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Estimation of the Stress-Intensity Factor Value in the Presence of an Adhesive Defect for a Damaged Plate Repaired with a Composite Patch

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Since the implementation of the process for repairing damage in aeronautical structures, the composite patch repair process continues to show its performance with respect to reducing the concentration of stresses in the vicinity of geometric discontinuities and, therefore, ensures a long lifespan of the repaired structure. Despite the advantages, which this process represents compared to conventional riveting, bolting and welding processes, this process still remains applicable for secondary structures. In fact, the exposure of the adhesive to temperature and humidity and the existence of flaws within the adhesive layer remain a major problem of its use. Indeed, during the implementation of this process, several defects are

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likely to become integrated into the adhesive layer (cavities, cracks, air bubbles, *etc.*) during the preparation of the surface of the damaged plate; this can lead to inadequate load transfer from the adhesive to the patch. The analysis of the effect of the presence of this type of defect is important for the evaluation of the different constraints in the different substrates. Our work is part of this context; its aim is to employ the finite-elements' method to examine the mechanical response of a 2024-T3 aluminium plate, which has been damaged and repaired using a composite patch subjected to tensile stress in the existence of a bonding defect with a square shape. The study takes into consideration notch and crack interaction effect in the damaged plate, on the one hand, and the position of the bonding defect, on the other hand. Several factors are highlighted, namely, the crack length, the applied load and defect position. The investigation of the stress-intensity factor and the stresses within the assembly substrates illustrates their dependence on various parameters, particularly, the defect position of the bonding.

Key words: stress-intensity factor composite patch, von Mises stress, shear stress, peel stress, bonding defect.

З моменту впровадження процесу ремонту пошкоджень в авіяційних конструкціях процес композитної латки продовжує демонструвати свою ефективність щодо зменшення концентрації напружень поблизу геометричних нерівностей і, таким чином, забезпечує тривалий термін служби відремонтованої конструкції. Незважаючи на переваги, які цей процес має порівняно з традиційними процесами заклепування, болтового з'єднання та зварювання, він все ще залишається прийнятним для вторинних конструкцій. Насправді, вплив температури та вологости на клей, а також наявність дефектів у адгезійному шарі залишаються основними проблемами його використання. Дійсно, під час реалізації цього процесу існує ймовірність вбудовування у адгезійний шар декількох дефектів (порожнин, тріщин, бульбашок повітря тощо) під час підготовки поверхні пошкодженої пластини, що може привести до невідповідної передачі навантаження від адгезиву до латки. Аналіза впливу наявности такого типу дефектів є важливою для оцінки різних обмежень на різних підкладинках. Наша робота є частиною цього контексту; її метою є використання методу скінченних елементів для дослідження механічної реакції алюмінійової пластини 2024-T3, яку було пошкоджено та відремонтовано за допомогою композитної латки, що піддавалася розтягуванню за наявности дефекту зчеплення квадратної форми. Дослідження враховує ефект взаємодії надрізу та тріщини в пошкодженій пластині, з одного боку, і положення дефекту зчеплення, з іншого боку. Було виділено декілька чинників, а саме, довжину тріщини, прикладене навантаження та положення дефекту. Дослідження коефіцієнта інтенсивности напружень і напружень у складальних підкладинках ілюструє їхню залежність від різних параметрів, зокрема від положення дефекту зчеплення.

Ключові слова: коефіцієнт інтенсивности напружень, композитна латка, фон Мізесові напруження, напруження зсуву, напруження відшарування, дефект зчеплення.

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1. INTRODUCTION

At present, all structures used in the various aeronautical and construction sectors present geometric discontinuities such as cracks, notches, delaminating and cavities, which are the cause of reduced structural life under mechanical or thermal stress. Once damage has been detected in the material, depending on its critical size, engineers must decide whether or not to repair the structure. Various solutions were presented, including the patch repair process, which offers several advantages over bolting, riveting and welding to improve the durability of the part. This method exhibits greater structural efficiency, with less structural damage than others. Several researchers have sought to develop a composite patch [1, 2] capable of transferring maximum stress from the damaged zone by optimizing its mechanical properties, shape, dimensions and above all the nature and volume fraction of the fibre, in order to provide high resistance to damaged structures, taking into account all the influencing parameters (mechanical load, humidity, temperature, *etc.*).

The patch repair technique, known for its effectiveness, offers several advantages over other techniques. Patching generally involves covering or reinforcing a damaged area with a similar or compatible material to restore its functionality and improve the life of the structure. The patch material minimally impacts static strength but significantly influences fatigue resistance [2]. The technique can be carried out by bolting, riveting or welding for metal alloys, but experimental, numerical and analytical studies have demonstrated the effectiveness of bonded patch repairs in composites for controlling crack propagation in thin plates [3]. Tsamasphyros *et al.* [4] conducted a study on composite patch repair using both analytical and numerical approaches. Wang *et al.* [5] investigated the analytical method for stepwise patch repair.

The most widely adopted repair method involves bonding a composite patch onto the damaged area. Technique in the aeronautics field and its use is becoming increasingly widespread. This technique consists of sticking a composite patch to the damaged region using an appropriate adhesive. The choice of repair method depends on the nature of the material to be repaired, the damage and its use [6]. Currently, we are seeking to develop a composite patch capable of transferring as much as possible the stresses of the damaged zone by optimizing its mechanical properties, shape, dimensions and especially the fibre's nature and volume fraction, in order to provide great resistance to damaged structures taking into account all influencing parameters (mechanical load, humidity, temperature, *etc.*). Several researchers [7–9] have studied the composite patches effectiveness and have carried out various optimization analyses regarding composite patch design capable of transferring maximum stress to the damaged area. Further experimental investigations have been carried out to improve the performance of composite repair joints by optimizing their geometric parameters [10, 11]. Mohammed *et al.* [6] investigated experimentally and numerically the influence of different shapes of composite-bonded patches. The finite element method was employed to evaluate how various parameters of the repair process affect the overall performance of structures repaired using composite patches [12].

Furthermore, a cracked aluminium plate was subjected to a nonlinear study employing a hybrid repair technique, which involves bonding a composite patch and drilling holes in opening mode. This investigation was carried out using finite element analysis methods [13].

On the other hand, the optimization of the adhesive layer takes precedence over that of the composite material due to its superior efficiency, given its role as the weakest link in the structure owing to its inferior mechanical properties compared to those of the plate and the composite. For this, the choice of an adhesive must be suitable for assembling the patch and the plate. This adhesive joint must be characterized for good use in repair [14]. For example, Dai *et al.* [15] investigated how adhesive properties and composite patch configurations influence the repair process of damaged aluminium alloy plates. Kwon *et al.* [16] analysed the adhesive layer to decrease the strain-energy release rate while repairing the cracked plate on one side.

Currently, the challenge for inspection engineers is the detection of different defects in the adhesive layer where non-destructive means of detection are not available [5, 9].

Indeed, the resistance of joints in assemblies is affected by the presence of bonding defects which will result in poor load transfer and consequently present a challenge for maintenance engineers to propose methods allowing detection and/or repair. Identify these defects using the means available to detect whether the bonding surface is healthy or presents defects [7, 11].

Current research aims to analyse the stress level within the adhesive joint to determine the high stress concentrations magnitude due to the presence of these geometric discontinuities.

For this purpose, it is essential to understand, through experimental and numerical analyses, the influence of the presence of defects in the adhesive layer on the global behaviour of the assembled structures. Recent researchers [8, 10, 13] have highlighted in their numerical analysis by finite elements the presence of defects in the adhesive and were able to analyse their effect on the global response of the assembled structures [17, 18] or in the case of repairing damaged plates with composite patches [19]. Kaddouri *et al.* [20] analysed numerically, using finite-elements' analysis, the fracture behaviour of a plate with damage in the form of a bonding defect, which was then repaired by a bonded composite patch where they studied the defect position and size effect. The size and shape of the bonding defect on the adhesive joint behaviour and consequently on the global response of an assembly was addressed by Heiderpour *et al.* [21], where it was shown that, if the defect size is important, it can lead to rapid damage to the structure.

Our work is part of this context and aims to determine the SIF in a 2024-T3 aluminium plate repaired with an epoxy carbon composite patch. The size effects of a crack emanating from a circular notch in the plate as well as the defect position of the bonding relative to the adhesive surface were taken into consideration to analyse the stress intensity factor. The level of von Mises and shear stresses in relation to the defect position were presented in this study.

2. MATERIALS AND MODELS

The analysis involves a damaged structure repaired using a composite patch. This structure contains a 2024-T3 aluminium plate measuring $125\times250\times2$ mm^3. The plate has a circular notch in the centre with a diameter of 6 mm (Fig. 1, *a*). A crack emanating from the notch will be considered in the study of variable length a (Fig. 1, *a*).

A composite patch will be applied to the damaged area of this plate for repair (Fig. 1, *b*). The length, width and thickness of the composite part are respectively $h_p = 80$ mm, $W_p = 80$ mm and $t_p = 2$ mm. This patch is presented in the form of a laminate of 16 layers whose stacking sequence is as follows $[0]_{16}$. This patch is bonded using Adekit A140 type adhesive with a thickness of $t_a = 0.2$ mm. The shape of the patch was

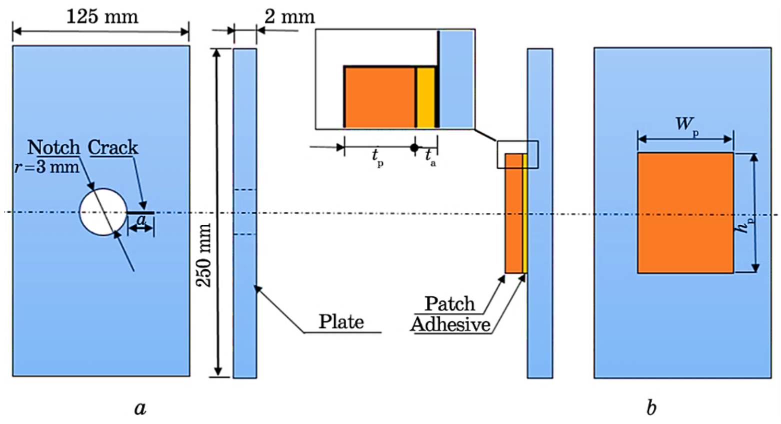

Fig. 1. Schematic representation of: aluminium 2024-T3 plate with crack emanating from notch (*a*), repaired plate with composite patch (*b*).

initially chosen square, as it is the most commonly used shape. The composite patch was simulated as unidirectional layer. This technique facilitates the incorporation of the real mechanical properties of each layer according to the fibres' directions, which is more realistic. The different mechanical properties necessary for the numerical model using the ABAQUS calculation code are derived from the tensile tests (Fig. 2) conducted on the different substrates [22].

From these curves, the different mechanical properties were presented in Table 1 and which are necessary for the numerical model.

The composite patch is based on high strength carbon fibre and an epoxy matrix. To introduce the patch mechanical properties, it was possible to experimentally determine the two different Young's moduli according to the longitudinal and transverse direction of the composite plate [23], but these two properties are not sufficient to successfully introduce the patch composite mechanical properties in the numerical analysis as being an orthotropic material, for this purpose both the carbon fibre and the epoxy matrix properties were introduced into the Cadec code designed especially for composites to determine the global properties of the patch based on the stacking sequence. The properties

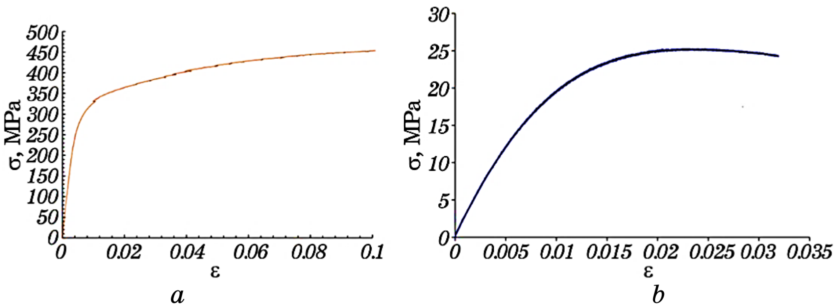

Fig. 2. Stress–strain curves for the 2024-T3 aluminium plate (*a*) and Adekit A140 adhesive (*b*).

TABLE 1. Aluminium plate and adhesive mechanical properties.

Parameter	Aluminium 2024-T3	Adhesive Adekit-A140
Young's modulus (E)	74400 MPa	2692 MPa
Tensile strength (R_m)	452 MPa	25
Yield strength ($R_{0.2}$)	230 MPa	14
Poisson's ratio (υ)	0.3	0.3
Shear modulus (G)	26000 MPa	1000
Elongation (A, %)	10	3.5

TABLE 2. Mechanical properties of the composite single layer oriented at zero degree.

Materials	$E1$ MPa	$E2$ MPa	$E3$ MPa	υ12	υ13	υ23	G12 MPa	G13 MPa	G23 MPa
Carbon/ Epoxy	128600	9766	9766	0.34	0.34	0.34	5252	4364	4364

determined by the Cadec code (essentially the two Young modules) were compared with those found experimentally where an error of 2.4% was found. The mechanical properties of the single-layer composite utilizing high strength carbon fibre are presented in Table 2.

3. ADHESIVE DEFECT

The strength of a composite patch repaired structure is significantly influenced by the adhesive's strength, which has the weakest mechanical properties compared to plate and composite. Indeed, the behaviour of the adhesive remains a complex subject without an exact solution. Indeed, adhesive failures can be influenced by operational and environmental factors during the application process such as cavities, air bubbles, cracks, impurities, *etc.* (Fig. 3). Additionally, poor surface preparation could be the primary cause of assembly failure.

The majority of studies in the realm of composite patch repair consider the adhesive to be a perfect third material where contact with the plate and with the patch is made over the entire surface of the damaged area, or in reality, it is necessary to consider the presence of defects in order to see their effect on the load transfer to the patch and consequent-

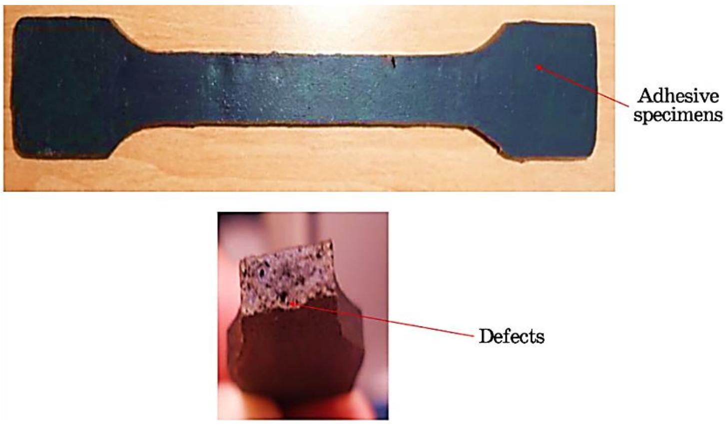

Fig. 3. Presence of defects during preparation.

ly on the repaired plate resistance. Our study is based in this context.

4. ANALYSIS METHODOLOGY

Our analysis (Fig. 4) concerns the plate, the composite patch and the adhesive, with consideration given to the defect position of the bonding (Fig. 3):

- for the plate, a comparison between repaired and non-repaired plates by determining the SIF at the crack tip;
- for the patch, determine peel stresses;
- for the adhesive, shear and von Mises stresses.

5. RESULTS

5.1. Mesh Selection

To achieve reliable results regarding to the damaged plate, the patch and the adhesive, it is necessary to choose an adequate mesh for the three substrates. The mesh was refined, particularly in the damaged area, and subsequently on the adhesive and the patch until stable stress values were attained, particularly at the notch level. Indeed, the von Mises stress variation analysis regarding the unrepaired plate mid-width (Fig. 5) show clearly that the mesh elements density has an influence in relation to the maximum value at the level of the notch where a variation of the value stress can reach 10%. However, far from the notch the density of mesh elements does not have a significant effect.

Likewise, the global plate response in terms of displacement load was analysed with changes in the mesh elements density (Fig. 6). The

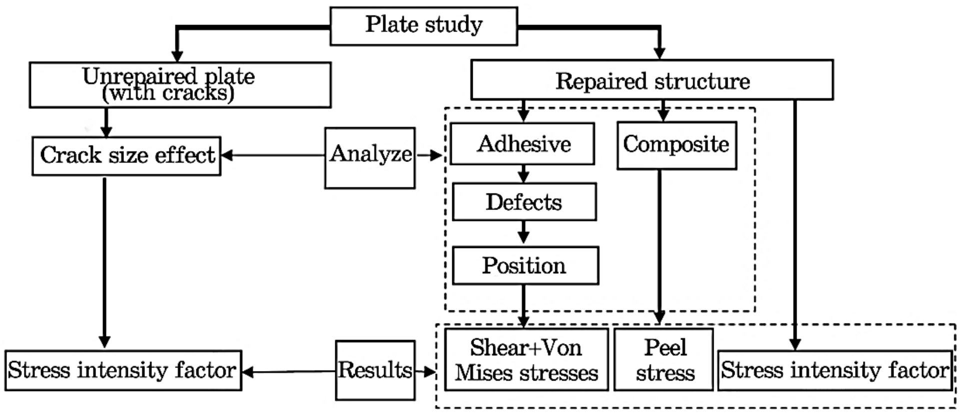

Fig. 4. Analysis methodology flowchart.

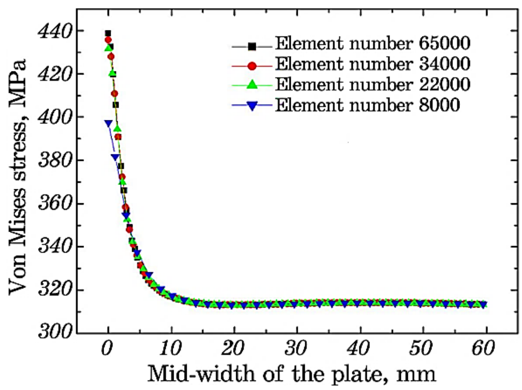

Fig. 5. Von Mises stress variation according to the unrepaired plate mid-width.

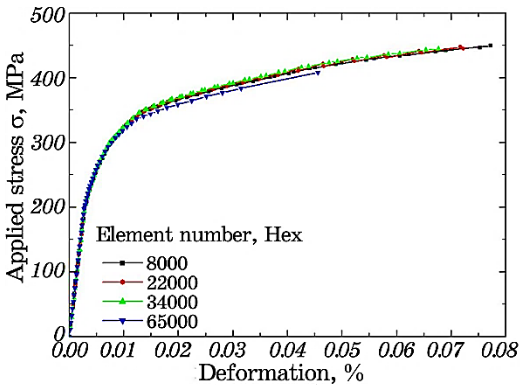

Fig. 6. Applied stress as a function of plate deformation for different numbers of mesh elements of type C3D8R.

obtained results show that the element density has no influence on the elastic part. On the other hand, mesh element density does have an influence on the plastic part, with a slight variation in stress and a deviation in plate deformation.

Finally, the type of mesh elements chosen is C3D8R, which is the most used for the mechanical analysis of structures. The density of mesh elements is varied in our study until it has a well-refined structure as shown in Fig. 4.

In the case of a notched plate with crack emanating from a notch, the damaged part of the plate has been refined more and more, as shown in Fig. 4, where the elements number varies as per to the crack size. At the notch level, refinement was done to a point where the circular shape appears clearly. Depending on the thickness of the structure, the

TABLE 3. The number of nodes and elements of unrepaired and repaired plate.

Crack length	Nodes/Elements	Semi-circular notch and crack	
		Unrepaired	Repaired
10 mm	Nodes	32022	50513
	Elements	20880	35280
30 mm	Nodes	39024	57515
	Elements	25426	39826

plate was meshed with 4 elements, while the adhesive layer has 2 elements, and the composite patch has 8 elements.

For the boundary conditions, a uniaxial loading was applied to the upper part of the plate with amplitude of $\sigma = 100$ MPa along the y-axis; the lower plate part is considered as embedded where the displacements and rotations are considered null.

5.2. Variation of K_I in Relation to Defect Position

To analyse how the presence of a bonding defect affects the fracture behaviour of the repaired structure, the presence of a square-shaped bonding defect with a surface area of 9 mm^2 was assumed at different locations on the adhesive surface (Fig. 8). A number of 14 defects positions were taken into account within the adhesive layer and given the symmetry we considered that the presence of the defect only on the upper part as shown in Fig. 8. For the analysis of the SIF at the crack tip, two cracks lengths (10 mm and 30 mm) emanating from the circular

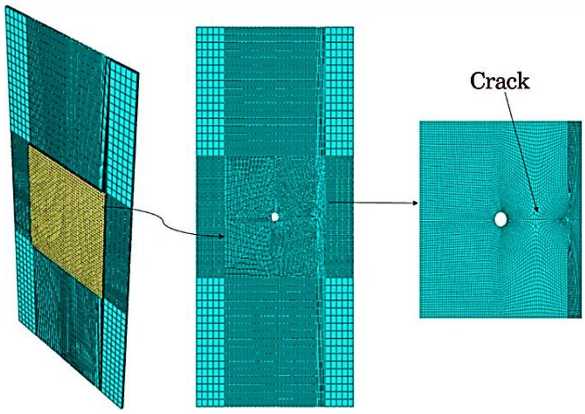

Fig. 7. Mesh details.

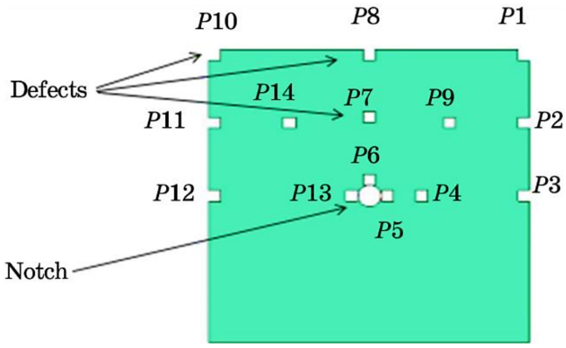

Fig. 8. Graphic representation of the different defect positions in the adhesive layer.

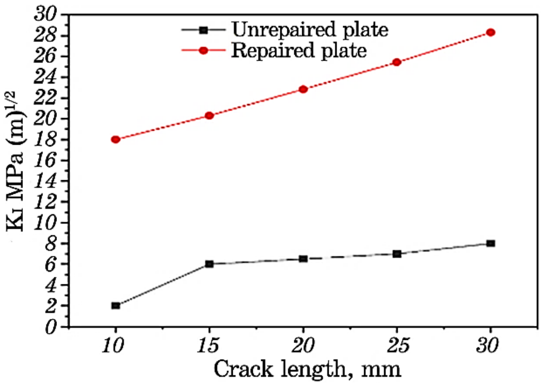

Fig. 9. The SIF variation as per of the crack length for a repaired and unrepaired plate.

notch were considered.

For each crack length, we varied the position of the defect according to the 14 possible cases. For defects 4 and 7, they are chosen so that their position will be in contact with the head of the crack. Defect 4 is located at the head of the 10 mm crack, while this same defect will be in position 7 for the size of the crack 30 mm.

5.2.1. Effect of the Repair Patch in the Absence of Adhesive Defect

In the first case, the analysis focused on evaluating the effect of the repair patch on the value of the SIF as a function of the crack length. The calculation of the SIF (K_I) as per of the crack length is presented in Fig. 9. It is clear in Fig. 9 that the composite patch absorbs the stresses in the damaged area via the adhesive used and minimizes the high

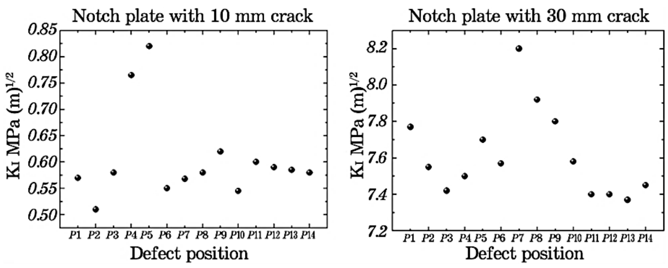

Fig. 10. SIF K_I variation as per of adhesive defect positions.

stress concentration at the crack and notch. The value of K_I at the crack tip augments with the increase in crack length and is reduced by almost 70% compared to the unrepaired plate.

5.2.2. Repaired Plate with Adhesive Defect

For this part of the study, the presence of defects at the 14 positions suggested in Fig. 5 was taken into account. We analysed the stress intensity factor value for two crack lengths ($a = 10$ mm and $a = 30$ mm). The first crack is located near the notch and far from the free edge of the patch, while the second crack is of significant length and situated near the defect, close to the free edge of the patch and the adhesive. The results of the SIF variation with respect to the different positions of the bonding defect are presented in Fig. 10.

For a crack length $a = 10$ mm, the SIF values are almost identical for the different defect positions. The lowest value is noted for defect position $P2$ and the highest value is for defect position $P5$ (Fig. 10, a). The stress intensity factor value for the case where the defect is in contact with the notch illustrates an increase of almost 60% compared to other positions. The defect position proximate to the notch and at the free edges ensures poor load transfer, leading to a high concentration of stresses.

For crack length (30 mm), the value of the SIF is very high compared to those of 10 mm of crack length. The lowest value is noted for defect position $P13$ and the highest value is for defect position $P7$. At these positions, the defect is at crack tip level, so load transfer to the patch is minimal, and the majority of stresses remain at crack level, resulting in a high SIF value in the plate (Fig. 10).

5.2.3. Shear Stress Level of the Adhesive (Notch Plate with 10 mm Crack) for Different Defect Positions

Analysing the variation of shear stress within the adhesive joint pro-

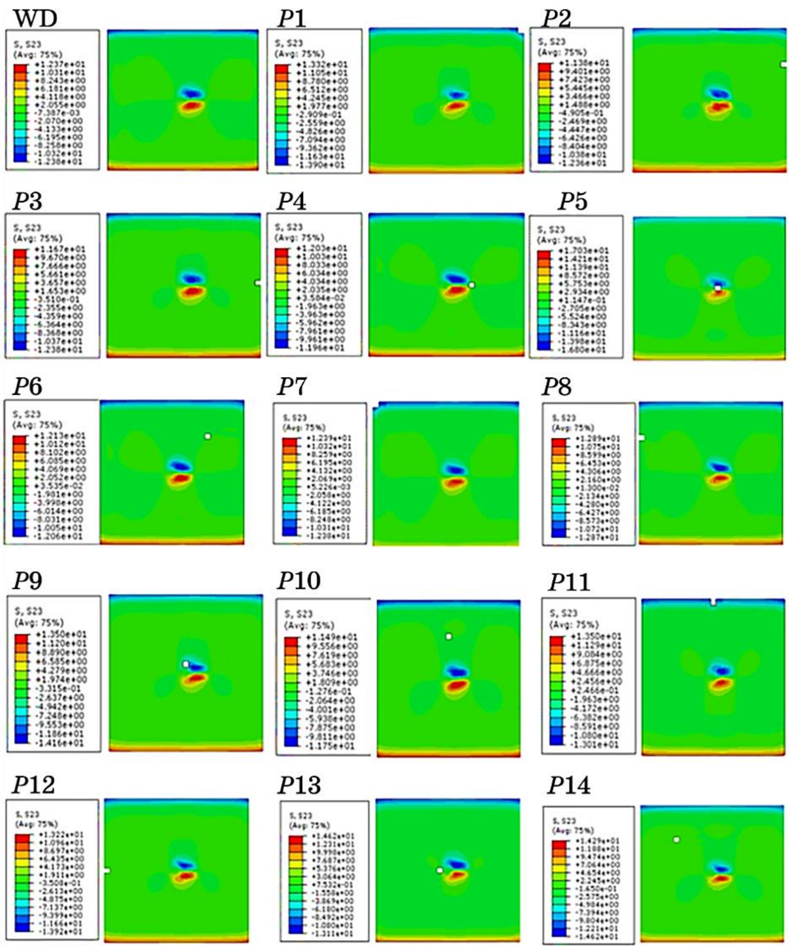

Fig. 11. Shear stress level in the adhesive joint as per of the position of the defect. (where WD: adhesive without defect, *P*: defect position in the adhesive).

vides a deeper understanding of the adhesive's role in load transfer and, consequently, in the failure behaviour of the repaired plate. For this analysis, the defect size of 9 mm^2, square in shape, was maintained at the 14 proposed positions (Fig. 11).

Figure 11 shows the analysis of the defect position effect on the level of shear stresses in the adhesive layer. The stress distribution clearly shows that the maximum shear stresses are concentrated at the two edges of the adhesive and in contact with the notch and the crack. In most cases of defect positions, the adhesive has a central inactive zone only a small area which is in contact with the notch and crack. Defects, which are far from areas of high stress concentration, do not disrupt the stress distribution in the adhesive layer. The shear stress value is generally maximal in the presence of the bonding defect except in the case where the defect is situated far from areas of high concentration of stresses.

5.2.4. Von Mises Stress Levels in the Adhesive for Different Defect Positions with a 10 mm Crack in the Plate

The adhesive in a damaged and repaired structure is subjected to various stresses. Therefore, it is also important to analyse the equivalent stress to understand, if the adhesive is operating in the elastic or plastic domain.

Figure 12 illustrates the analysis of the effect of the bonding defect position on the value of the von Mises stress in the adhesive. It is ob-

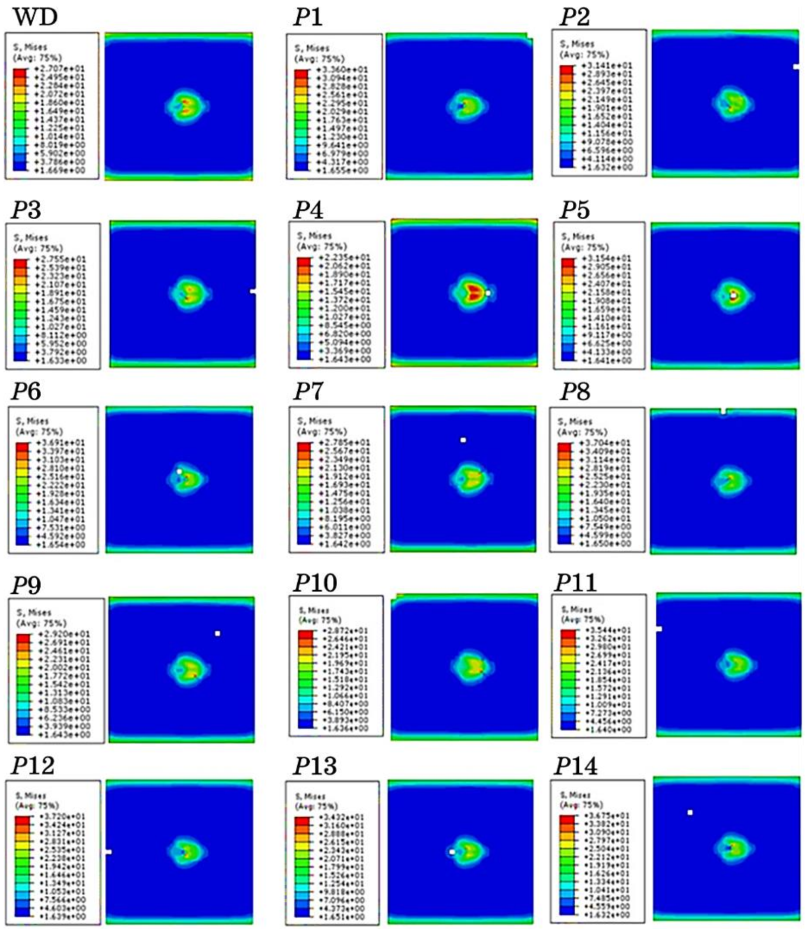

Fig. 12. Von Mises stress levels in the adhesive for different defect positions defect (notched plate with crack length $a = 10$ mm).

served that for this minimum crack length of 10 mm, the defect position significantly influences the von Mises stress value and, consequently, the adhesive joint strength.

The presence of a crack emanating from a notch causes a significant stress concentration within the plate, consequently increasing the load transfer to the patch significantly, inducing the adhesive to absorb a large amount of this load. Without a bonding defect, the von Mises stress exceeds its rupture limit by a significant margin, indicating that the adhesive under this loading condition may experience delamination.

The presence of the bonding defect increases the von Mises stress value, and this difference based on the defect position. It is observed that position 8 of the defect significantly affects the von Mises stress value, as this position is in contact with both the notch and the crack.

5.2.5. Maximum Von Mises Stress and Shear Stress Level in the Adhesive for Different Defect Positions with 10 mm Crack in the Plate

Based on the results presented in Figs. 11 and 12 regarding the stress level in the adhesive joint, an attempt was made to group the maximum von Mises values and shear stresses for each defect position. Figure 13 illustrates the maximum von Mises and shear stresses variation as per the defect position. It is observed that when the adhesive defect is located proximate the crack or notch, the stress concentration is higher and the shear stress value is therefore greater on the crack side and when the defect is situated on the free edge of the adhesive.

For this crack size, most defect positions in the adhesive layer result

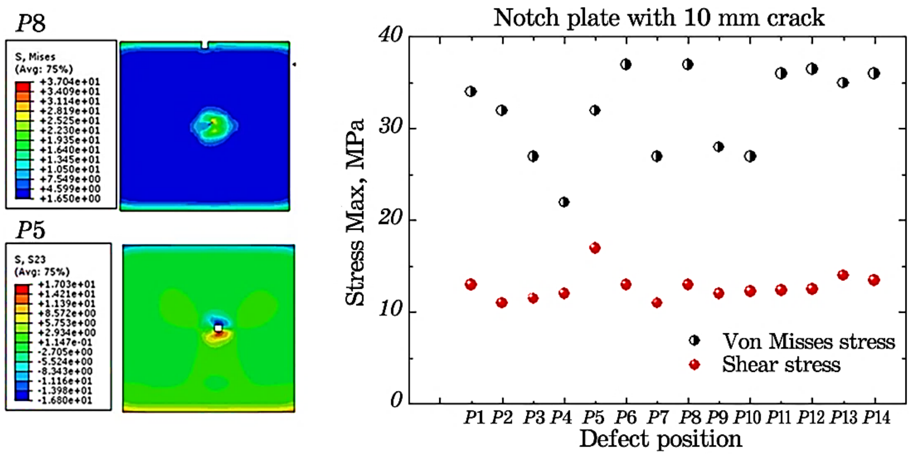

Fig. 13. Maximum von Mises stress and shear stress variation as per of bond defect position.

in a significant increase in the von Mises stress, which can greatly exceed the failure stress value of the adhesive.

5.2.6. Peel Stress Levels in the Composite Patch for Different Defect Positions with a 10 mm Crack in the Plate

Figure 14 shows the value of the peeling stress in the patch, which varies according to the defect position. These peeling stresses are concentrated at the level of contact with the crack, the notch and at the two edges of the patch. For this crack length and considering the significant the plate size, the composite patch is not subjected to significant

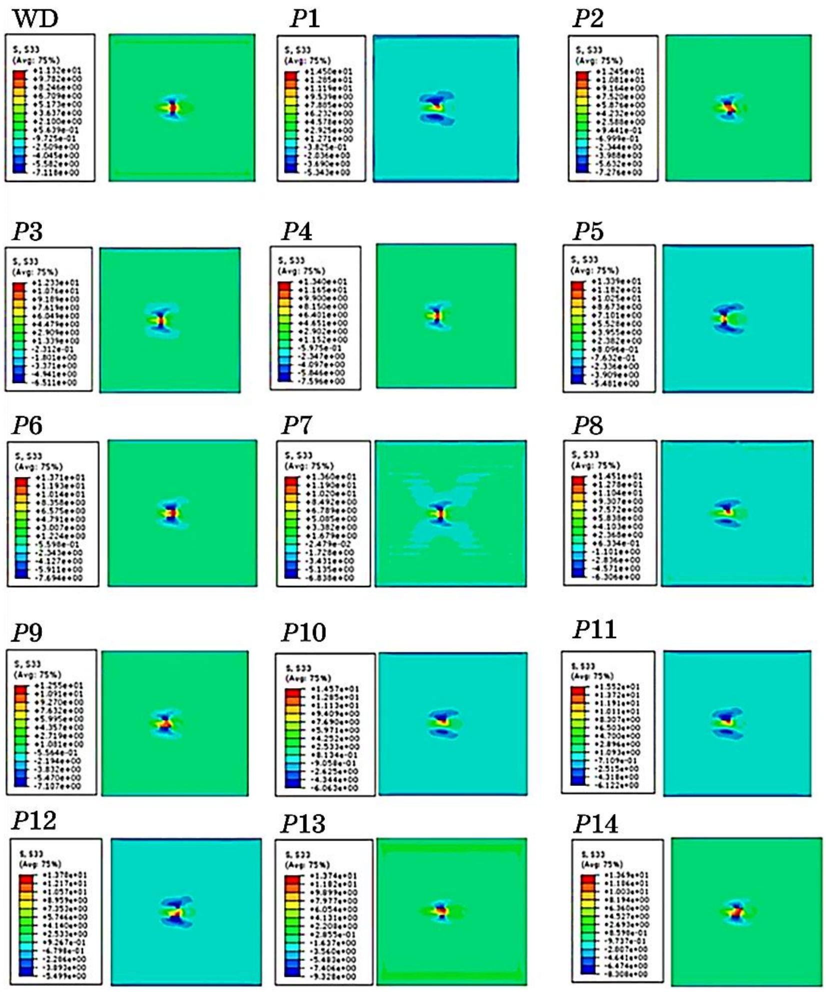

Fig. 14. Peeling stress level in the patch as per of defect position.

peel stress. The presence of a bonding defect only minimally disturbs the peel stress value in the patch, given its minimal size.

5.2.7. Shear Stress Levels in the Adhesive for Different Defect Positions with a 30 mm Crack in the Plate

As the crack size augment, the adhesive becomes highly stressed, and the shear stress value becomes higher. Figure 15 illustrates the shear stress level in the adhesive as per of defect position for a crack length of 30 mm, where it varies according to the position of the defect in the adhesive layer.

For this significant crack length, and considering the small defect

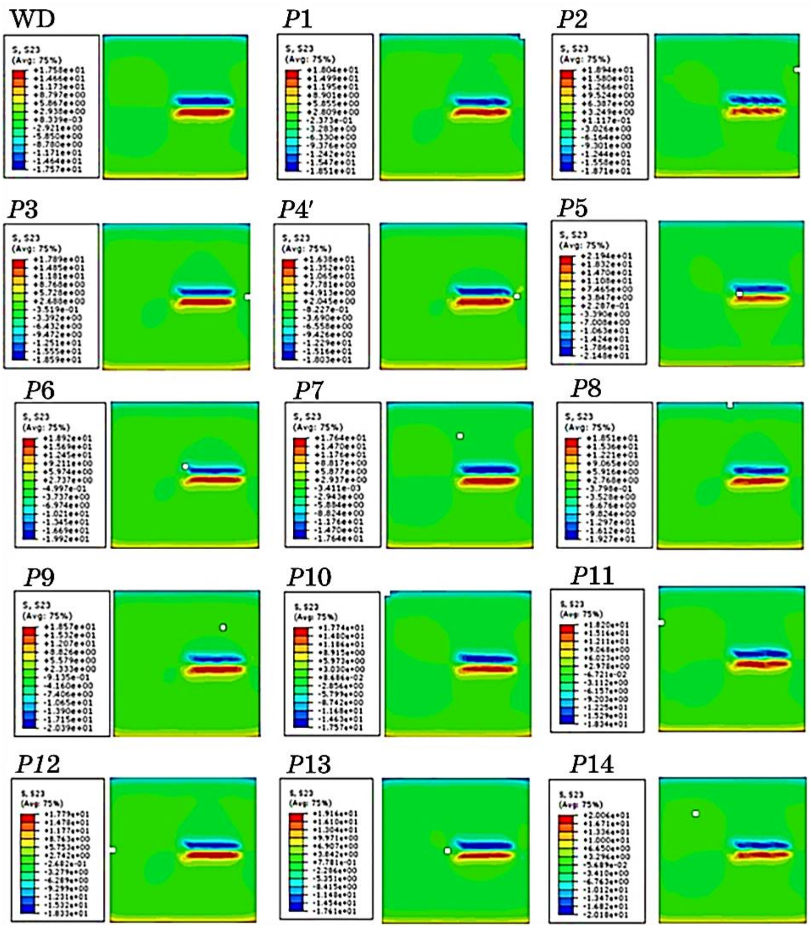

Fig. 15. Shear stress level in the adhesive for different defect positions (notched plate with crack length $a = 30$ mm).

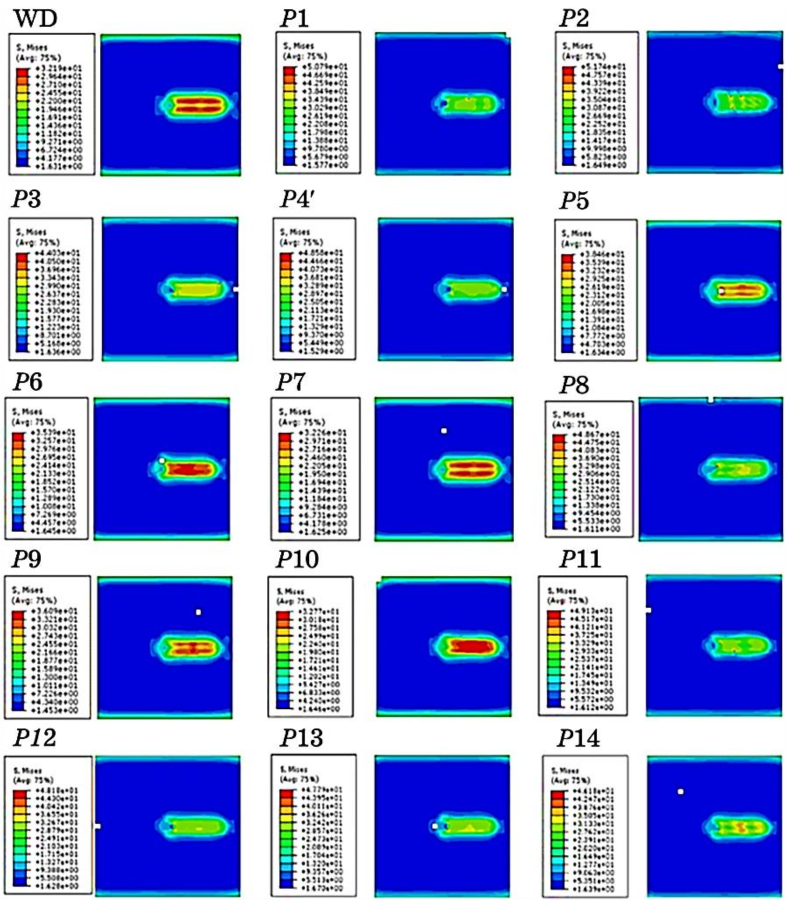

Fig. 16. Von Mises stresses level in the adhesive for different defect positions (crack emanating from notch of length $a = 30$ mm)

size, the majority of shear stresses are concentrated at the contact point with the crack. Even the adhesive edges are not heavily stressed.

5.2.8. Von Mises Stress Levels in the Adhesive for Different Defect Positions with a 30 mm Crack in the Plate

For this 30 mm crack length at plate level, Figure 16 shows the von Mises stress values are very high for any defect position. Relative to all defect positions, the von Mises stress value is well above the adhesive failure stress. Similarly, to shear stress, the von Mises stresses are concentrated in proximate to the crack.

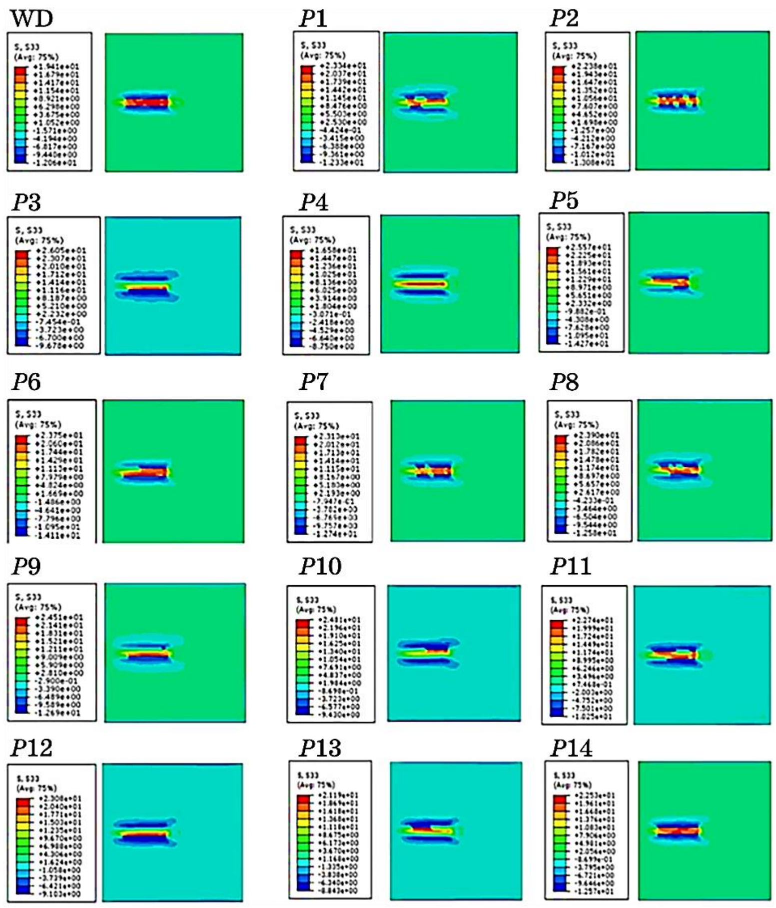

Fig. 17. Peeling stress level in the patch as per of defect positions.

5.2.9. Peel Stress Levels in the Patch for Different Defect Positions with a 30 mm Crack in the Plate

In Figure 17, it is evident that the peeling stress concentration is always in the zone where the crack is located in the plate.

5.2.10. Maximum Von Mises Stress and Shear Stress Variation as per of Bonding Defect Position for Different Defect Positions with 30 mm Crack in the Plate

Figure 18 shows the maximum von Mises stress and shear stress variation in the adhesive layer as a function of different bonding defect posi-

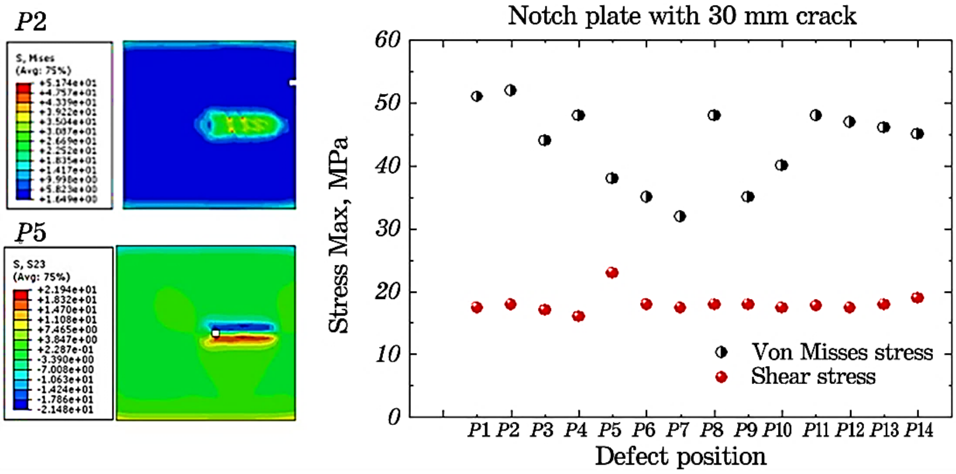

Fig. 18. Maximum von Mises and shear stresses' variation in the adhesive layer as per of bond defect position.

tions. The highest shear stress value is noted in the case where the defect is situated at position ($P5$). On the other hand, the zone of high von Mises stress concentration is noted at crack level, and increases if the defect is located approximately this zone and at the free edge level ($P2$).

6. CONCLUSION

The work presented in this study aims to investigate the impact of the presence of a square shape defect according to different positions in the adhesive layer. The study involves considering the determination of the stress intensity factor in the plate, the von Mises and shear stresses in the adhesive joint and peel stresses in the composite patch. Based on the presented results, the following conclusions can be drawn.

The presence of a crack emanating from a notch generates more stress concentration in the plate and therefore its repair by the composite patch bonding process is important.

Patch repair augment the plate strength and reduces the stress concentration at the notch and crack. The SIF value decreases by more than 50% for the case of the repaired plate.

The presence of a defect in the adhesive layer, even in minimum size, influences the value of the shear stress and stress placed in the adhesive joint and consequently on the load transfer to the patch so that the value of the intensity factor stress increases considerably depending on the position of the defect. For a minimum crack size, the presence of the defect slightly influences the stress values in the adhesive joint. However, if the crack size in the plate is large, the presence of the bonding defect generates a considerable variation in the contents in the adhesive joint and consequently high SIF values.

If the defect in the adhesive layer occurs near the notch, the crack or at the free edge, there is a high shear and von stress value and poor load transfer to the patch.

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