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# Probabilistic Fracture Mechanics Analysis of Crack Propagation in Composites Under Tensile Loading

**Sid Ahmed Reffas**
University of Sidi Bel Abbes

**Belaid Mechab**
University of Sidi Bel Abbes

**Mohamed Cherfi**
University of Sidi Bel Abbes

**Abstract**: Reliability engineering is a discipline dedicated to the study and evaluation of structural systems, aiming to assess their ability to perform required functions under specified conditions over a defined period. This study presents a numerical investigation into the damage prediction of composite structures subjected to tensile loading, employing three-dimensional finite element analysis. The influence of material properties, fibre orientation, thickness (ep), and the length-to-thickness ratio (L/ep) is examined within the framework of probabilistic fracture mechanics for composite damage. The Monte Carlo simulation method is utilised to estimate the damage distribution function. Failure probability is evaluated by incorporating both statistical uncertainties in the basic variables and model uncertainties. Probability density functions are derived by fitting histograms to theoretical models, with Lorentzian, Gaussian, and ninth-order Polynomial distributions considered. The Gaussian distribution provides the most accurate approximation of the strain probability density function, offering a reliable estimate of the mean value.

**Keywords:** Composite, Finite element method, Safety, Fracture mechanics, Monte Carlo method

## Introduction

A composite material is defined as a macroscopic assembly of two or more constituents with different chemical or physical properties, whose combination results in global properties superior to those of the individual materials. Typically, a composite is composed of a reinforcement phase, such as continuous or discontinuous fibers, and a matrix that provides cohesion and protection to the reinforcement while transferring mechanical loads. Composite materials offer several major advantages: excellent specific strength (high strength-to-weight ratio), tailored stiffness, good resistance to fatigue and corrosion, and the ability to design structures with custom anisotropic mechanical properties. This high adaptability opens up significant prospects in demanding sectors such as aerospace, space, ground transportation, energy, and civil engineering (Solis et al.2018; Ranz et al.207; Charrier et al.2016; Tasdemir et al.2019; Pernice et al.2015; Fletcher et al.2016).

Damage to aeronautical structures represents a major challenge for the aerospace industry, with direct implications for safety, maintenance, and the lifespan of aircraft. Throughout their lifecycle, aircraft are subjected to various mechanical, thermal, and environmental stresses. Damage phenomena can manifest in several forms, including fatigue, corrosion, impacts, composite delamination, and structural cracks (Cao et al.2010; Tvergaard and Hutchinson., 1992; Tvergaard.,1990; Salem et al.,2024; Turan et al.,2007; Ibrahim et al.,2018).


- Selection and peer-review under responsibility of the Organizing Committee of the Conference

The detection and prevention of these degradations are crucial for ensuring the safe and efficient operation of aircraft. With the introduction of composite materials, new types of damage have emerged, such as delamination and interlaminar cracks. These forms of degradation are often less visible on the surface, making their detection more complex and requiring advanced inspection methods. In conclusion, the issue of damage in aircraft is a critical challenge that requires rigorous management, combining material innovations, advanced inspection techniques, and predictive maintenance strategies. The evolution of materials and detection technologies plays a key role in improving safety and extending the lifespan of aircraft (Di vito et al.2019; Maachou et al. 2024; Talbi et al.2025; Song et al.2019; Bayandor et al.2003). Reliability engineering focuses on evaluating structural systems' performance under specified conditions over time. This study conducts a numerical analysis of composite structures under tensile loading using 3D finite element methods. The effects of material properties, fibre orientation, thickness (ep), and length-to-thickness ratio (L/ep) are examined through probabilistic fracture mechanics. Damage distribution is estimated using Monte Carlo simulation, incorporating uncertainties in both input variables and model assumptions. Probability density functions are obtained by fitting histograms to theoretical distributions. Among the models considered—Lorentzian, Gaussian, and ninth-order polynomial are presented.

## Geometric Model

The objective of this study is to perform interlaminar damage tests in mode I on unidirectional composite specimens subjected to a tensile load of **σ = 50 MPa**. The samples used had a standardized geometry, with a length of **230 mm**, a width of **35 mm**, and a thickness ranging from **1 mm** to **3 mm**, depending on the configurations studied. The specimen geometry and the loading scheme are shown in **Fig. 1**. Various stacking sequences of composite layers were investigated, including **[0°/90°/0°/90°]**, **[45°/0°/45°/0°]**, and **[−30°/0°/30°/0°]**, to assess the influence of fiber orientation on fracture behavior.

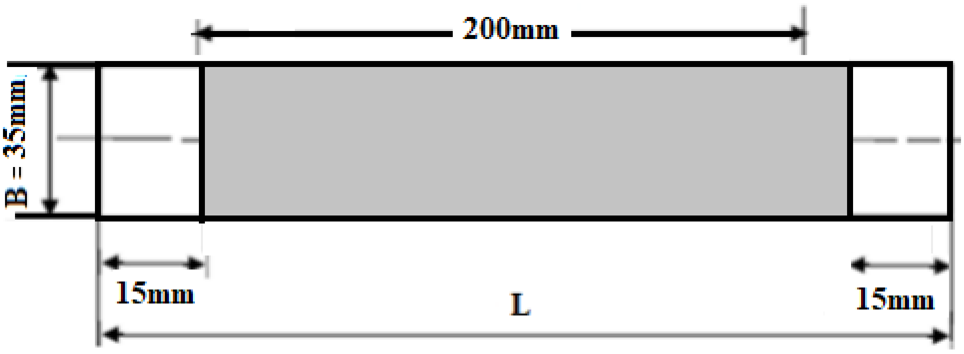


Figure 1. Descriptive model of the studied geometry.

### The Boundary Conditions

The boundary conditions for fixation, in accordance with the symmetry conditions of the geometry, were applied in the initial phase of the study. These conditions are defined in 3D as follows: point **(A)** is fixed along the **X** axis, while point **(B)** is free. This modeling ensures the compliance with the geometric constraints imposed by the symmetry of the structure while enabling the simulation of crack behavior under loading.

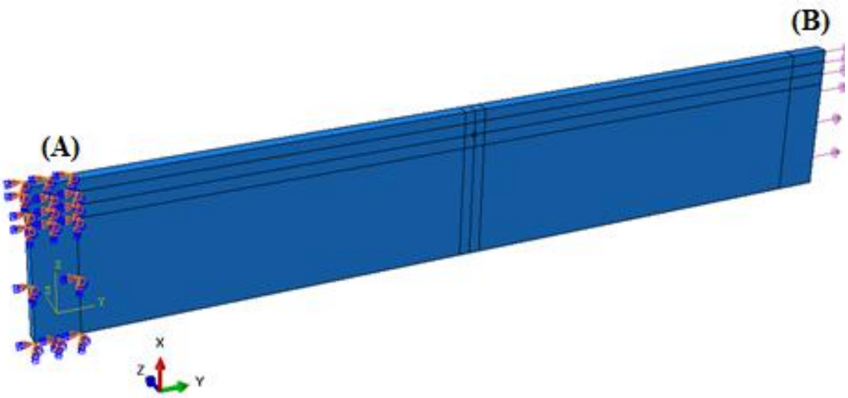


Figure 2. Boundary conditions of geometric model.

### Mechanical Properties

The material's mechanical characteristics of the different materials are presented respectively in Table 1

Table 1. Mechanical characteristics of the different materials

| The material's | Al 2024T3 | Glass/epoxy | Graphite/epoxy | Boron/epoxy |
|---|---|---|---|---|
| $E_1$ (GPa) | 72 | 150 | 127.5 | 200 |
| $E_2$ (GPa) | | 25 | 9.00 | 19.6 |
| $E_3$ (GPa) | | 25 | 4.80 | 19.6 |
| $\upsilon_{12}$ | 0,3 | 0.21 | 0.342 | 0,30 |
| $\upsilon_{13}$ | | 0.21 | 0.342 | 0.28 |
| $\upsilon_{23}$ | | 0.21 | 0.38 | 0.28 |
| $G_{12}$ (GPa) | | 7.2 | 4.8 | 7.2 |
| $G_{13}$ (GPa) | | 5.5 | 4.8 | 5.5 |
| $G_{23}$ (GPa) | | 5.5 | 2.55 | 5.5 |

## FEM Analyses

The finite element method has been extensively used in fracture mechanics in various forms. One of the major challenges in modeling cracked structures lies in the geometric description of the crack. In the finite element method, the crack is explicitly modeled and is an integral part of the mesh boundaries. In this study, the software used is the finite element analysis code **ABAQUS[17]**, version **6.11**. An initial mesh consisting of **10,568 elements** was employed, which was refined several times to reach **41,353 elements**, with intermediate refinements of **17,811**, **25,736**, and **34,058** elements. The results of the **KI** integrals for each refinement were nearly identical, confirming the convergence of the solutions. It is noteworthy that for each refined mesh, the region around the crack tip was specifically refined multiple times to ensure result stability. The crack tip was modeled using focused elements, consisting of five contours. The solutions obtained using this modeling were compared to those using five contours, and the results were almost identical, validating the adopted approach.

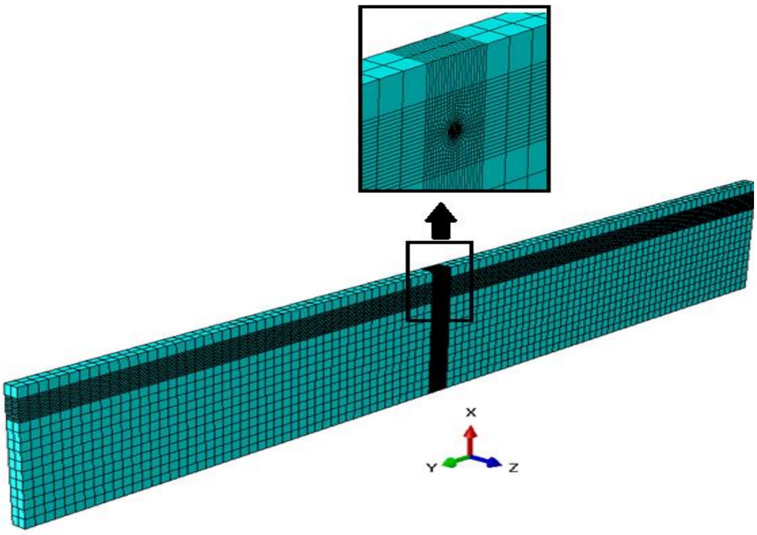


Figure 3. Mesh used for the structure.

## Results and Discussion

### Effect of Material Properties

Figure 4 shows the variation of the stress intensity factor **KI** as a function of crack size **a** for three composite materials: **Boron/epoxy**, **Glass/epoxy**, and **Graphite/epoxy**. All curves exhibit an increasing trend, indicating that **KI** rises with crack size. The **Graphite/epoxy** composite displays the highest **KI** values, which translates to lower resistance to cracking and a higher susceptibility to crack propagation. In contrast, the **Boron/epoxy** composite shows the lowest **KI** values, suggesting better fracture toughness compared to the other two materials. These results highlight the significant role of material-specific properties in fracture behavior and crack propagation resistance.

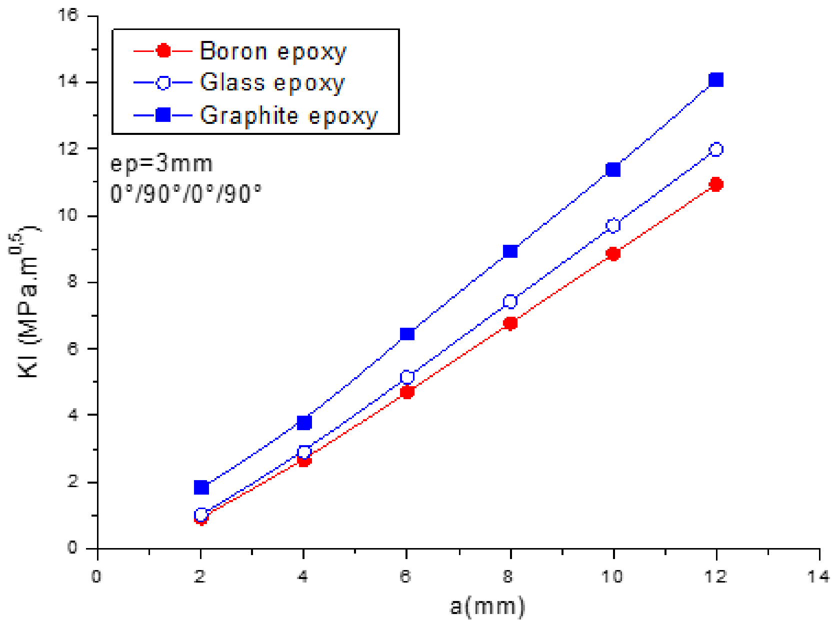


Figure 4. Variation of the stress intensity factor KI as a function of crack length aaa for three composite materials: Boron epoxy, Glass epoxy, and Graphite epoxy

**Effect of Ply Orientation**

Figure 5 illustrates the variation of the stress intensity factor **KI** as a function of crack length **a** for a Boron/epoxy composite, considering three ply orientation configurations: **[0°/90°/0°/90°]**, **[45°/0°/45°/0°]**, and **[−30°/0°/30°/0°]**, with a constant thickness of **3 mm**. The results clearly highlight the significant influence of ply orientation on the material's fracture behavior. The **[−30°/0°/30°/0°]** configuration yields the highest **KI** values, reaching approximately **19.84 MPa·m$^{0.5}$** for a **12 mm** crack, indicating reduced resistance to crack propagation. In contrast, the **[45°/0°/45°/0°]** and particularly the **[0°/90°/0°/90°]** configurations show substantially lower **KI** values, with a minimum around **10.84 MPa·m$^{0.5}$** for **a = 12 mm**, suggesting enhanced fracture toughness. These findings demonstrate the critical role of ply orientation in optimizing crack resistance in composite structures.

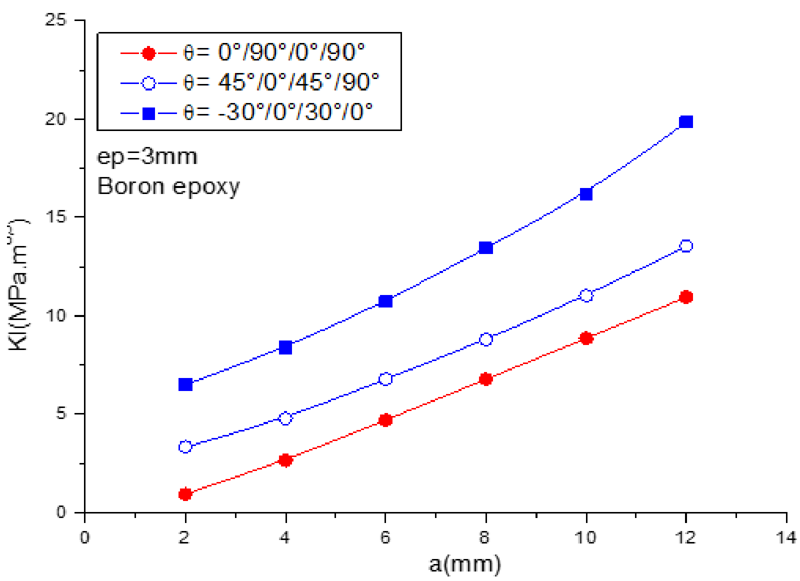


Figure 5. Variation of the stress intensity factor KI as a function of crack length (a) for three ply orientation configurations: (θ=0∘/90∘/0∘), (45∘/0∘/45∘) and (−30∘/0∘/30∘).

**Effect of Thickness**

Figure 6 depicts the variation of the stress intensity factor **KI** as a function of crack length **a** for a Boron/epoxy composite with a **[0°/90°/0°/90°]** stacking sequence, considering three different thicknesses: **1 mm**, **2 mm**, and **3 mm**. The analysis reveals a significant influence of thickness on the fracture behavior of the material. The **1 mm** thick configuration exhibits the highest **KI** values, reaching approximately **19.84 MPa·m$^{0.5}$** for a **12 mm** crack, indicating reduced resistance to crack growth and increased susceptibility to failure. In contrast, a thickness of **2 mm** yields a lower **KI** value of around **14.07 MPa·m$^{0.5}$**, suggesting a notable improvement in fracture toughness. The **3 mm** thickness shows the lowest **KI** values, approximately **10.84 MPa·m$^{0.5}$**, reflecting better crack resistance. These results clearly demonstrate that increasing ply thickness enhances the material's toughness and limits crack propagation, emphasizing the critical role of thickness in the structural design of fiber-reinforced composites under mechanical loading.

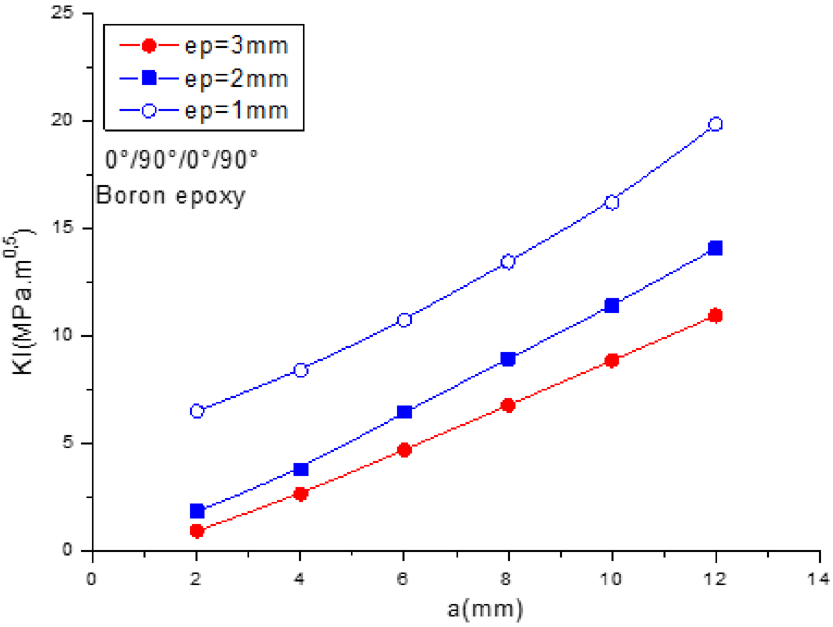


Figure 6. Variation of the stress intensity factor KI as a function of crack length (a) for three distinct thicknesses: 1 mm, 2 mm, and 3 mm

**Effect of the (L/ep) Ratio**

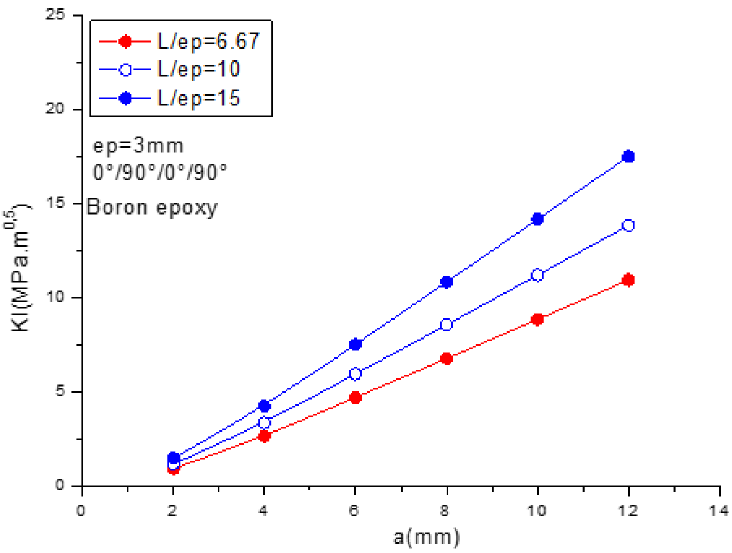


Figure 7. Variation of the stress intensity factor KI as a function of crack length (a) for three distinct length-to-thickness ratios (L/ep): 6.67, 10, and 15.

Fig.7 shows the evolution of the stress intensity factor **KI** as a function of crack length **a** for a Boron/epoxy composite laminate with a **[0°/90°/0°/90°]** stacking sequence, considering three different length-to-thickness ratios (**L/ep**): **6.67**, **10**, and **15**. The analysis highlights the significant influence of relative thickness on the crack propagation behavior of the composite. The configuration with **L/ep = 15** yields the highest **KI** values, reaching approximately **13.84 MPa·m$^{0.5}$** for a **12 mm** crack, indicating reduced resistance to crack growth and greater susceptibility to failure. In contrast, for **L/ep = 10**, **KI** increases to about **17.50 MPa·m$^{0.5}$**, suggesting enhanced fracture toughness. Finally, the case of **L/ep = 6.67** shows the lowest **KI** values, around **10.84 MPa·m$^{0.5}$**, reflecting better resistance to crack propagation. These findings emphasize the critical role of structural thickness in enhancing the mechanical performance of composite materials under fracture conditions

**Effect of Loading**

Figure 8 illustrates the variation of the stress intensity factor **KI** as a function of crack length **a** for a Boron/epoxy composite laminate with a **[0°/90°/0°/90°]** stacking sequence, subjected to two types of loading: mechanical and thermal. Under mechanical loading, **KI** reaches approximately **10.84 MPa·m$^{0.5}$** for a **12 mm** crack, indicating lower resistance to crack propagation and a higher susceptibility to failure. Conversely, under thermal loading, **KI** is reduced to around **8.47 MPa·m$^{0.5}$** for the same crack length, reflecting improved fracture toughness. This contrast highlights the significant influence of loading conditions on crack behavior. Thermal loading appears to enhance resistance to crack growth, emphasizing the importance of accounting for service conditions in the design and durability assessment of composite structures.

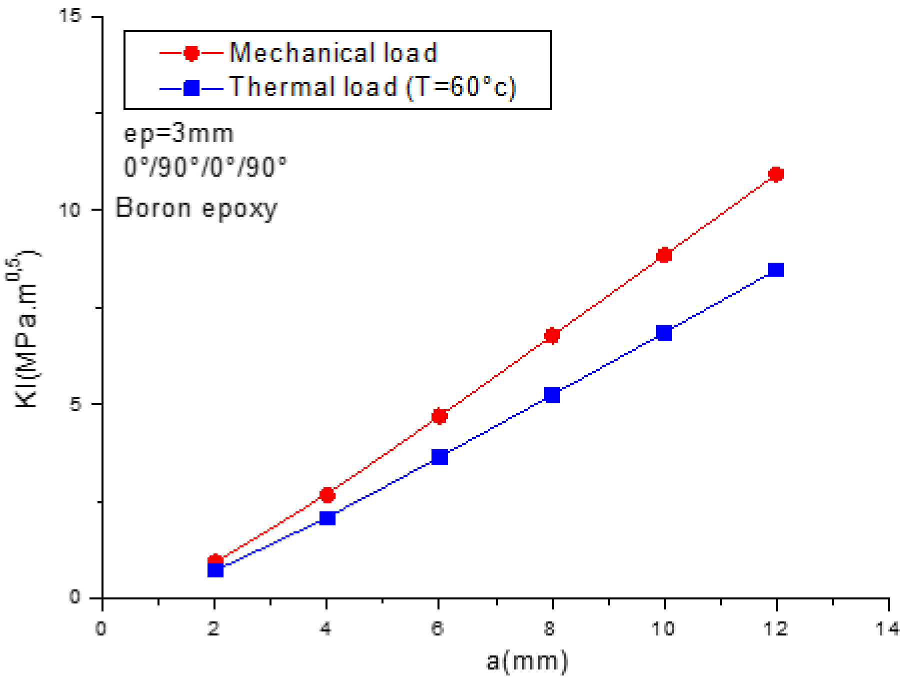


Figure 8**.** Variation of the stress intensity factor KI as a function of crack length aaa, under two types of loading: mechanical and thermal.

## Probabilistic Analysis

A cracked structure is considered, subjected to random loading, with mechanical and geometric characteristics that are also uncertain. These uncertainties are represented by a random vector **X** of **N** dimensions, whose components model the various uncertain parameters of the system, including the applied loads. The random variables considered include geometric parameters (**a**, **t**, **W**, **L**), material properties such as the elastic modulus **E**, Poisson's ratio **ʋ**, the hardening exponent **n**, and the applied stress $\sigma_{ap}$ (with $\sigma_{ap}$ **= 50 MPa**). Any or all of these variables can be statistically modeled as random variables. Consequently, any relevant fracture-related response, such as the stress intensity factor **KI**, must be evaluated in a probabilistic framework to properly account for the inherent uncertainty in the system.The probability density function (PDF) is estimated using the Monte Carlo method, which is based on random sampling of the system's input random variables. For each realization of the input random vector, the system response is computed, yielding a dataset that reflects the overall behavior. A statistical analysis of these simulated responses is then conducted to empirically estimate the distribution of the random variable. This stochastic approach provides a rigorous framework for modeling the effects of uncertainty on the system's response. To ensure statistical accuracy and reliable convergence of the results, a total of $10^5$ independent simulations was performed in the context of this numerical study. Figure 9 shows the histograms of KI(X) obtained from simulations performed using the Monte Carlo method. The probability density function (PDF) is determined by adjusting these histograms using theoretical models. It is thus clearly bserved that the Gaussian distribution provides a satisfactory approximation of the distribution of KI(X), accurately reflecting the statistical behaviour of the response. Furthermore, this adjustment provides an accurate estimate of the mean value, confirming the relevance of the approach adopted for the probabilistic evaluation of the results.

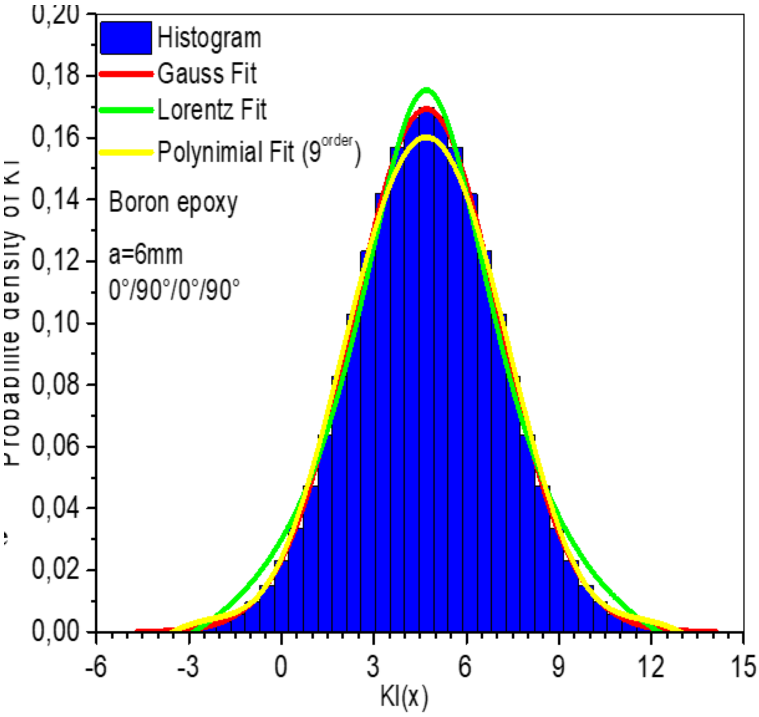


Figure 9. Histogram and probability distribution function of the stress intensity factor KI.

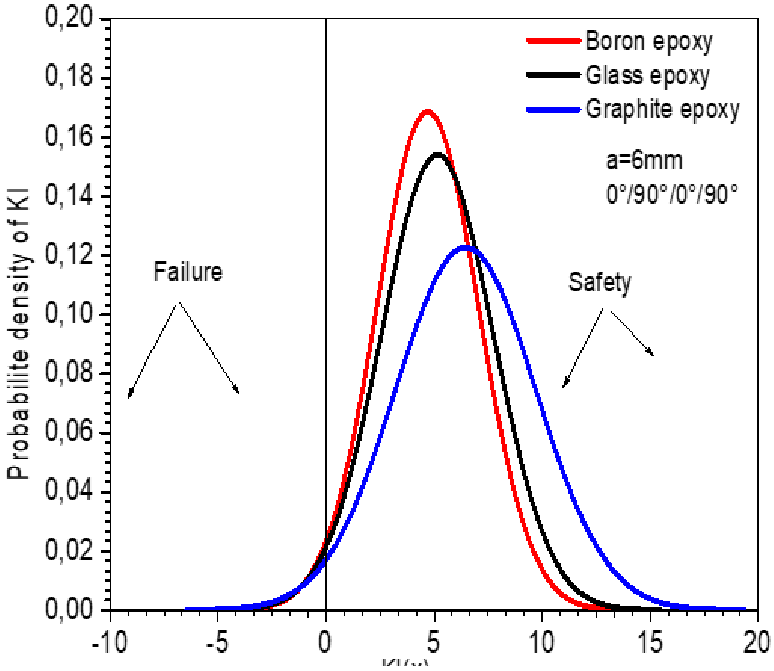


Figure 10. Probability density functions of the stress intensity factor KI for different composite materials.

Figure 10 illustrates the failure probability of the stress intensity factor (KI) for different composite materials: boron/epoxy, glass/epoxy, and graphite/epoxy. It is observed that the boron/epoxy composite exhibits a significantly lower failure probability compared to the other two materials. This improved performance is partly due to the superior mechanical properties of carbon, which provide greater resistance to crack propagation. In contrast, the glass/epoxy and graphite/epoxy materials show higher failure probabilities, indicating increased sensitivity to stress. Moreover, uncertainties related to the intrinsic properties of the materials contribute to a wider margin of error in estimating the risk of failure. Therefore, the choice of material plays a critical role in structural reliability, as the failure probability varies significantly depending on the type of composite used.

## Conclusion

The appearance of cracks and their gradual propagation constitute one of the main risks of failure in industrial structures. In order to prevent such failures, the objective of this work is to study damage to composite materials through a three-dimensional analysis based on the finite element method. To do this, several influential parameters were taken into account, including the mechanical properties of the materials, the geometric characteristics of the structure, the mechanical loading conditions, and the orientation of the composite's constituent layers. Particular attention was paid to predicting crack propagation. To this end, a probabilistic approach based on the Monte Carlo method was adopted to assess the reliability of reinforced structures. This analysis aims to better understand the impact of uncertainties inherent in material properties and loading conditions on the durability of composite structures. We conclude that:

- The **Graphite/epoxy** composite displays the highest **KI** values, which translates to lower resistance to cracking and a higher susceptibility to crack propagation. In contrast, the **Boron/epoxy** composite shows the lowest **KI** values, suggesting better fracture toughness compared to the other two materials. These results highlight the significant role of material-specific properties in fracture behavior and crack propagation resistance.
- The case of **L/ep = 6.67** shows the lowest **KI** values, around **10.84 MPa·$m^{0.5}$**, reflecting better resistance to crack propagation. These findings emphasize the critical role of structural thickness in enhancing the mechanical performance of composite materials under fracture conditions
- Under mechanical loading, **KI** reaches approximately **10.84 MPa·$m^{0.5}$** for a **12 mm** crack, indicating lower resistance to crack propagation and a higher susceptibility to failure. Conversely, under thermal loading, **KI** is reduced to around **8.47 MPa·$m^{0.5}$** for the same crack length, reflecting improved fracture toughness. This contrast highlights the significant influence of loading conditions on crack behavior. Thermal loading appears to enhance resistance to crack growth, emphasizing the importance of accounting for service conditions in the design and durability assessment of composite structures.
- The Gaussian distribution provides a satisfactory approximation of the distribution of KI(X), accurately reflecting the statistical behaviour of the response. Furthermore, this adjustment provides an accurate estimate of the mean value, confirming the relevance of the approach adopted for the probabilistic evaluation of the results.

## Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

## Conflict of Interest

* The authors declare that they have no conflicts of interest

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* Data can be accessed upon request from the corresponding author.

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## Author(s) Information

**Sid Ahmed Reffas**
LMPM, University of Sidi Bel Abbes,
Department of Mechanical Engineering,
Sidi Bel Abbes 22000, Algeria
Contact e-mail: *reffas_ahmed@yahoo.fr*

**Belaid Mechab**
LMPM, University of Sidi Bel Abbes,
Department of Mechanical Engineering,
Sidi Bel Abbes 22000, Algeria

**Mohamed Cherfi**
LMPM, University of Sidi Bel Abbes,
Department of Mechanical Engineering,
Sidi Bel Abbes 22000, Algeria

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