



RESEARCH ARTICLE

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MIXED-MODE CRACK PROPAGATION ANALYSIS IN ORTHOTROPIC PLATES WITH CENTRAL AND HOLE-EDGE CRACKS UNDER TENSILE LOADING

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ARTICLE INFO

Article History

Received: March 16, 2026

Reviewed: April 16, 2026

Accepted: May 15, 2026

Published: September 30, 2026

Keywords:

Orthotropic Materials,
Crack Propagation,
Tension,
Crack Orientation,
Stress Intensity Factor.

ABSTRACT

The inhomogeneity and anisotropy in orthotropic bodies make their analysis and damage mechanisms more important and complex. To simplify the analysis and facilitate numerical implementation, we assume that the material is homogeneous. This assumption allows us to use classical analytical models while maintaining a consistent representation of the overall mechanical behavior. The aim of this work is to analyse crack propagation in orthotropic materials under tensile stress. Two configurations are studied: the first is a central crack of length (2a), and the second is two cracks of length (a) at the ends of a hole in the center of the plate. Two main factors were considered: the size of the crack and the orientation of the crack. The results made it possible to define the cracking mode (MODE I, II or III) and to calculate the values of the stress intensity factors corresponding to each mode. It was found that the orientation of the crack causes a shear failure mode and that the stress concentration generated by the hole in the plate accelerates crack propagation.



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I. INTRODUCTION

The study of crack propagation in orthotropic composite materials is of paramount importance for ensuring the reliability of aeronautical, aerospace and civil engineering structures. These materials, whose mechanical properties vary depending on the direction, are even more complex when there are geometric discontinuities such as fixing or lightening holes, which cause stress concentrations that can start and guide crack propagation, compromising structural integrity. Much research has focused on crack behavior in the vicinity of holes. For example, Brighenti [1-3] used numerical and analytical methods to study this phenomenon in isotropic plates, examining the influence of mechanical and geometric variables such as Poisson's ratio, boundary conditions, crack length and initiation angle. His results showed that each of these parameters significantly affects the buckling load. Furthermore, the stress concentration factor (SCF), established as a reliable prediction parameter by M.P. Savruk [4], provides a better understanding of the mechanisms of stress concentration and crack propagation in orthotropic plates with holes, thus facilitating a more accurate prediction of failure and optimisation of the design of anisotropic structures under severe stresses. However, as pointed out by Whitney and Nuismer [5], the direct application of these concepts to orthotropic composite laminates can lead to inconsistencies, notably the "hole size effect". This phenomenon highlights the need to consider an average stress field over a characteristic area, rather than the point stress value at the end of the crack or hole. Work such as that of Ahmed Bougueroua and Hamoudi Bouzard [6] allows for accurate analysis of crack propagation and the associated plastic zone in composite and multilayer materials, contributing to better prediction of fracture behavior under different loading modes. At the same time, several studies have focused on characterizing the specific behavior of carbon/epoxy composites. Guo and Sun [7] have shown that dynamic mode I fracture toughness remains comparable to static toughness even at high propagation speeds, which is crucial information for predicting damage under dynamic loads. Hwang and al [8] demonstrated the significant influence of crack propagation direction and interface layer orientation on interlaminar toughness, paving the way for the optimisation of stacking sequences.

The generalisation of fracture mechanics concepts to anisotropic materials was formalised by Sih, Paris and Irwin [9], who established that stress fields in the vicinity of a crack always exhibit a singularity in $r^{-1/2}$ and that stress intensity factors can be defined in a manner analogous to the isotropic case. At the microscopic scale, work such as that of Yujia and al [10] have elucidated, via in situ SEM observations, that the final failure of unidirectional composites results from the connection of a multitude of fiber cracks via the matrix or interfaces, a process dictated by the thickness of the matrix layer between the fibers and the random distribution of their strength. Studies on fatigue behavior have also made major contributions. Jelić and al [11] and Putić and al [12] characterised the decisive influence of fiber orientation and interlaminar shear stresses on fatigue strength and crack propagation rate in $0^\circ/90^\circ$ and $\pm 45^\circ$ oriented laminates. More recently, Michel and al [13] developed and validated data reduction methodologies, such as the Hartman-Schijve and simple scaling approaches, to reproducibly determine worst-case crack growth curves and critical fatigue thresholds, which are essential for the design and certification of aeronautical structures according to a damage tolerance philosophy. In this context, this study focuses specifically on a little-explored problem: the simultaneous propagation of a crack at the edge of a hole and a central crack in an orthotropic carbon/epoxy plate. However, this configuration is critical in many engineering applications. Our objective is to characterize the stress intensity factor (SIF) for each fracture mode, taking into account the anisotropy of the material and the disturbance of the stress field induced by the hole. To do this, we use advanced numerical methods, including finite element simulations to validate our models. The results obtained aim to improve the criteria for predicting crack propagation and to propose recommendations for the design of perforated composite structures subjected to tensile stresses.

II. GEOMETRIC MODEL

The model studied consists of a rectangular plate measuring 100 mm (length) by 50 mm (width) by 2 mm (thickness). The study examines two geometric configurations. The first configuration consists of a plate with a central hole, at the periphery of which two diametrically opposed longitudinal cracks are initiated. Each of these cracks has a length of a . The second configuration involves a plate without a hole, but containing a single central crack, also with a length of $2a$ (see Figure 1).

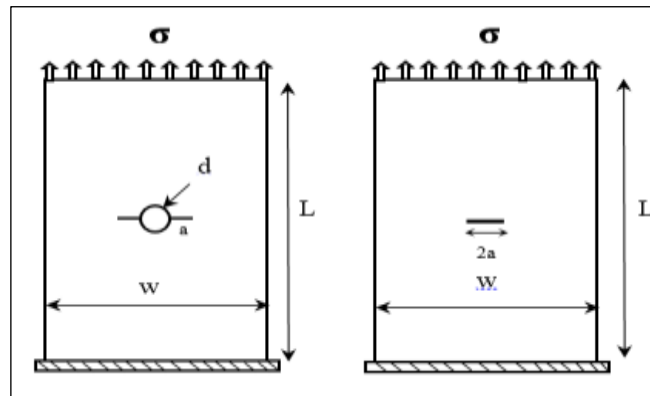


Figure 1: The geometry of the two plates.

Source: Authors, (2026).

The calculations are based on the properties of the material "carbon/epoxy 230GPa", whose homogeneous mechanical characteristics are listed in table 1.

Table 1: Material characteristics.

E_1 GPa	$E_2=E_3$ GPa	$\nu_{12}=\nu_{13}$	ν_{23}	$G_{12}=G_{13}$ GPa	G_{23} GPa	ρ kg/m ³
121	8.6	0.27	0.4	4.7	3.1	1490

Source: Authors, (2026).

Under a tensile force of 50 MPa, the ends of the plate move only along the perpendicular axes. The stress intensity factors (SIF) K_I and K_{II} are calculated numerically by ANSYS Mechanical using the stress and displacement field obtained by finite elements. The underlying theoretical expressions are presented below for the two configurations studied. For the central crack, the SIFs in modes I and II are given respectively by:

$$K_I = \sigma^\infty \cos^2 \beta \sqrt{\pi a} \quad (1)$$

$$K_{II} = \sigma^\infty \sin \beta \cos \beta \sqrt{\pi a} \quad (2)$$

For diametrically opposed cracks in a uniformly loaded medium, the FICs in modes I and II are given by:

$$K_I = \alpha \sigma^\infty \cos^2 \beta \sqrt{\pi a} \quad (3)$$

$$K_{II} = \alpha \sigma^\infty \sin \beta \cos \beta \sqrt{\pi a} \quad (4)$$

Grant's formula [14]

With

$$\alpha(a/r) = \frac{0.6866}{0.2772 + \frac{a}{r}} + 0.9439$$

β is the angle of inclination of the crack.

a is the length of the crack.

To validate our modelling approach, a comparison was made with the results published in the study by [K. Madani, S. Touzain, X. Feaugas, M. Benguediab, M. Ratwani]. [15]. The results obtained (see Figure 2 and Table 2) show very satisfactory agreement with those of the reference model, with a relative error of less than 2.7%, thus confirming the reliability and accuracy of our simulation methodology.

Table 2: Validation of the model by relative error (%).

a (mm)	K _I hole+crack (our result) MPa (m) ^{1/2}	K _I hole+crack [15] MPa (m) ^{1/2}	Error %	K _I central crack (our result) MPa (m) ^{1/2}	K _I central crack [15] MPa (m) ^{1/2}	Error %
1,5	16,357	16,8079	2,68	5,089	5,17	1,57
2,5	19,012	19,2243	1,1	6,6386	6,7	0,92
3,9	21,666	21,4618	0,95	8,3	8,5	2,35
5	23,881	23,6993	0,77	9,609	9,8	1,95
6,3	26,592	26,0263	2,17	10,952	11,0153	0,57
7,5	29,299	28,8007	1,73	12,152	11,9724	1,5
8,9	33,18	32,6492	1,63	13,5667	13,408	1,18
10	37,175	37,3031	0,34	14,74	14,8436	0,7
11,5	44,498	44,1945	0,69	16,375	16,3988	0,15

Source: Authors, (2026).

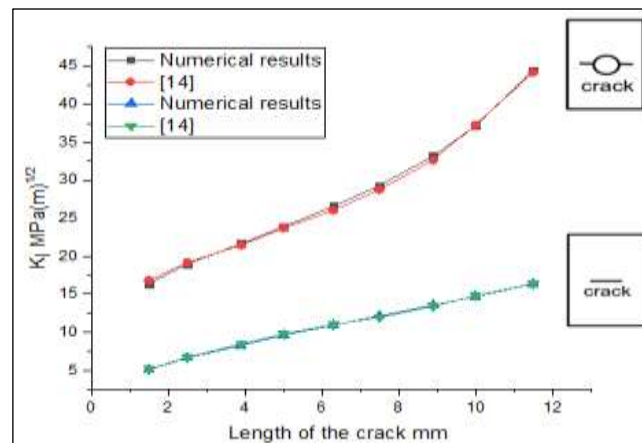


Figure 2: Variation curve of FIC (stress intensity factors) as a function of crack length.

Source: Authors, (2026).

III. RESULTS AND DISCUSSIONS

III.1 CRACK PROPAGATION PATH

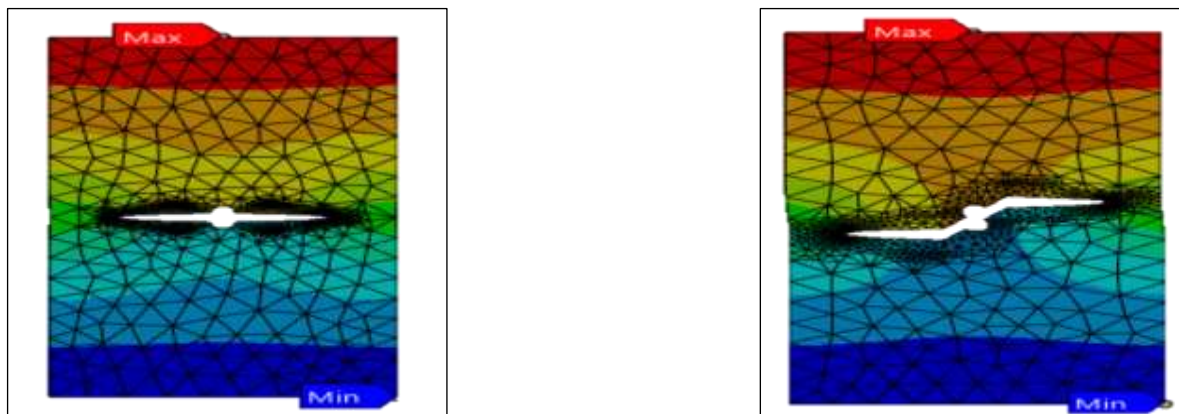


Figure 3: Crack propagation path at the edge of the hole at orientations of 0° and 45°.

Source: Authors, (2026).

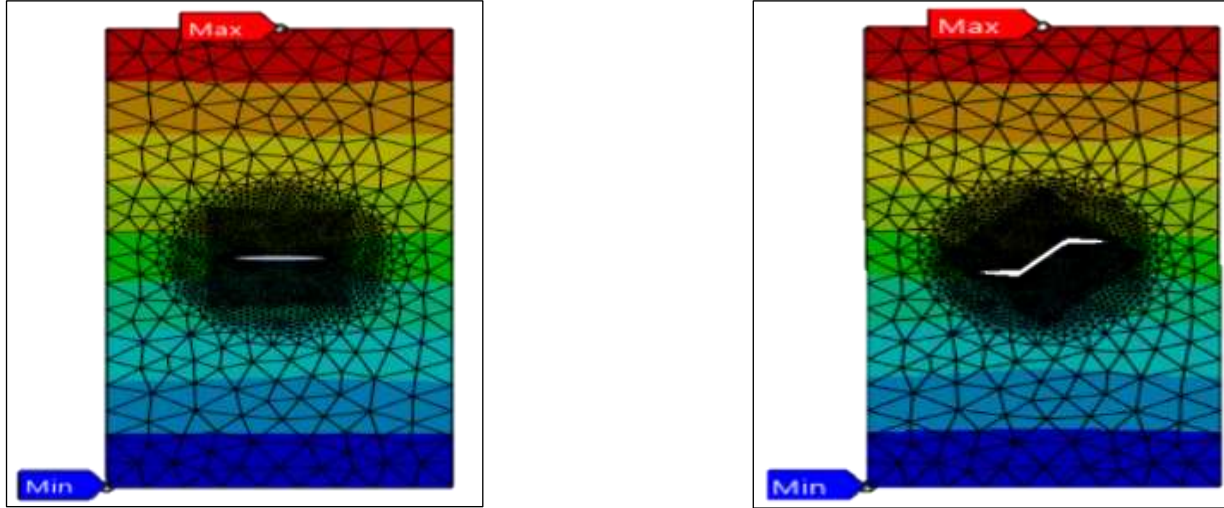


Figure 4: Crack propagation path at the center at orientations of 0° and 45° .
Source: Authors, (2026).

When examining Figures 3 and 4, it can be seen that the crack propagates in a direction perpendicular to the applied tensile stress. The shear mode is more clearly visible in the crack located at the edges of the hole, at an angle of 45° .

III.2 STRESS INTENSITY FACTOR

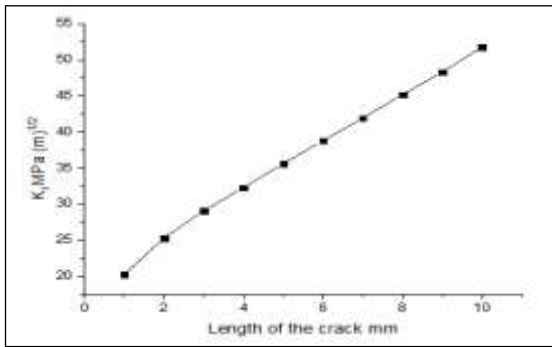


Figure 5: Variation in stress intensity factor as a function of crack length.
Source: Authors, (2026).

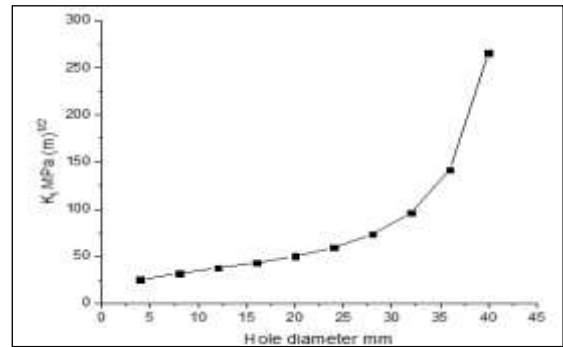
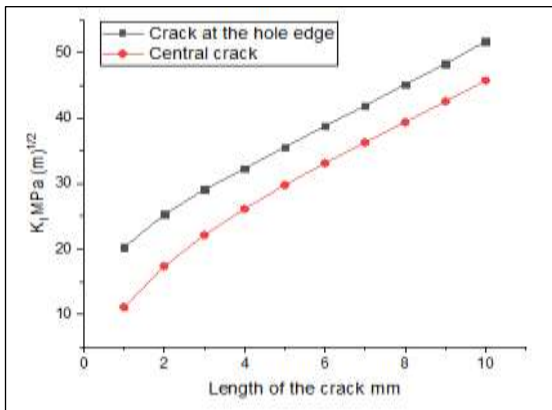
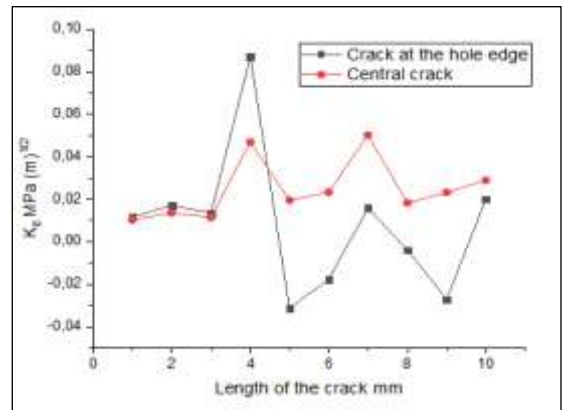


Figure 6: Variation in stress intensity factor as a function of hole diameter.
Source: Authors, (2026).

Figures 5 and 6 examine two different configurations of a plate with a circular hole cracked at both ends. In the first configuration, the hole diameter was set at 4 mm and the crack length was varied, whereas in the second configuration, the crack length was set at 2 mm and the hole diameter was varied. It can be seen that the FIC values increase proportionally to the increase in crack length and hole diameter. It can also be seen that the two configurations give very similar FIC results if the sum of the lengths of the two cracks and the diameter of the circle is the same in both cases.



(a)



(b)

Figure 7: Variation of the FIC in mode I (a) and mode II (b) as a function of crack length at 0° .
Source: Authors, (2026).

In figure (a), we observe that the FIC values in mode I increase with the increase in crack length. We also observe that the FIC values in mode I are higher in the plate containing a cracked hole compared to the one with only a central crack. This is due to the stress concentration caused by the hole. Figure (b) shows the variation of the stress intensity factor in mode II as a function of crack length for an orientation of 0° . The results show that, for the central crack, the K_{II} values remain very low and close to zero over all the lengths studied. This behavior reflects a symmetry in the stress field around the central crack, which greatly limits the appearance of a shear component when the crack is oriented at 0° . However, for the crack located at the edge of the hole, K_{II} shows significant variations, with both positive and negative values depending on the length of the crack. This instability of mode II is attributed to the disturbance of the stress field induced by the presence of the hole, which breaks the symmetry of the problem and generates local shear stresses, even when the orientation of the crack theoretically favors mode I.

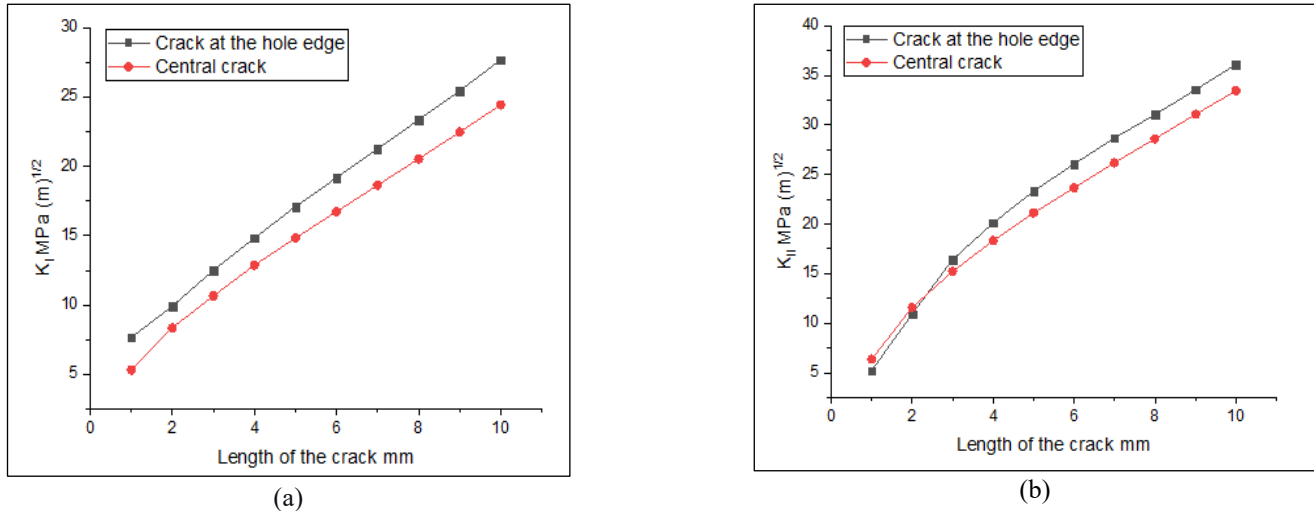


Figure 8: Variation of the FIC in mode I (a) and mode II (b) as a function of crack length at 45° .
Source: Authors, (2026).

It can be seen that the FIC values in mode I are reduced compared to the 0° orientation, unlike the FIC values in mode II, which increase with increasing crack length. This indicates the presence of two modes: opening (mode I) and shear (mode II).

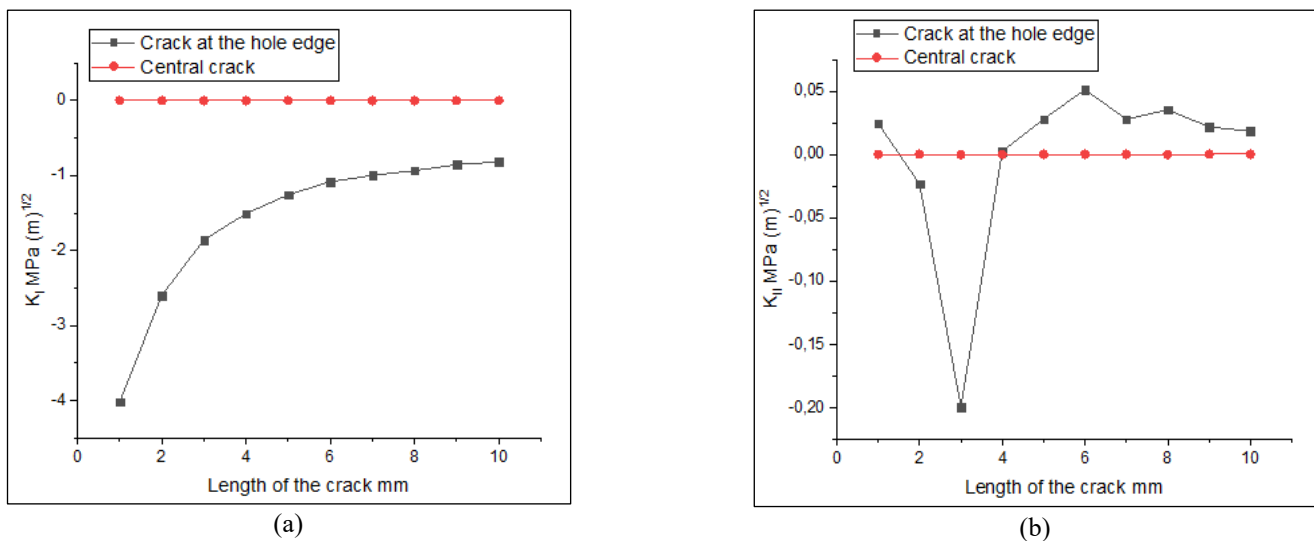
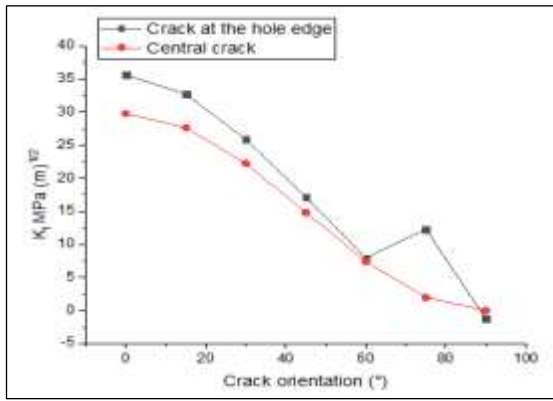
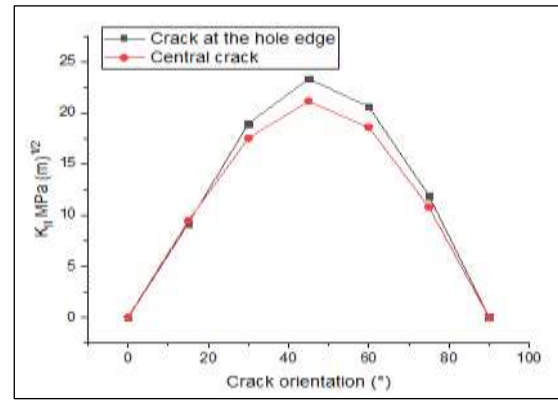


Figure 9: Variation in FIC in mode I (a) and mode II (b) as a function of crack length at 90° .
Source: Authors, (2026).

At an orientation of 90° , the FIC values in modes I and II for a central crack tend towards 0. Similarly, the FIC values in mode I in the case of the crack located at the edge of the hole increase, but with negative values until they reach zero. Figure (b) shows the evolution of K_{II} for a crack orientation at 90° , a configuration in which mode II is mechanically favored. For the central crack, the K_{II} values remain virtually zero and stable regardless of the crack length. This result confirms that, despite the 90° orientation, the geometric symmetry of the system prevents the development of significant shear at the crack tip. Conversely, the crack initiated at the edge of the hole has strongly negative K_{II} values, with a marked minimum for an intermediate crack length. This evolution reflects a clear dominance of mode II, resulting from the interaction between the crack and the stress field, which is strongly disturbed by the hole.



(a)



(b)

Figure 10: Variation of the FIC in mode I (a) and mode II (b) as a function of the crack orientation.

Source: Authors, (2026).

It can be seen that the FIC values in mode I decrease as the crack angle increases, whereas the FIC values in mode II increase gradually as the crack angle increases, reaching a maximum value at 45°, then gradually decrease to reach 0 at an orientation of 90°.

IV. CONCLUSIONS

This study was conducted to determine crack propagation at hole edges. The results allow us to draw the following conclusions. The crack propagation path is perpendicular to the applied tensile stress. Under tensile loading, the stress concentration generated by the hole in the plate accelerates crack propagation. The SIF has equal values for configurations where the sum (crack length + diameter) is identical. The longer the crack, the higher the stress intensity factor (SIF), and therefore the faster the crack propagates. The orientation of the crack causes a shear failure mode. For an orientation of 0°, mode II remains secondary, but can become locally significant in the presence of a geometric discontinuity such as a hole. The significant decrease in K_{II} indicates an intensification of shear near the crack tip, which can accelerate propagation through a sliding mechanism.

V. AUTHOR'S CONTRIBUTION

Conceptualization: Lina Saifi and Zohra Labed.

Methodology: Lina Saifi and Zohra Labed.

Investigation: Lina Saifi and Zohra Labed.

Discussion of results: Lina Saifi and Zohra Labed.

Writing – Original Draft: Lina Saifi and Zohra Labed.

Writing – Review and Editing: Lina Saifi and Zohra Labed.

Resources: Lina Saifi and Zohra Labed.

Supervision: Lina Saifi and Zohra Labed.

Approval of the final text: Lina Saifi and Zohra Labed.

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