure 6 – Curve Energy (G_I) according to the true distance different properties of the composite

Effect of fiber orientation

This section of the study investigates the impact of fiber orientation in laminates as a determining factor that can enhance structural resistance against damage. The load transfer inside the delamination zone is facilitated by its rigidity, which is achieved through the alignment of the fibers. Consequently, the aim is to assess the amount of the braking force by adjusting the stiffness of the composite material.

Figure 7 illustrates the curve force-displacement for four different fiber orientations, namely [0/30/-30/0]s, [0/45/-45/0]s, [90/0/90/0]s, and [0/90/0/90]s, to evaluate the performance of the fiber orientation. The results indicate that the orientation [0/30/-30/0] exhibits superior performance in comparison to the other three orientations, namely [0/45/-45/0]s, [90/0/90/0]s, and [0/90/0/90]s, respectively.

The energy distribution along the delamination zone, as depicted in Figure 8, reveals that the energy value of (GI) is comparatively smaller for [0/30/30/0]s than in the other three samples. This observation confirms the plate's resistance to failure for [0/30/30/0]s.

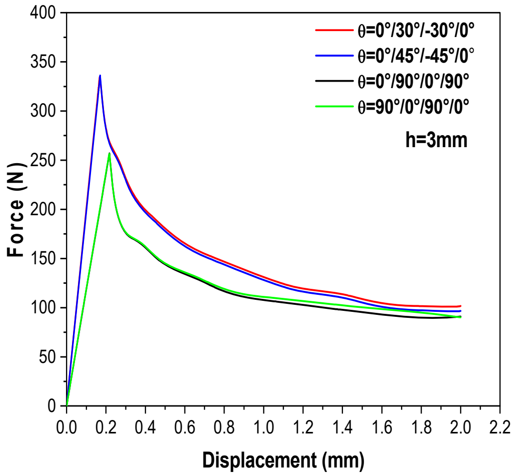

Figure 7 – Curve force-displacement in Mode I for different fiber orientations of carbon epoxy

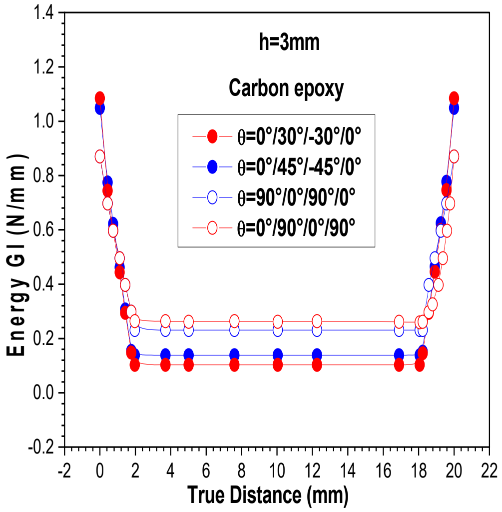

Figure 8 – Curve Energy (GI)according to the true distance for different fiber orientations for a thickness, h=3mm

Effect of the thickness of the composite

The force-displacement curves of the specimens at various thicknesses, specifically 1, 2, and 3mm, are depicted in Figure 9. In the initial loading phase, the force exhibits a linear relationship with the increment in applied displacement. The load experiences a sudden decrease following the peak load, suggesting the presence of unstable delamination crack propagation. The beam with a thickness equal to 3 mm gives excellent performance superior to those of beams with a thickness of 1 mm and 2 mm, respectively, because to reach the beam fracture for a thickness equal to 3 mm, it is necessary to apply a force higher than 300N compared to that applied to the beams of thickness 1 mm and 2 mm which are significantly lower.

Figure 10 illustrates the energy distribution along the delamination zone. It is evident that at a thickness of h=3mm, the energy value of (G_I) is lower than that for other thicknesses. This decrease in energy value enhances the composite structure's resistance to failure.

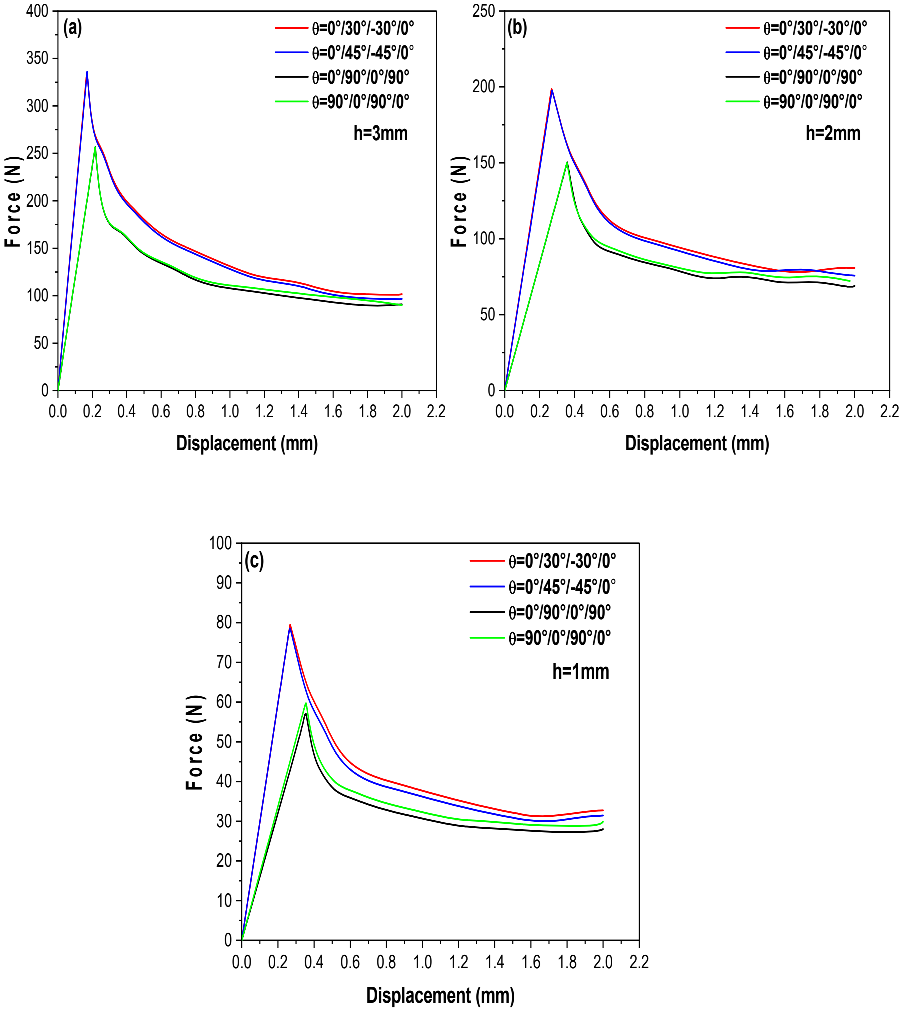

Figure 9 – Curve force displacement in Mode I for three different thicknesses of carbon epoxy

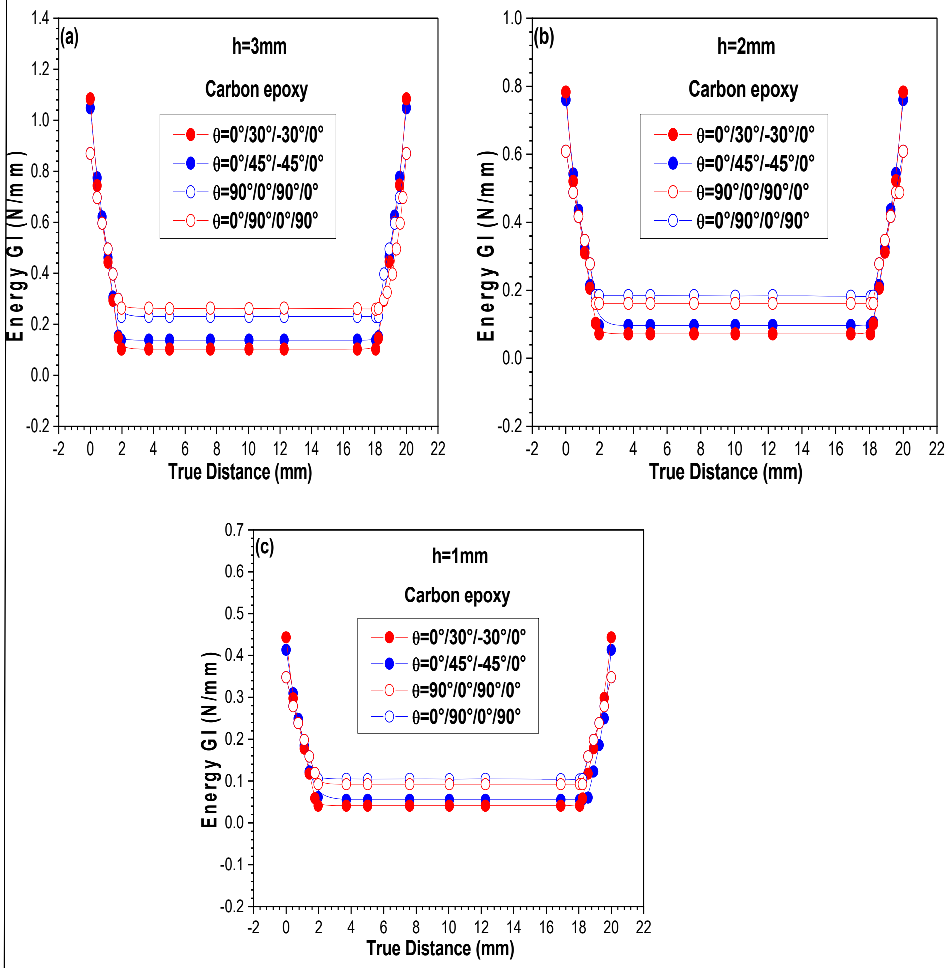

Figure 10 – Curve Energy GI according to the true distance for different thicknesses of carbon epoxy

Analytical solution of the prediction of delamination

To comprehend the significance of the random variables, it is imperative to initially examine the sensitivity of the displacement δ(x) concerning the uncertainties associated with the input parameters (refer to

Table 2). By calculating the dispersion of the mechanical reaction about the scatter of the input parameters, it is possible to derive sensitivity measurements. The authors have integrated two FORTRAN programs to analyze the multi-layered composite pipe. The first program computes the mechanical response by determining the stress distribution, while the second program employs Monte Carlo simulations to calculate the probabilistic response. To ensure a high level of accuracy in the obtained results, a total of 105 simulations were conducted.

The abovementioned factors are denoted as stochastic variables that exhibit distinct distribution classes and parameters. Effectively handling the uncertainties present in the system is crucial to guarantee safety in the design process, thus averting hazardous circumstances. Plate uncertainties connected with geometry (Length (L) and thickness (h)) and material properties (Young's modulus (E) and fiber orientation (θ)) are modeled using eight random variables.

Table 1 – Random variables and the corresponding parameters

Variable	Mean	Coefficient of variation (COV)
E (MPa)	120. 10^3	1%
L (mm)	120mm	2%
B (mm)	20mm	2%
h (mm)	3mm	2%
θ(°)	0°/30°/-30°/0°	2%

The histogram plot of the displacement δ(x) obtained from the Monte Carlo simulations is depicted in Figure 11. The calculation of the probability density function (pdf) involves the process of fitting a theoretical model to the histogram. The Gaussian distribution is a reliable approximation of the displacement δ(x) probability density function, accurately estimating the average, as seen in Figure 11.

Figure 12 displays the failure probability for the displacement δ (x) in different materials, specifically glass/epoxy and carbon/epoxy. It is worth mentioning that the carbon/epoxy composite has a decreased likelihood of failure compared to the glass/epoxy composite, as shown in Figure 12. The presence of uncertainties related to the type of material and the orientation of fibers significantly contributes to a notable augmentation in the margin of failure. The likelihood of failure ultimately depends on the selected materials and the orientation of the fibers.

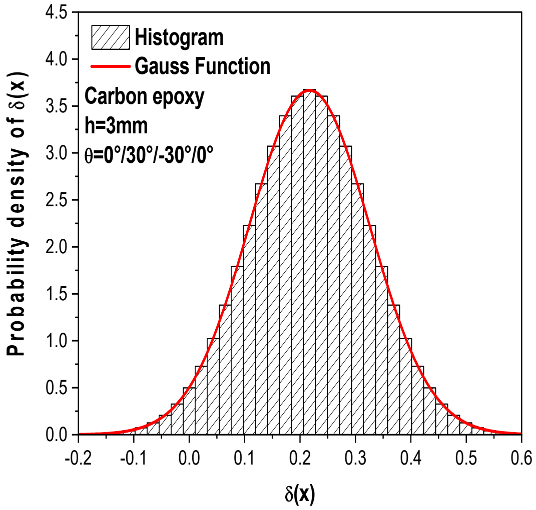

Figure 11 – Histogram and the probability density of the displacement δ(x) (Carbon epoxy, h=3mm, θ=0/30/-30/0)

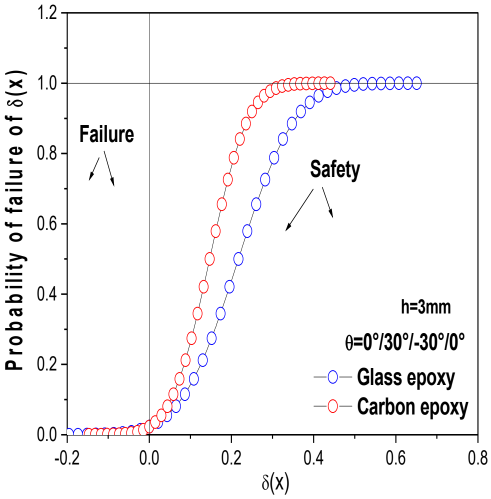

Figure 12 – Probability of displacement failure δ(x) for different properties of the composite

Conclusions

Because of their exceptional stiffness and strength, composite materials are widely used in various industries, including aircraft, transportation, automotive engineering, building infrastructure, and more. The current work investigates the mechanical response of composite structures subjected to peel loading through the development of analytical and numerical methods. Our parametric analysis is more detailed and more deepened than those found in the literature.

A methodology for predicting delamination propagation of interlaminar fracture in Mode I of composite structures under the peel test with the Virtual Crack Closure Technique (VCCT) approach is proposed in this study using a three-dimensional finite element analysis of a composite beam. The effects of the properties of the composite, the fiber orientation, and the thickness are presented. The numerical results are in good agreement with those of the analytical solution found in the literature (equation 14).

The Monte Carlo method was used to predict the damage of the composite. The structure failure probability is computed, considering the statistical uncertainty associated with the fundamental variables and the model uncertainty. The probability density function, or the pdf, is obtained by fitting the histogram using theoretical models. It is important to note that the mechanical properties parameter is vital in determining the degree to which the composite structure offers increased durability.

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Métodos analíticos y numéricos para estimar la probabilidad de fractura interlaminar en Modo I de estructuras compuestas bajo el ensayo de pelado

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CAMPO: mecánica
TIPO DE ARTÍCULO: artículo científico original

Resumen:

Introducción/objetivo: El presente trabajo utiliza un enfoque numérico y analítico para predecir la probabilidad de fractura interlaminar en el Modo I de una estructura compuesta bajo la prueba de pelado.

Métodos: El método de elementos finitos, que incorpora el método de cierre virtual de fisuras (VCCT), se utiliza para examinar la delaminación de la estructura compuesta. La investigación exploró los efectos de muchos aspectos, incluida la dimensión, la alineación de las fibras y las propiedades del compuesto.

Resultados: Los resultados numéricos coinciden significativamente con la solución analítica registrada en el cúmulo de literatura actual. La técnica de Monte Carlo predice la función de distribución del daño compuesto. Como se indicó anteriormente, la probabilidad de falla estructural se evalúa considerando tanto la incertidumbre del modelo como la incertidumbre estadística vinculada a las variables esenciales.

Conclusión: La función de densidad de probabilidad (pdf) se obtiene ajustando modelos teóricos específicos al histograma. La durabilidad de las estructuras compuestas depende principalmente de sus propiedades mecánicas.

Palabras claves: compuesto, delaminación, prueba de pelado, método VCCT, durabilidad.

Аналитические и численные методы оценки вероятности межслойного разрушения в первом режиме композитных структур при испытании на отслаивание

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РУБРИКА ГРНТИ: 55.09.43 Композиционные материалы
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Резюме:

Введение/цель: В данной статье используется численный и аналитический подход для прогнозирования вероятности межслойного разрушения в первом режиме композитной структуре при испытании на отслаивание.

Методы: Метод конечных элементов, включающий в себя метод виртуального закрытия трещин (VCC), используется в изучении расслаивания композитной структуры. В ходе исследования были изучены многие аспекты, включая размеры, выравнивание волокон и свойства композита.

Результаты: Численные результаты в значительной степени согласуются с аналитическим решением, описанным в современной литературе. Методом Монте-Карло прогнозируется функция распределения повреждений композитных материалов. Как указывалось ранее, вероятность разрушения конструкции оценивается с учетом неопределенности модели и статистической неопределенности, связанной с основными переменными.

Вывод: Функция плотности вероятности получена путем подгонки конкретных теоретических моделей к гистограмме. Долгосрочность композитных структур в первую очередь зависит от их механических свойств.

Ключевые слова: композитные материалы, расслаивание, испытание на отслаивание, метод VCC, долговечность.

Аналитичке и нумеричке методе за процену вероватноће интерламинарног лома у Моду 1 композитних структура путем теста љуштења

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ОБЛАСТ: механика
КАТЕГОРИЈА (ТИП) ЧЛАНКА: оригинални научни рад

Сажетак:

Увод/циљ: У раду је коришћен нумерички и аналитички приступ за предвиђање вероватноће интерламинарног лома у Моду 1 композитне структуре током теста љуштења.

Методе: Метода коначних елемената, која укључује методу виртуелног затварања прслине (Virtual Crack Closure – VCC), користи се за испитивање деламинације композитне структуре. Истражују се ефекти многих аспеката као што су димензије, правци пружања влакана и својства композита.

Резултати: Нумерички резултати се у великој мери слажу са аналитичким решењем из актуелне литературе. Техника Монте Карло предвиђа функцију дистрибуције оштећења композита. Вероватноћа структурног лома процењује се узимањем у обзир и несигурности модела и статистичке несигурности повезане са основним варијаблама.

Закључак: Функција густине вероватноће изведена је уклапањем специфичних теоријских модела у хистограм. Трајност композитних структура зависи, пре свега, од њихових механичких својстава.

Кључне речи: композит, деламинација, тест љуштења, метода VCC, трајност.

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