J-Integral Evaluation of Repaired Cracks in AA7075-T6 Structures Subjected to Uniaxial Tensile Stresses

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Highlights

- This study provided an overview of the performance and behavior of a repaired plate.
- AA7075-T6 alloy repaired with a boron-epoxy patch bonded with FM73 Adhesive layer.
- The results in a considerable decrease in the value of the J-integral.
- The best results obtained from composite with the fibers collinear with load.
- The crack mouth opening displacement (CMOD) could be reduced by 90–97%.

Abstract

Bonded repairs using composite patches over metallic structures have been evaluated as a cost effective method to increase the life of damaged structures. The J-integral is a widely applied fracture mechanics parameter relating to the energy release associated with crack growth and is a measure of the deformation intensity at the crack tip. In practice, the calculated J-integral can be compared with a critical value for the material under consideration to predict fracture. This study aimed at providing an overview of the behavior of a cracked plate of AA7075-T6 alloy repaired with a boron- epoxy patch bonded with FM73 Adhesive layer. The Finite Element Method (FEM) using Abaqus Software 6.14 predicted the performance. The results show a considerable decrease in the value of the J- integral. This is due to the beneficial effect of the patch on the stress state at the crack tip. The best results were obtained from a unidirectional composite fibres orientation of 0°, where the fibers oriented parallel to the direction of load. A parametric analysis has been carried out to evaluate the effect of lay-up, load variation and crack mouth opening on the J-integral. It was found that the crack mouth opening displacement (CMOD) was reduced by 90–97%.

Keywords: AA7075-T6; J-Integral; Cracks; Adhesive bonding; Boron/epoxy; CMOD.

1. Introduction

Structural fatigue cracking is a result of the usage of aircraft and will eventually occur in time with all aging aircraft. These cracks are common in aluminium alloys such as AA7075 and AA7079, especially in the T6 temper condition. These alloys are tailored for high strength, but also results in decreased crack initiation/growth performance and corrosion resistance. The demand for extended usage and variation in load spectra requires the revision of maintenance programs. Sometimes, structural modifications and increasing repairs of the primary structure, to ensure that the required level of structural integrity is retained. The shape of the structure also significantly affects the fatigue life; square holes or sharp corners lead to elevated local stresses where fatigue cracks can initiate. Generally, aerospace structural elements inevitably include numerous geometrical discontinuities. For instance, aircraft structures include a large number of open holes as well as fastener holes for mechanical joints, which incorporate bolts, rivets and location pins. Such holed elements are inherently vulnerable, particularly under tensile and fatigue loading conditions. This is due to the introduction of stress concentration at the edge of the holes [1]. Many materials contain physical discontinuities, which are given the generic term of notches. When a notched material is loaded, local stress and strain concentrations occur. These phenomena may result in micro-cracks that develop and coalesce with one another until they form a macroscopic crack, which propagates until the total breakdown of the material occurs. Aeronautical components may be subjected to multiaxial stress states of varying amplitude leading to fatigue damage. This can lead to catastrophic failure as shown in Figure 1 [2].

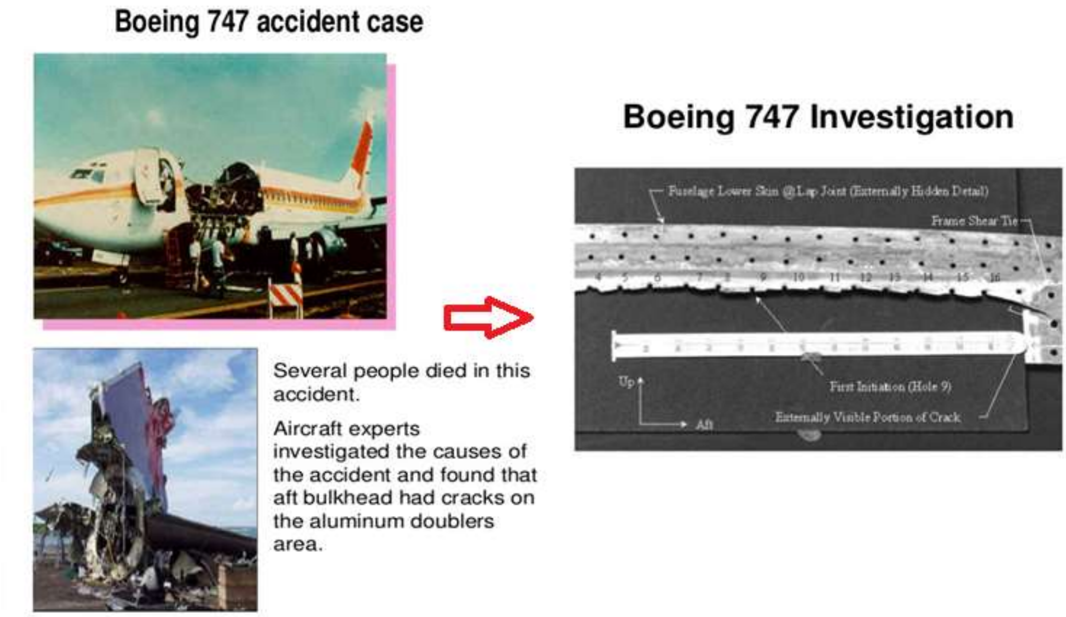


Fig 1: Examples of aircraft fatigue failures [2]

The most common repair/reinforcement technique is the mechanical fastening of a plate over the damaged area to redistribute the load and reduce the stress concentration in the damaged zone. The mechanical fastening is less desirable because of the non-uniformity of the stress distribution and the creation of stress concentration zones around the fasteners. Bonded composite repairs of locally damaged metallic structures has gained considerable interest in aircraft structural maintenance and life extension in recent decades, where the US Air Force and aerospace industry have shown considerable interest. The Aeronautical Research Laboratory in Australia has pioneered composite repair doublers bonded to metal substructures [3], which have been used in development programs and partially in fleet repair programs, as an alternative to bolted repairs [4]. They showed that the bonded composite repair improved the durability of aircraft structures under practical conditions. The use of the adhesively bonded composite patches as a repair method has many advantages compared to the conventional mechanically fastened repair methods [5]. The bonded joints allow for a reduction in aircraft operating costs by performing repairs of damaged parts instead of exchanging them. The Composite Patch Bonded Repair (CPBR) is a method that can be used for repairing both metallic and composite structures. The advanced composite materials have many advantages, which make them ideal for reinforcement and structural repairs. These advantages include the high specific stiffness, light weight, corrosion resistance, directional dependence of the material properties, capacity to be moulded to complex shapes, and the potential to provide variable stiffness and increase the strength and fatigue life which results in effective crack retardation. The CPBR method includes the following steps: surface preparation prior to bonding, the imposition of the composite patch, a curing cycle of the composite and the adhesive film, and the final treatment [6, 7]. While component replacements and extensive large scale repairs often cause long downtime periods in depot environments, even more effort is required for disassembly of larger parts of the fuselage or wing. Usually this is limited to major overhaul and life extension programs of the fleet. If technically feasible, a local repair or reinforcement of the structure is more economical.

Numerical analysis is a tool, which can provide very useful information regarding the mechanical performance of composite bonded repairs. However, to date, numerical models have been only used for calculating the stress field of the repairs and optimising the patching. The past research has been aimed at understanding the phenomenon of initiation and propagation of cracks to predict the life of aeronautical structures. Significant efforts have been devoted to the repair or reinforcement of the damaged or weakened part of structure to restore the structural effectiveness and thereby ensure the safety of the structures. The most investigated case deals with the stress intensity factor (SIF) at the crack tip in the presence of the patch repair in order to improve the fatigue life of the cracked structures. Many numerical methods using finite element analysis have been developed to obtain SIF values. Various authors have computed the stress intensity factors at the crack tip of repaired cracks. Ramji et al [8] have found that, in the case of an asymmetrical patch, the unpatched surface has an SIF value that exceeds that obtained in a repaired panel. Umamaheswar and Ripudiman Singh [9] performed finite element modeling and analysis of single-sided composite patch repairs applied to thin aluminum sheets. They determined the SIF variation through the thickness of the panel assuming a straight crack front. Abdelkader Nour et al [10] investigated the dynamic behaviour of a composite helicopter blade based on the Westergaard crack formulation. The investigation included the application of the extended finite element method (XFEM) for the determination of the SIF at the crack tip, followed by a comprehensive discussion on near crack tip fields for a helicopter blade composed of orthotropic materials. Several numerical simulations were provided to illustrate the validity, robustness and efficiency of the proposed approach to evaluate the mode I stress intensity factors and J-integrals in composites. Hosseini-Toudeshky et al [11, 12] performed fatigue crack growth tests of single-sided repairs of thick and thin panels, which included center inclined cracks. Various patch lay-up configurations and various composite patch thicknesses were investigated. One important aspect in the design of a bonded patch is an accurate tool for predicting stresses, stress intensity factors and failure strength. With the increase in computational power, the use of numerical methods (especially the finite element method), has given insight into the mechanical behavior of defects under the patch repair. The constraints on the external patch thickness are aerodynamic considerations and the induced load eccentricity due to neutral axis offset [13].

Crack appearance and growth can seriously endanger the reliability of structures and components in operation. Therefore, it is important to assess their influence on the structural integrity. Several parameters can be used for such a task, one of the most common being the SIF. A limiting factor is that this is relevant for elastic behaviour of material in the zone ahead of the crack tip. In ductile fractures, when the material exhibits elastic-plastic behaviour ahead of the crack tip, different fracture mechanics parameters should be used. Therefore, a good way to design a patch repair is to find the optimal shape for the patch, in order to obtain the maximum safety-cost ratio [14]. This matter is of importance from both an economic and a technical point of view [15, 16].

The J-integral can be developed for both linear and nonlinear elastic theories. When a plastic zone of considerable size appears near the crack tip, it is no longer possible to describe the stress and strain fields using a single parameter, as was the case with the SIF. Hence, it is necessary to introduce parameters, which are not limited by linear-elastic material behaviour, such as the crack tip opening displacement and the J-integral. Unlike the linear-elastic fracture mechanics, in the case of elastic-plastic fracture mechanics, stable crack growth may occur prior to reaching the critical parameter values. In this case, the fracture is ductile rather than brittle.

A fundamental issue in fracture mechanics is the determination of criteria for the growth of pre-existing cracks in materials. It is equally important to establish whether the various parameters measured in standard laboratory experiments (such as the experimental J-integral) is applicable for describing crack growth in arbitrary structures. These issues are well resolved in the context of elastic materials. For linear elastic materials, Griffith's approach states that a crack extends if the thermodynamic crack driving force, characterized by the energy release rate G, becomes equal or larger than the crack growth resistance [17]. The Irwin approach postulates that a crack grows when the crack tip stress intensity factor K reaches a critical value[18]. The Griffith and Irwin criteria are equivalent for linear elastic materials, since energy release rate and stress intensity factor are related. Standard methods are available to determine the crack growth resistance R and the critical stress intensity factor, and it is widely accepted that these parameters are valid for arbitrary structures since they do not depend on the experimental loading conditions or specimen geometry. For materials and structures where crack growth is accompanied only by limited plastic deformation (small-scale yielding), the engineering approach is to treat this as a perturbation of the linear elastic case and apply the Griffith and Irwin criteria. This is done occasionally with the crack length extended by the radius of the crack tip plastic zone. For crack growth in elastic–plastic materials under large-scale or general yielding conditions, the common approach is to use criteria based on the crack tip opening displacement [19], Rice's J-integral [20] and the energy dissipation rate [21,22] .

However, the use of each of these criteria is somewhat problematic: The crack tip opening displacement is difficult to determine experimentally, since measurements should be taken in the interior of a specimen [23]. The J-integral approach suffers from conceptual difficulties when applying it to elastic–plastic materials [24], and the energy dissipation rate is strongly dependent on the size and geometry of the structure which makes the transferability of the data from a test specimen to an arbitrary structure difficult [25]. Amongst these parameters, the J-integral based approach is used most widely and is the focus of this paper.

The J-integral was proposed in 1968 by Rice [26] to characterize the intensity of elastic– plastic crack-tip fields. It is defined as a contour integral, which describes the energy per unit area needed for the creation of two new surfaces in a cracked body submitted to loading. Numerical methods allow the evaluation of the J-integral for any cracked or notched component under different loading and constraint conditions [27]. Several authors studied damaged aerospace structures and materials by means of finite element methods and showed the importance of J-integral evaluation for failure and structural integrity. The determination of the J-integral is crucial for predicting the reliability of structures, and therefore several methods have been developed in order to obtain this quantity [28, 29].

Courtin et al [28] investigated the advantages of the J-integral approach for calculating stress intensity factors as part of a linear elastic fracture mechanics analysis. The determination of the stress intensity factor distribution was a crucial point. The aim of their work was to test several existing numerical techniques reported in the literature. Both the crack opening displacement extrapolation method and the J-integral approach were applied in 2D and 3D finite element models. The results obtained were in good agreement with those found in the literature. Since knowledge of the field near the crack tip is not required in the energetic method, the J-integral calculations seem to be a good technique to deal with the fatigue growth of general cracks.

A computational method to perform the modelling procedures required for the three-dimensional J-integral in finite strain elastic plastic problems is described, as well as the domain integral method. Finally, some discussions and conclusions are given for the present work, where J-integral is numerically obtained using a contour integral method based on FE analysis results on Abaqus 14 [30]. The resulting values of J-Integral are presented relative to various parameters (load, fiber orientation, repair patch thickness and CMOD). The non-linear three-dimensional finite element method is used to evaluate the J-integral of non-repaired and repaired cracks with a bonded boron fiber composite patch. The effects of the patch layer orientations and the crack length on the J-Integral are highlighted.

2. Evaluation of the J-integral

For a measure of the fracture mechanics safety and patching efficiency criterion at the repaired crack, a numerical approach of the J-integral was used in the Finite element model in this study.

Abaqus/Standard provides a procedure for such evaluations of the J-integral, based on the virtual crack extension/domain integral methods .The following section explain how J-Integral is evaluate in the finite element method according to Abaqus Software.

The Finite element method provides a useful means to conduct virtual experiments and analyse the behavior of the cracked plate under various configurations. It has been one of the most prevalent numerical tools in the field of fracture mechanics since the early 1960s. Abaqus/CAE, a commercial nonlinear finite element code developed by SIMULIA Inc., was used to perform the analysis. The contour integral method was used to define the onset of cracking and was requested as an output parameter to calculate the J-integral at the crack tip. This method uses the domain integral technique to expand the area integral in the two-dimensional case and the volume integral in the three-dimensional case [30]. Tunç et al showed the benefit of finite element software in the study of various parameters in a three dimensional constitutive model for solid propellants in order to investigate the effects of viscoelasticity, large deformation, temperature, pressure and softening in monotonic and cyclic loadings [31].

Finite element (FE) computations of contour integrals are of increasing importance in defect assessment of cracked structures. Very often, such contour integrals can easily be obtained from commercial FE programs [30]. For instance, for time-independent elastic–plastic problems, Abaqus offers an efficient and robust routine to compute the J-integral using a domain integral method. Even for arbitrary stress–strain laws, calculation of the J-integral is straightforward, requiring only tabulated stress–plastic strain data. For defect assessment of components operating at high temperatures (in the creep regime), calculation of the C(t)-integral is needed. Abaqus/CAE includes modeling and post-processing capabilities for fracture mechanics analyses. These features provide interactive access to the contour integral fracture mechanics technology in Abaqus/Standard. Several fracture-specific tools are available, such as those for creating seam cracks, defining singularities, selecting the crack front and crack tip, defining q-vectors or normals to the crack front, and creating focused meshes. With these tools, models can be created to estimate J-integrals, stress intensity factors, and crack propagation directions. In this technology brief, a standardized compact tension specimen is modeled, and J-integral results are compared with those generated from applicable American Society for Testing and Materials (ASTM) standards and from a laboratory testing method. It is shown that Abaqus results are in very close conformance with the experimental results. Taking these difficulties into account, it could be interesting to study other possibilities to obtain the SIF distribution. The second kind of methods reported in the literature is an energetic one.

There are other possibilities to obtain the SIF distribution. The second kind of method reported in the literature is energetic one. It consists in determining the J-integral values. This quantity, introduced by Rice [26], is originally a two-dimensional line integral. Considering a path Γ which encloses the crack tip and with initial and final points which lie on the two crack faces, this integral can characterize the energy release associated with the crack growth and is defined as follows:

$$J = \int_{\Gamma} \left\{ w_e n_1 - \sigma_{ij} n_j \frac{\partial u_i}{\partial x_1} \right\} ds \ldots\ldots\ldots (1)$$

where w_e is the elastic deformation energy density and Γ is an open contour surrounding the tip of the crack. This is supposed to be rectilinear along the axis of the crack. We denote by:

$\vec{n}$: The normal outside the contour,

$\sigma_{ij}\ n_j$: The stress applied to the contour,

and u_i : the corresponding displacement (see Figure 2).

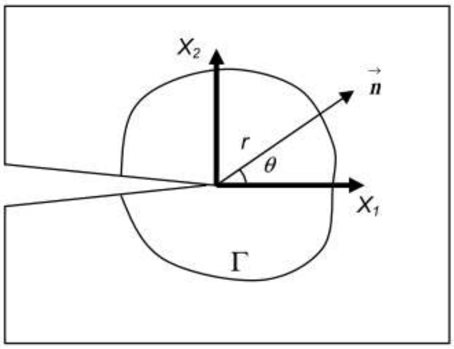


Fig 2: Integration contour

3. Geometrical and materials properties

The variation of different fracture parameters for repairing a pre-cracked aluminum substrate with a single side patch has been investigated. A three-dimensional finite element model consists of three subsections, namely the cracked plate, the adhesive layer and the composite patch. Due to symmetry, only one-half of the repaired plate is modelled. Quadratic elements with twenty nodes and elastic plastic behavior are used to define the plate. The geometry of the plate and composite repair patch is represented in Figure 3. The aluminum plate of AA7075-T6 is characterized by its height H = 220mm, its width W = 70mm and thickness of 2mm containing a crack of length a, emanating from circular notch of radius R=3mm. This plate is repaired with a boron-epoxy patch of dimensions: H = 70mm, W = 70 mm and thickness of 1.4 mm. The adhesive is of type FM 73 with the same dimension as the patch and of 0.25mm thickness. Different crack lengths are modelled. The general material properties of aluminum panel, composite patch and adhesive are given in Table 1. The structure made up of the plate, the adhesive and the patch is subjected to uniaxial tension with an amplitude σ =200MPa. The boundary conditions of fixing, subordinated to the conditions of symmetry of the geometry, were introduced into the initial phase. These conditions are represented as follows in 3D:

$U_y = UR_x = UR_z = 0$ (X Symmetry axis)

$U_x = U_y = U_z = UR_x = UR_y = UR_z = 0$ (Embedding)

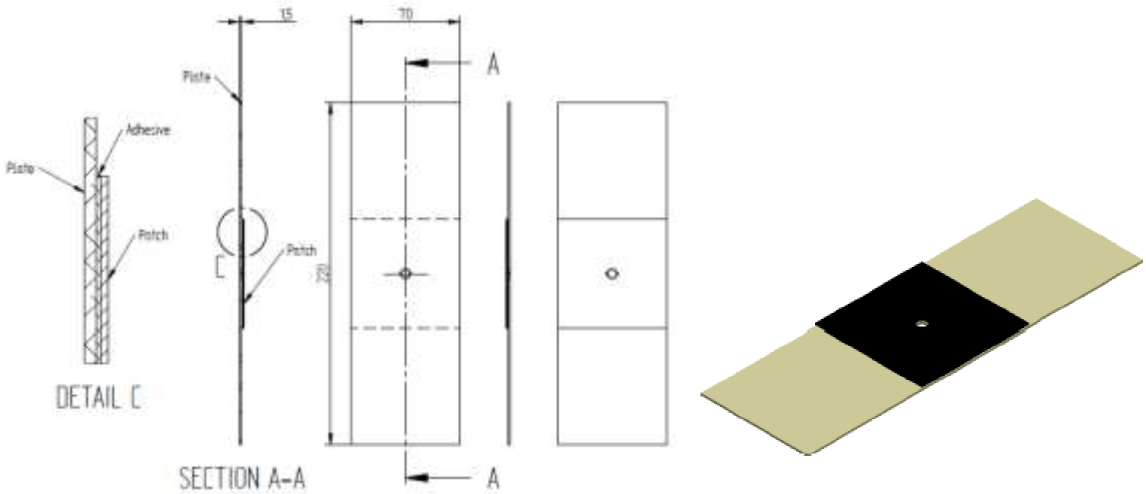


Fig 3: Geometry of the repair model considered

Table 1: Mechanical properties of the various materials.

Types	Plate	Patch	Adhesive
Materials	AA7075-T6	Boron/epoxy [3]	FM-73 [24]
Properties	E=68100MPa υ_{12}=0.3 σ_e= 535MPa UTS=582 MPa	E_1=208116MPa E_2=25440MPa E_3=25440MPa υ_{12}=0.17 ,υ_{13} =0.02 υ_{23}=0.25 G_{12}=7240MPa G_{13}=7240MPa G_{23}=4900MPa	E= 1890MPa υ_{12}=0.35

Standard tensile tests were carried out on Aluminum 7075-T6 and FM73 adhesive. The obtained stress–strain curves are presented in Figures 4 and 5 respectively. The specimen dimensions follow the ASTM E8 standard [32].

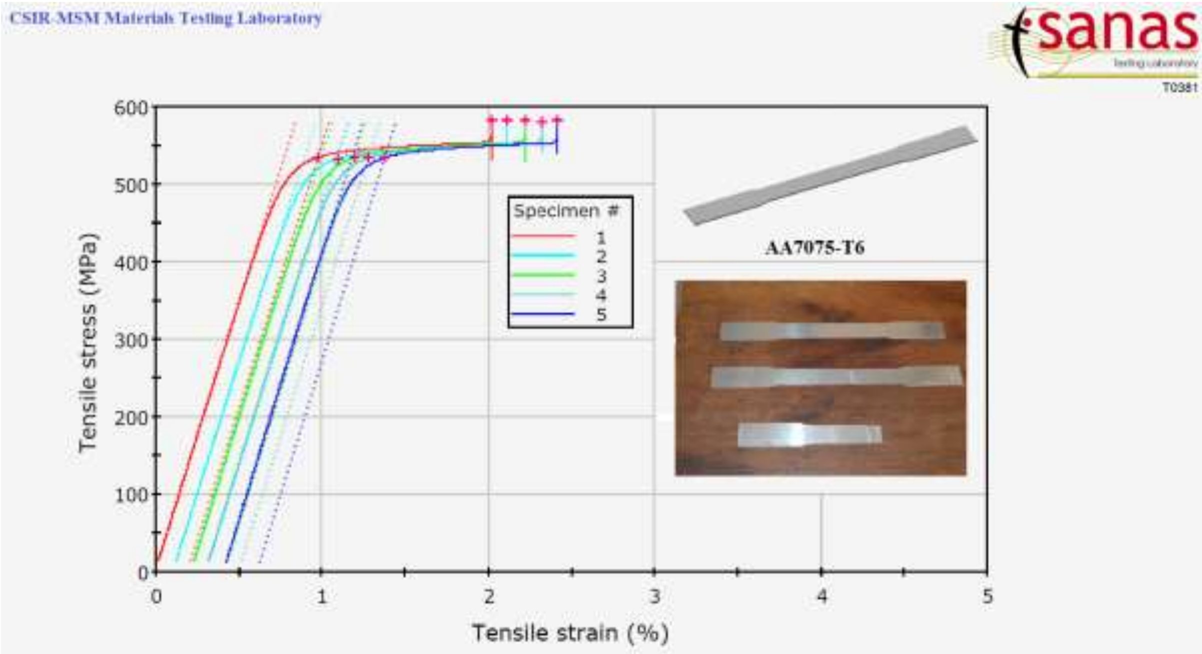


Fig 4: Stress–strain curves of aluminum alloy 7075-T6

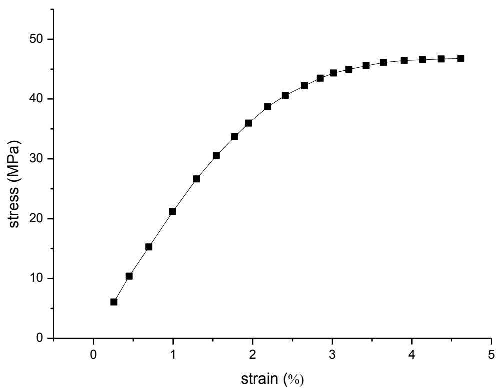


Fig 5: Stress–strain curve of FM-73 adhesive [34]

4. Finite element model

Many materials contain the physical discontinuities generally described using the generic term of notch. When a load is applied to a notched material, microscopic cracks can appear and coalesce with others until they form a macroscopic crack of size which is propagated until the total rupture of the material occurs. Composite material patches can be used in aeronautics for the repair of notched metal structures. The estimate of the performances of the repair of the aeronautical notched structures requires determining the criteria of rupture for different loading conditions.

The crack behavior was analyzed by computing the J-integral at the crack front of a longitudinally pre-crack in the specimens. The numerical simulation of three dimensions crack propagation is known to be tricky for reasons related to the mesh near the crack front.

The geometry was partitioned near a crack. The circular lines centered at the crack tip, as shown in Figure 6, define this partitioning. This strategy facilitates the generation of a focused mesh. The mesh was sufficiently refined in the vicinity of the crack tip to increase the accuracy in the local area and predict the J-integral correctly. All models have been analyzed by means of quadratic elements under plane stress and linear-elastic plastic hypotheses, which were generated using 3D hexagonal shapes and was modeled with 20 nodes reduced integration quadratic brick elements (C3D20R). A typical mesh used in the numerical analyses is represented in Figure 7. It shows the overall mesh of the specimen and mesh refinement at the crack tip region. Symmetric conditions were fully used and only a half of the model was studied in order to reduce the computation time.

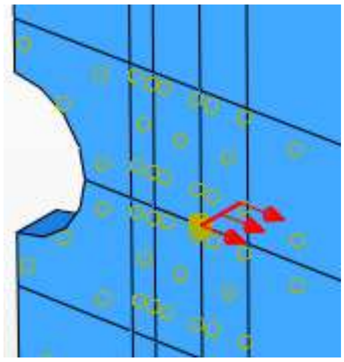


Fig 6: Partitioned three-dimensional part with the crack direction

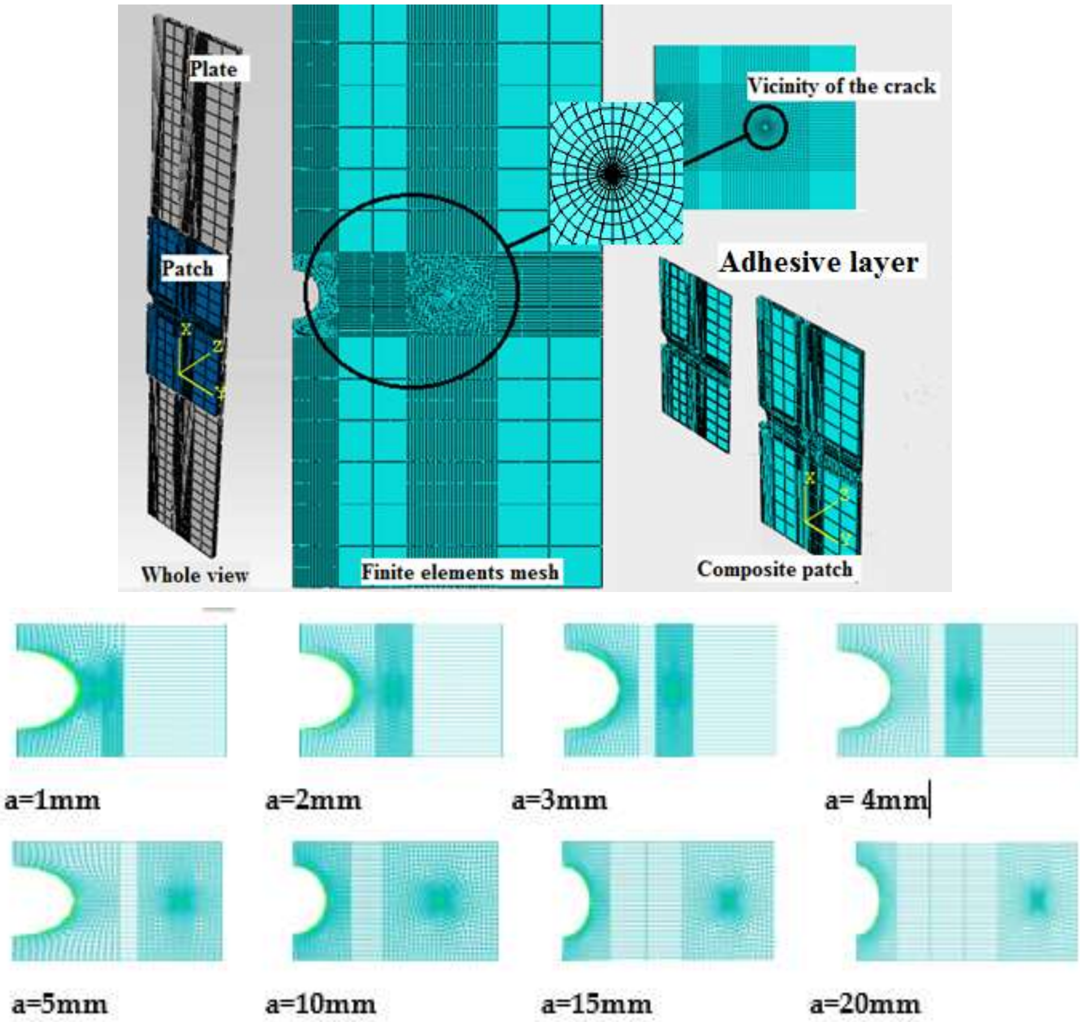
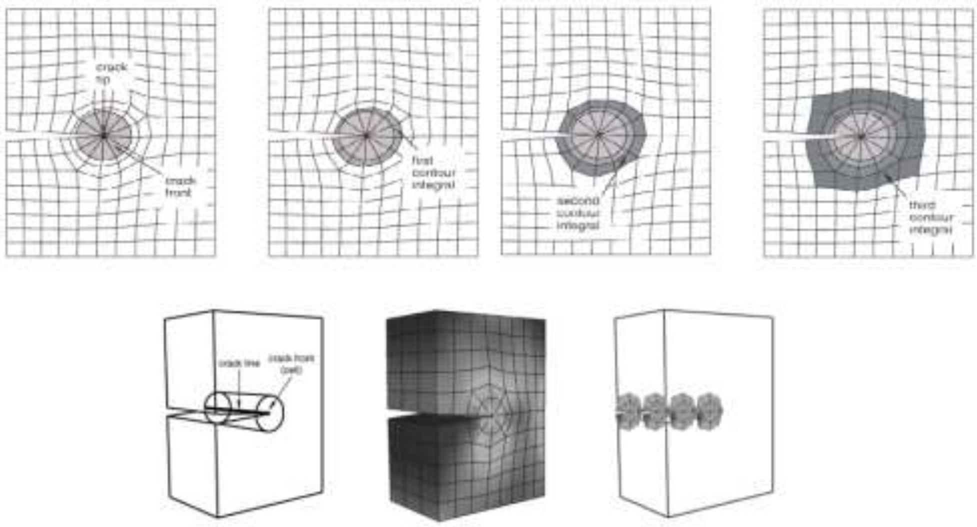


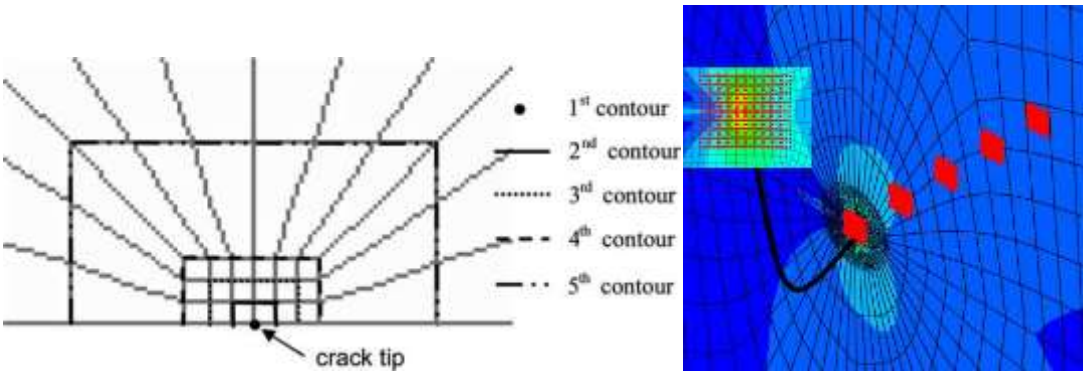
Fig 7: Typical finite element model of the plate and patch with various crack lengths

The J-integral at the crack tip was computed to predict to the repair efficiency in order to predict the repair durability. Contour integral method was used to define the onset of cracking. It was requested as an output parameter to calculate the J-integral at the crack tip. The J-integral is evaluated using a domain integral method [30] as described in equation (1). With several contour integral evaluations are possible at each location along the crack front. In a finite element model, each evaluation can be thought of as the virtual motion of a block of material surrounding the crack tip. Each such block is defined by contours: each contour is a ring of elements completely surrounding the crack tip or crack front from one crack face to the opposite crack face as illustrated in Figure 8. These rings of elements are defined recursively to surround all previous contours. This technique provides a better result if a focused mesh is used at the crack tip. This integral is theoretically path independent. However, it is widely accepted that the first contour does not provide good results because of numerical singularities.

Therefore, the J-integral have been obtained from the second contour or even further from the crack tip in order to get a convergent value. Abaqus computes contour integrals at each node along the crack line, as shown in Figure 8(b). To request contour integral output to evaluate J-integral is well explained in Abqus user Manual at section ***1.2.11 Requesting contour integral output***.



(a)



(b)

Fig 8: (a) Contour integral based calculation method at each node along the crack [30]

(b)Various contours for the calculation of the J-integral along the crack line with the 3D mesh.

To obtain an optimum numerical result, it is important to choose the meshing methods or finite element selection based on the case studies and software used. A new approach for modelling discrete cracks in mesh-free methods was introduced and described by Rabczuk et al [33]. In this method, the crack can be arbitrarily oriented, but its growth is represented discretely by activation of crack surfaces at individual particles. The crack is modelled by a local enrichment of the test and trial functions with a sign function (a variant of the Heaviside step function), so that the discontinuities are along the direction of the crack. The discontinuity consists of cylindrical planes centered at the particles in three dimensions and lines centered at the particles in two dimensions. The model is applied to several 2D problems and compared to experimental data.

4.1. Effect of convergence (mesh)

In order to obtain reliable results, the choice of the 3D element types is the key to avoid the divergence of the calculations and to obtain an optimized result. From the point of view of mesh, the quadratic elements "C3D20, A 20-node quadratic brick" is an excellent element for linear elastic calculations. Due to the location of the integration points, stress concentrations at the surface of a structure are well captured. The refinement of the mesh also shows its influence on the accuracy of numerical results, number elements higher than 23000 leads to similar values and much more precise while preventing the divergence of the results (Fig. 9).

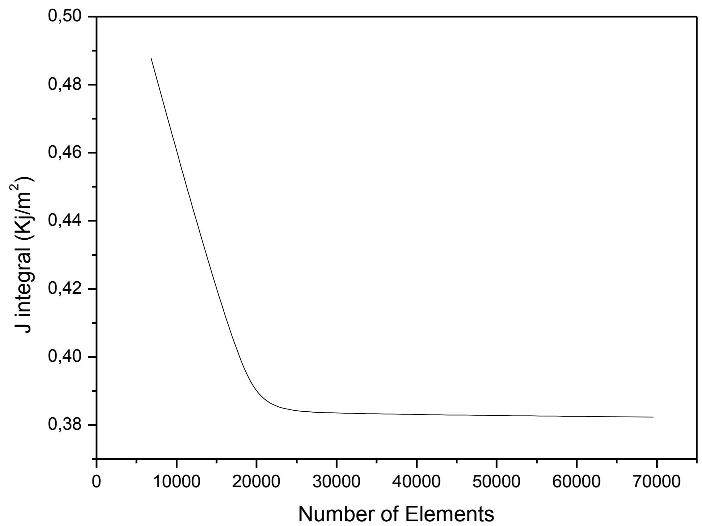


Fig 9: Refinement of the mesh to avoid the divergence of the calculations and to obtain an optimized result

5. Results and discussion

5.1. Effect of the patch and the crack length

One of the principal geometrical characteristics of the crack is the length. Figure 10 presents the variation of the J-integral along the length of a crack for both repaired and non-repaired plates under mode I loading. The J-integral was determined for various crack lengths, starting at a/W= 0.571 and increasing in 5 mm steps. According to this figure, the J-integral is strongly influenced by the presence of the patch.

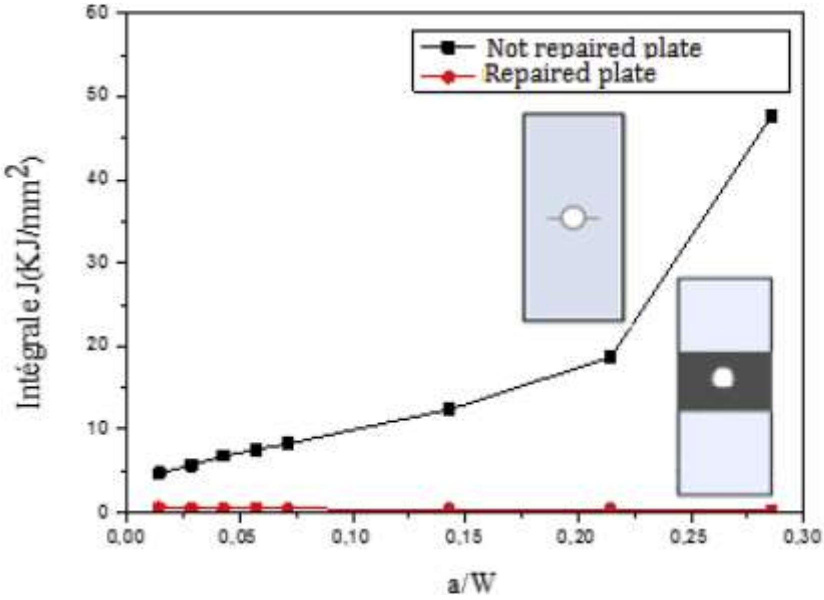


Fig 10: J-integral vs crack length for unrepaired and repaired plate

Figure 10 shows the variation of J-integral with the crack length for both patched and unpatched cracked plates. Two behaviors are observed: The first is that the J-integral increases with crack length for the unpatched plate. The second observation is that the J-integral is reduced by the application of the repair patch.

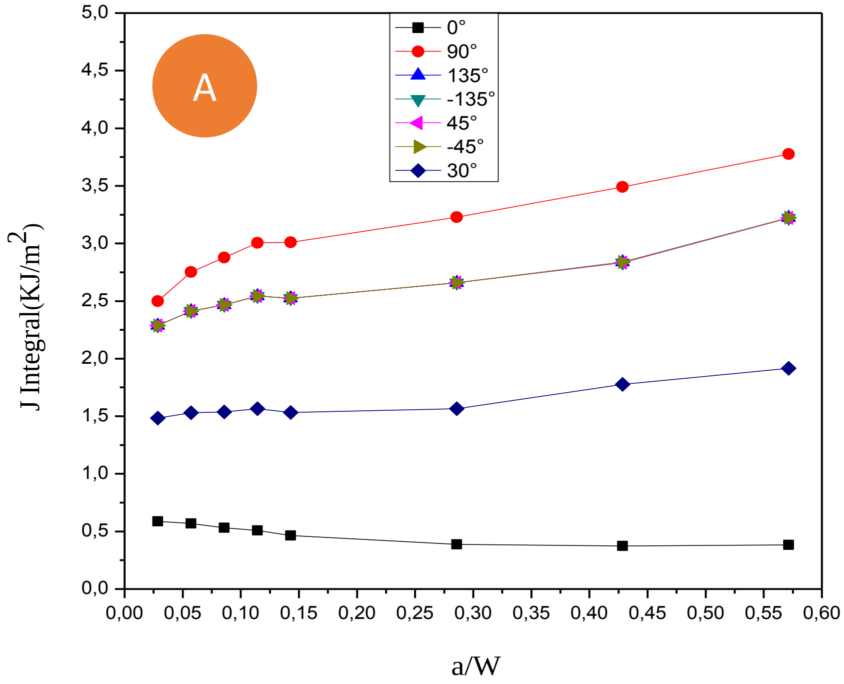
The relative difference between the J-integral of the repaired and non-repaired plates increases significantly with the propagation of the crack. The maximum reduction of J-integral is approximately 99%. This means that there is a very significant reduction of energy at the crack tip and the fatigue life of the structure can be improved. The load is transferred into the patch through the adhesive by shear forces, as confirmed Wahid et al [34]. Their work showed that the repair patch reduces the shear stress at the crack tip, thereby minimizing the plastic zone around the crack tip, commensurate with a reduction in the J-integral. The nature of the plastic zone that is formed ahead of a crack tip plays a very important role in the determination of the type of failure that occurs.

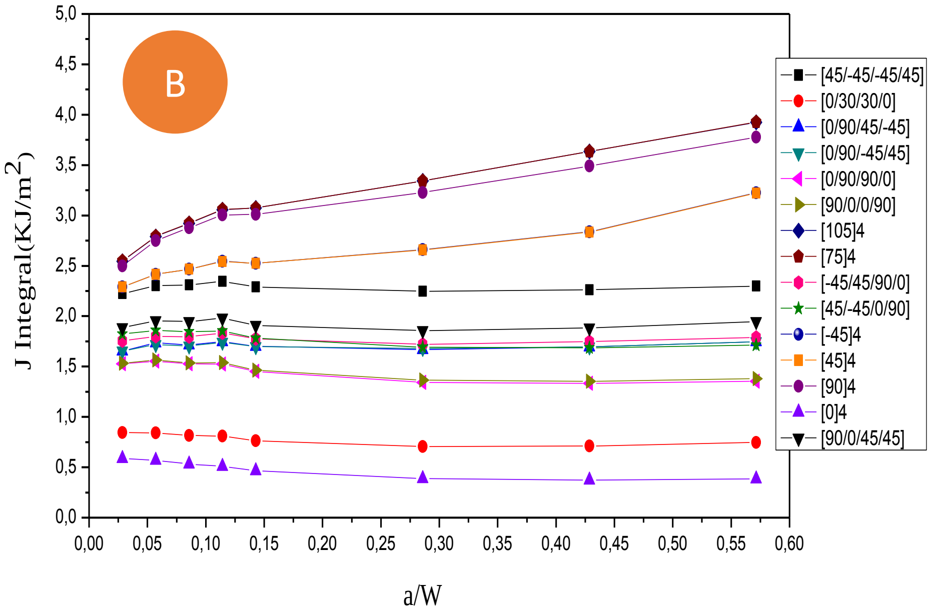
The reduction of J-integral is important to the design of the repaired cracked plate because this value defines the patch efficiency. As J decreases, the crack propagation decreases. As the reduction ratio increases, the crack propagation decreases. On the other hand, as this ratio decreases, the possibility of fracture increases.This last parameter corresponds to the beneficial effect of the application of the repair technique can be seen. One can thus confirm that the use of a composite patch offers an enormous advantage for repaired and consequently increasing the service life.

5.2. Effect of the fiber orientation and the number of plies on the repair

Researchers has studied the effect of different geometry and material parameters, to evaluated the J integral for different specimens with varying cracks. Msekh et al predicted the macroscopic tensile strength and fracture toughness of fully exfoliated nanosilicate clay epoxy composites accounting for the interphase behavior between the polymeric matrix and clay reinforcement. The effect of the interphase zones, e.g. Thickness and mechanical. They show through numerical experiments that the interphase thickness has the most influence on the tensile strength while the critical strain energy release rate of the interphase zones affects the dissipation energy depending on the interphase zone thickness[35-36]. Hamdia et al presented a methodology to evaluate the performance of different models used in predicting the fracture toughness of polymeric particles nanocomposites. The models' performance is compared and evaluated comprehensively accounting for the parameter and model uncertainties. The model selection probability is obtained with respect to the different reference data. They also studied further and presented a methodology for stochastic modelling of the fracture in a model containing an epoxy matrix and rigid nanoparticles surrounded by an interphase zone. The stochastic model is based on six uncertain parameters: the volume fraction and the diameter of the nanoparticles, Young’s modulus and the maximum allowable principal stress of the epoxy matrix, the interphase zone thickness and its Young’s modulus. They found that the variance in the fracture energy was mostly influenced by the maximum allowable principal stress and Young’s modulus of the epoxy matrix. [37-38].

Therefore, for our study the material selection, the fibre orientation and the number of plies drive the behavior of the composite material repair patch. Figure 11 presents the J-integral against the crack length for various fiber orientations parameters. Patch thicknesses of one, four and eight plies were considered.





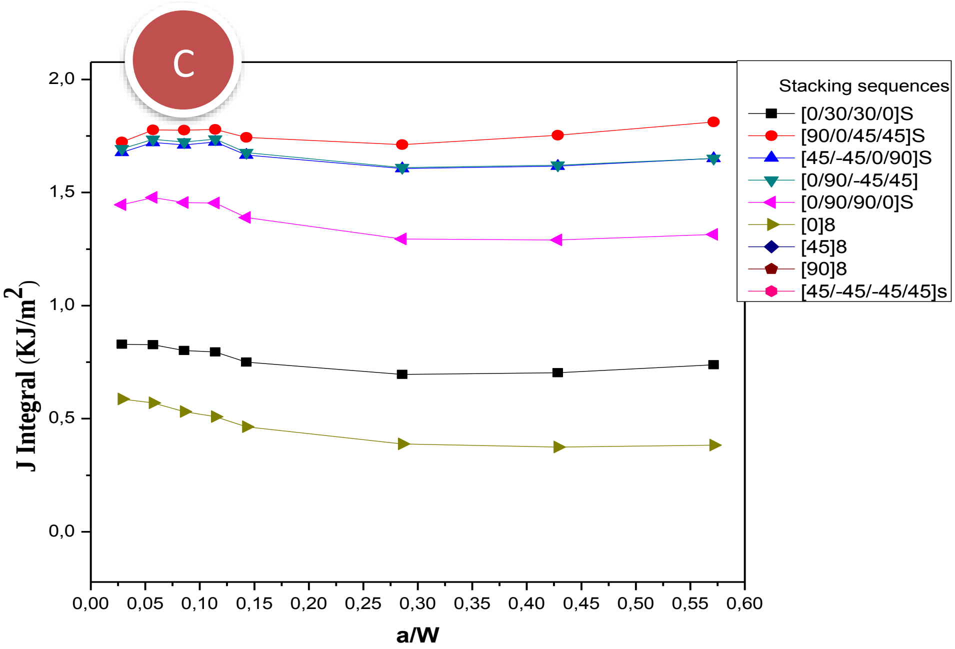
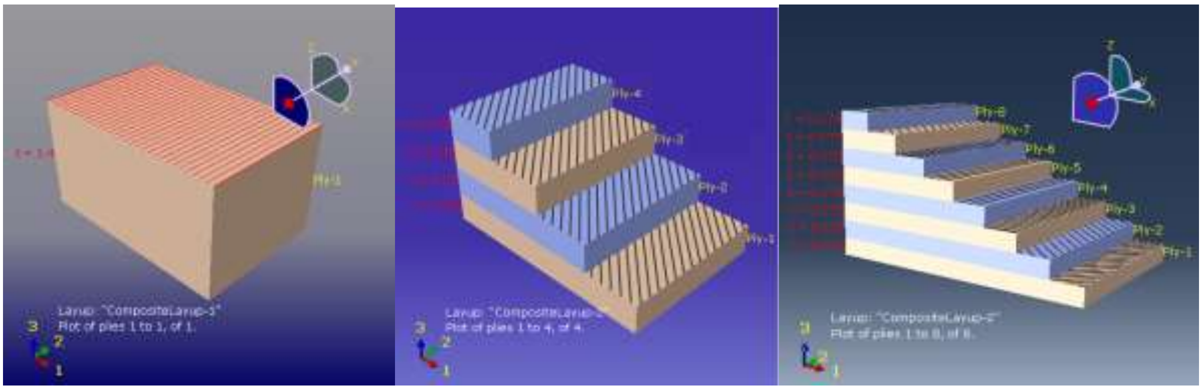


Fig 11: Variation of the integral J according to the size of crack for various orientations of composite patch fibers (A) One ply (B) four plies (C) eight plies

In all the cases, the curves take asymptotic forms. In the case of the asymptotic applying to a decrease in the value of the J-integral, this behaviour attributed to there being stress transfer from the cracked aluminium plate to the composite patch throughout the adhesive layer. An increase in the J-integral with crack length is associated with the orientation of fibers having a direct influence on the absorption of the stress fields at the crack tip. The 0° fiber direction is associated with the lowest J-integral values, as also noted by other authors [39-40].

5.4. Effect of the number of plies

The number of plies selected for the composite patch depends on the amount of damage, while the ply orientation depends on the direction of the damage, as well as the loading directions [41]. The effect of the number of plies on the J-integral is shown in Figure 12. It is noted that the total thickness of the patch is constant regardless of the number of plies. The effect of this number on the performance of repair is negligible and consequently, it is useless to increase the number of plies with same stacking orientation with the same thickness. This indicates that the effectiveness of the ply orientation depends on the loading direction and the crack direction.



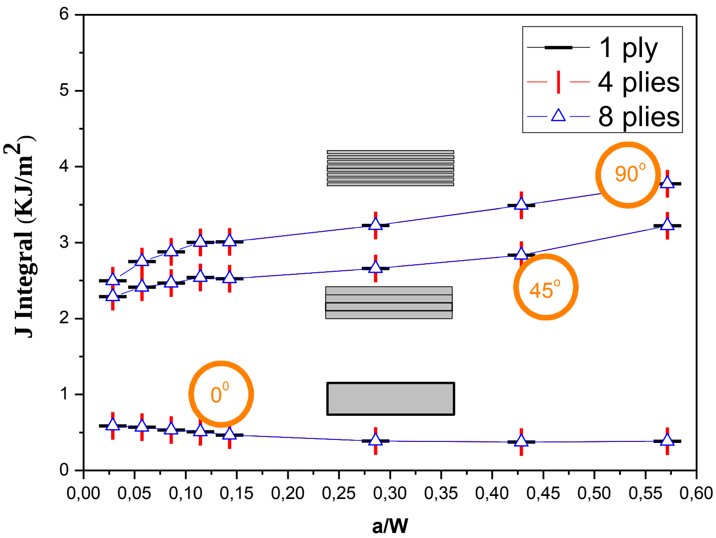


Fig 12: Variation of the J-integral with crack length for various numbers of plies

Figure 13 shows the three-dimensional model of the cracked plate, where the crack face along with crack front and the crack tip are illustrated.

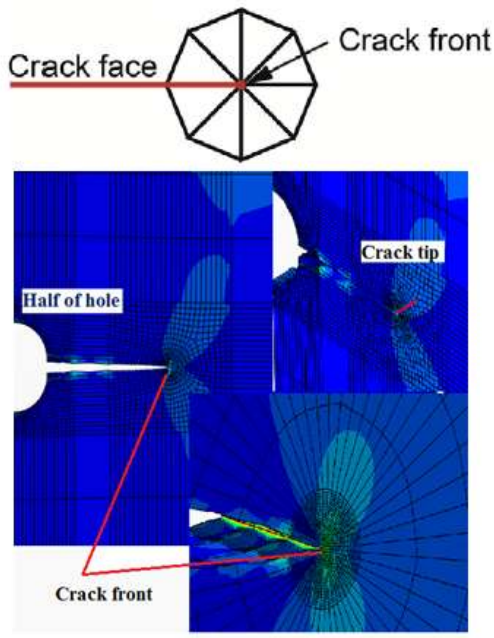


Fig 13: Three-dimensional model of the cracked plate

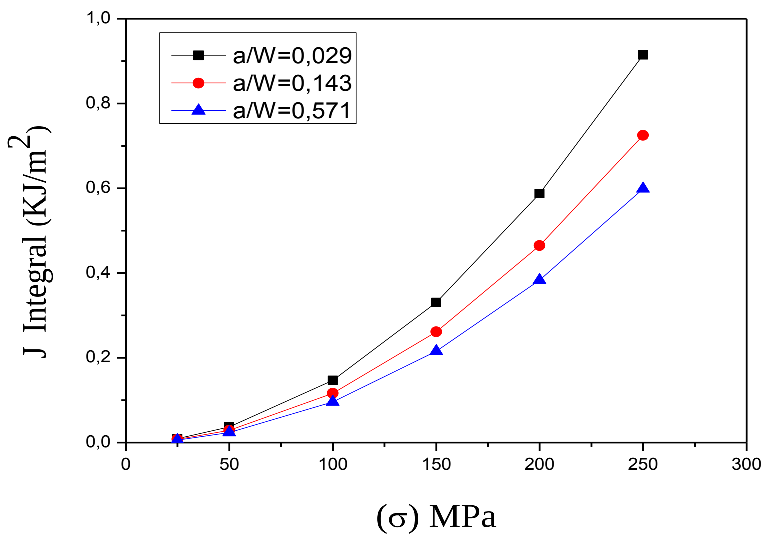


Fig 14: Variation of the J-integral with the applied loading

5.5. Effect of loading on the J-integral

Figure 14 presents the variation of the J-integral with the applied loading for three different crack lengths. The fibers are orientated perpendicular to the crack at an angle of 0°. The J-integral increases with the increase in applied loading. The calculation of the rate of increase in the J-integral is made for 100MPa and 250MPa. This rate is about 84% for a crack length of

1mm and of the same order for a crack length of 20mm. The rate of increase in the J-integral with applied load is therefore constant.

The effect of the intensity of load on the J-integral at the crack tip is illustrated in Figure 15 for various crack lengths. One can see that the effect of the loading is less prominent for a stress of less than 100MPa. The effect of the loading on the J-integral of a notched and repaired plate reduces for crack lengths of more than 10mm, where the J-integral becomes stable. This behavior is due to the shear stress field at the crack tip under the patch becoming smaller, minimizing the plastic zone around the crack tip. The reduction in the J-integral due to the repair patch improves the fatigue life of the structure.

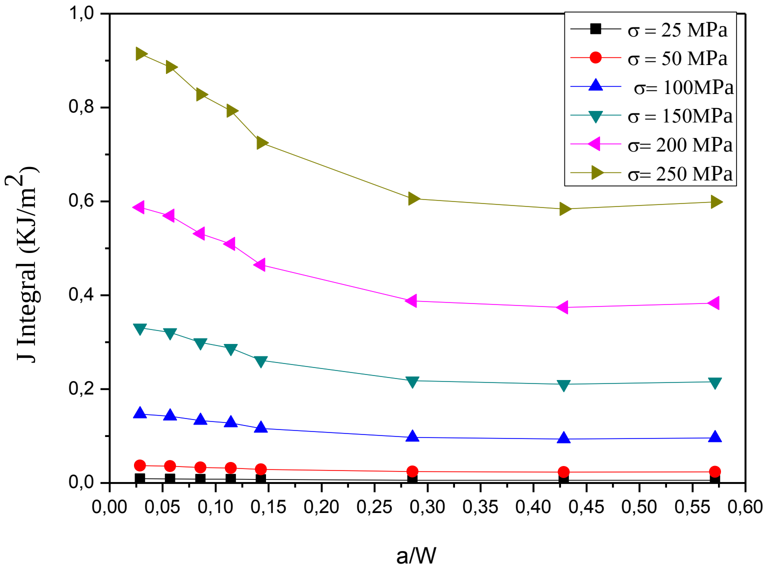
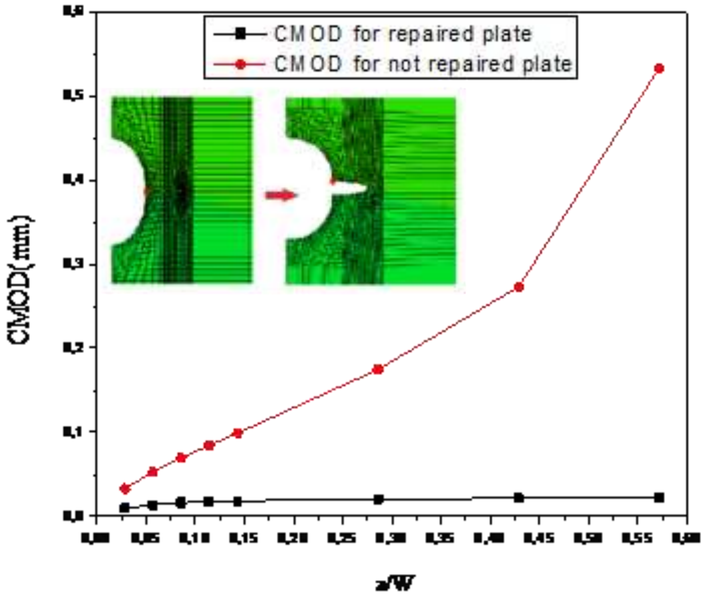


Fig15: Variation of the J-integral with crack length at various stresses

5.6. Crack mouth-opening displacement (CMOD) calculation

The effectiveness of the patch repair was further confirmed by the calculation in Abaqus of the Crack Mouth Opening Displacement (CMOD) for both the unrepaired and repaired plates. Figure 16 shows the variation of the CMOD relative to crack length. This variation is similar to that of the J-integral, where the presence of the composite repair patch at a 0^o orientation can decrease the CMOD up to 96%. This confirms the reduction in energy at the tip of the crack, leading to an improvement in the fatigue life of the structure.



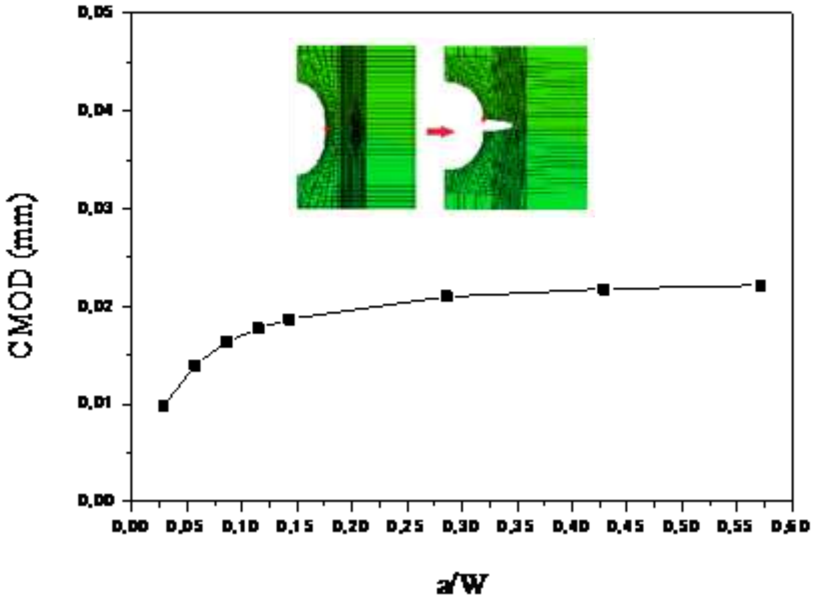


Fig 16: CMOD against crack length for a repaired plate

The variation of the CMOD of the original notched and the repaired plate shows the stability of the crack when the length exceeds 10mm (Fig. 16). These results are in agreement with those presented for effect of loading on the J-integral. Another effect that was studied was the effect of the loading on CMOD. Figure 17 shows the variation of the CMOD with the applied loading. This figure clearly illustrates the linear relationship between the CMOD and the applied loading. We note that CMOD values increase with increasing loading and more so with crack length.

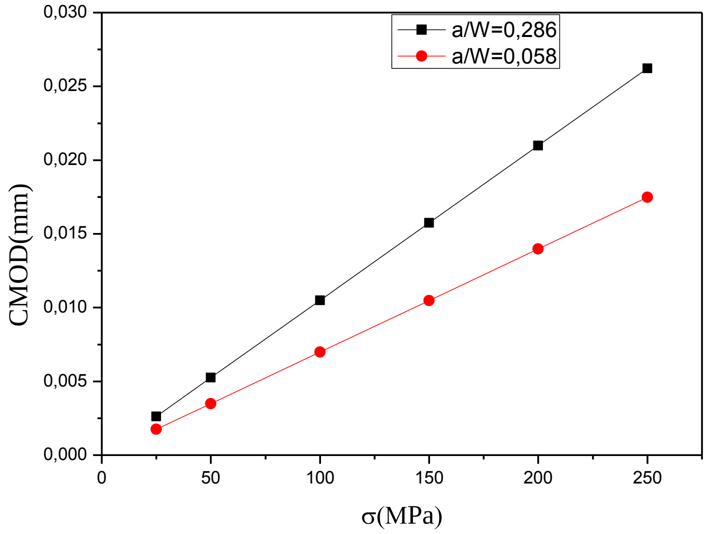


Fig17: Variation of CMOD with the applied loading

6. Conclusions

This study reviewed the option of using a boron-epoxy composite patch for the repair of a cracked 7075-T6 aluminum panel. Several key parameters were exanimated-using FEM to evaluate the crack repair behavior according to crack and load variation. The J-integral at the crack tip was computed to predict the repair efficiency in order to determine the repair durability. The overall results can be summarized as follows:

- One of the principal geometrical characteristics of the crack is the length. The reduction of J integral is important to the design of the repaired cracked plate because this parameter defines the patch efficiency.
- The increase in the size of the crack led to an appreciable increase in the J-integral in the unrepaired notched structure, while the values of the J-integral for the repaired structure are significantly lower.
- The refinement of the mesh shows its influence on the precision of the numerical results, the numerical elements superior to 23 000 leading to similar values and much more precise while preventing the divergence of the results.

- The repairing of the cracked plate by means of bonded composite patches results in the absorption of more dissipated energy, resulting in a significant reduction of the J-integral at the crack tip crack mouth opening displacement CMOD by 90%, which is also dependent upon crack size.
- The panel with the bonded composite repair shows a reduction of the J-integral value of 97% when compared to the non-repaired panel, which improves the fatigue life. This shows the beneficial effect of the patch. One can thus confirm that the use of a composite patch offers an enormous advantage for repaired cracks with the aim of increasing the service life.
- The J-integral increases with an increase in applied load. Once the crack length exceeds 10mm this behavior then approaches an asymptotic state.
- The value of the J-integral is minimized when the fibers orientation of the repair patch is at 0°, which is perpendicular to the crack in our study. Based on this it is recommended to utilise the fibers orientation for the composites layups in the perpidencular direction to the damage direction to obtain the optimum results.
- The number of plies does not have an effect on the variation of the integral J. Consequently, it is useless to increase the number of plies with same stacking orientation with the same thickness.
- The effectiveness of the ply orientation depends on the loading direction and the crack direction.

The repair patch is effective in decreasing the crack growth rate and thereby enhancing the fatigue life of the structure. This is achieved by the patch absorbing some of the stresses at the crack tip thereby reducing the magnitude of the J-integral.

Future work

The understanding of this present work in mechanical behavior and fracture mechanics and the effect of patch repair on different crack sizes form the future work to conduct experimental investigation of crack behavior of AA7075-T6 repaired with boron composite patch.

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