

Impact of bonding defect on the tensile response of a composite patch-repaired structure: Effect of the defect position and size

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Abstract. Adhesive bonding has seen rapid development in recent years, with emphasis to composite patch repairing processes of geometric defects in aeronautical structures. However, its use is still limited given its low resistance to climatic conditions and requirement of specialized labor to avoid fabrication induced defects, such as air bubbles, cracks, and cavities. This work aims to numerically analyze, by the finite element method, the failure behavior of a damaged plate, in the form of a bonding defect, and repaired by an adhesively bonded composite patch. The position and size of the defect were studied. The results of the numerical analysis clearly showed that the position of the defect in the adhesive layer has a large effect on the value of J-Integral. The reduction in the value of J-Integral is also related to the composite stacking sequence which, according to the mechanical properties of the ply, provides better load transfer from the plate to the repair piece through the adhesive. In addition, the increase in the applied load significantly affects the value of the J-Integral at the crack tip in the presence of a bonding defect, even for small dimensions, by reducing the load transfer.

Keywords: bonding defect; J-integral; peel stress; repair patch; shear stress

1. Introduction

The cyclic stresses that the metal structures of aircraft are subjected to during flight can initiate fatigue micro-cracks in stressed areas (for example wings, spar, and doors) and corrosion which, in the long term, may affect the reliability of the equipment. While there are several methods of repairing geometric defects, the most used one concerns the repair by adhesively-bonded composite patch.

The composite patch repair method is currently widely used in several fields, especially the aeronautical sector. The basic principle is to repair the damaged area with an adhesively bonded patch made of composite material. This method has many advantages over the old method using metal-based rivets on the defect area, generating micro cracks associated with drilling the holes. The composite patch has a relatively low stiffness/weight ratio, which gives it an advantage over the metal patch. In addition, the stacking sequence, and the nature of the fibers, play an important role in its use. The goal of all research is always to understand the phenomenon of crack initiation and propagation, which ends the life of aeronautical structures. Significant efforts have been devoted to the optimization of the reinforcement of the weakened part of the structure to restore the structural efficiency and thus ensure the safety of the structures. Other works dealt with the microstructure enhancement by adding reinforcements (Tiwari *et al.* 2022, Tiwari and Shaikh 2022).

The repair of cracks in aluminum structures by composite patch has been studied to a great extent. The success of the repair depends on the coherence between the base structure material and the patch, the adhesive used, the surface treatment, as well as the skills of the repairing operators.

The first research on the repair of cracked aluminum structures was known from the end of the 1970s by Baker A (2002, 2012), in particular for the repair of aerospace panels using bonded composite patches, in which the stress intensity factors at the crack tip were reduced under monotonous and cyclic loading. Naboulsi and Mall (1997, 1996, 1999) performed several finite element analyzes to predict the fatigue crack growth rate of cracked aluminum plates repaired with a composite patch from data on the material's crack growth rate. Toudeshky *et al.* (2009, 2005) conducted numerical and experimental studies on the effect of patch lamination on fatigue crack propagation of a repaired aluminum plate, and reported that the service life of the repaired sample can be increased in the range of 30% to 85% depending on the patch lamination. However, load transfer from the damaged area to the patch remains a challenge for researchers in order to minimize the stress concentration in the damaged plate, and thus increase its service life. Several methods have been proposed, namely the shape of the patch, which has been widely studied numerically and experimentally. Some studies have been carried out on the shape of the free edge of the patch to limit the peak shear stress in the adhesive. The aim of this work is to assess the influence of the shape of the free edges of the composite patch on the reduction of these peak stresses. Xiong and Raizenne (1996) analyzed the effect of patch geometry by modifying its thickness and the beveling

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angle of its edges. They were able to show that patches with a small thickness reduced the stresses in the adhesive and essentially at the level of its edges. In the work of Fekih *et al.* (2012), a three-dimensional nonlinear finite element analysis was accomplished to determine the variation of the J-Integral along the crack front of a structure repaired with a composite patch. The authors demonstrated the effect of the dimensions of the patch (length, width, and thickness) in order to obtain a better configuration of the patch to minimize stress concentrations in the damaged area. Jiang *et al.* (2019) determined the effects of fiber orientation on the strength capacity of repaired composite structures. Liu *et al.* (2019) numerically studied multi-layered composite laminates with various fiber orientations under patch bonding repair conditions. The authors determined that the minimum stress intensity factor value was found for a repair by a three-layer composite laminate with fiber orientation [90/90/90]. Zarrinzadeh *et al.* (2017) experimentally and numerically analyzed the effect of the shape of the patch on the behavior of a cracked aluminum pipe, repaired by a glass/epoxy composite patch, under fatigue stress load. The authors were able to determine optimized designs of patch repaired pipes under overload to prevent peeling. Actually, the rectangular or square shape of the patch remains the most used. The nature of the fibers was taken into consideration, and the results clearly showed that it is necessary to choose a composite with high mechanical properties in order to ensure good load transfer, without forgetting the stiffness ratio between the composite and the plate so that there will be no deformation in the plate outside the damaged area or deformation of the patch if the latter has low mechanical properties compared to the plate. Other researchers have been interested in the stacking sequence analysis. Wang *et al.* (2014) analyzed the Young's modulus of unidirectional glass fiber reinforced polymer (GFRP) composites for wind energy applications. Analytical, numerical, and experimental evaluations were presented. In order to explore the effect of fiber orientation angle on the Young's modulus of composites, from the basic theory of elastic mechanics, the authors developed a procedure that can be applied to evaluate the elastic stiffness matrix of GFRP composites as an analytical function of fiber orientation angle (from 0° to 90°). Makwana and Shaikh (2019) proposed a new perspective to repair cracked aluminum panels with bonded composite patches in the form of a hybrid composite (carbon and glass reinforcements) to reduce the repair costs. The stress intensity factor and interfacial stresses were estimated by finite element analysis, and the debonding onset load was evaluated under pure tensile mode. The hybrid composite patch enabled the reduction of stress intensity in the cracked panel and control of interfacial stresses in the adhesive layer. The same authors (Makwana and Shaikh 2021) evaluate the same overall approach, but considering different volume fractions of the patch constituents to induce varying stiffness. The composite patch stiffness was derived by the rule of hybrid mixture and modified Halpin Tsai equation. The results revealed that the hybrid composite patch provided sufficient reinforcement to reduce the stress intensity and interfacial stresses. Higher glass

content showed to reduce interfacial stresses at the patch edges.

Madani *et al.* (2010) experimentally studied the application of the bonded composite technology to reduce stresses at commonly occurring stress concentrations such as holes and notches. The mechanical behaviour of several plates with notches of various forms was investigated by tensile tests. The authors showed that the single or double patch provides better resistance to damaged plates regardless of the shape of the notch. Tenchev (2008) conducted an experimental and numerical study of the static and fatigue performance of a composite adhesive repair on 5HS/RTM6 composite intact coupons and coupons incorporating adhesively bonded (FM300-2) stepped flush joints. The results showed that this adhesive joint configuration, which is widely used in repairs, significantly increases the static strength as well as the fatigue life of the composite. Botelho (2009) studied the fatigue behavior of repaired aramid fiber/epoxy composites. The work presented the structural repair influence on tensile and fatigue properties of a typical aramid fiber/epoxy composite used in the aerospace industry. According to this work, the aramid/epoxy composites with repair presented high tensile strength values. Therefore, the fatigue test results showed that the repaired aramid/epoxy composite exhibited high cycle fatigue strength compared to the unrepaired composite. Ait Kaci *et al.* (2017) studied, by a finite element analysis, the von Mises stresses distribution in the adhesive layer and the J-Integral for a damaged plate repaired by a hybrid composite patch. Kaddouri *et al.* (2019) used a hybrid composite as a repair patch, and showed that the position of the aramid or carbon fibers in the hybrid composite has a consequence in the strength of the repaired structure. In most finite element analyzes of the mechanical or failure behavior of repaired structures, the composite is considered to be a single block with global mechanical properties. However, in reality the composite consists of several layers whose mechanical properties differ depending on the orientation and volume fraction of fibers. Most research in the field of bonding has not taken into account the presence of bonding defects in numerical calculations. The analysis of stresses in the adhesive layer is important because the latter is the weak link of the structure, since its mechanical properties are weakest and therefore can rapidly degrade. However, little research has been devoted to investigating the presence of bonding defects. Recently Aicha *et al.* (2015) studied, by the finite element method, the adhesive shear stresses distribution with and without presence of defects. The authors showed that shear stresses reach maximum values near the defect, especially if these defects are at the free edge of the adhesive where the stress concentrations are high. Elhannani *et al.* (2017) analyzed the effect of the position, number, and shape of the bonding defect on the distribution of shear stresses in the adhesive layer used to assemble two 2024-T3 aluminum plates. The authors have shown that the presence of the bonding defect has a negative effect on shear stresses in the adhesive layer and, therefore, on the durability of the assembly. Regardless of the size of the defect, the maximum stresses are always located at the edge

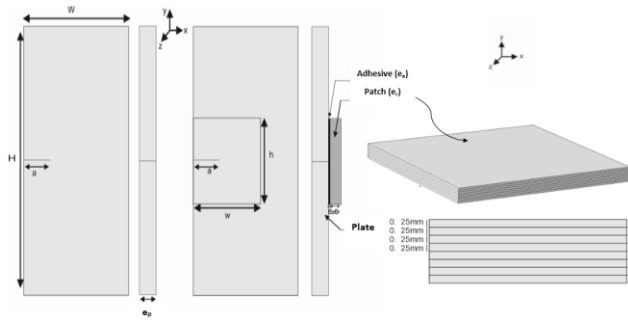


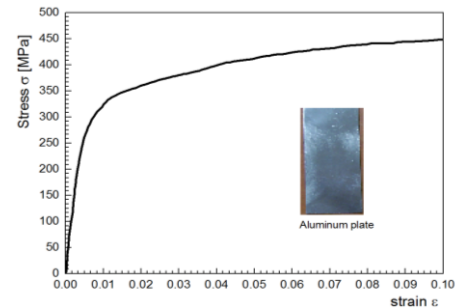
Fig. 1 Geometric model

of the adhesive. Kaddouri *et al.* (2019) numerically analyzed, by the finite element method, the value of the J-Integral for a cracked and repaired plate in the presence of a square-shaped bonding defect, whose position was variable in the surface of the adhesive. The authors presented the variation of the different stresses in the patch and the adhesive according to the geometric and mechanical parameters of the patch, as well as according to the position and the size of the defect. Other studies, such as that of Feng *et al.* (2018), have analyzed the competition between the failure of the patch and its detachment from the structure. The experimental results indicated that the dominant mode of failure is the cohesive failure of the adhesive, accompanied by partial cracks at 45° and 90° of the matrix of the composite patch. In addition, a finite element model was established to predict the tensile strength and describe the damage mechanism. The numerical results showed good agreement with test results, and indicated that matrix cracks in the composite start before adhesive failure. Recently, Kaddouri *et al.* (2020) analyzed, by the finite element method and by using the Abaqus computer code, the variation of the J-Integral in a damaged plate repaired by a composite patch. The authors proposed a geometric modification, in which a removal of material of 0.2 mm is carried out according to the thickness of the plate at the level of the damaged zone where the adhesive will be inserted into the plate. The mode of simulation of the composite as a multilayer and as equivalent property material was taken into consideration, as well as the presence of the bonding defect. The authors showed that the presence of a defect significantly affects the value of the J-Integral and the various stresses in the patch and the adhesive.

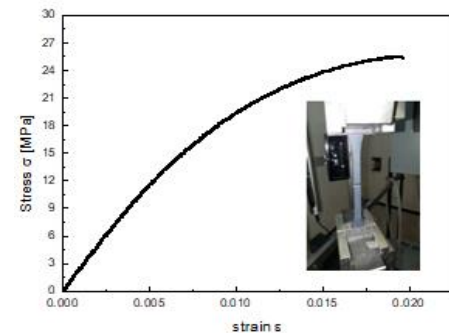
The present work falls within this context. The objective is to analyze, by the finite element method, the failure behavior of a damaged 2024-T3 Aluminum plate repaired by an adhesively-bonded composite patch. The influence of the orientation of the fibers, the applied load, as well as the position and size of the defect, were demonstrated on the transfer of load from the damaged plate to the composite patch. The results of the numerical analysis clearly showed that the use of a composite considerably reduces the J-Integral. The presence of the defect of considerable size on positions such as near the crack or on the free edge of the adhesive considerably influences the repair quality and, therefore, the reduction of stresses in the damaged area.

Table 1 Dimensions of the different substrates

	Length mm	Width mm	Thickness mm
Plate	$H=250$	$W=125$	$e_p=2$
Adhesive	$h=80$	$w=80$	$e_a=0.2$
Patch	$h=80$	$w=80$	$e_r=2$



(a) 2024-T3 Aluminum plate



(b) Adekit A140 adhesive

Fig. 2 Tensile stress-strain curve (Madani *et al.* 2010).

2. Geometric model and mechanical properties

A 2024-T3 aluminum plate was considered, with the following dimensions: height $w=125$ mm, length $L=250$ mm and thickness $e=2$ mm, as shown in Fig. 1. A lateral crack with variable dimensions was introduced in this plate, which will then be repaired by a composite patch. This patch is bonded to the damaged area using the Adekit A140 epoxy adhesive (Fig. 1).

The dimensions of the different structures are shown in Table 1.

The mechanical properties of the plate (2024-T3 Aluminum) and of the adhesive (Adekit A-140) (Table 2) are taken directly from the tensile tests carried out in the LASIE laboratory (Laboratory of Engineering Sciences for the Environment) in France (Madani 2010, Fig. 2). However, for the composite patch, the mechanical properties were estimated by calculating the homogenization between the mechanical properties of the matrix and the fiber.

The adhesive plays the role of assembly between plate and patch and it ensures the transfer of load from the damaged area to the patch. For this purpose, the adhesive must have the minimum thickness to keep its main characteristic which is adhesion. In most studies in this field, the adhesive used has a thickness that does not exceed 0.2 mm. Indeed, if the adhesive takes on a higher thickness,

Table 2 Mechanical properties of the 2024-T3 Aluminum alloy and Adekit A140 adhesive (Madani *et al.* 2010)

Property	Materials		Description
	Aluminum	Adhesive	
E (MPa)	69000	2690	Young's modulus
G (MPa)	26500	1120	Shear modulus
ν	0.3	0.3	Poisson's Ratio

Table 3 Mechanical properties of the fiber, the matrix and the patch composite according to the direction of the fiber 0° (Madani *et al.* 2010)

Materials	
Carbon Fiber	Epoxy Matrix
$E_1=235$ GPa- $E_2=12.9$ GPa	$E=3.7$ GPa
$E_3=12.9$ GPa- $G_{12}=8.05$ GPa	$G_{12}=1.38$ GPa
$G_{13}=8.05$ GPa- $G_{23}=8.05$ GPa	$\nu_{12}=0.33$
$\nu_{12}=0.27$ $\nu_{13}=0.27$ - $\nu_{23}=0.33$	

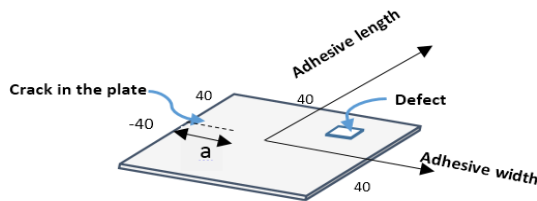


Fig. 3 Presentation of the presence of a defect in the adhesive layer

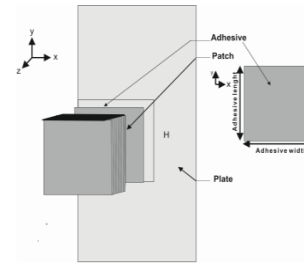
it becomes a third material and does not ensure the load transfer. Therefore, since the adhesive is the weak link of the structure due to the lower mechanical properties, all the load transferred from the damaged area remains in the adhesive and failure of the assembly will be rapid.

The composite patch was modeled in multilayers according to the different orientations of the fibers in each layer. This modeling will make it possible to introduce the real mechanical properties of each layer according to the directions of the fibers, which is coherent with the real behavior of the composites. In this part, homogenization equations in the CADEC code were used to estimate the mechanical characteristics of the composite patch (see Table 3) Madani *et al.* (2010) based on the fiber properties of carbon and epoxy matrix.

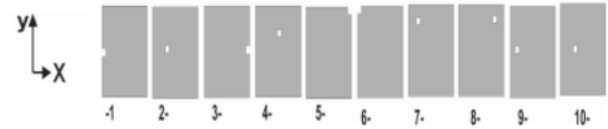
In order to see the effect of the composite fibers' orientation in the patch on the overall behavior of the repaired structure, two stacking sequences were proposed: $[0_{16}]$ and $[0_2/75_2/-75_2/90_2]_S$ (Mokhtari *et al.* 2017).

In order to analyze the effect of the presence of bonding defect on the load transfer from the plate to the patch and therefore on the quality of the repair and the value of the J-Integral at the level of the crack tip, presence of a defect was included in the adhesive layer, considering a square shape and random position. The most defective positions are chosen near the crack, at the crack and at the adhesive free edges. The geometric model of the structure is the same as that shown in Fig. 1, except that the adhesive layer contains a geometric defect as shown in Fig. 3.

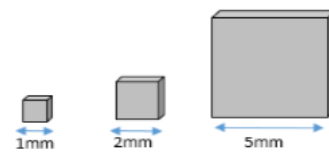
Several positions of the defect have been chosen in the adhesive layer (near the crack, at the level of the free edge),



(a) Representation of the damaged plate repaired by composite patch



(b) Positions of defect in the adhesive layer



(c) Scheme of the different dimensions of the square defect

Fig. 4 Schematics of defect positions and dimensions

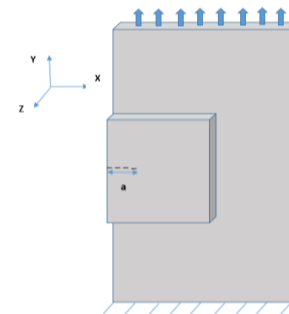


Fig. 5 Model of the repaired structure under tension

since these are the sites of stress concentrations, where stresses are high. On the other hand, the core of the adhesive remains almost inactive in most cases (Fig. 4).

To evaluate the effect of the bonding defect size on the failure behavior of the damaged structure repaired by a composite patch, 10 defect positions were considered in the adhesive layer (Fig. 4(b)) with three different dimensions (Fig. 4(c)). Two stacking sequences for the composite patch were selected, as well as two values of the applied stress.

3. Boundary conditions

The boundary conditions for the repaired plate in tension are reproduced in the following manner.

- Embedding the lower face of the plate $u_1=u_2=u_3=UR_1=UR_2=UR_3=0$.
- Tensile stress applied to the upper face with amplitude of $\sigma=50$ and 100 MPa.

The numerical analysis was carried out by the finite element based Abaqus code.

The adhesive was considered as a third material so that

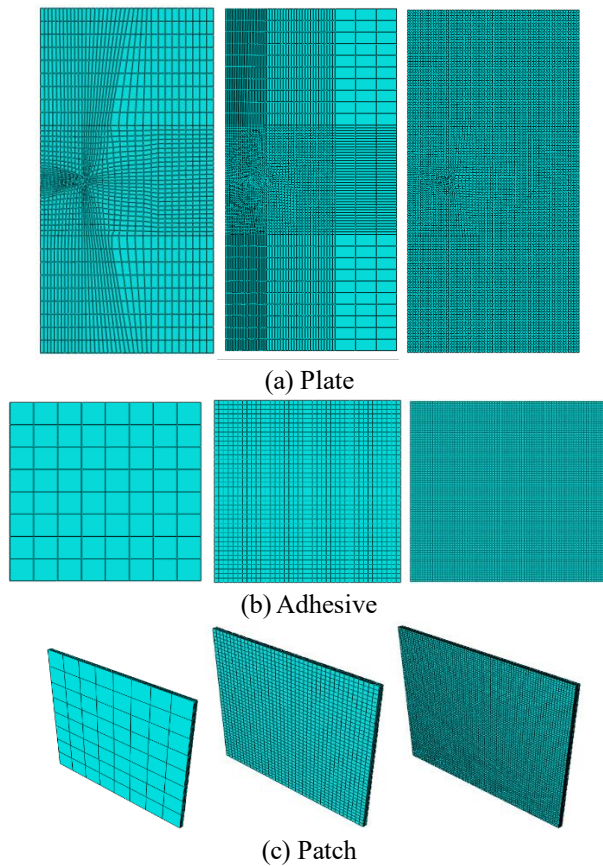


Fig. 6 Representation of the selected meshes with increase in mesh density

one could introduce its actual mechanical properties. Contact is considered to be perfect between the different layers (patch/adhesive, plate/adhesive and between the different layers of the composite). An elastoplastic analysis is considered for the plate and the adhesive by introducing the plastic part of the two materials. For the composite patch, the mechanical properties were determined by the CADEC code, which is especially designed to determine the engineering constants of composites, depending on the fibers' orientation in each layer of the composite patch.

4. Modelling details and convergence analysis

To study the influence of the mesh refinement on the stress distributions, the structural hexahedral linear mesh type was initially fixed, while the mesh density was varied to establish the optimal mesh size. Fig. 6 shows the mesh of the structure according to the number of nodes

The meshes of Figs. 6 (a)-(b)-(c) were obtained by modifying the number of elements for each substrate to a size which makes it possible to obtain a regular mesh. For these meshes, the "biased" option available under Abaqus is used to create a refined mesh essentially towards the area of the crack tip. Using this technique, the number of elements can be varied until reaching a stability of the value of the different stresses in the patch, the plate, and the adhesive, by using elements of smaller size.

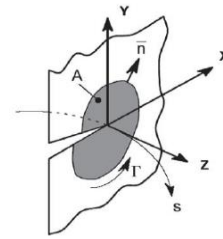


Fig. 7 Contour of the J-Integral calculation (Rezgani *et al.* 2017)

Table 4 the number of mesh of elements for different substrates

Materials	Number of elements
2024-t3 Aluminum	39750
Adekit A140	1600
Composite patch	12800

In most of the studies carried out in relation to the behaviour of repaired structures, the mesh elements of type C3D8, C3D8R, C3D8H, C3D8I have been tested. These types of elements are the most frequently used in the various analyses, because of by their qualities. In this work, C3D8R elements were selected for the analysis.

The J-Integral, which quantifies the intensity of the stress and strain fields at the bottom of the crack and predicts the durability of the repair, is calculated.

The J-Integral is widely accepted as a parameter of Fracture Mechanics for the response of both linear and nonlinear materials. It is related to the release of energy associated with the propagation of cracks and constitutes a measure of the intensity of the deformation at the level of a notch or a crack, in particular for the non-linear materials.

Abaqus/Standard provides a procedure for such evaluations of the J-Integral, based on the methods of integral of domain extension/virtual crack integral methods.

The present study uses the integral domain approach, originally developed by Shih *et al.* (1986), to calculate the energy restitution rate along the curved front of superficial cracks in three-dimensional (see Fig. 7). The local value of the mechanical energy release rate at each point under a static load condition is given by

$$J(s) = \lim_{\Gamma \rightarrow 0} \int [Wn_1 - \sigma_{ij} \frac{\partial u_i}{\partial x_1} n_j] d\Gamma \quad (1)$$

Where Γ is an extremely small contour in the normal plane to the crack front in s , n_j is the normal unit vector at the contour Γ , W is the deformation energy density, σ_{ij} is the component of the nominal stress tensor, u_i is the vector displacement, and X_1 is the local Cartesian coordinate system at locations on the crack front.

After results analysis, the choice for the model mesh was based on the following data (Table 4 and Fig. 9). Table 4 shows the number of mesh elements for the different structure materials.

The plate was meshed with five layers of elements in the thickness direction, the adhesive was discretized with a single layer of elements through its thickness, and the patch was meshed with eight layers of elements through its

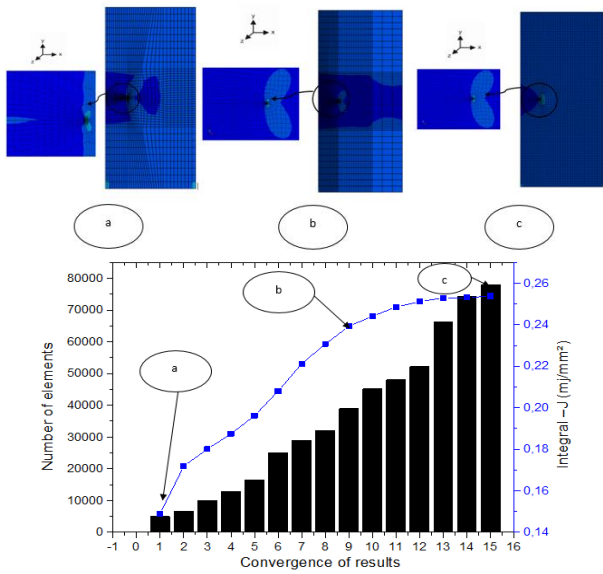


Fig. 8 Convergence of results (crack=30 mm)

thickness, in which each layer is modelled by a single element.

The mesh was refined near the zone of the crack tip with an element size of 0.315 mm, by using at least 20 elements at the front of the crack tip. The number of elements used in this analysis was 54150.

5. Analysis and results

Following previously found results, the type and density

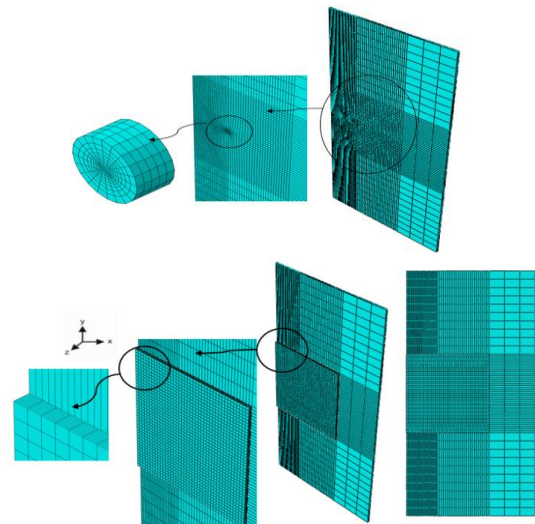


Fig. 9 Mesh details of structure.

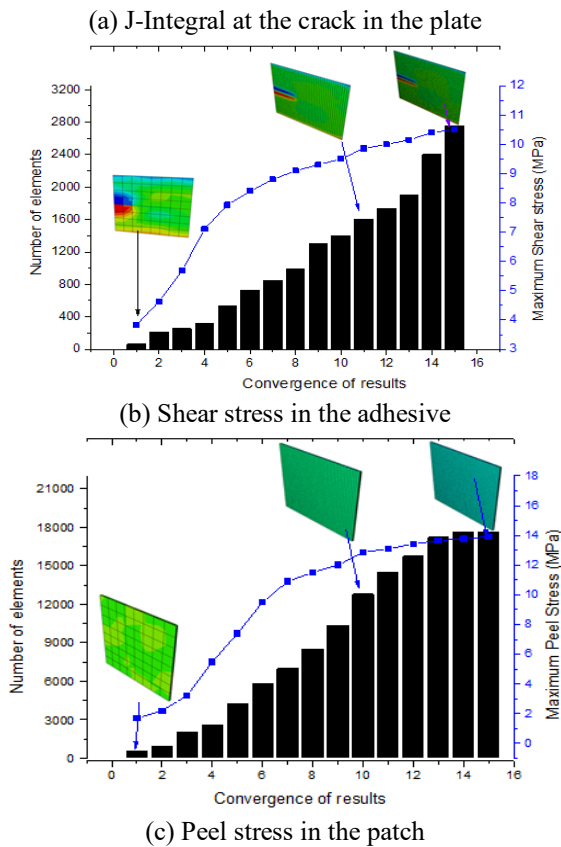


Fig. 10 Variation of the J-Integral as a function of the crack length in a damaged plate repaired by a composite patch without a defect in the adhesive layer.

of mesh elements was fixed in order to assess the variation of J-Integral and stresses in the damaged and patched structures by the numerical analysis.

5.1 Effect of the applied load

Fig. 10 shows the variation of the J-Integral as a function of the crack length for two values of the applied load.

It was noted that the repaired plate by composite patch bonding at the damaged area provides efficiency to the plate by restoring a large part of its stiffness and, therefore, considerably reducing the value of the J-Integral. For short

crack lengths, patch repairing is of little benefit. However, if the crack length is important, the stress concentration is more significant and, therefore, the effectiveness of the patch becomes more visible since a significant reduction in the value of the J-Integral is noted. The increase in the applied load leads to a systematic increase in the value of the J-Integral, although it remains lower than that of the unrepaired plate, regardless of the crack length. For a crack length of 5 mm, the percentile reduction in the value of the J-Integral for an applied load of 50 MPa is 76.12% and, for a load of 100 MPa, it is 74.19%. On the other hand, if the crack length is maximum ($a=30$ mm), patch repairing shows its efficiency, and the reduction of the J-Integral value is 3.68% for an applied load of 50 MPa, and 94.42% for a load applied of 100 MPa.

5.2 Effect of stacking sequence

The choice of stacking sequence in a laminate used as a repair patch is also important. This effect was taken into consideration by evaluating two laminates with different fiber orientations (see Table 4). The variation of the J-Integral is similar irrespective of the stacking sequence. The value of the J-Integral is low for the patch with stacking sequence of $[0_{16}]_s$, but this value increases if the patch stacking sequence is $[0_2/75_2/-75_2/90_2]_s$. For the stacking sequence $[0_{16}]_s$, the patch has the highest mechanical properties according to the loading direction and, therefore, it absorbs more stresses. However, if the orientation angle of the fibers tends towards 90° , the mechanical properties of the patch decrease and, therefore, less load is transferred from the damaged area. If the crack length is too small compared to the width of the plate, the effect of the stacking sequence is small.

Fig. 11 represents the variation of the J-Integral as a function of the crack length for a plate repaired by a carbon/epoxy composite patch for the stacking sequences $[0_{16}]_s$ and $[0_2/75_2/-75_2/90_2]_s$, and for the two values of applied stress.

The stacking sequence plays a decisive role on the load transfer through the adhesive in the damaged area and, consequently, on the value of the J-Integral in the plate, and also on the different stresses in the adhesive and the composite patch. It can be seen from Fig. 10 that, if the fiber orientations are according to the stacking sequence $[0_{16}]_s$, the mechanical properties of the patch become important and, consequently, significant stresses are absorbed from the damaged area by the composite patch. On the other hand, if the fiber orientation is according to the stacking sequence $[0_2/75_2/-75_2/90_2]_s$, the mechanical properties of the patch become low and, therefore, a poor load transfer and high J-Integral values are found. For short crack lengths, the fiber orientations in the different layers of the composite do not have a major effect on the J-Integral, leading to a difference of 18% between the two stacking sequences. If the crack length is important, the stress concentration is high, and the patch shows its efficiency in the case of high mechanical properties (stacking sequence $[0_{16}]_s$), shown by a reduction of 31% in the J-Integral value. By increasing the applied stress, the same phenomenon is observed, just as the J-Integral values increases. The

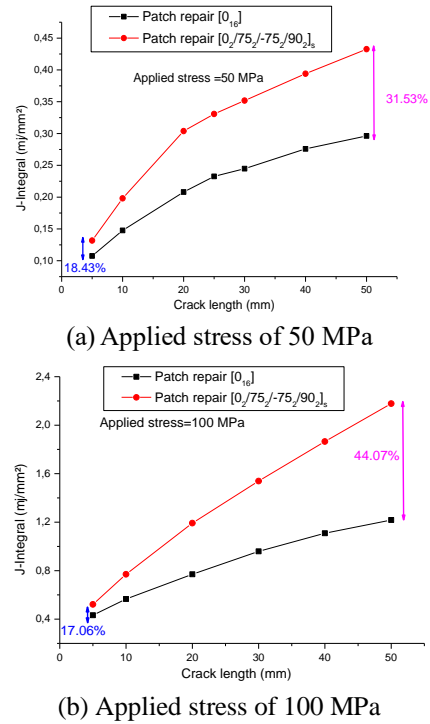


Fig. 11 Variation of the J-Integral as a function of crack length for a repaired plate with stacking sequences $[0_{16}]_s$ and $[0_2/75_2/-75_2/90_2]_s$, and the two values of applied stress

Table 5 Different stacking sequences used in the composite. (Mokhtari *et al.* 2017)

	S1	S2	S3	S4	S5	S6
Stacking sequence $[0_{16}]_s$		$[0_2/15_2/-15_2/90_2]_s$	$[0_2/30_2/-30_2/90_2]_s$	$[0_2/45_2/-45_2/90_2]_s$	$[0_2/60_2/-60_2/90_2]_s$	$[0_2/75_2/-75_2/90_2]_s$

difference in the J-Integral values for the two patches (two stacking sequences) is clearly noticeable (44% reduction of the J-Integral if the crack length is important).

On the other hand, the effect of the stacking sequence was also analyzed such that the orientation of the layers which are outside the composite patch remain fixed $[0^\circ]$, while the internal layers vary so that their orientation varies from 15° to 75° . This variation in orientation of the fibers leads to a variation in the mechanical properties of the composite patch. (see Table 5).

The reduction in the J-Integral value varies according to the stacking sequence and the crack length. If the crack length is minimal (5 mm) the percentile reduction in the J-Integral is less than if the crack length is large. The load transfer is better when the stress concentration is high at the damaged area (Fig. 12(a)).

If the applied load increases, the gain in reduction in J-Integral varies with the crack length (Fig. 12(b)).

The J-Integral increases with increasing of the crack size. The lowest values of the J-Integral are noted for a patch repair with stacking sequence $[0_{16}]_s$. For this orientation, the composite has high mechanical properties and, therefore, the load transfer from the damaged plate through the adhesive is improved, and thus a significant gain is found in the reduction of the J-Integral value.

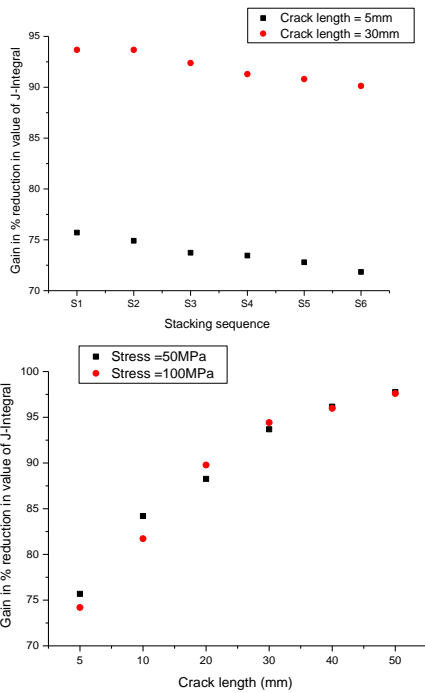


Fig. 12 Variation of the J-Integral as a function of crack length for different stacking sequences

Table 6 Number of mesh elements for different defect sizes in the adhesive layer

Defect size	Number of elements
Defect size=1 mm	1978
Defect size=2 mm	1993
Defect size=5 mm	2000

5.3 Effect of the presence of bonding defects

To evaluate the effect of the bonding defect size on the fracture behavior of the damaged and repaired structure by a composite patch, 10 defect positions were considered in the adhesive layer (Fig. 4(b)) with three different dimensions of the defect (Fig. 4(c)). Two stacking sequences for the composite patch were highlighted as well as two values of the applied stress. For this part of the study, only two crack lengths were considered. For this case the type of mesh chosen is the same as in the previous study, except that the number of elements changes according to the size of the crack in the plate and the defect in the adhesive layer, as shown in Table 6.

The analysis of the fracture behavior of the damaged structure repaired by composite patch in the presence of a bonding defect of variable size depends on several parameters, namely the stacking sequence, the applied load, the nature of the patch and the crack length.

Fig. 13 shows the variation of the J-Integral as a function of the position of the defect for two crack lengths: $a=10$ mm and $a=30$ mm.

- Crack size effect (applied load of 50 MPa)
- Applied load 100 MPa

Fig. 14 shows the variation of the J-Integral as a function of the position of the defect for two crack lengths:

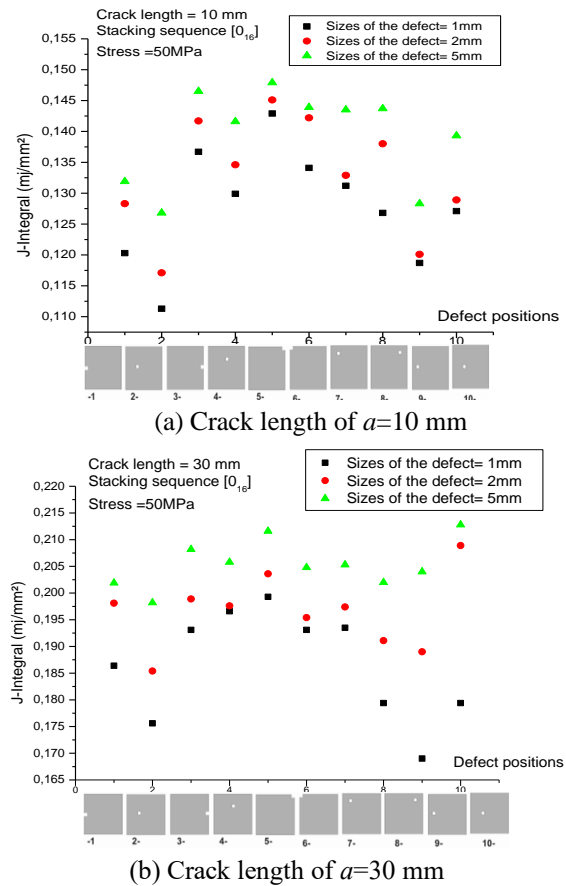


Fig. 13 Variation of J-Integral as a function of defect position for two crack lengths and applied stress=50 MPa

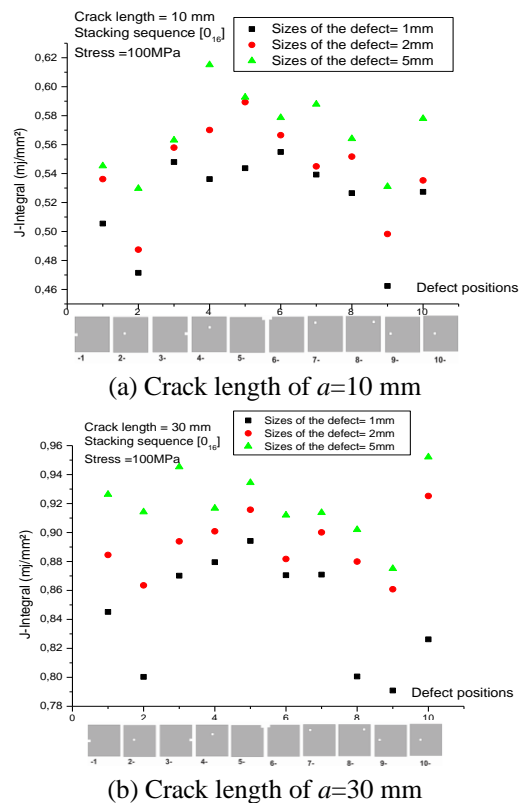


Fig. 14 Variation of J-Integral as a function of defect position for two crack lengths and applied stress=100 MPa

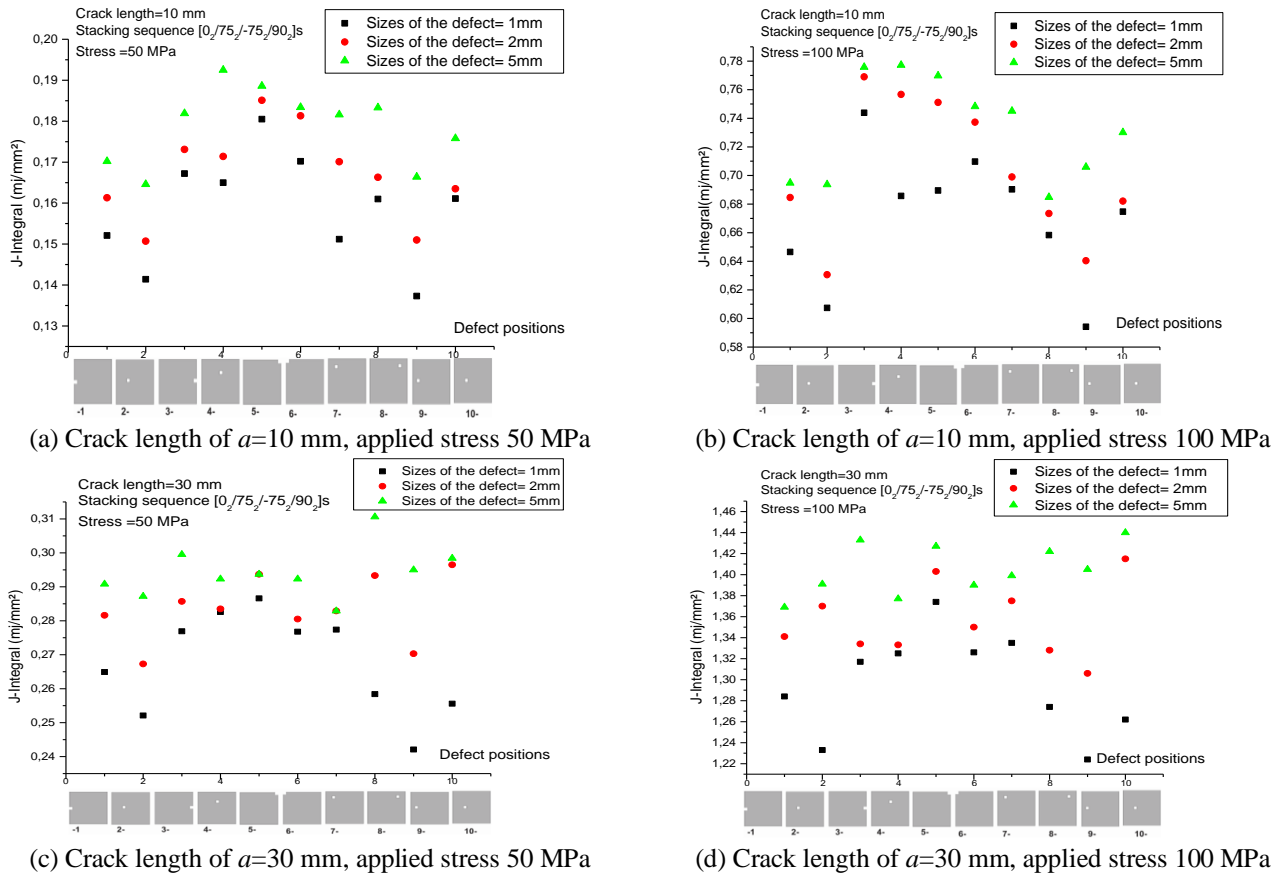


Fig. 15 Variation of J-Integral value as a function of defect positions for different defect sizes, crack length, applied stress and stacking sequence

$a=10$ mm and $a=30$ mm, under an applied stress of 100 MPa. The repair patch has a stacking sequence of $[0_{16}]_s$.

Fig. 15 shows the variation of the J-Integral as a function of the position of the defect for two crack lengths: $a=10$ mm and $a=30$ mm, applied stress=50 MPa and 100 MPa and stacking sequence of $[0_2/75_2/-75_2/90_2]_s$.

It is clearly noticeable that, if the defect size is minimal and the structure is subjected to a low applied stress, the value of the J-Integral is not too much affected. By increasing the applied load, the value of the J-Integral sharply increases and can reach high values of more than 75%. This increase also depends on the position of the defect.

If the defect occurs near the crack or at the free edge, the value of the J-Integral increases. Position 5 of the defect (at the free edge) has the highest values of the J-Integral. As the crack length increases, the stress concentration increases and, thus, more load is transferred to the adhesive, which deforms and absorbs a large part of this stress concentration. However, a smaller amount of load is transferred to the patch and, therefore, high J-Integral values appear. As the applied load increases, the value of the J-Integral considerably increases. In addition, if the defect size is large, the stress absorption gradually decreases and the adhesive transmits less loads to the patch and Thus, the J-Integral value becomes significant. Position 10 of the defect has minimum values of the J-Integral if the crack length is small ($a=10$ mm) for any defect size.

However, if the length of the crack increases and if the bonding defect is in the vicinity of the crack and even at the level of the crack tip, the load transfer to the patch becomes less significant, and a small amount of the high stress concentration in the plate will be transmitted to the patch, resulting in an increase in the value of the J-integral. By considering the stacking sequence $[0_2/75_2/-75_2/90_2]_s$, the mechanical properties of the patch decrease, leading to an increase of the J-Integral. This increase depends on the load, the crack length and the position and size of the defect.

• Stress level in the adhesive layer

The stress level in the adhesive layer clearly shows the distribution of maximum and minimum stresses depending on where there is maximum load transfer and high stress concentration. This stress distribution depends on the nature of the patch, its stacking sequence and size of the crack in the plate and the position of the defect.

-Variation of the von Mises stress

Fig. 16 shows von Mises stresses in the adhesive layer for a defect position at the free edge of the adhesive, a crack length of 10 mm in the plate repaired by a patch with a stacking sequence $[0_{16}]_s$ and subjected to an applied stress of 50 MPa. The value of the von Mises stress in the adhesive layer slightly increases compared to the faultless case. A further increase in this stress is noted with increasing defect size.

For this crack length ($a=10$ mm), which is minimal

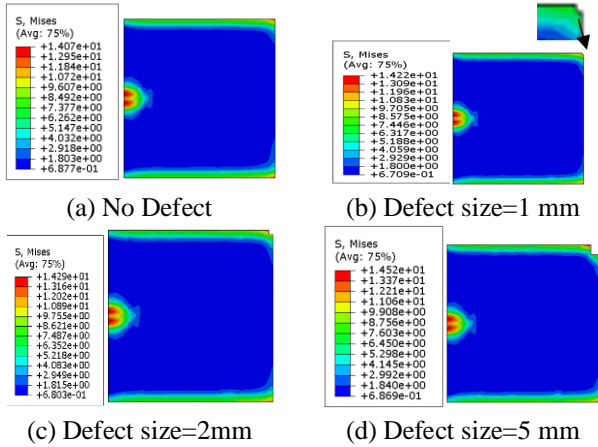


Fig. 16 Level of the von Mises stress in the adhesive layer for a position of the defect at the level of the free edge (crack length 10 mm, stacking sequence $[0_{16}]$)

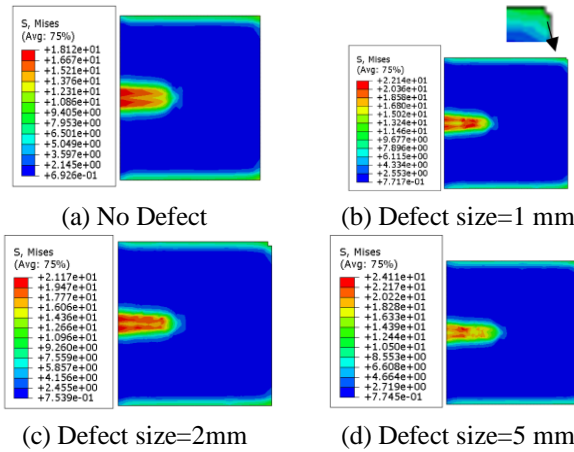


Fig. 17 Level of the von Mises stress in the adhesive layer for a position of the defect at the level of the free edge (crack length 30 mm, stacking sequence $[0_{16}]$)

compared to the width of the plate and the patch, the values of the von Mises stress are small for the different defect sizes for an applied stress of 50 MPa, although slightly exceed the elastic limit of the adhesive, which is 14 MPa. Marked von Mises stress concentrations are localized at the crack vicinity and near the defect, if its size is large. In the presence of the defect, the value of the von Mises stress increases by almost 1.3%. However, if the defect size is large (5 mm), the value of the von Mises stress in the adhesive layer increases by almost 2.9%.

However, if the crack length increases to $a=30$ mm (Fig. 17), the value of the von Mises stress considerably increases as well, and exceeds the elastic limit even for a minimum size of the defect. If the size of the crack increases, a high stress concentration region appears in the plate. In this case, the adhesive transfers more stress to the composite patch so that the value of the von Mises stress in the adhesive layer increases by 22.24% compared to the small crack case. In the presence of a bonding defect, even with minimal size, the value of the von Mises stress increases by 18.15%.

This value of von Mises stress can reach maximum values for a defect size of 5 mm. For this defect size, the

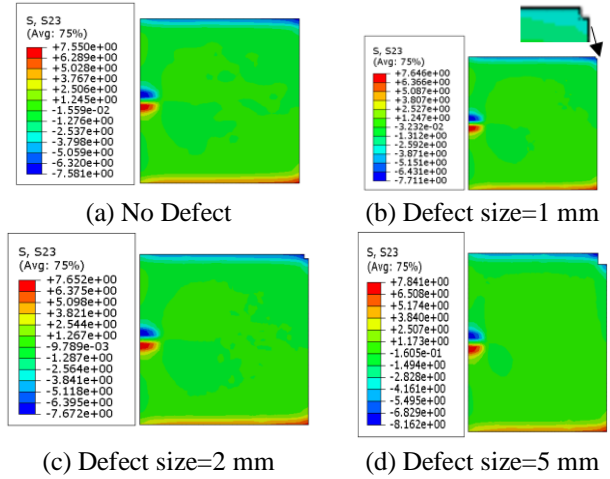


Fig. 18 Level of the shear stress in the adhesive layer for a position of the defect at the level of the free edge (length of the crack 10 mm, stacking sequence $[0_{16}]$)

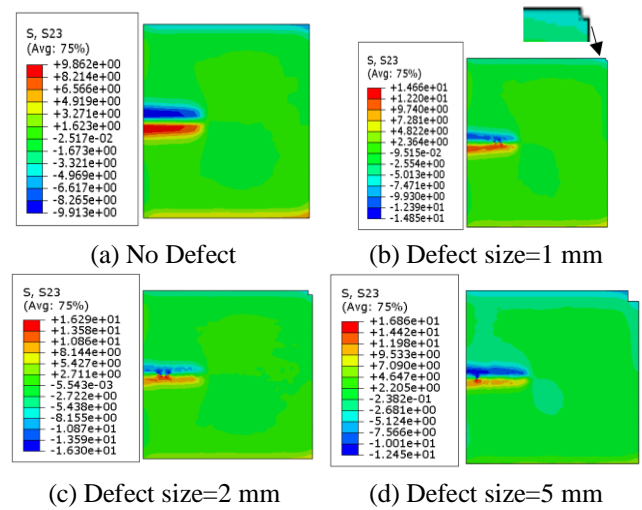


Fig. 19 Level of the shear stress in the adhesive layer for a position of the defect at the level of the free edge (length of the crack 30 mm, stacking sequence $[0_{16}]$)

von Mises stress almost reaches the failure limit of the adhesive.

-Variation of the shear stress

Fig. 18 shows the level of shear stresses in the adhesive layer for a defect position at the free edge of the adhesive. It is clearly seen that shear stresses slightly increase with increasing size of the bonding defect. In the presence of the defect, the shear stress increases by 19%. However, if the size of the defect increases by 4 mm, the shear stress increases by 21.30%. The shear stresses are symmetrical on either side of the crack, and they are concentrated at the level of the crack and the free edge of the adhesive layer.

If the crack length increases to $a=30$ mm (Fig. 19), the value of the shear stress sharply increases (by 37% compared to $a=5$ mm), although depending on the size bonding defect. In the presence of a defect of minimum size, the value of the shear stress increases by 33%. If the size of the defect is 5 mm, the shear stress increases by 41.51%.

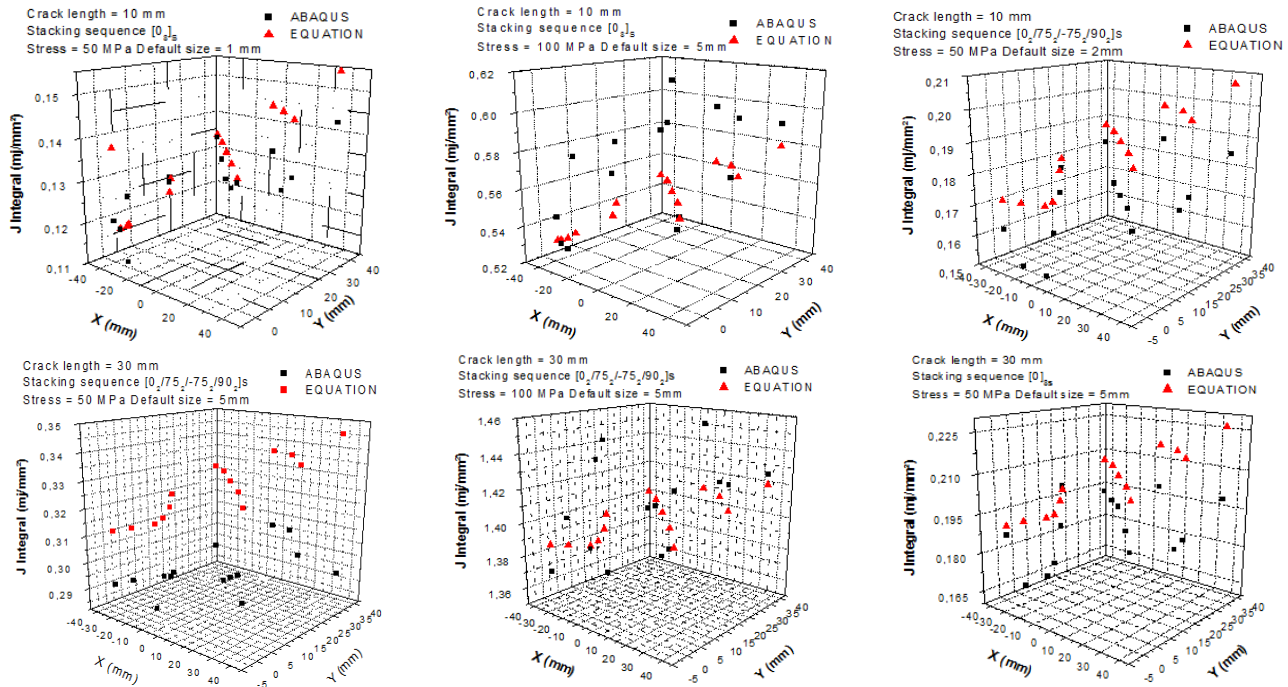


Fig. 20 Variation of the value of the J-Integral according to the position of the defect for different parameters according to the numerical analysis and the optimization equation

Table 7 Calculation of Θ for the two stacking sequences

	Young modulus E_1	Young modulus E_2	Ratio of Young modulus $\Theta = E_1/E_2$
$[0]_{16}$	128525	97664.5	1.31598483
$[0_2/75_2/-75_2/90_2]_s$	52080	124800	0.41730769

6. Optimisation

Through the analysis of the various parameters influencing the failure behavior of the structure damaged and repaired by an adhesively-bonded composite patch, the parameters were grouped together so that an equation is established that allows estimating the value of the J-Integral without going through the numerical calculation using Abaqus. With this purpose, the MINITAB statistics software - version 14 was used. This software is particularly well suited to the statistical analysis of small, well-structured data tables, descriptive statistics, analysis of variance, methods relating to correlation and to the simple and multiple regression, time series, tests of independence, nonparametric methods, principal component analysis, discriminant analysis, statistical quality control, and experimental designs.

The parameters used in this analysis were inserted into the MINITAB software and were optimized so that the J-Integral is a function of the defect position and area, stacking sequence, crack size and applied stress.

The result of the J-Integral equation is given below.

$$J = -0,457 + (x \times 0,0002) + (y \times 0,0001) - (s \times 0,0013) + (\theta \times 0,4168) - (a \times 0,0076) + (p \times 0,0098) - (x \times \theta \times 0,0002) - (y \times \theta \times 0,0002) - (s \times \theta \times 0,0006) - (\theta \times a \times 0,0099) - (p \times \theta \times 0,0056) + (a \times p \times 0,0004)$$

where xy =Defect position, s =Defect surface, Θ =ratio of Young modulus a =Crack size, and σ =applied stress.

In the present case, two stacking sequences S1 and S2 were used, and the longitudinal (E_1) and transverse (E_2) Young modulus ratio for the patch were also introduced, as shown in Table 7.

By comparing the results of the numerical analysis in Abaqus with those of the optimized equation, an error which varies from 0.16% to 13.34% was found (Fig. 20) in J-Integral depending on the parameter chosen, namely stacking sequence, applied stress, defect size and crack size.

7. Conclusions

This work aimed to evaluate the tensile response, as J-Integral measurements, of a composite patch-repaired 2024-T3 aluminum plate depending on the position and size of the bonding defect. The analysis led to the conclusions:

- The composite patch reduces greatly the value of the J-Integral, especially if its mechanical properties are high. Thus, the stacking sequence plays an important role in reducing the value of the J-Integral at the crack tip, shear stresses in the adhesive and peel stresses in the patch.
- Higher load transfer is achieved with $[0]_{16}$ patch stacking sequence, and consequently, the measured J-integral reduces.
- If the length of the initial crack is minimal, the position and the size of the defect have little influence on the J-Integral.
- The J-Integral, peel stresses in the patch, and shear stresses in the adhesive highly depend on the defect position and size.
- The numerical analysis enabled highlighting several parameters in the evaluation of the J-integral.

- A mathematical model was established to evaluate the J-Integral without using Abaqus. This model presents values close to the numerical models, with errors between 4% and 13% depending on the parameters.

Thus, with this work, design guidelines are provided for the repair of cracked aluminum with bonded composite patches, together with relevant information on the repair layout to attain the best results, thus expediting the design process.

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