Visual Abstract

Composite lay-up configuration effect on double and single sided bonded patch repairs

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ABSTRACT. Understanding the failure modes of damaged or cracked structures and repaired by bonding a composite patch is an essential point to improve its resistance to failure and subsequently extend its service life. In the present study, a 3D finite element analysis using ANSYS software was performed to elucidate the failure modes of the repaired structures by double and single sided bonded composite. The plate is represented by an aluminum plate (Al2024 T3), cracked at the edge and repaired by three types of laminates, with different fiber orientation in order to determine its effect on the repair. The contact interfaces patch-adhesive and aluminum-adhesive were modeled by cohesive zone modeling (CZM) using bilinear interface of delamination (BID) method to determine the failure at the adhesive layer. The obtained results show the importance of the impact of the composite patch fiber orientation on the structure design for suitable repair.

KEYWORDS. Composite patch; Bonded repair; Overlap; Crack; Adhesive layer.

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INTRODUCTION

The replacement of damaged structures is often costly; hence, the use of reinforcement techniques as a solution to increase the service life and damage tolerance for cracked plates becomes in this case unavoidable. The bonded composite patch is one of the most effective strengthening technics, which has been widely used over the past decades in comparison with other conventional methods such as welding, bolting and riveting. The adhesively bonded repair method significantly reduces the stress intensity factor KI (SIF), and greatly prevents the creation of stress concentration zones such as in rivet or bolt repairs, as well as the change in the micro-structural state caused by thermal loads due to the welding process repair [1]. Furthermore, this technique holds great promise, because composite materials have good features: they are resistant to high mechanical and thermal loads, they do not corrode and they are easy to fabricate. One of the most valuable aspects of designing a bonded composite repair is to obtain an effective tool to evaluate: the distribution of stresses and deformation along the structure, the stress intensity factors for the three modes of opening and the breaking strength. With the growth of the power of computer tools, the use of numerical methods for structural analysis, in particular the finite element method, has contributed significantly to the understanding of the mechanical behavior of structures repaired with a bonded composite patch. Several researchers have highlighted the effectiveness of this technique, Harth-Smith was among the pioneers in this field in the early 1970s [2], he derived an explicit analytical solution for the static load carrying capacity of the single-lap adhesive bonded joint configuration, in addition, he has quantified the influence of adhesive plasticity in shear. We may also mention researchers like Sadek et al. [3], they have investigated the effect of corrosion on the quality of repairs. Albedah et al. [4] have worked on the analysis of the single and double sided bonded configuration with circular patch shape using finite element method, according to them, the use of the double-sided bonded configuration leads to a significant reduction in stress concentration at the crack tip, and the substrate is more relieved and recovers the maximum its mechanical properties. Also Bouiadjra et al. [5], have deduced that the repair by a composite patch with a trapezoidal shape gives a considerable reduction of the SIF as well as a beneficial reduction of the repair cost, others focused on optimizing the design of the material and geometry, both for the composite patch and the adhesive layer. Mathias et al. [6] have optimized the global orientation of the composite part and the adhesive layer thickness. Bhise et al. [7] have investigated the optimization of circular patches for the reinforcement of damaged carbon fibers under unidirectional tensile conditions, using genetic algorithms. Moreira et al. [8] have carried out the scarf configuration for bonded repair technique under a static and dynamic three-point bending, using finite element analysis method, in order to simulate its strength and fatigue life time. Other researchers such [9], have revealed the effect of hygrothermal loading on stress-strain behavior especially for composite materials, Nachtane et al. [10] have clarified this effect in an experimental study, showing that the reduction of fracture strength because of the moisture absorption at 50°C increase with the increase of the strain rate. Thus, a significant amount of previous research was conducted to determine the effect of some parameters on the mechanical, thermal and hydrothermal behavior of structures damaged and repaired with composite patches, such as: the shape and the geometry of the composite patch, the type and the thickness of the adhesive film.

In this context, the present numerical study was carried out with the aim of better investigation on the failure modes of cracked and repaired Aluminum plate with single and double sided bonded composite technique. The plate is subjected to unidirectional tensile load. Five types of laminates with fiber orientations ($[45/-45]_4$, $[0]_8$, $[30/-30]_4$, $[60/-60]_4$, and $[90]_8$) are used in order to clarify the influence of the angular orientation of the fibers on the effectiveness of the bonded repair technique. The results showed that the stress intensity factor (KI) was sufficiently reduced in Mode I at the crack tip region, for the five laminates. On the other hand, the deboning phenomena in the adhesive layer region are strongly related to the fiber orientation of the composite part.

MECHANICAL AND GEOMETRICAL PROPRIETIES

In the present work, two models of repair configuration have been analyzed by a 3D finite element using ANSYS 18.1 software for fissured plates. The first model is a double-sided bonded configuration, it consists of a composite patch with eight layers of carbon/epoxy, bonded to the two opposite sides of an aluminum alloy plate (2024 T3), just at the cracked region by means of an adhesively epoxy resin (ET5401) with a 0.2 mm thick, the latter has high mechanical characteristics and important resistance to peel and shear stresses. On the other hand, a reliable numerical analysis for the knowledge of the behavior of the adhesive-plate and adhesive-patch composite contact interface is essential. This zone is simulated by the cohesive zone modeling method (CZM) using bilinear approach, which allows a better investigation on the fracture behavior of materials by adopting a relation between traction-separation, known as the cohesive law. The maximum normal and shear stress are respectively 25 MPa, 15 MPa. The mechanical and geometrical properties of the structure-patch-glue are presented in Tab. 1. The second model is a single sided bonded joint configuration, its' similar to the first one, but the composite patch is only installed on one face of the structure. The geometry for the two configurations is illustrated in Fig 1. Double sided bonded repair (Fig.1-a), and single sided bonded repair (Fig.1-b).

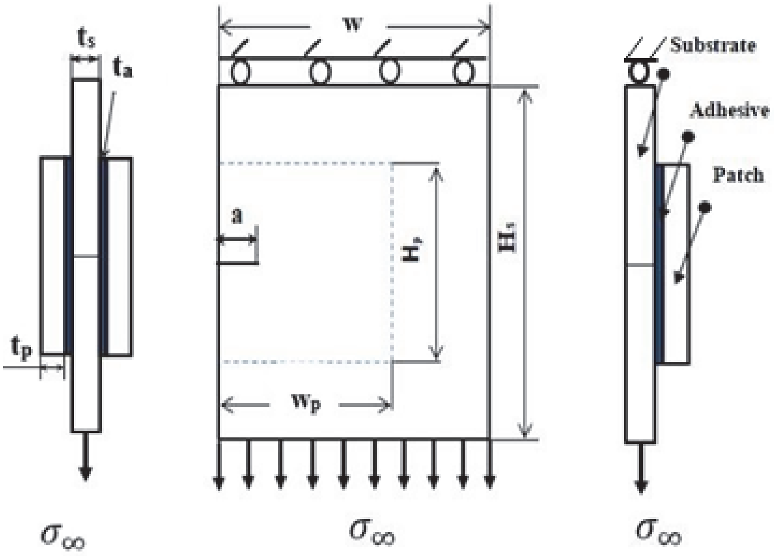
Three categories were obtained from five specimens with different orientations, in order to calculate their stress intensity factors in mode I and their total deformations.

The first named "A", with a high in plane stiffness in load direction, and their orientations are $[0°]_8$ and $[30°/-30°]_4$.

The second category "B", with medium in plane stiffness, consisting of patches with an orientation of $[45°/-45°]_4$.

The last category "C" whose in plane stiffness is low, having orientations of $[90°]_8$ and $[60°/-60°]_4$.

The geometry used in this study is a square-shaped aluminum plate of 120 mm side, cracked at the middle with a length 'a', just at one edge of the plate. The edge cracked aluminum plate was chosen similar to that proposed by Ayatollahi et al.[11]. The structure was subjected to a static tensile load (70 MPa), perpendicular to the crack length. After computation of the SIF in mode I for unpatched plate, the structure is repaired thereafter with the three categories of laminates cited above having 45 mm width and 90mm length.



a: double sided bonded repair b: single sided bonded repair

Figure 1: Composite patch repair configuration.

This is for the purpose of showing the effectiveness of the bonded repair technique and to find the most adequate orientation which allows to obtain a better repair.

Materials	Aluminum alloy 2024T3	Carbon/epoxy Composite	Epoxy Resin ET5401
Geometrical proprieties mm	w H_s t_s 120 120 3	w_p H_p t_p 45 90 1.6	t_a 0.2
Longitudinal young modulus E_x(GPa)	72	121	3.78
Transversal young modulus E_y(GPa)	72	8.6	3.78
Transversal young modulus E_z(GPa)	72	8.6	3.78
Longitudinal Poisson ratio ϑ_{xy}	0.29	0.4	0.35
Transversal Poisson ratio ϑ_{xz}	0.29	0.27	0.35
Transversal Poisson ratio ϑ_{yz}	0.29	0.27	0.35
Longitudinal shear modulus G_{xy}(GPa)	27	3.1	1.54
Transversal shear modulus G_{xz}(GPa)	27	4.7	1.54
Transversal shear modulus G_{yz}(GPa)	27	4.7	1.54

Table 1: Mechanical and geometrical proprieties.

FINITE ELEMENT ANALYSIS

Each of the two configurations, single or double sided bonded repair was made up of three materials with different in plane stiffness. The aluminum-adhesive and the patch-adhesive contact zones were modeled by cohesive zone modeling (CZM), using the bilinear delamination interface approach (BID). The cohesive interface element is used to simulate bonded joints, the behavior of these elements is expressed in terms of tensile-separation law. However, in the simulation of bonded joints, the adhesive layer of the model has a finite thickness which cannot be neglected, so the Finite Thickness Cohesive Elements, in this case, can be used to simulate bonded joints by setting the initial stiffness equal to the actual stiffness of the adhesive, such that the cohesive element of finite thickness is the outcome of a cohesive of zero thickness incorporated into a solid linear elastic masse material. Contact 174 and 3D target 170 in Ansys software was set to mesh the cohesive zone. The results describing the distribution of the stress intensity factor KI, and the maximum of the total deformations were obtained from a structural static study. An 8 mm length element was designed to generate an automatic mesh of the entire assembly, either for double or single sided bonded repair. A particular mesh is generated at the crack edge with an element of 0,2 mm length. The whole was meshed with solid186 and solid185 eight node break finite element mesh, with five bodies in the case of double-sided bonded repair, containing 25982 elements with 68452 nodes, (7352 elements with 33404 nodes for the substrate, 1035 elements with 7588 nodes for the adhesive, and 8280 elements for the laminate with 9936 nodes), and three bodies for single sided repair, containing 15163 elements with 44573 nodes. Typical mesh for a single sided repair is shown in Fig 2.
The sizes of the elements were chosen after performing a convergence study. Once a mesh dependency was identified, additional FE analyses were performed and the parametric study is carried out along the crack front and the results are presented and discussed in the next section.

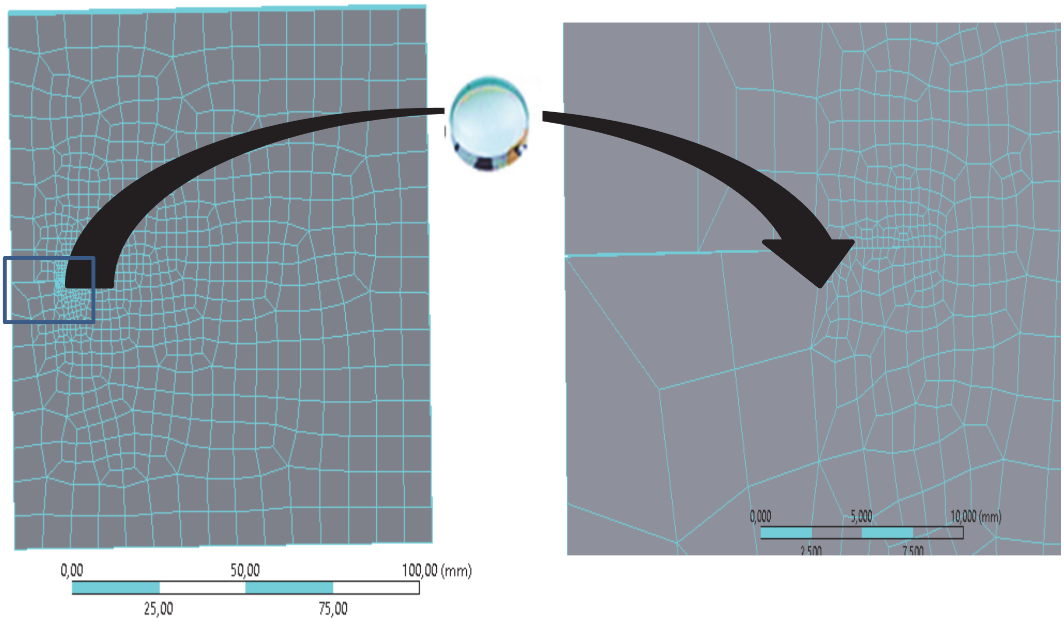


Figure 2: Typical mesh for a single sided composite repair.

RESULTS AND DISCUSSION

Fig. 3 shows the distribution of the stress intensity factor (KI) as a function of the crack length to plate length ratio (a/w) for an unrepaired aluminum plate. The numerical results obtained show agreement with those obtained by Ayattolahi et al. [11], which are also in good agreement with the analytical results of Sih [12]. The behavior of the stress intensity factor shows an increase with the increase of the crack length ratio. These same remarks have been found by other researchers working on plate crack analysis [13, 14]. However, the stress intensity factor values increase with the increase of the crack length, this is convincing since the stress concentration at the crack tip becomes important. A numerical analysis on the bonded composite repair of a cracked plate was established in order to show the effectiveness of this technique and to evaluate the rate of reduction of the stress intensity factor and the maximum of total deformation.

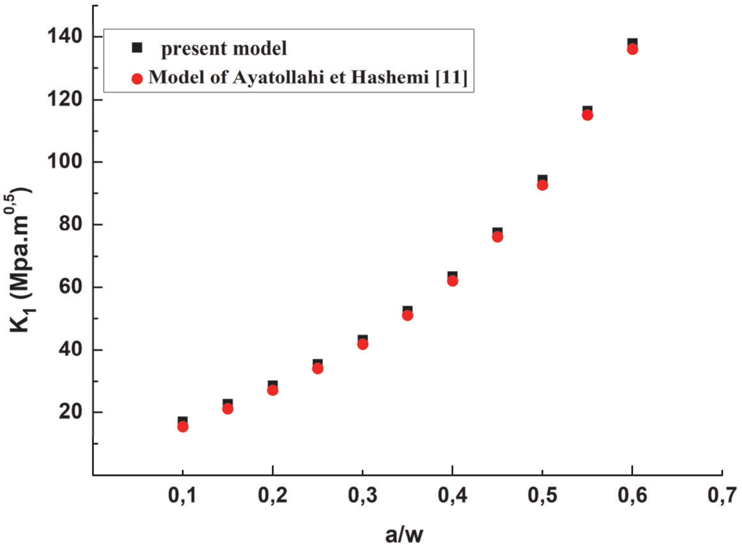


Figure 3: Stress intensity factor for unpatched cracked plate.

Effect of the in-plane stiffness on the SIF

As shown in the previous section, the SIF for pure mode I reaches high values despite the crack length is at only ten percent of the plate wide. Fig. 4 and 5 show the distribution of the stress intensity factor as a function of the crack length ratio, it is clear that the stress intensity factor KI values are reduced when compared to an unrepaired plate in Fig1, especially in the case of a double-sided configuration. This remark was mentioned by Albedah et al. [15]. it is quite clear that the value of the stress intensity factor has almost decreased by half for the first configuration (single sided repair), and much more for the second one (double sided repair) compared to that presented in Fig 3. This difference between the two configurations is firstly due to the large contact area of double sided bonded configuration, which implies a high load transfer capacity, secondly, the mixed loading (bending and traction) in the case of simple sided configuration, due to the shift of the centroid from the loading line.

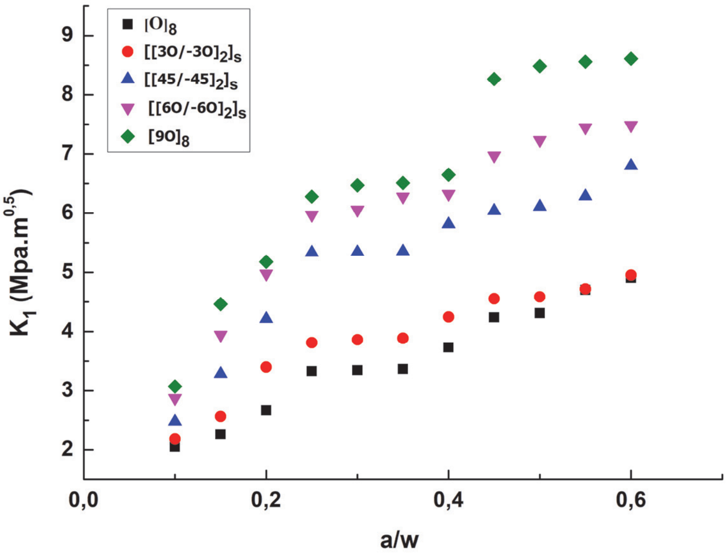


Figure 4: Stress intensity factor for double sided bonded repair.

It was noticed, in Fig. 4 and Fig. 5, that for a value of crack length (a/w) around 0.25, a remarkable difference in the SIF for the three categories mentioned above, especially for the double sided configuration Fig 4, where this difference appears clearly because the effect of bending is null due to the symmetry. It is clear that the "A" category which represents the fibers orientations [30°/-30°]$_4$ and [0°]$_8$, whose in-plane stiffness is high compared to the other two categories, is the most effective in terms of reducing the stress intensity factor parameter, On the other hand the "A" category characterized by the lowest stiffness is consequently the worst, because the fibers orientation of the latter is perpendicular to the loading direction, which mean that the "A" category with the fibers oriented in loading direction carry the normal stress more than the other categories. As shown in the Fig. 4 and Fig. 5, the stress intensity factor distribution for different values of the crack length ratio is almost regular.

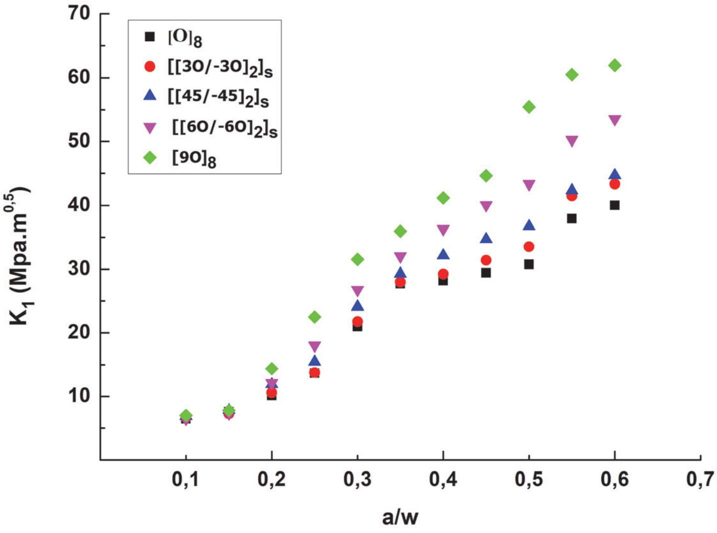


Figure 5: Stress intensity factor for single sided bonded repair

Two essential points should be noted. The first; when the length of the crack reaches almost one third of the length of the plate, the difference in efficiency between the patches becomes clear. The second; when the crack length exceeds half of the composite patch length for the single sided bonded configuration, the repair by bonded composite patch loses its effectiveness. This is due to the bending effect in this configuration.

Effect of the in-plane stiffness on the deformation

Bouiadjra et al. [5] and Okafor et al. [16] have performed various uniaxial loading tests on cracked plates repaired with boron-epoxy patches for different geometric shapes: octagonal, rectangular, circular, and elliptical.

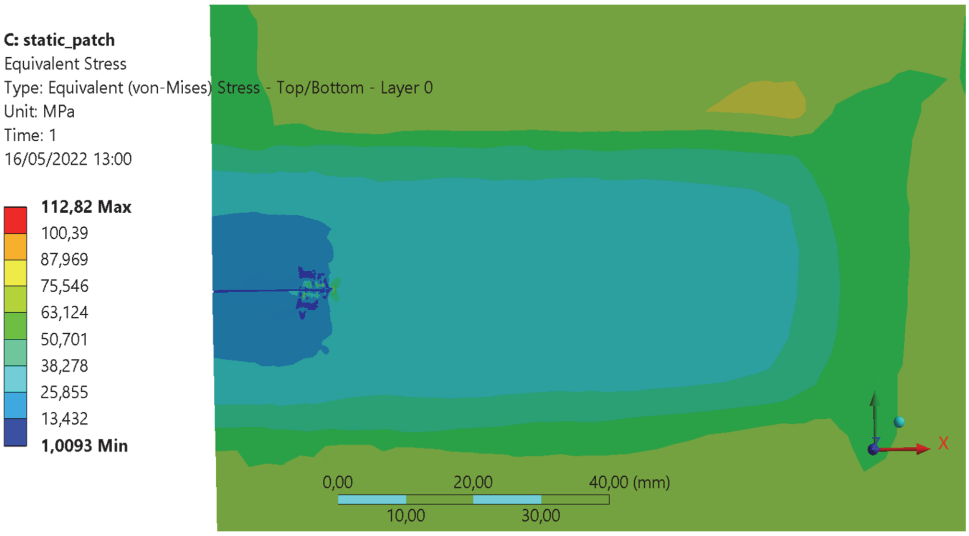


Figure 6: Equivalent stress in an Aluminum cracked and reinforced plate.

They found that the stress concentration in the plate, just in the region of the crack decreases significantly with the application of the patch. the same remark is illustrated in Fig. 6, we see a relieved area around the crack line where the stresses are decreased, while at the edge of the patch became important that can create a detachment of the patch in this area. Contrary to the structure, the stress of the first layer of the composite patch adjacent to the plate, which is shown in Fig 7, is maximum near the bottom of the crack and minimum at the edges of the patch. This justifies the principle of load carrying from the cracked plate to the composite patch.

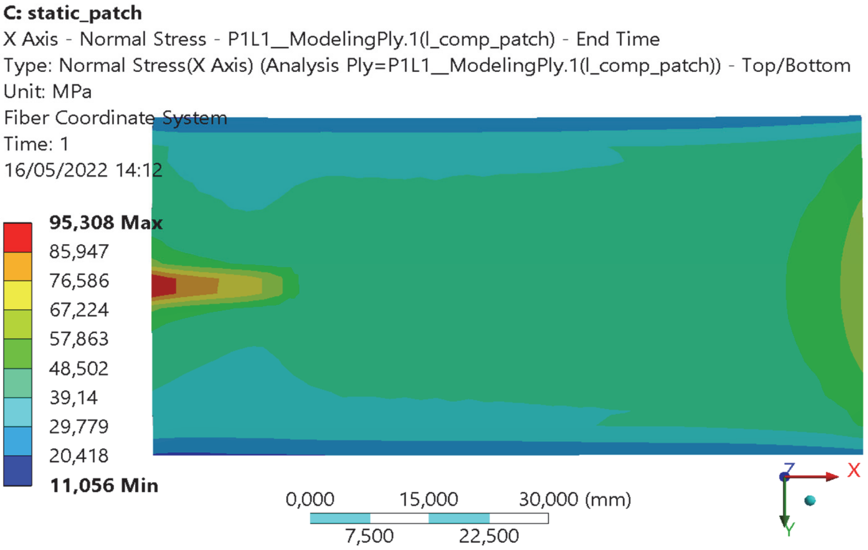


Figure 7: Normal stress distribution in first layer of the patch.

Fig. 8 and Fig. 9 represent the distribution of the maximum of total deformation. It follows from these two figures that a patch with a medium stiffness represented by the category "B" whose orientation of the fibers is $[-45/45]_4$ is more adequate in terms of deformation. However, a very stiff patch, such as the category "A", does not necessarily mean an adequate repair. On the other hand, patches with low stiffness ($[90°]_8$,$[60°/-60°]_4$) are the least performing, especially in the case of the double sided configuration where the bending effect is totally null, it's why the shape of the curve presented in Fig. 8 is more regular than that of double sided repair in Fig 9 especially concerning orientations ($[90°]_8$, $[60°/-60°]_4$), Where the fibers of the composite patch are perpendicular to the tensile load line, and the load carrying capability is revealed with the absence of the bending effect.

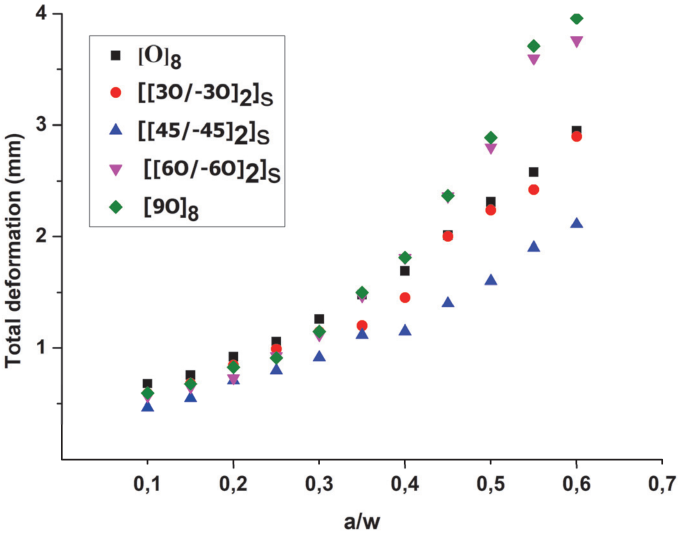


Figure 8: Maximum of the total deformation for single sided composite repair.

As shown in Fig. 8 and Fig. 9, the deformations in single bonding configuration are much higher than in double bonding configuration, this is due to the bending effect caused by the displacement of the centroid. All curves in each of the two figures have almost the same trend, except for those with low stiffness in Fig.9 ([90°]$_8$, [60°/-60°]$_4$), where the gradient increases from the beginning. This indicates that the prediction of repair failure in the case of category "A" appears very early compared to the other two categories. Indeed, low stiffness patches have the capacity of load transfer, but have a low resistance to normal loads because of their fiber orientation. On the other hand, they do not have the possibility to eliminate or reduce sufficiently the stress concentration at the edges of the patch and the bottom of the crack. Category "B" patches, with an orientation of [45°/-45°]$_4$ are the most performing in terms of total deformation, in both configuration simple or double sided bonded repair. This can be explained by the fact that the latter have a good load transfer capacity and resist well to normal and shear stresses.

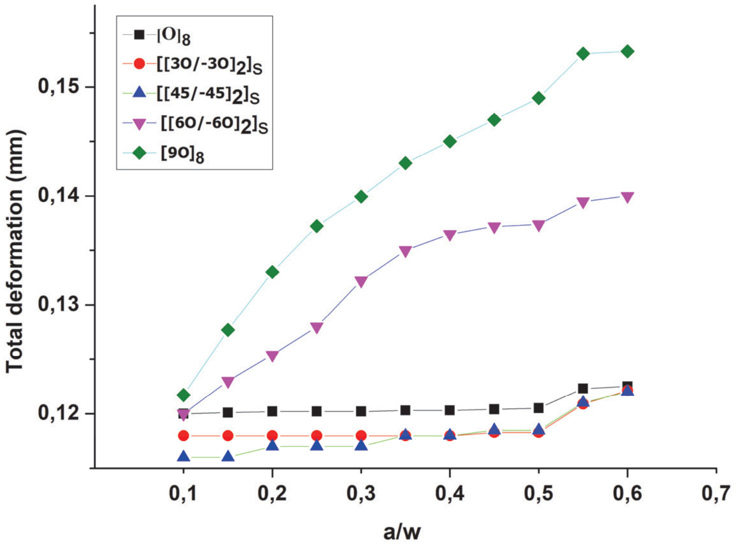


Figure 9: Maximum of the total deformation for double sided composite repair.

In a recent paper realized by Kaman et al. [17], they deduced that the fiber orientation angle affects significantly the effectiveness of repair. Also Cheng et al. [18] experimentally studied the effect of three types of orientations with low, medium and high in-planes stiffness of circular patch composites ([90°]$_4$, [45°/-45°]$_s$ and [0°]$_4$), bonded to a plate with hole and subjected to uniaxial tensile loading. For failure loading analysis of the un-notched plates, they deduced that the lay-up configuration ([45°/-45°]$_s$) gave the best results (89.9% of the specimens).

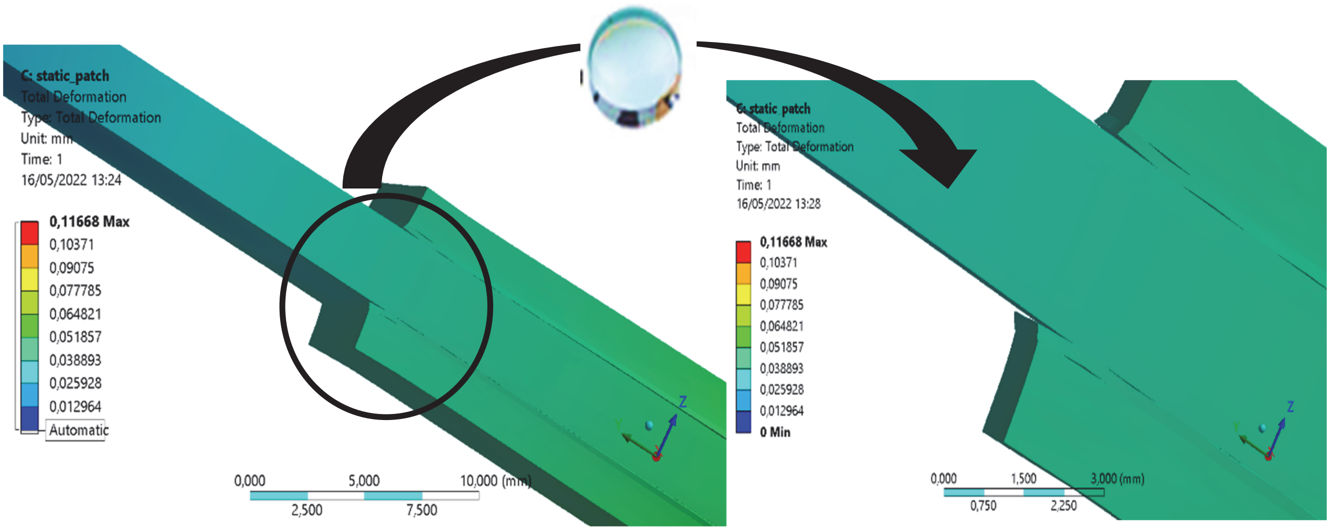


Figure 10: Deformation of the repair with patch orientation [45°/-45°]$_4$

This observation is coherent with the results of the present paper. After analyzing the maximum of total deformation distribution due to stresses in "A," "B," and "C" categories of specimens with externally bonded patches under static tensile loading. It is important to notice that both of these cases led to the same outcome, even although the damage modes were different. Also, the same observation can be seen from Fig 10, Fig. 11 and Fig. 12, Which represents the maximum of total deformation of the assembly (structure - patch - adhesive), for a double configuration model and a crack length (a/w= 0.25) for orientations $[45°/-45°]_4$, $[0°]_8$ and $[90°]_8$ respectively. In Fig 10, it can be seen that the shape of the patch is stable, this means that the patch shows good tensile and shear strength, and that the breakage of the repair is initiated at the ends by the failure in the adhesive part. For patches with high stiffness (Fig 11), it is clear that the shape of the patch is deformed, this is due to the compressive stresses perpendicular to the direction of the fibers under the Poisson's effect.

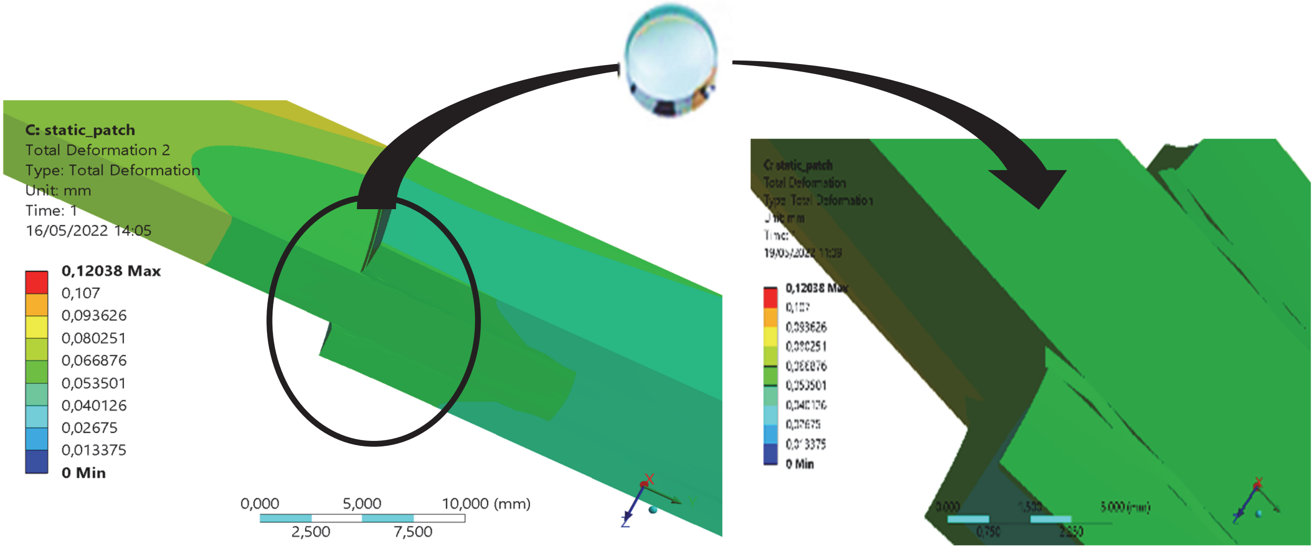


Figure 11: Deformation of the repair with patch orientation $[0°]_8$

In contrast, the breakage of the adhesive part in patches with orientation $[0°]_8$ is initiated at the ends, and it is greater than that of patches with orientation $[45°/-45°]_4$, this comes down to the fact that the rigid patches are very resistant to normal stresses, this is why the intensity factor KI with these patches is reduced, while their shear resistance is low, which causes rupture in the adhesive part.

In the third case represented by category "C" in Fig 12, the tensile load is perpendicular to the direction of fiber orientation.

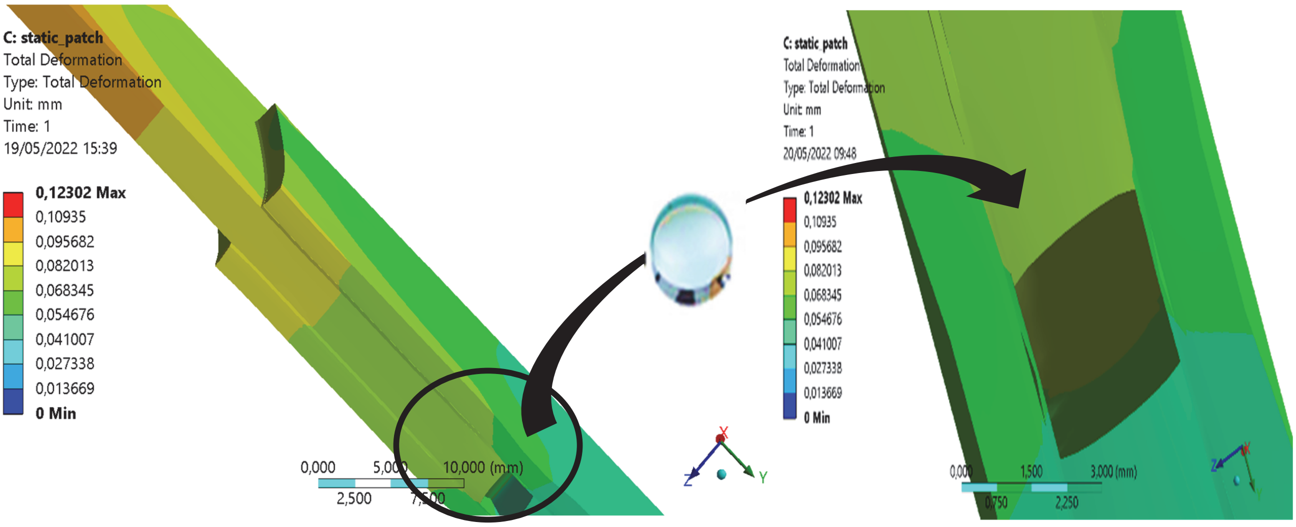
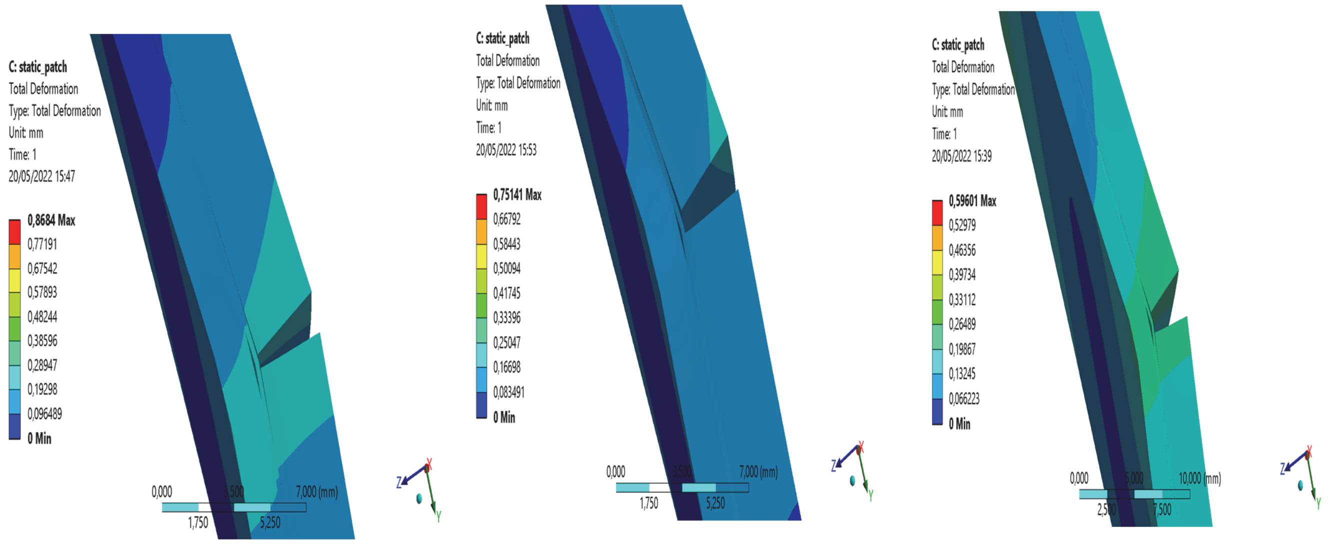


Figure 12. Deformation of the repair with patch orientation $[90°]_8$

In this case, the failure of the repair is initiated at the composite patch as shown in Fig. 12. In contrast, adhesive failure is delayed compared to the previous two categories, because the ability of normal and shear loads carrying is low. This explains the poor quality of these patches in terms of strength, and reduction of the stress intensity factor.



a: $[90°]_8$ b: $[45°/-45°]_4$ c: $[0°]_8$

Figure 13: deformation of the repair (single sided configuration)

For the single sided bonded joint configuration, the deformation of the patches with $[90°]_8$, $[45°/-45°]_4$, and $[0°]_8$ are shown in Figs. 13.a, 13.b, and 13.c, respectively. It is remarkable that the failure in all the three types is initiated at the crack tip. The total deformation in the set with orientation $[0°]_8$ is the lowest compared to the other orientations, this is due to the fact that the bending effect is the most dominant loading, so a tension in the loading direction is more important and finally the patches with fiber orientation in the loading direction ($[0°]_8$) are the strongest

CONCLUSIONS

This study has shown revealed the effect of the angular orientation of composite patch on the repair efficiency, the occurrence of the failure at the adhesive part or the composite patch under consideration is strongly affected by this parameter. The previous results showed that the reduction of the stress intensity factor is achieved for both configurations (single and double). The real concern is the failure of the repair in the adhesive layer and/or in the composite patch. For the double sided bonded composite configuration, the category "C" with low stiffness where the orientations are $[90°]_8$ represents the worst patches orientations, since the values of the stress intensity factor are high compared to the other categories "A", and "B", as well as the values of the total deformation, and the repair is susceptible to break up at the composite patch firstly, because the normal stress is relatively high specially at the crack tip region, due to the fact that the fibers are perpendicular to the loading line. Moreover, the rigid patches (category "A") gave good results for the reduction of the stress intensity factor, while it causes the failure of the adhesive at the adhesive-plate interface part early than the category "B", because it's bad in the resistance to the shear stresses, which are also responsible of the adhesive part decohesion. The patch with orientations that alternate between 45° and -45° gave better results for both single or double sided repair bonded composite repair configuration.

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