

Finite Element Analysis and J-integral of Repair Using Isotropic Bonded Patches on a Cracked Perforated Plate in an Aircraft Wing

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Abstract. Geometric discontinuities and microstructural defects can generate localized stress concentrations and promote crack propagation in aeronautical structures. This study numerically and analytically investigates the mechanical behavior of an isotropic cracked aluminum plate containing a central circular hole, with particular emphasis on the effectiveness of bonded isotropic patch repair. A finite element model was developed in ABAQUS to evaluate the stress intensity factor (SIF) and J-integral for cracked perforated plates subjected to uniaxial tensile loading. The numerical results were compared with analytical solutions for different crack lengths and diameter-to-width ratios (d/W), providing a validation of the finite element model. The results show that the bonded patch reduces the stress intensity factor by approximately $35\% \pm 2\%$ and the J-integral by approximately 40% compared with the unrepaired configuration, demonstrating its effectiveness in reducing stress concentration near the crack tip. The analysis also shows that increasing the crack length and the d/W ratio leads to higher SIF and J-integral values, while the effectiveness of the patch decreases for larger hole-to-plate width ratios. These findings demonstrate the potential of bonded isotropic patches as a local repair technique for damaged aeronautical structures and highlight the importance of accounting for crack geometry and structural discontinuities in repair design. The conclusions are based exclusively on analytical and numerical analyses under linear elastic isotropic assumptions and should therefore be further investigated for fatigue loading, composite materials, and more complex service conditions.

Keywords: patch; FEM; sif; j-integral; hole plate; crack.

Introduction

In the regulation of aeronautical structural mechanics, the durability and safety of aircraft structural components are of paramount importance because the elements are subjected to repeated aerodynamic and structural loads. This is particularly true for the thin metal skin of the aircraft, which provides resistance to mechanical loads, where each takeoff and landing phase causes repeated cycles of stress, leading to progressive fatigue, damaging and weakening the structure. Cracks formed in damaged structures are therefore a constant concern for maintenance managers, as they can jeopardize operational safety and lead to a deterioration in the service life of critical components. The mechanical behavior of fractured structures fixed using bonded patches is investigated in this work, a method used in the aerospace industry to reduce stress and restore mechanical strength. The stress intensity factor (SIF) is the only metric utilized to answer this issue by specifying the stress field around the fracture tip. It is also used alongside the J-term to calculate the propagation and stability of fractures in elastic substances. As a result, the FEM (Finite Element approach) reference refers to the finite element method for modeling the mechanical behavior of damaged and restored structures.

To date, several studies have explored different modeling methods for predicting crack propagation and evaluating associated parameters. In one such study, Souiyah et al. [1] used the finite element approach to forecast crack propagation directions and assess SIFs, and the results have been confirmed using analytical and numerical data. The key variable at the heart of this work is the stress intensity factor (SIF). This can be described by displacement, tension, Strain occurs in the near field of a crack in a linear elastic solid [2]. Many other researchers have studied different quantities such as the evaluation the J-integral by [3,4] and the energy release rate (or energy release ratio) according to [3,5] or the concentration factor calculated by [3,6,7]. Each offers a complementary angle to provide insights into crack behavior. For their part, Fekih et al. [8] examined the impact of patch shape on durability and dependability of the repair and showed that star-shaped patches are the most effective at reducing the J-integral.

Several studies have examined the influence of bonded patches on the fracture behavior and durability of cracked metal structures. Mahadesh Kumar et al. [9] compared four different patch geometries square, rectangular, circular, and elliptical and demonstrated that the rectangular geometry, with its maximum length parallel to the crack, resulted in the greatest reduction in the crack intensity factor (SIF). The authors also suggested modifying the patch design by extending the reinforcement zone, proposing an angled patch that saves 28% of material for a given SIF value, or reduces the SIF by 10% for a given amount of material. Furthermore, El-Sagheer et al. [10] studied the effectiveness of glass-fiber-reinforced polymer (GFRP) composite patches for repairing inclined cracks, while Baghdadi Mohammed et al. [11] used a finite element method to investigate the effect of the composite patch's shape on repair performance. Finally, Safa Chahrazad Djebbar et al. [12] evaluated the influence of patch geometry on the material's

overall reactivity in a 2024-T3 aluminum structure with a central circular notch. Despite these advances, research dedicated to cross-validation between analytical and numerical solutions remains limited, even though such an approach is essential for evaluating the reliability of finite element models and for drawing more comprehensive conclusions regarding the failure behavior of complex aerospace structures, such as wing ribs or spars.

We want to address this gap by applying the finite element technique (FEM) to investigate the factors that impact the intensity of stresses around the margins of holes in isotropic rectangular plates., with and without patches, while comparing the numerical results with those obtained analytically. The main research questions are as follows: QR1—How does the aspect ratio (d/W) influence the distribution of SIF and the J-integral? QR2—To what extent does the presence of a bonded patch reduce these critical parameters? QR3—How well do the FEM results agree with the analytical solutions under identical loading conditions?

In this regard, this article contributes in three ways: (i) It offers a thorough comparison of the stress intensity factor and the J-integral in analytical and numerical models., (ii) it offers a parametric analysis of the effects of d/W on stress reduction, and finally, (iii) it methodically validates the suitability of FEM for modeling cracked and repaired aeronautical structures. While Section 2 provides information on the methodology and geometric models, Section 3 explains the analytical and numerical results, and Section 4 discusses the practical implications, limitations, and prospects of this study.

1. Methodology and geometric models

The geometrical discontinuity in the rib of an aircraft wing provides a concentration of loads and destroys structures, which causes cracks to occur. To explore the stress intensity factor and J-integral surrounding an aircraft wing using the finite element method, we considered an isotropic rectangular perforated plate (aluminum alloy) as a test piece. The cracking effect on the perforated plate generates stress intensity factors in the presence of the hole, which are then used to obtain the various parameters. For our research, we used isotropic plates of limited width w with a hole removed from a wing rib. The plate's dimensions are 100 mm long, 50 mm wide, and 1 mm thick. The panel has a [2-10] mm fracture near the margin of the hole. The panel was exposed to 1 MPa of unidirectional tensile force. This was accomplished by increasing the diameter-width ratio (d/W) from 0.05 to 0.3.

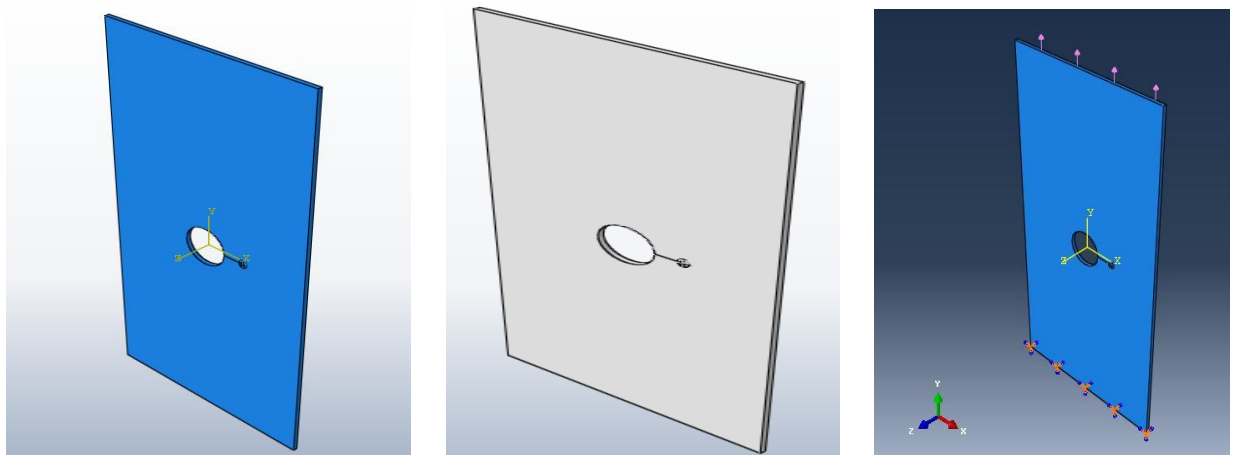


Fig. 1. - Geometric models of a perforated plate with a crack on the edge without a patch

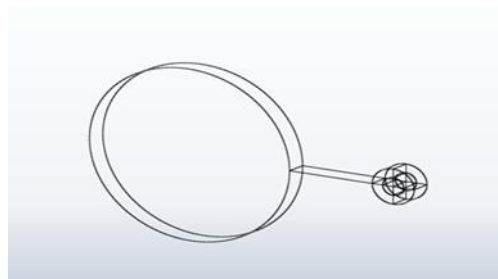


Fig. 2. - Geometric model of a perforated circular plate with an edge crack

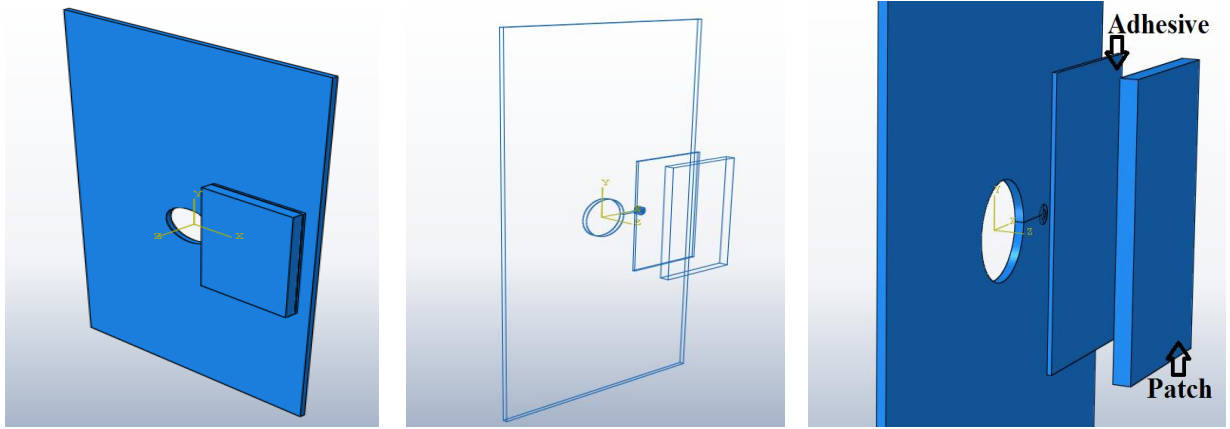


Fig. 3. - Geometric models of a perforated plate with a crack on the edge with patch.

For an isotropic material exhibiting linear elastic behavior, the stress field around a crack in a linear elastic body is described by the stress intensity factor (SIF). The SIF depends on the crack's type, loading level, and geometry. According reference [13], this parameter can be determined for a crack that originates from a hole in an infinite body:

$$K_I = f\left(\frac{a}{r}\right) \sigma \sqrt{\pi a} \quad (1)$$

where σ - stress (MPa)
 a - crack length (mm)
 f - Geometric correction factor
 K_I - $\text{MPa}\sqrt{\text{mm}}$

It is generally known that in mechanics of linear elastic fracture, the rate of energy restitution J is equal to the integral J 's value and has the following connection with the stress intensity factor K_I :

$$K_I = \sqrt{J E'} \quad (2)$$

$$J = \frac{K_I^2}{E'} \quad (3)$$

With:

$$E' = \frac{E}{1-\mu^2} \quad (4)$$

where E - modulus of elasticity MPa
 μ - Poisson's ratio
 K_I - $\text{MPa}\sqrt{\text{mm}}$
 J - MPa. mm

The normalized stress intensity factor (SIF) and normalized J-integral vary, as determined by the ratio of the repaired structure's SIF and J-integral to those of the unrepaired structure along the crack face. The normalized J-integral is computed using the following equation :

$$K_{I \text{ normalized}} = \frac{K_{I \text{ Patch}}}{K_{I \text{ not Patch}}} \quad (5)$$

$$J_{\text{normalised}} = \frac{J_{\text{Patch}}}{J_{\text{not Patch}}} \quad (6)$$

2. Materials

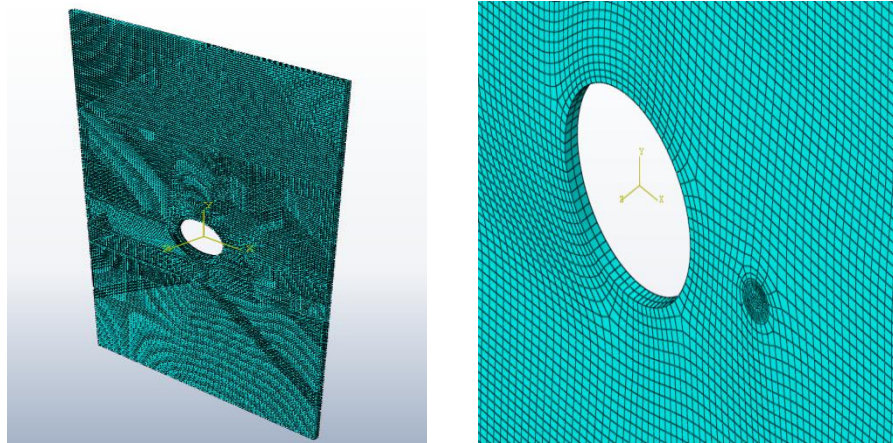
The aluminum alloy has a Poisson's ratio of 0.33 and a Young's modulus of 68.8 GPa. The patch, whose mechanical properties are listed in Table 1, measures 30 mm in height, 20 mm in width, and 5 mm in thickness. It is fully bonded to the damaged area with Glue FM 73 adhesive. The adhesive has a Poisson's ratio of 0.33 and a coefficient of elasticity of 1.83 GPa. The adhesive is 30 mm high, 20 mm wide, and 0.3 mm thick.

Table 1. Mechanical properties [14,15].

Material	Plate with hole	Patch	Adhesive
Young's modulus (MPa)	68800	68000	1830
Poisson's ratio	0.3	0.3	0.33

3. Finite element modelling

In numerical calculations that use finite elements, selecting the right mesh is crucial for achieving a convergent solution with dependable results. The precision of these calculations is closely tied to the quality of the mesh. The stress intensity and J-integral factors for isotropic plates with circular holes were calculated using the finite element method. These results were checked against analytical equations to confirm their accuracy. In the second part of the study, the impact of patch effects on stress intensity factors and J-integrals was analyzed, both with and without the presence of a patch. Additionally, work conducted using the finite element method through ABAQUS software [16] was used to compare numerical results with analytical ones. It is known that areas with geometric irregularities near a cut have high stress gradients, so the mesh in these regions is made finer and small elements are used. Since the mesh is key to determining stress values or stress intensity factors, these values depend on the element type, the number of elements, and the boundary conditions. Figure 4 illustrates the mesh used. The 'C3D20R' element, which has 20 nodes, was selected because rectangular hexagonal elements are effective for computing stress intensity factors. The mesh is rectangular, generated by ABAQUS, and it is refined around the holes to reach a stable maximum stress value. Table 2 clearly shows the numerical validation of the stress intensity factor comparing the analytical method with different element types. The results indicate that the Hex mesh type provides better outcomes than other mesh types. To assess the speed of mesh convergence, the number of elements was varied (Table 3). The results for a medium and affine mesh were better than those for a standard mesh. This suggests that computation time is an important factor, and that as the number of elements increases, the stress intensity factor values decrease, with convergence achieved when the number of finite elements reaches 35268. This mesh setup provides satisfactory results and will be used in further examples.

**Fig. 4.** - Finite element mesh of the perforated plate with an edge crack.**Table 2.** Validation of calculations with mesh type

crack length mm	Stress intensity factors (analytic) MPa.mm ^{1/2}	Stress intensity factors (FEM) MPa.mm ^{1/2}		
		Element Shape	Hex	Hex-dominated
		Mesh type	C3D20R	C3D20R
2	6.0913		6.071	6.231
4	6.9205		6.926	6.992
5	7.1958		7.196	7.262
7	7.7939		7.777	7.849
9	8.5768		8.543	8.622
10	9.061		9.043	9.125

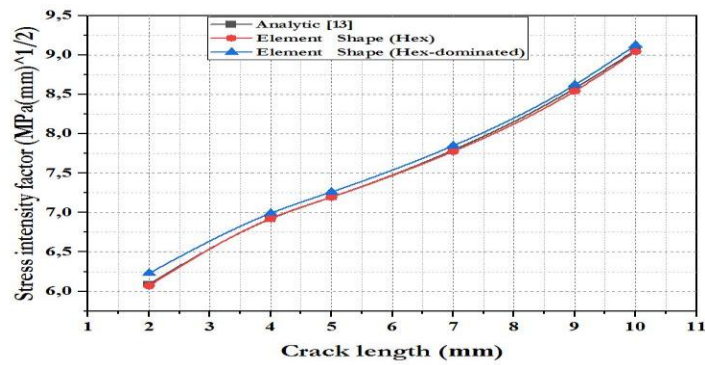


Fig. 5. - Analytical digital validation and mesh type

Table 3. Number of finite elements and type of element.

Element Shape	Mesh type	Number of nodes	Elements Number	Stress intensity factors (FEM)
Hex	C3D20R			
Normal mesh		69186	9698	7.615
Medium mesh		127604	22792	7.194
Refined mesh		196758	35268	7.196

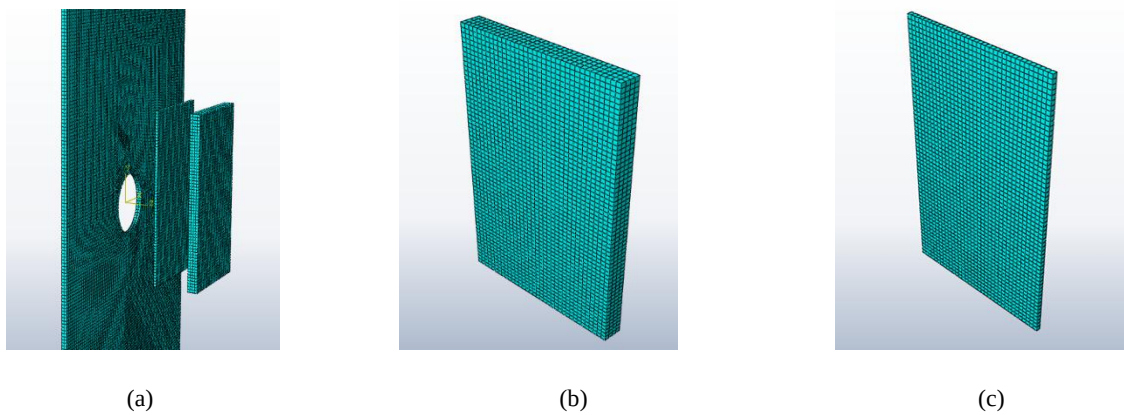
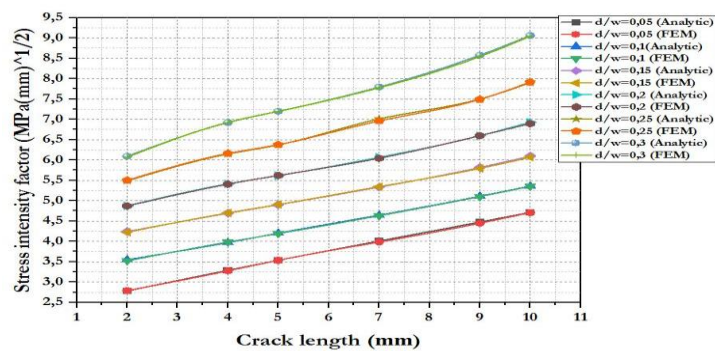


Fig. 6. - (a) Cracked plate (b) Patch (c) Adhesive

4. Results and discussion

4.1 Analysis of the stress intensity factor at the edge of a hole in a rectangular plate

Fig. 7. - Analytical stress intensity factor and FEM as a function of crack width and d/w

We compared and presented the results from analytical methods and finite element method (FEM) regarding the stress intensity factor in a plate with a hole under tension, while applying specific boundary conditions. The results show that the stress intensity factor increases with fracture length, which aligns with the typical mechanical behavior observed in such scenarios. since a longer crack generates greater stress concentration at its tip, favoring crack propagation. Similarly, a higher d/W ratio, indicating a more centered crack, generates a higher stress intensity. The comparative graph between K_I values from analytical calculations and those obtained from FEM simulation (for three crack lengths: 2, 5 and 10 mm, and three d/W ratios: 0.05, 0.2 and 0.3) confirms these trends. Both approaches show good overall agreement, despite some deviations at the highest d/W values and for large cracks, where FEM provides slightly higher results. These differences are attributable to the simplifying assumptions of analytical methods (ideal geometry). This analysis therefore confirms the reliability of numerical simulations, which not only prove to be consistent with analytical results, but also more relevant in the precise modeling of the various fracture mechanics problems involved (complex configurations, uniform loading), while FEM enables geometric effects and real stress distributions to be better integrated.

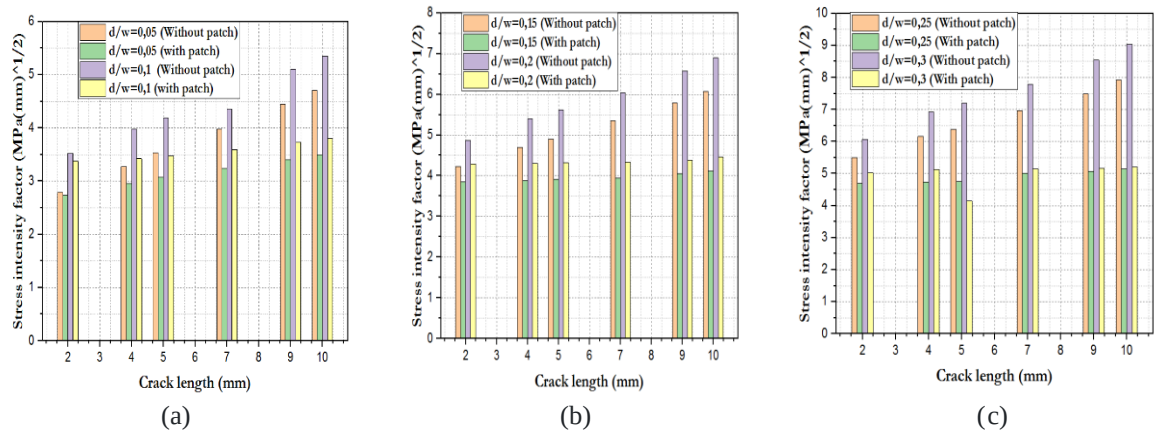


Fig. 8. - Variation du facteur d'intensité de contrainte analytique avec et sans patch en fonction de la longueur de la fissure et du rapport d/w

The findings indicate that the unrepaired plate experiences very high mechanical stresses, especially at the crack tip, while the patch significantly lowers these stresses. This occurs because the patch has an isotropic, absorbing, and dissipative property that helps spread out the stress concentration, thereby reducing the rate at which the crack spreads over time. Figures (8a), (8b) and (8c) provide an illustration of this, since for d/W values in the ranges [0.05-0.1], [0.15-0.2] and [0.25-0.3] respectively, the K_I factor remaining below 4, 4.5 and 5.5 $\text{MPa}(\text{mm})^{1/2}$ respectively, replaces 5, 6.5 and 9 $\text{MPa}(\text{mm})^{1/2}$ in the case of plate repair, the latter being subject to the same d/W ratio. These results clearly demonstrate, on the one hand, the patch's overall favorable impact, and on the other, the increasingly preponderant d/W ratio: the higher the ratio, the greater the stress concentration, particularly for long cracks. Thus, the highest K_I peaks are reached at $d/W = 0.25$ and 0.30 , reflecting the fact that large openings are more prone to fracture. However, it is in these critical cases that the patch plays its role most effectively, enabling K_I to be significantly reduced. In conclusion, this analysis shows the importance of controlling geometric parameters (hole size, crack length) and using local reinforcements such as isotropic patches to limit stress concentrations and improve the durability of cracked structures.

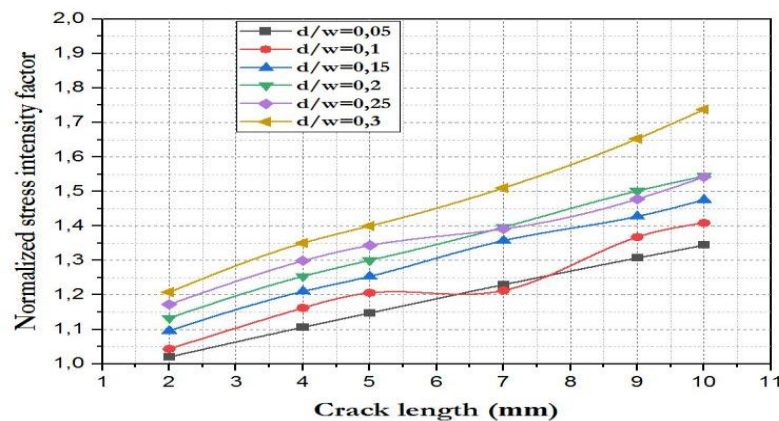


Fig. 9. - Variation of normalized stress intensity factor as a function of crack length and d/w

Based on results for cracked, repaired, and unrepaired hole plates, the study aims to analyze the variation of the normalized stress intensity factor as a function of diameter/width ratio (d/W) and crack length. It is evident that the normalized intensity factor significantly decreases for repaired plates, reaching a maximum value of less than 1.75, indicating greater resistance to crack spall propagation than for unrepaired, cracked plates, and thus establishing the validity and reliability of a finite element model. This can be seen in the representative graph, which highlights the combined effect of geometry and cracking on stress concentration: for all the configurations considered in this study, the value of the intensity factor increases progressively with increasing crack length, in line with fracture mechanics. Nevertheless, this growth becomes significantly more significant when the d/W ratio is at its highest, testifying to the heightened vulnerability of open structures with large openings. Thus, plates with a low $d/W=0.05$ ratio are subject to the lowest values presented for the factor, while the most critical are found with $d/W = 0.3$, particularly for long cracks where normalization goes beyond 1.8. This form of curve hierarchy is a reminder of the very strong interaction between geometry and cracking: the larger the hole, the more it favours the effects of stress concentrations generated around cracks. For this reason, it is essential in structural design to minimize openings in order to reduce stress concentrations and slow crack initiation or propagation, particularly in areas sensitive to fatigue or cyclic loading.

5.2. Analysis of the J- integral at the edge of a hole in a rectangular plate

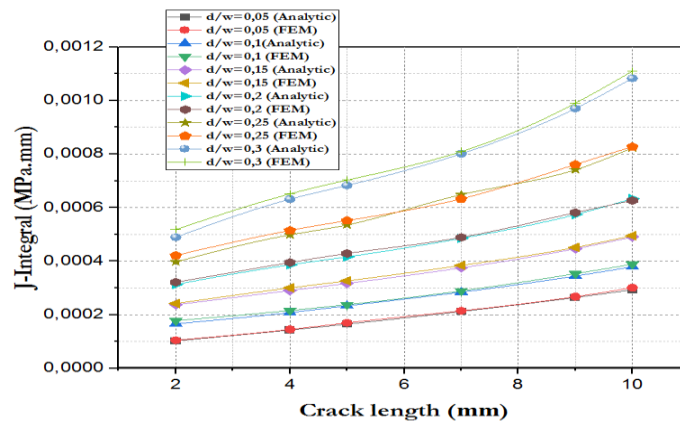


Fig. 10. - Variation of the analytical J-integral and MEF as a function of crack length and d/w

In this section of the paper, we have analyzed the results of the finite element method (FEM) on the evolution of the J-integral during tensile stress on a drilled plate under imposed boundary conditions. The part studied concerned the joint behavior of crack length and geometric diameter/width ratio (d/W) on the value of the J- integral, indicating that these two parameters were decisive for the mechanical behavior of the structure. The J-integral was found to increase progressively as the crack lengthened, reflecting an increase in the energy available for crack propagation in accordance with fracture mechanics. This trend is all the more marked the higher the d/W ratio, both for d/W ratios of 0.25 and 0.3, confirming the aggravating role of a wide opening on plate brittleness. Initial conclusions drawn from the J-integral distributions point to a relationship between this magnitude and the geometric parameters tested. The comparative graph shows good agreement between the analytical and numerical methods, even if the results provided by the FEM method are slightly superior, particularly for long cracks. This slight overestimation by FEM is precisely due to its finer integration of local effects and geometric shapes, which can be overlooked by analytical methods, all the more justifying the use of numerical simulations in critical cases where it is important to accurately assess the risk of failure. The non-linearity of the curves in fact testifies to acceleration in crack propagation above a critical size. All in all, this study shows that simultaneous increases in crack length and d/W ratio lead to a significant rise in the J-integral, and hence in fracture energy, and underscores the need for numerical models to ensure the proper behavior of perforated structures subjected to high stresses.

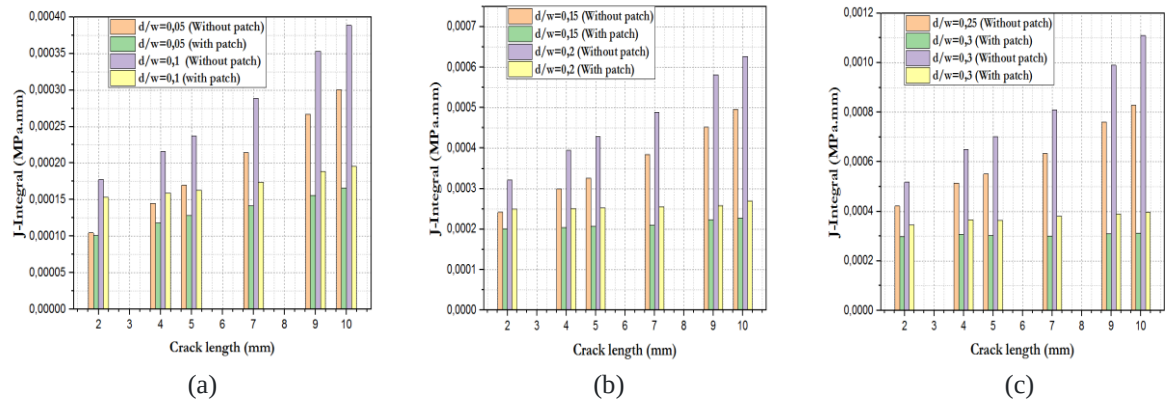


Fig. 11. - J-integral with and without patch as a function of crack length and d/w

Figures (11a), (11b), and (11c) show the variation of the J-integral as a function of fracture length for various diameter/width ratios (d/W), comparing the situations of mended and unrepaired plates. Generally speaking, the results show that the J-integral increases with crack growth, reflecting a rise in the energy required for propagation and thus an increase in the risk of failure. For low d/W ratios between [0.05 and 0.1] (Fig. 11a), the J-integral remains relatively low, not exceeding 0.00020 MPa-mm for the repaired plate, while it reaches over 0.00035 MPa-mm for the unrepaired plate, underlining the marked effectiveness of the patch at these dimensions. For intermediate ratios [0.15-0.2] (Fig. 11b), the J-integral remains below 0.0003 MPa-mm in the repaired cases, compared with over 0.0006 MPa-mm for the unrepaired plates, indicating a still significant, if slightly attenuated, stress reduction. Finally, for the highest ratios [0.25-0.3] (Figure 11c), values reach 0.0004 MPa-mm for repaired plates and up to 0.0010 MPa-mm for unrepaired plates, revealing critical structural behavior. The protective effect of the patch, while still present, becomes less effective as the hole size increases. The results show that the lower the d/W ratio, the more effective patch repair is in reducing stress concentrations and crack opening rates. On the other hand, when the opening is larger, patch repair, although still useful, remains insufficient to restore the mechanical integrity of the structure. This behavior clearly shows that the initial geometry of the defect is decisive and that bonded repairs have their limits in the critical configurations studied.

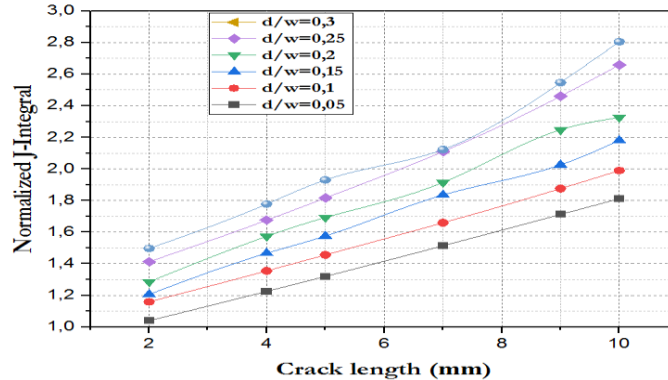


Fig. 12. - The normalized J-integral as a function of crack length and d/w

Figure 12 presents the normalized J-integral's fluctuation with fracture length and diameter/width ratio (d/W), for repaired and unrepaired cracked plates. The results show a continuous rise in the normalized J-integral with crack elongation, reflecting increasing stress concentration in the vicinity of the defect. This tendency is present for all configurations, but is all the more marked when the d/W ratio is high. Indeed, for low values of d/W (0.05 and 0.1), the rise in the integral remains moderate, as mechanical behavior is much more stable and resistance to crack propagation is more robust. On the other hand, for higher ratios (0.25 and 0.3), the normalized J-integral rises more rapidly, exceeding significant values of 2.5 for the largest cracks, indicating a risk of fracture. Plates with numerous openings are therefore clearly more fragile in the face of crack evolution, even when repaired. This graph, too, shows the amplifying effect of the d/W ratio on the mechanical response of the structure, and the importance of controlling the geometry of the openings. The clear ordering of the curves in relation to d/W shows the predominant role of this criterion in the intensity of stresses at the end of the embedding. Basically, this analysis illustrates the imperative need to control the size of geometric defects or resort to reliable reinforcement solutions in order to optimize the fracture resistance of cracked plates under mechanical loads.

Conclusion

This research has enhanced the understanding of how damaged aeronautical structures, especially cracked aluminum plates reinforced with isotropic adhesive patches, behave mechanically. A thorough investigation was conducted using a combination of analytical methods and the finite element method (FEM) to examine how the stress intensity factor (SIF) and the J-integral change under various geometric and mechanical setups. The findings indicate that when a small crack is situated close to the edge of a hole experiencing mechanical stress, it acts as a significant source of stress concentration, promoting crack growth and ultimately affecting the structure's durability over time. The comparison between the analytical and numerical solutions validated the relevance of the simulation framework based on an FEM model. The model used, including a C3D20R mesh, well-defined boundary conditions, and local refinement around the crack, achieved good consistency with the theoretical results, thus demonstrating the suitability of the numerical approach for handling cases that are more complex than those targeted by conventional analytical models. A key finding of this study is undoubtedly the demonstration of the effectiveness of an isotropic patch bonded to the crack level. This repair technique is capable of reducing the SIF and the J-integral, demonstrating its ability to reduce stress concentration in the vicinity of the injured region. It should be mentioned that the reduction is even more pronounced for a low or intermediate geometric ratio d/W , confirming that patches are more effective on small wings. On the other hand, when the d/W ratio is no longer low, the effectiveness of the patch decreases. This may encourage optimization of the dimensions and positioning of the reinforcement in order to maximize its beneficial effects.

Analysis of the normalized variations in the SIF (stress intensity factor) and the J-integral revealed the significance of crack geometry and opening for the mechanical response of the plate under stress. These two quantities increase more rapidly with crack length for large openings, revealing critical configurations that may compromise structural stability. Thus, the results offer a deeper comprehension of the local processes governing both fracture growth and healing efficacy.

In conclusion, this study, which highlights the benefits of combining numerical modeling and analytical analysis, proves fruitful in the field of crack propagation in complex aeronautical structures by highlighting the importance of local repairs using bonded patches in enhancing damage tolerance and structural safety, although the effectiveness of these repairs depends heavily on several factors, namely the geometry of the crack, the patch material's mechanical characteristics and the degree of adhesion between the surfaces.

Finally, our study also opens up new avenues for research by extending our investigation to composite materials subjected to multiaxial stress conditions, in the context of aging, fatigue, and real environmental conditions, which will yield results that are more representative of the situations encountered in aeronautical operations.

In summary, this research provides a solid basis for optimizing repair strategies in aeronautical maintenance, both by offering powerful analysis tools and concrete solutions for designing more reliable, durable, and safer repaired structures, thereby improving the performance and longevity of contemporary aeronautical systems.

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