Visual Abstract

Use of combined CZM and XFEM techniques for the patch shape performance analysis on the behavior of a 2024-T3 Aluminum structure reinforced with a composite patch

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ABSTRACT. The presence of a geometric discontinuity such as a crack or a notch can cause the failure of a structure during its use. Under various mechanical or thermal stresses, a high concentration of stresses can take place at the level of these discontinuities, which in most cases will lead to the total failure of the structure. The service life of these structures can be improved with the use of the repair technique by bonding a composite patch. This technique is of significant interest in several fields, especially with the use of composite materials. This technique is widely used in aeronautics and ensures a long life of damaged structures. Current research aims to optimize the shape size and fiber's nature of this composite patch in order to ensure good load transfer by reducing the stresses in the damaged area. In this work, a finite element method is used to analysis the effect of the shape of the patch on the global response of a 2024-T3 aluminum structure in the presence of a central circular notch. The composite patch is of the carbon/epoxy type bonded through an A-140 Adekit type adhesive on the damaged part of the plate. The analysis consists in determining the force-displacement curves of the repaired structure by using the combination of the two techniques, XFEM for the

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damage of the aluminum plate 2024-T3 by the automatic creation of the crack and CZM for the analysis of the adhesive debonding. The analysis takes into account the damage in the plate and in the adhesive. However, for the composite patch, and since there will be no damage, we have just analyzed the effect of its shape and essentially the shape of its edges on the load transfer and consequently on the resistance of the structure under loading in tension. Two main patch shapes have been highlighted, namely the square and circular shape. The results show clearly that the shape of the patch's edges has an impact on the stresses reduction in the plate and subsequently ensures good resistance in terms of force-displacement curve and consequently delays the peeling of the adhesive.

KEYWORDS. XFEM; CZM; Patch repair; Debonding; Resistance, Aluminum 2024-T3.

INTRODUCTION

The repair of damaged structures using composite patches is now widely used, especially in the aeronautical industry [1, 2], with this technique we can delay the crack propagation and thus improve the fatigue life. Few works have studied the effect of preventive reinforcement of structures on the crack initiation. To optimize the performance of the repair by patch composite, several parameters must be considered, such as the patch thickness, the fibers and matrix nature, the patch property and staking sequence and the adhesive thickness. The effects of parameters that affect the behavior of the crack propagation have been investigated in most studies such as, the influence of composite patch size and shape [3], number of plies and their orientations [4], asymmetry of the repaired structure [5], tensioning of the part prior to bonding the composite patch [6], plasticity [7], imperfect bonding of the composite patch [8], residual stresses [9], or aging of the patch and adhesive [10-12].Other authors have aimed to optimize the patch geometric shape in order to transfer more and more stresses to the crack head or to the damaged area [13-16]. Under mechanical loading, the composite or adhesive strength depends on many parameters such as surface preparation, defects or adhesive shape along the patch free edges [17], the presence or absence of a gradient thickness towards the free edge of the composite patches. It is well known that near the free edges of the composite patch, transverse shear stresses take maximum values in the adhesive [18] which affect the overall mechanical response of the reinforced structure. The deposition of an adhesive bead with a well-controlled profile along the free edge of the composite patches reduces shear stresses [19, 20]. On the other hand, we note that some studies have treated the shape of the free edge of the patch in order to limit the maximum shear stress in the adhesive [21]. Xiong and Raizenne [22] optimized the angle and the zone length of the composite patch thickness reduction; they showed that patches with decreasing thickness reduce stress in the adhesive because the geometric singularity is less pronounced. Further work has been done on optimizing the shape of the composite patch [23]. The case of circular or elliptical shaped reinforcements has also been treated analytically based on the Eshelby inclusion method [24] and considering the reinforced area as an inclusion of higher stiffness than the rest of the plate. The calculation of stresses in an orthotropic elliptical reinforcement is described by Rose [25], a large number of studies have been performed on polygonal shaped plates. They are generally based on this elliptical inclusion method and on Rodin's algorithm [26] which allows adapting Eshelby's method to polygonal and polyhedral inclusions. Duong studied the case of a plate reinforced by a polygonal patch in a symmetrically way [27], in an asymmetrically way [28] and in the framework of large displacements [29]. Benkheira and al [30] studied the effectiveness of the double patch; they proved that the use of the double patch reduces significantly the stress intensity factor compared to the single one. The stress intensity factor decreases asymptotically with the thickness of the patch, the relative difference between the FIC of a double patch and a single one is almost constant. The thickness gain decreases as the patch thickness increases.

Additionally, using the appropriate patch shape can reduce the level of residual thermal stresses due to adhesive bonding; which means less repair costs and subsequently the adhesive generates less stress which can improve the durability of the repair composite**.**

The main objective of this work is to analyze numerically by finite element method, using the XFEM and CZM techniques, the fracture behavior of a 2024-T3 aluminum plate damaged and repaired by patch composite. The patch shape effect, mainly the shape of its edges on the load transfer from the damaged plate to the composite patch, has been highlighted. The obtained results show clearly that the use of a composite patch reduces significantly the different stresses in both plate and adhesive. On the other hand, modifying the shape of the patch edges ensures load transfer and minimizes stress concentration in the adhesive joint. The optimization of the patch edges is essential to ensure both load transfer and durability of the repaired structure.

GEOMETRICAL MODEL

Consider an elastic aluminum plate 2024-T3 with height, H= 140 mm, width, W=50 mm, thickness, e=2 mm this plate has a central circular notch of diameter D=20mm.The plate is subjected to an imposed displacement of 15 mm. The carbon/epoxy composite patch is bonded through an A140 Adekit type adhesive on the damaged area. The dimensions of the composite patch are : Length h=50 mm, Width W=50 mm and Thickness e_p =1.77 mm, on the other hand for the adhesive we considered a thickness of 0.2mm. The geometric finite element model is shown in Fig. 1.

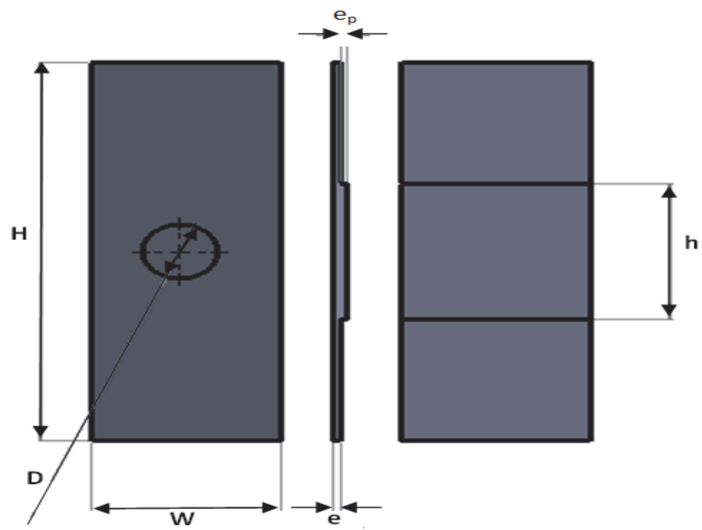


Figure 1:Geometrical model of the plate with a central circular notch with a square patch

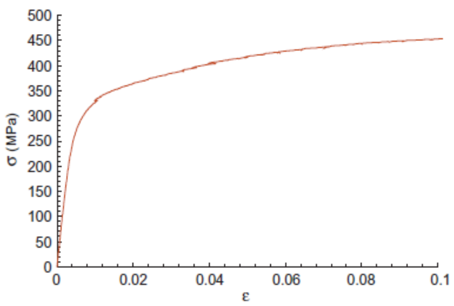


Figure 2: Tensile stress-strain curve of aluminum plate [10]

Material	Aluminum 2024-T3
Yield stress	230MPa
Maximum stress	452MPa
Percent elongation	2.4%
Young modulus	68.8GPa
Poisson coefficient υ	0.33

Table 1: Material Mechanical properties of Aluminum

MECHANICAL PROPERTIES OF THE SUBSTRATES

Tensile tests carried out on a 2024-T3 aluminum plate allowed us to have the characteristic curves shown in Fig. 2 [10]. From this curve we can determine the mechanical properties of the material as shown in Tab. 1. The stress-strain in the non-linear part of the aluminum plasticity as well as the coordinates of the last point of the fracture

point curve were introduced into the Abaqus code as damage parameters to simulate an increase in the fracture level/damage after ultimate stress has been achieved. The plasticity model therefore extends beyond the ultimate stress. The mechanical properties of the plate (Aluminum 2024-T3) come directly from the tensile tests carried out at the LASIE laboratory in France (Fig. 2).
The interlaminar failure of the composite patch was not taken into account in this analysis. It is a question of promoting only the separation between the plates (composite / aluminum). The composite patch is a laminate of the carbon / epoxy type. The mechanical properties of the composite used in this study are listed in Tab. 2.

Composite Patch		
Carbon Fiber	Epoxy Matrix	Composite (0° direction)
E_1 = 235 GPa	E_1 = 3.7 GPa	E_1 = 109000 MPa
E_2 = 12.9 GPa	G_{12} = 1.38 GPa	E_2 = 8819MPa
E_3 = 12.9 GPa	υ_{12} = 0.33	E_3 = 8819MPa
G_{12} = 8.05 GPa		G_{12} = 4315MPa
G_{13} = 8.05 GPa		G_{13} = 4315MPa
G_{23}= 8.05 GPa		G_{23}= 3200MPa
υ_{12} = 0.27		υ_{12} = 0.342
υ_{13} = 0.27		υ_{13} = 0.342
υ_{23}= 0.33		υ_{23}= 0.380

Table 2: Mechanical properties of the used laminates, [10] E: Young's modulus, ν: Poisson's ratio, G: shear modulus

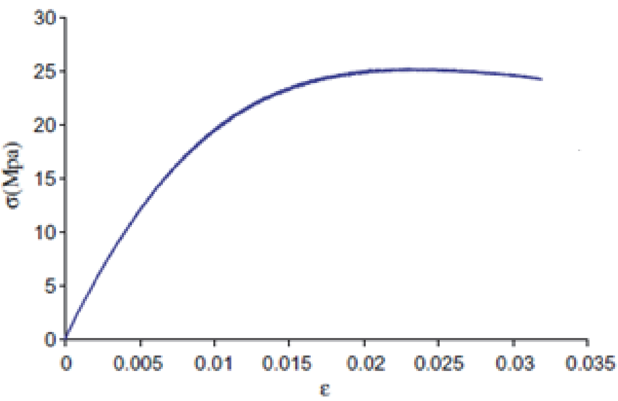


Figure 3: Adekit A-140 adhesive strain/strain curve [10].

Material	Adekit A-140
Young's modulus [MPa]	2600
Energy release rate in mode I	0.5
Energy release rate in mode II	2.41
Cohesive tensile strength	35.9
Cohesive shear force	30.9

Table 3: Mechanical Properties of the Adekit A-140.

The composite is of the carbon / epoxy type. This type of material has effective mechanical properties which give it better resistance to mechanical stress. Carbon / epoxy is widely used in repairing cracks in the aeronautical, aerospace and even civil engineering industries. The analysis was performed for composite laminates namely, carbon / epoxy. For the composite patch, a stacking sequence was used in order to see the effect of the orientation of the fibers on the performance of the composite and therefore on the transfer of stresses from the damaged area. The orientation angles of the layers are measured from the longitudinal direction along Y. The composite material is manufactured by Hexcel Composite and has been characterized by Airbus. The 14-ply single-sided repair patch with six 0_ plies, four 45_ plies, two -45_ plies and two 90_ plies. The patch stacking sequence is $[0, 45, -45, 0, 90, 0, 45]_s$.

The Adekit A140 was chosen because of its use in several areas, including aeronautics. It has good mechanical properties up to a temperature of 453 K and resists short exposures up to 488 K loads (vibrations and shocks); moreover, it is a product resistant to aging and aggressive environments. The tensile curve is shown in Fig. 3. The mechanical and fracture properties of the adhesive are shown in Tab. 3.

BOUNDARY CONDITION AND MESH MODEL

The boundary conditions for the plate repaired or not by composite patch are shown in Fig. 4.
We considered an embedding of the lower face of the plate with displacements $U_1 = U_2 = U_3 = 0$ and rotations $UR_1 = UR_2 = UR_3 \neq 0$,
On the other hand, on the other side of the plate a displacement is applied with amplitude U1 =15 mm.
The two faces on the embedded side and on the free side are blocked in displacement as shown in Fig. 4 in order to be close to the tensile test where these two faces are fixed in the jaws of the tensile machine.
The finite element analysis of the repaired plate configurations, shown in Fig. 4, is performed using the ABAQUS finite element code. A three-dimensional finite element model of such a structure involves several degrees of complexity. In order to capture the essential characteristics of the global response.

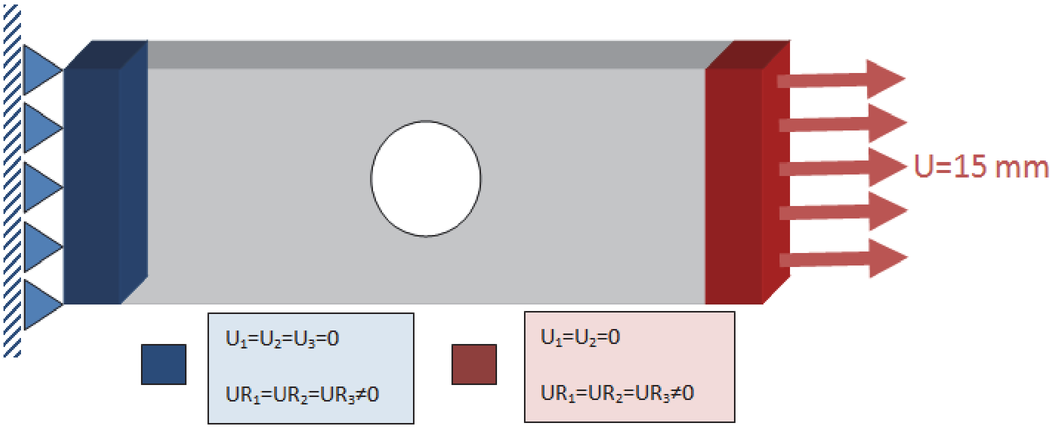


Figure 4: Presentation of conditions at the limits.

In numerical finite element calculations, the choice of mesh is important in order to have the convergence calculation with reliable results translated by the number of nodes and their layout, which characterizes the element and its density in the mesh structure. The mesh elements used in this analysis are of type (C3D8R). A refined mesh is made in the regions around the notch to capture the maximum stresses that were virtually stress concentration and initiation of crack growth while a coarser mesh is used for the remainder of the structure in order to reduce the calculation time.
To simulate patch detachment with crack propagation in the plate, the non-linear behavior of aluminum was presented using 26920 solid element elements C3D8R where the XFEM model is implemented and also C3D8R for the patch. For each structure, the number varies with the patch shape. Fig. 5 shows a detail of the mesh used for the three plate/cohesive/patch elements. No interaction was introduced between the surfaces. The adhesive was modeled as an interface (zero thickness) with typical COH3D8 elements and a number that exceeds 7200 elements depending on the shape of the patch. It is therefore necessary to introduce the break parameters listed in Tab. 4.

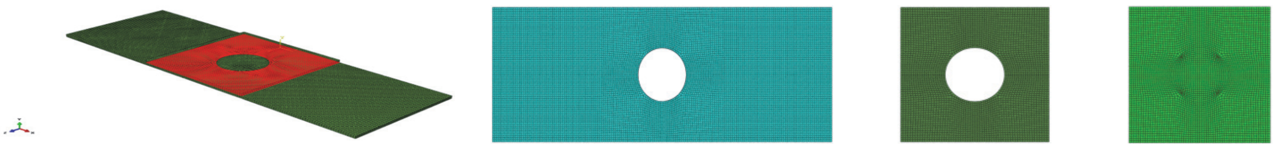

(a) (b) (c)

Figure 5: Presentation of the mesh model of the different substrates a) plate al, b) adhesive and c) patch.

Mesh of different substrates	Plate	Adhesive	Patch
Number of elements	19034	686	7200
Mesh type	C3D8R	COH3D8	C3D8R

Table 4: A detail of the mesh used for the three plate/cohesive/patch elements

RESULTS AND ANALYSIS

The validation of the results with the experiment relies much more on the mesh sensitivity in analysis of the type and density of the mesh elements. We compared the experimental results with those obtained by numerical calculation in order to validate our numerical model. After an adequate choice of the type and number of mesh elements, we were able to validate our numerical model where the result of the force-displacement curve shows a good agreement between the experimental and that resulting from the numerical model (Fig. 6).

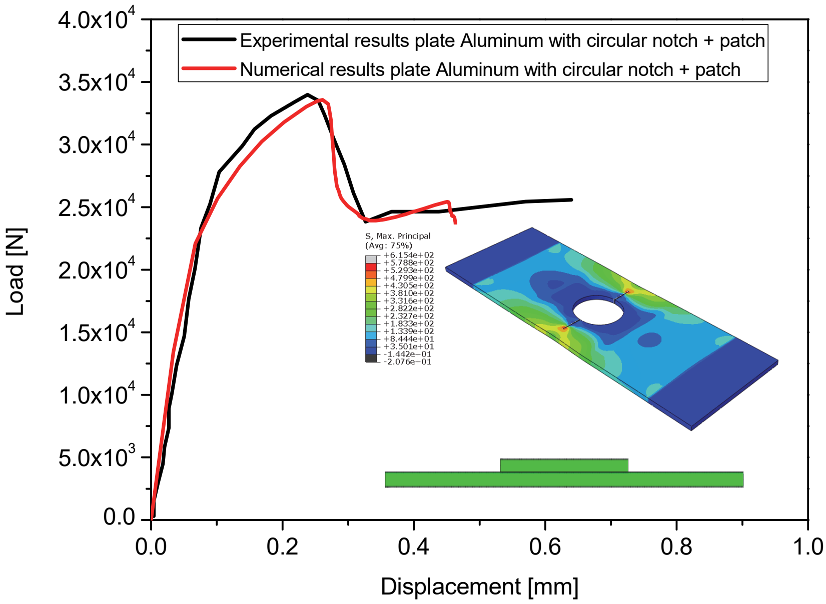
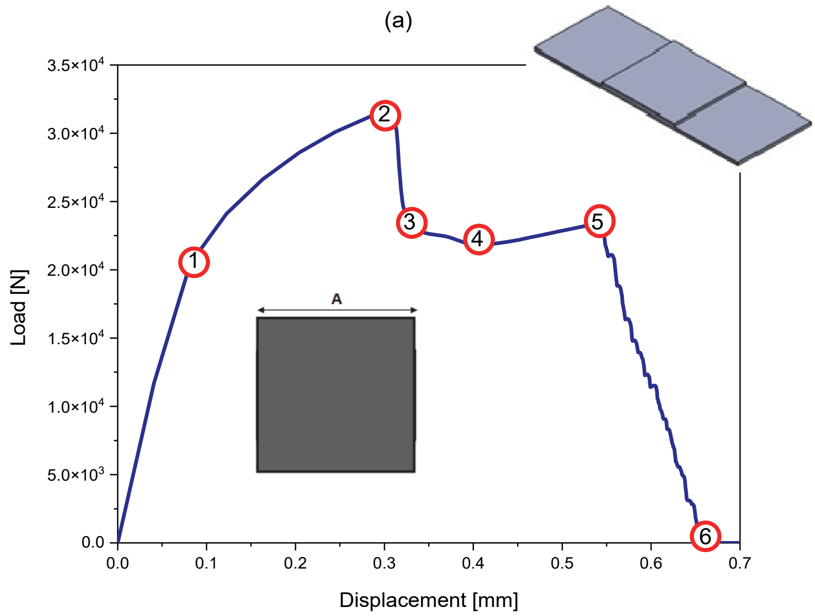


Figure 6: Validation of the force-displacement curve of the numerical model with experimental result

EFFECT OF PATCH SHAPE (CIRCULAR AND SQUARE)

In our first analysis we tried to see a comparison between the two forms of the circular and square patch. According to the results, of the two tensile curves elongation force (Fig.7), and since the two patches cover the entire width of the plate, one notices that there is not a big difference in the maximum strength. Except for the maximum displacement, the patch repaired per square patch has more displacement since the patch covers more surface than the circular one.

It is clear that the stress levels are almost similar for the two reinforced plates for square and circular patch. The area of high stress concentration at the two edges of the patch is well extended in the case of a circular patch than a square one. The square patch has more surface area. At the notch, the stresses are the same for both patch shapes. Once the detachment begins, it is noted that the area of high stress concentration for the circular patch repair case is more extensive than that of the square patch especially at the notch.



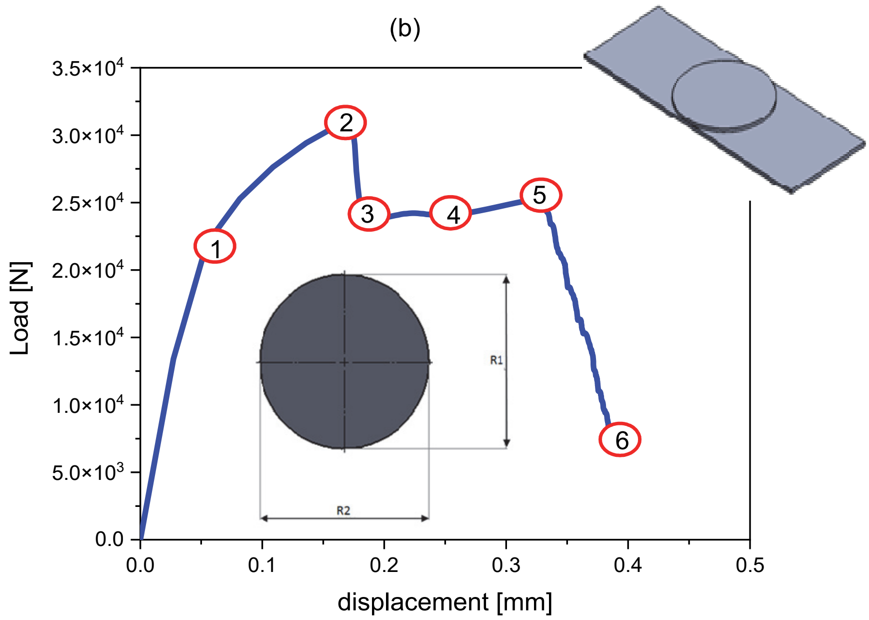


Figure 7: Force-displacement curve of the plate repaired by a) square patch and b) circular patch.

This variation in the stress level is directly related to the transfer of load through the adhesive where it is noted that the stresses of high intensities are located at the level of the free edges and at the level of the notch for both repair cases (Fig. 9). Once the tensile load increases. This area will be more extensive. The square patch repair case has a small size of the high stress concentration area as for the circular patch case. Once the maximum force is reached, the square patch shows more damage than the circular one. This area will be wider as the applied force increases. Once reached the force needed to propagate the damage into the adhesive. The circular-shaped adhesive has less bonding surface which means that the patch-repaired plate continues to resist the load even after the peeling appears. The stress level in the composite patch is highly dependent on the load transfer in the adhesive, it is clear that the square patch has higher stresses than the circular one; this clearly shows the efficiency of the square shape. The square patch transfers better the stresses of the damaged area and presents a homogeneous distribution of the stresses at these two edges.

As the force applied increases and at the same time the damage to the adhesive spreads, the square patch continues to transfer the stresses of the damaged area and has more transfer surface unlike the circular patch that transmits less stress at the same time as the damage of the continuous adhesive.

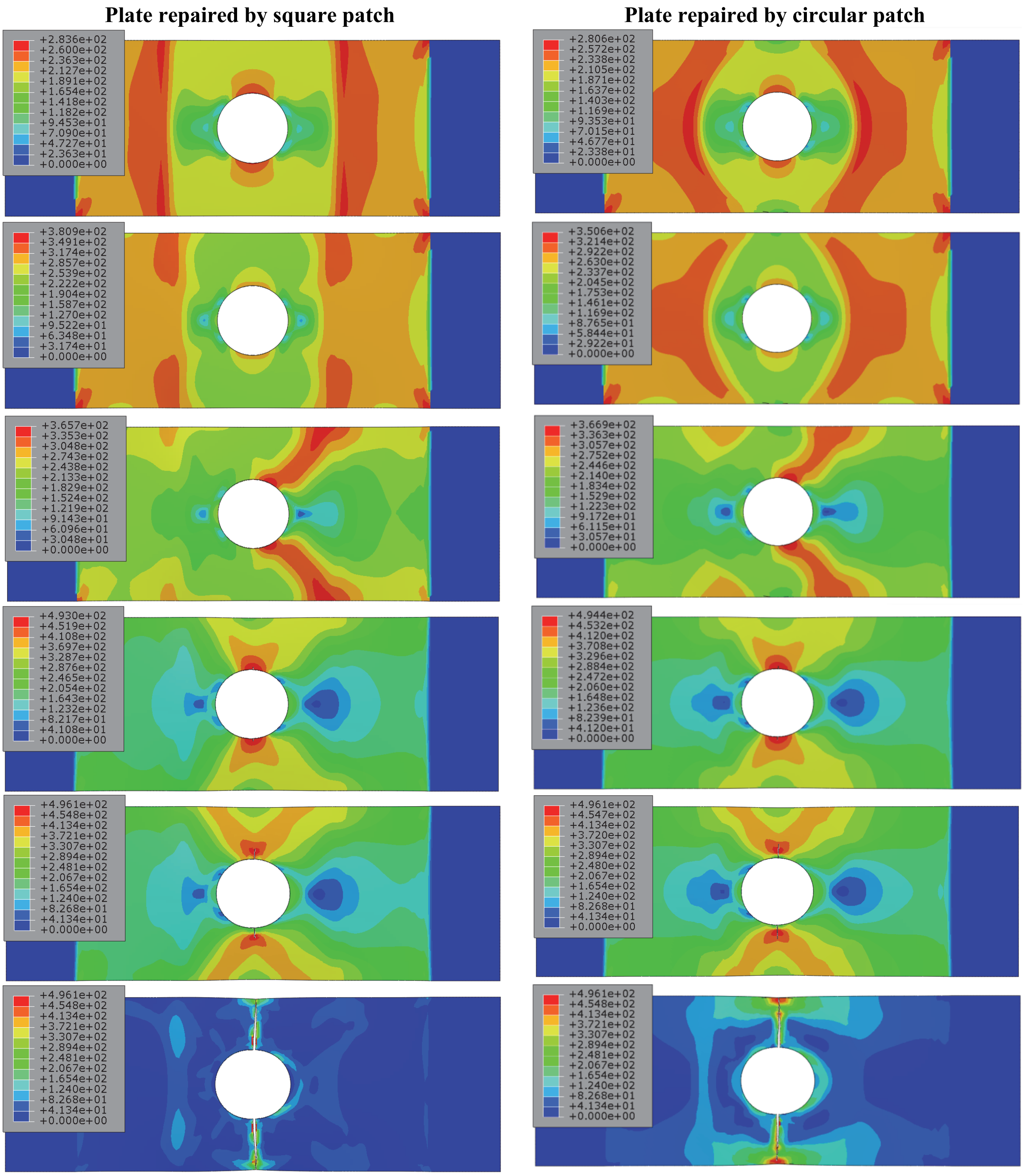


Figure 8: Stress levels in the repaired plate for different applied loads.

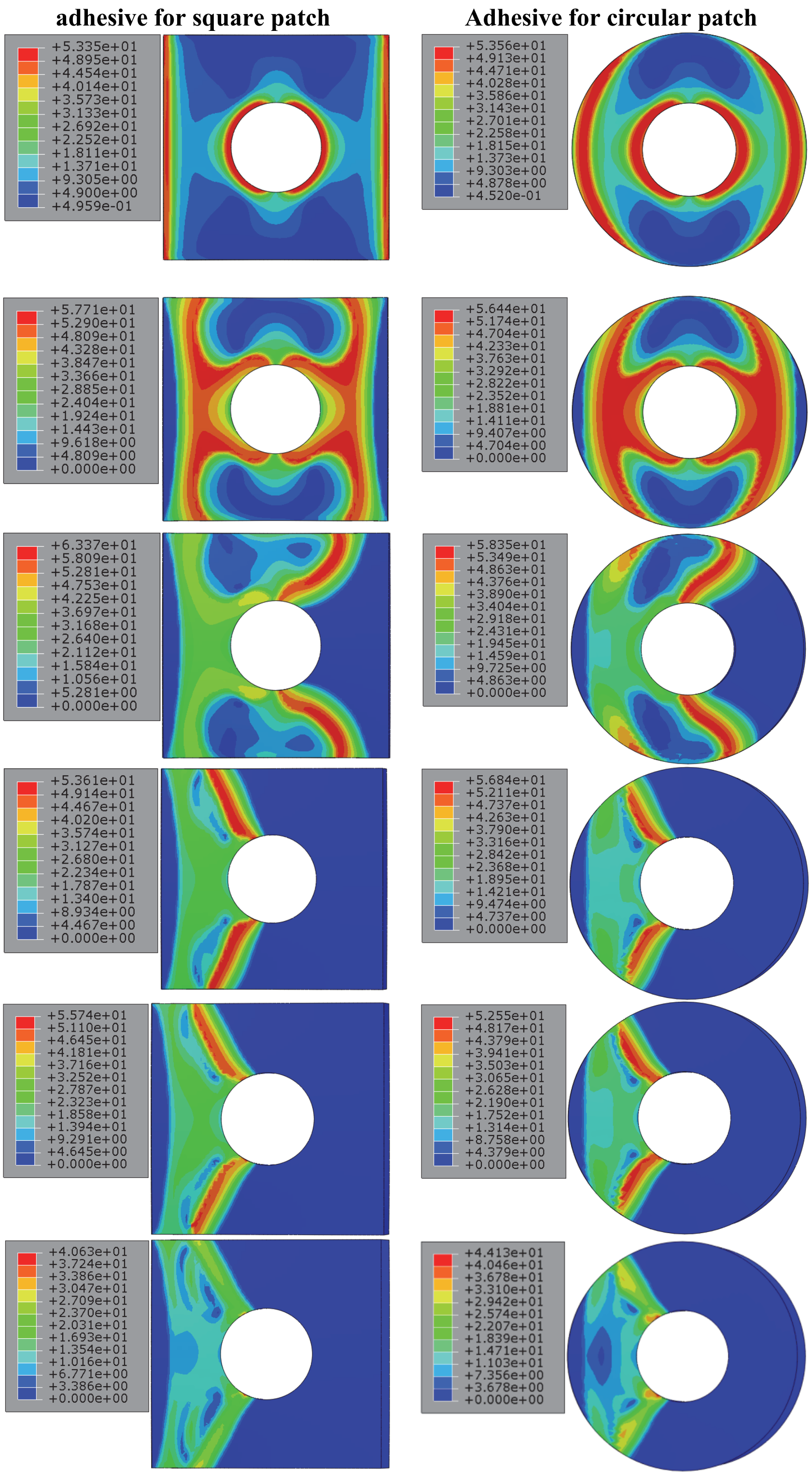


Figure 9: Stress levels for different loads applied in the adhesive.

EFFECT OF GEOMETRICAL MODIFICATION OF PATCH EDGES

Square patch

In order to better transfer the stresses of the damaged area and ensure less damage to the adhesive, we tried to change the shape of the corners of the square patch as shown in the Fig.10.a.

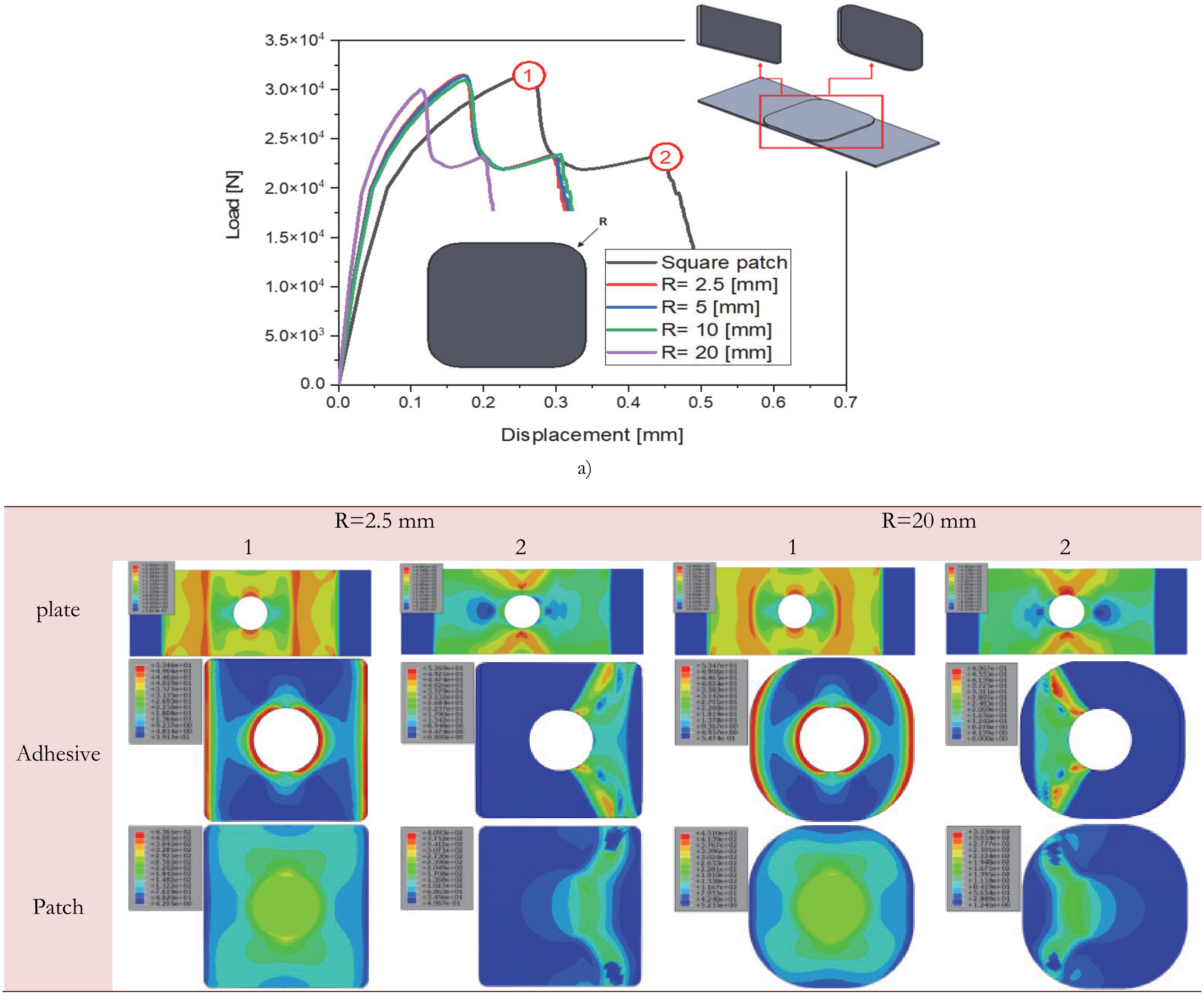


Figure 10: a) Traction curves associated with the geometric modification of the patch, and b) Stress levels in different substrates for two applied loads level.

It should be noted that when changing the edges of the patch, the tensile curves have the same shape and almost the same maximum force for the different values of ‘a’ and ‘b’. Except for a slight variation if the values of a and b are maximum. At this point, the patch covers less of the damaged area.

The geometric change of the patch has no influence on the load transfer and the value of the stresses in the plate (Fig. 10b). Practically we have the same distribution of stresses in the plate, except that the size of the area of high stress concentration in the case where a=b= 20mm is more extensive. The stress concentration at the notch is the same.

For applied loads that are close to the maximum value, the geometric change of the patch a=b=20mm ensures a good load transfer only for the case or a=b=5mm. On the other hand, once the debonding appears, the geometric modification of the edges with a=b= 2.5mm ensures a good continuity in the stress transfer.
For adhesive, detachment appears quickly when the free edges of the patch are modified with a=b=20mm, the patch has less surface and therefore less stress transfer, the edges of the adhesive are close to the damaged area and therefore the area of high stress concentration.
The analysis of the maximum force and the maximum displacement according to the parameters of modification of the corners of the patch is present in Fig.11.We note that the maximum force drops slightly if the dimensions of the radius of the edges are small, a considerable fall is to be noted if parameters 'a' and 'b' are high.

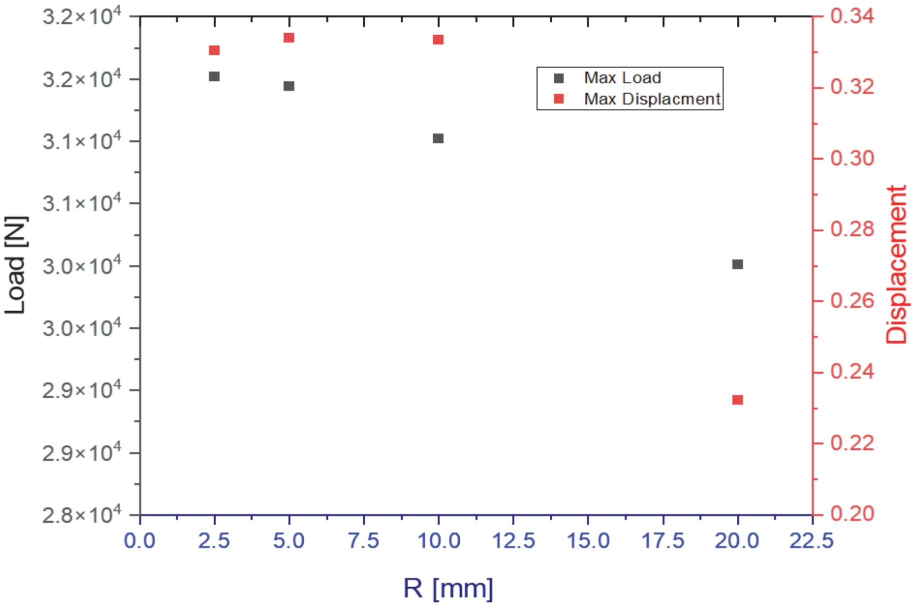
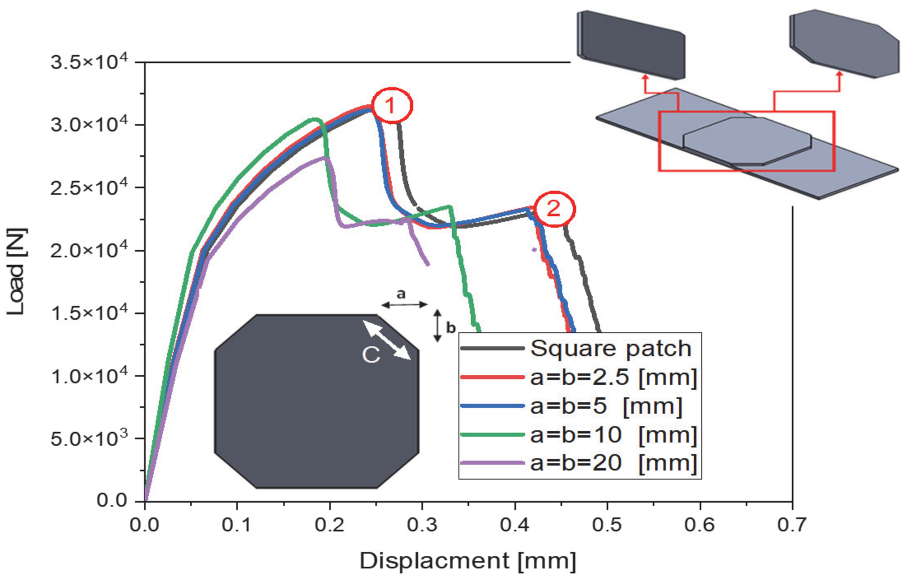
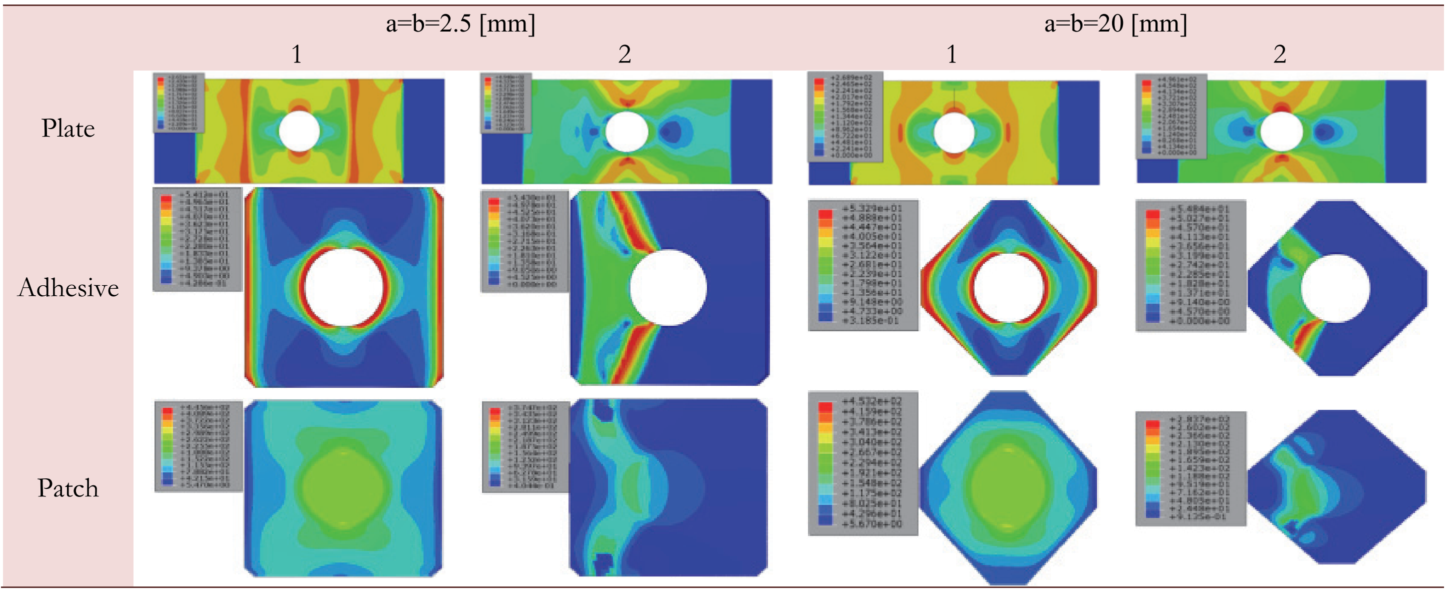


Figure 11: Presentation of the maximum force values and displacement according to the corner radius of the patch.

A second modification was proposed taking into account a triangular shape of the corners of the patch with a variation of 0parameters 'a' and 'b' (Fig.12.a). The tensile curves and stress level in different substrates associated with this change are shown in the Fig.12.



a)



b)

Figure 12: a) Traction curves associated with the geometric modification of the patch, and b) Stress levels in different substrates for two applied loads level.

It is clear that for these change of the corners of the patch, if the parameters 'a' and 'b' are small in front of the patch width, no influence is noted in relation to the maximum force and displacement. However if 'a' and 'b' take important values the bonding surface will be reduced and therefore a low resistance of the repaired structure. A considerable drop is noted in relation to the traction curve.
The stress level in the repaired plate is shown in Fig. 12b. It is clear that the small values of the two parameters 'a' and 'b' do not have a great influence on the stress distribution in the damaged area and even far away from it, however if the dimensions are large. High stresses remain in the damaged area and even around the patch. A small area covered by this patch is present. The patch with the modification of a= b =20 mm has less load transfer and the area of high stress concentration is very reduced compared to the case where a=b=2.5 mm. The patch with the modification of a= b =20 mm has less load transfer; the constraints are concentrated at the central area. On the other hand, the area of high stress concentration is very small compared to the case where a=b=2.5mm. The debonding is extended over more areas when the modification of parameters 'a' and 'b' is significant.
When the applied load reaches a higher level, the damage to the adhesive is significant. The patch with the modification a=b=20 mm of its edges ensures a transfer of load on a small area concentrated in the middle which will cause the rapid rupture of the structure. However, for the case where the patch presents a change of corners with a = b = 2.5 mm, even after the appearance of the debonding it continues to transfer the stresses to a larger surface.
With regard to the level of stress of the adhesive, it is clearly noted that the distribution of stress is practically the same in both configurations, except that the case where a=b=2.5 mm the adhesive transmits more stress than in the case of a=b=20 mm. Once the damage of the adhesive begins, in the case of the patch modification of a=b=20 mm the detachment spreads rapidly into the adhesive given the small adhesive surface and the stress concentration at a small area. For modification a=b=20 mm, the distance between the free edges and the notch is reduced resulting in an area of high stress concentration. As the load increases the damage of the adhesive is done quickly in the modification a=b=20 mm.
The variation of the maximum tensile load and the displacement resulting from the tensile curves according to the different changes made to the corners of the patch is shown in Fig. 13.The optimal values for the maximum values of the force and displacement are noted for the modification of the edges of the patch a=b= 2.5mm.
A third modification concerning the edges of the patch while giving a curved shape in order to minimize the stresses at the edges of the adhesive is shown in Fig. 14. The purpose of this change is to minimize the stresses that are in contact with the edges of the plate. For this case we set b=30 mm fixed and the parameter 'a' vary.

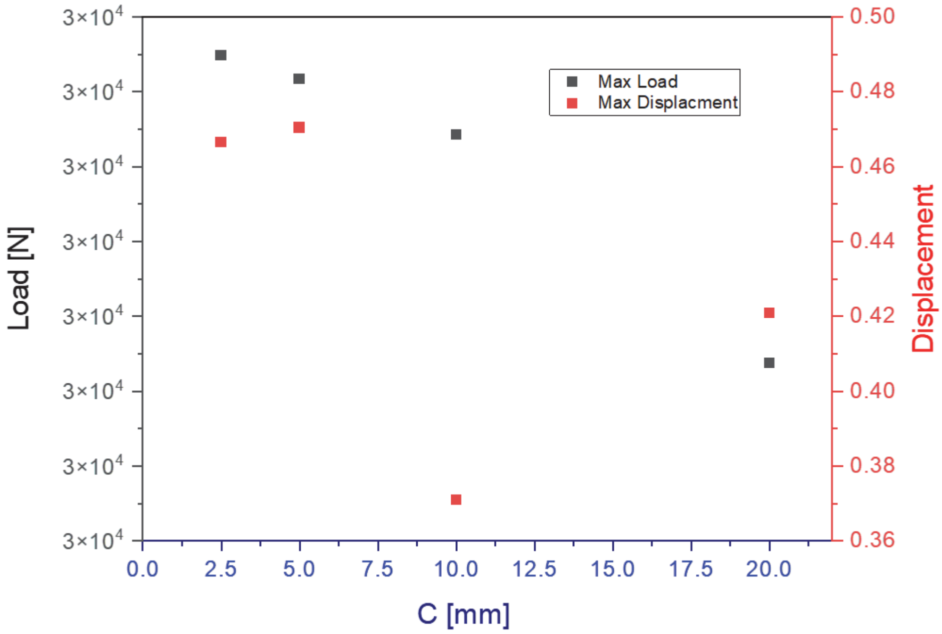
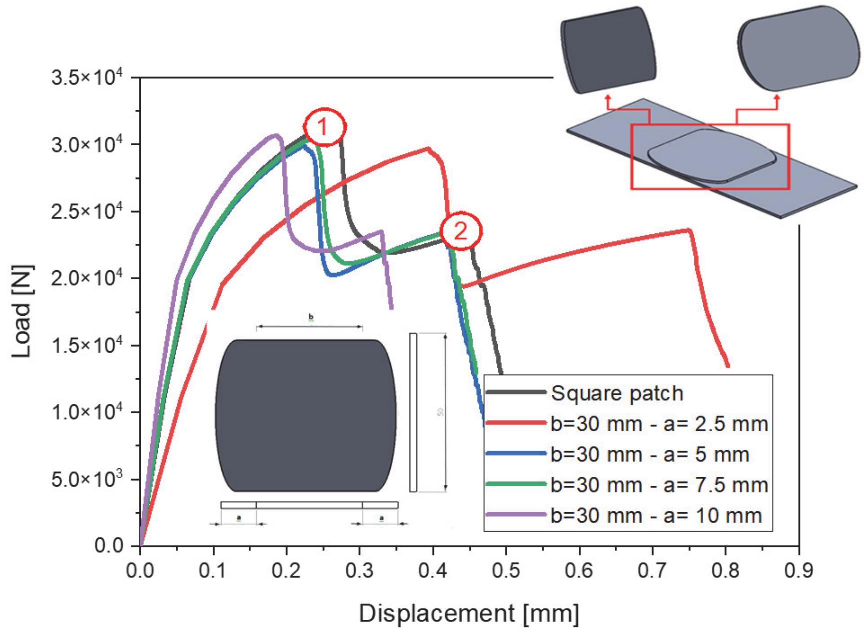
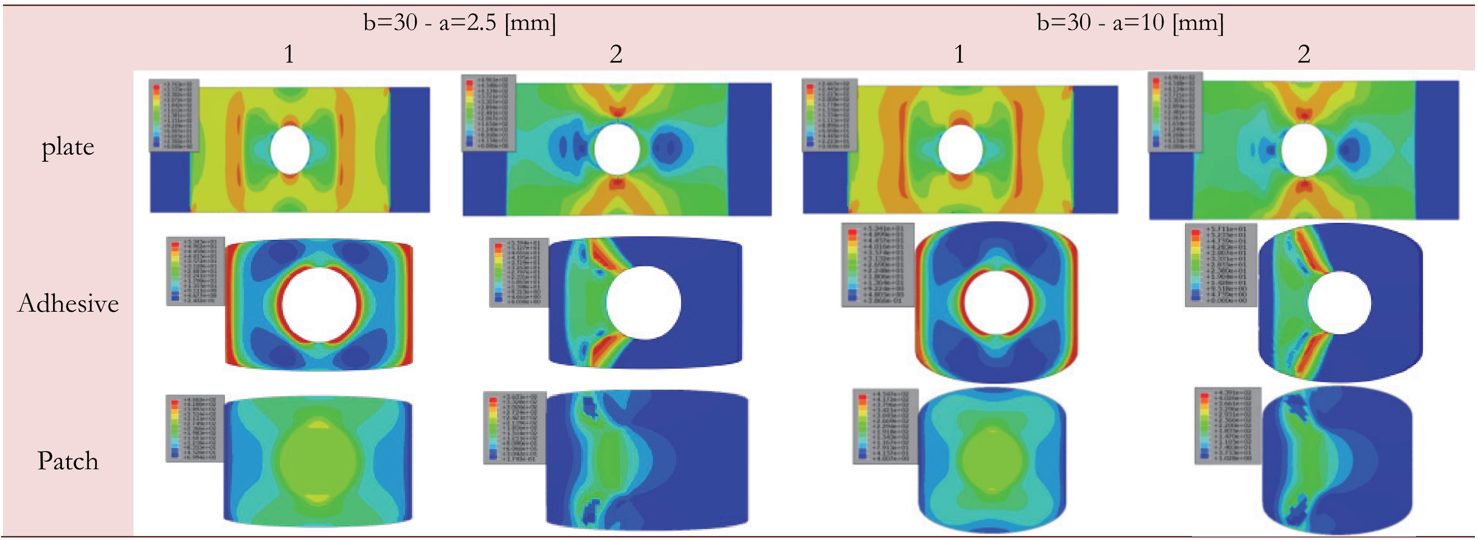


Figure 13: Variation of the maximum tensile force and maximum displacement according to the geometric parameters 'a' and 'b' of the modification of the edges of the patch.

It is clear that for this modification, the tensile curves (Fig. 14 a) are not too affected and that the value of the maximum force is almost the same except for the case where a= 10mm and b=30mm. However, the maximum displacement is affected by these values, when the parameter "a" increases the elongation of the structure decreases. The modification a=2.5mm presents a better configuration for the patch, since it gives us a good resistance of the repaired structure.
The stress level analysis shows clearly that the area of high stress concentration is more extensive in the case of modification a=10mm (Fig. 14 b). At the notch level, we have practically the same distribution regardless of the modification made. Once the load is increased, the modification of a=10mm transmits less stress to the patch, and the plate has high stresses. The crack appears in this structure and the rupture is fast. For the modification of a=10mm, there is a decrease in stress at the edges of the plate. This curve shape of the patch improves the load transfer.



a)



b)

Figure 14: a) Traction curves associated with the geometric modification of the patch, and b) Stress levels in different substrates for two applied loads level.

The stress level in the patch shows that regardless of the change made, the patch ensures the stress transfer of the damaged plate.
The stress level in the adhesive shows that the stress distribution is practically the same regardless of the values of parameters ‘a’ and ‘b’.
The rounding created at the corners of the patch improves the stress distribution in the adhesive and minimizes the stress concentration due to the patch-edge plate interaction. The maximum stresses are concentrated at the edges of the notch. These stresses increase with the increase of the applied load. Once the applied load reaches the value necessary to damage the adhesive during the load transfer, a zone of detachment appears at the edges; its size depends on the values of the two parameters ‘a’ and ‘b’. If the value parameters ‘a’ is high, the area of disbonding is more remarkable since it will have an interaction edge notch and a zone of fore stress concentration will be localized.
This detachment zone propagates as the applied load increases. This causes low resistance vis-à-vis the tensile load when the value of parameter ‘a’ is significant.

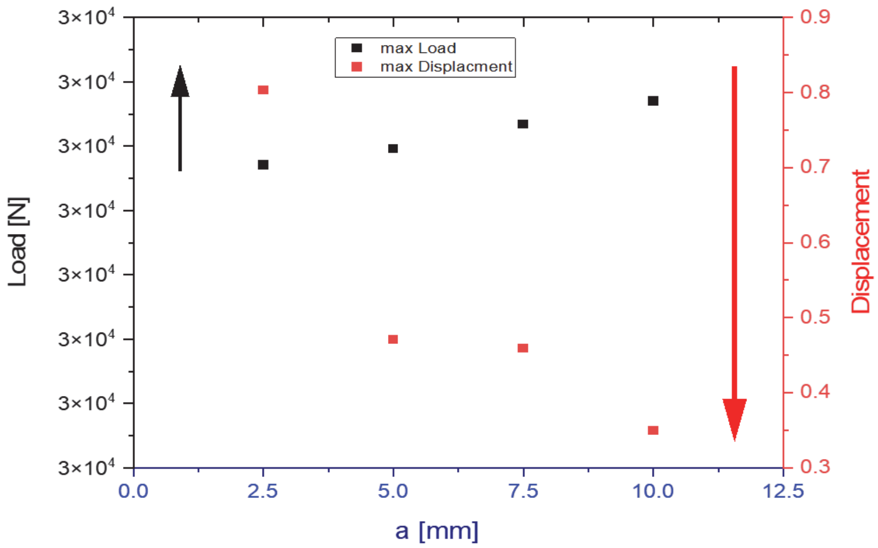
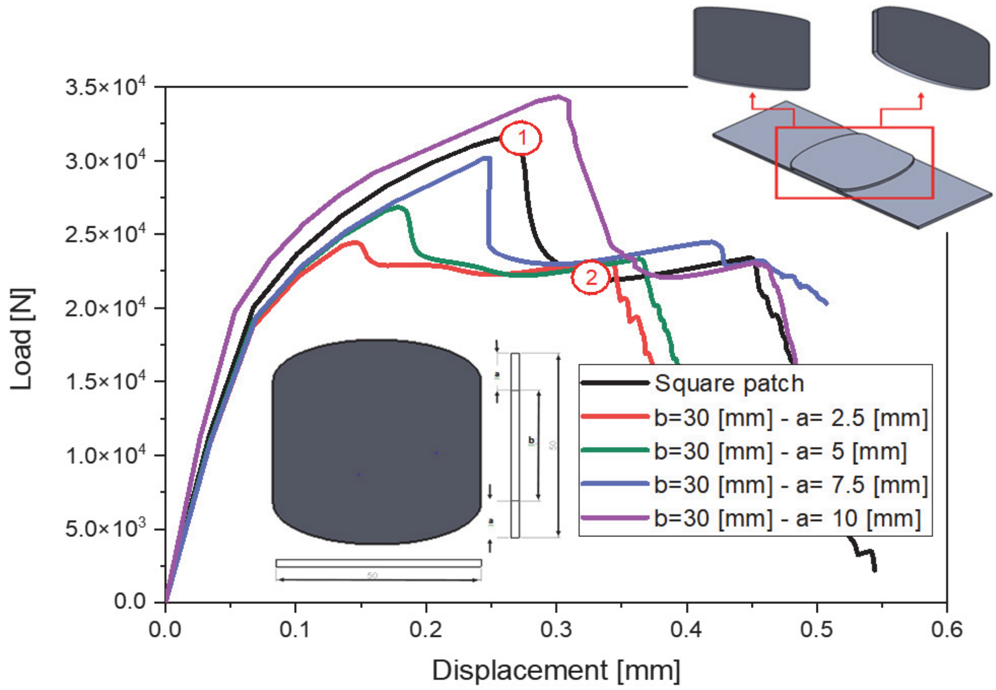
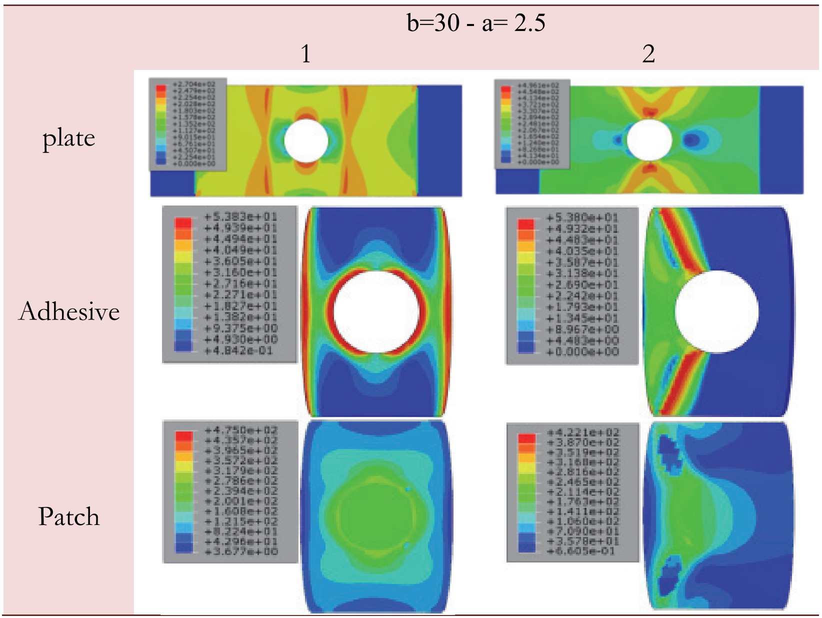


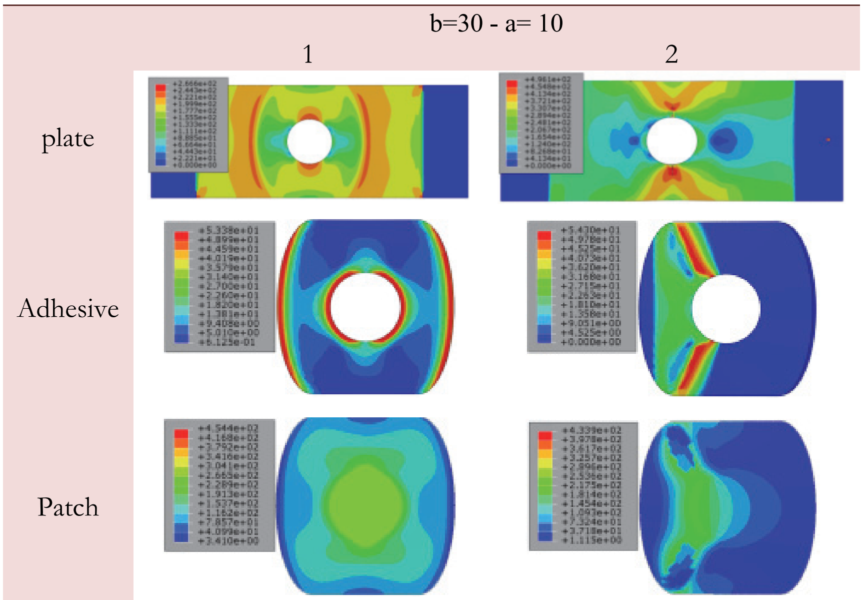
Figure 15: Variation of the maximum tensile force and maximum displacement according to the geometric parameter “a” of the modification of the edges of the patch.

The maximum values of the applied force and elongation of the structure under tensile tests are shown in Fig. 15. It is clear that the value of the parameters ‘a’ has a considerable influence on the strength and ductility of the repaired structure. The higher the value of the ‘a’ has increased the elongation and the maximum force of the structure therefore decreases a sudden rupture.
Fig. 16 shows another change to the opposite of the one shown above, or we have reversed so that the fixed b value follows 50 mm and we have varied ’a’. The different values of the parameter 'a' in the corner of the patch were analyzed digitally in tensile order to estimate the influence of this parameter on the resistance of the structure.
Fig.16a shows the tensile curves for the different values of ‘a’. It is clear that in the preceding example if ‘a’ increases the strength of the plate improves significantly.



(a)





b)

Figure 16: a) Traction curves associated with the geometric modification of the patch, and b) Stress levels in different substrates for two applied loads level.

The stress level in the plate associated with different values of the parameter 'a' and for the different applied loads clearly shows that the stress distribution in the plates is practically the same regardless of the value of the parameter 'a' of the modification brought to the corner of the patch (Fig. 16b). The constraints are more concentrated at the edges of the patch if the value of 'a' is minimal. At the notch level, the stresses are less concentrated for the patch repair case with a change whose value of the 'a' parameter is significant.

However, the level of stress in the patch is noted that regardless of the change made to the corners of the patch by varying the parameter 'a', the patch ensures a load transfer from the damaged area. The load transfer rate depends heavily on the shape of the patch and therefore on the value of 'a'. The stresses are concentrated in a small area when 'a' equals 10 mm but if the value of 'a' equals 7.5 mm the area of high stress concentration is more extensive and therefore a better load transfer. Once reaching the maximum force the detachment appears quickly in the case or at less than 5 mm and spreads rapidly which causes poor stress transfer in the patch. A small area continues to transmit the stresses of the damaged area which causes a rapid break in the structure.

The analysis of the stress level in the adhesive and therefore its damage is presented in the Fig. 16b.

The maximum value of the tensile force as well as the displacement for the various modifications made to the patch are shown in Fig. 17. It is clearly noted that for this shape of the patch, all the modifications made to the edge of the patch improve clearly the maximum values of force and displacement especially for a significant modification of the parameter 'a'.

Circular patch

For our second part of our study we tried to make the same changes to the circular patch.

In the first step we tried to keep the width of the patch the same as the width of the plate on the other hand we tried to minimize the height of the patch as shown in Fig. 18.a. The effect of this change in patch shape on the global response of the damaged and repaired structure in terms of the force-displacement tensile curve is shown in Fig. 18.a. It is clearly noted that if the height of the patch decreases the strength of the repaired structure decreases by decreasing its maximum tensile force. A decrease in patch height of 5mm hardly affects the strength of the structure. The displacement value of the structure is not affected by this change since the width of the patch is the same.

We note clearly that the distribution of tresses in the covered area is practically the same for the two changes made to the patch, on the other hand, outside this area, we note a difference in distribution of stresses. The 45mm patch height case has a better distribution. Once the applied force increases, the influence of the height of the patch appears clearly. With the onset of detachment, if the patch height is reduced the damage of the adhesive appears and spreads rapidly causing improper load transfer.

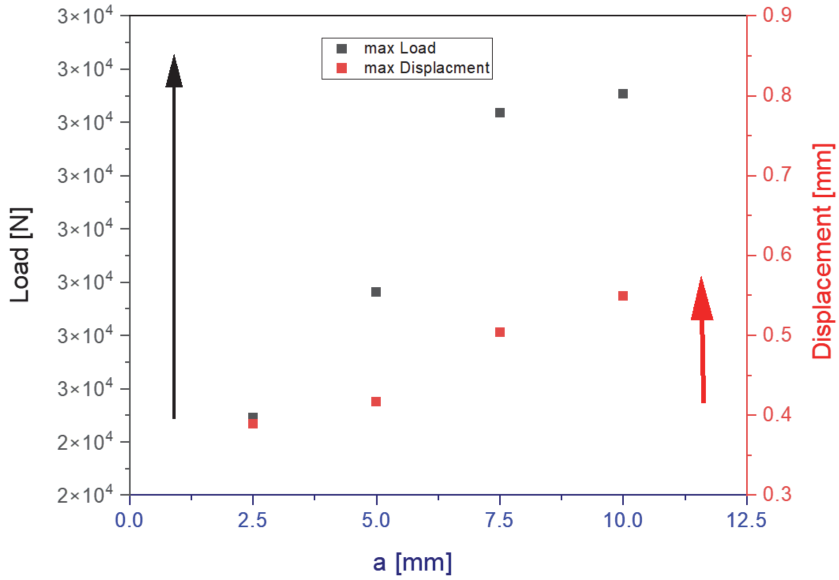
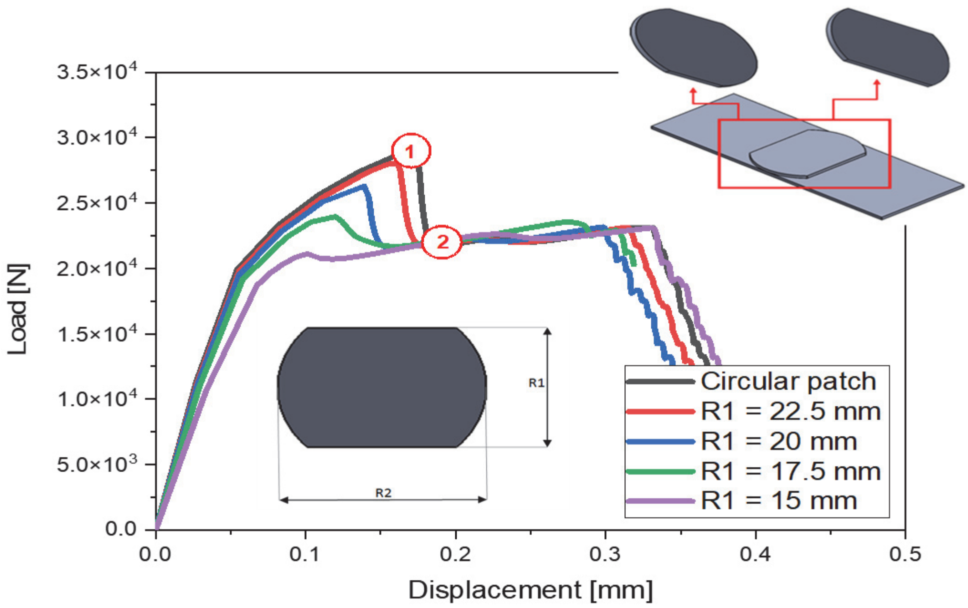


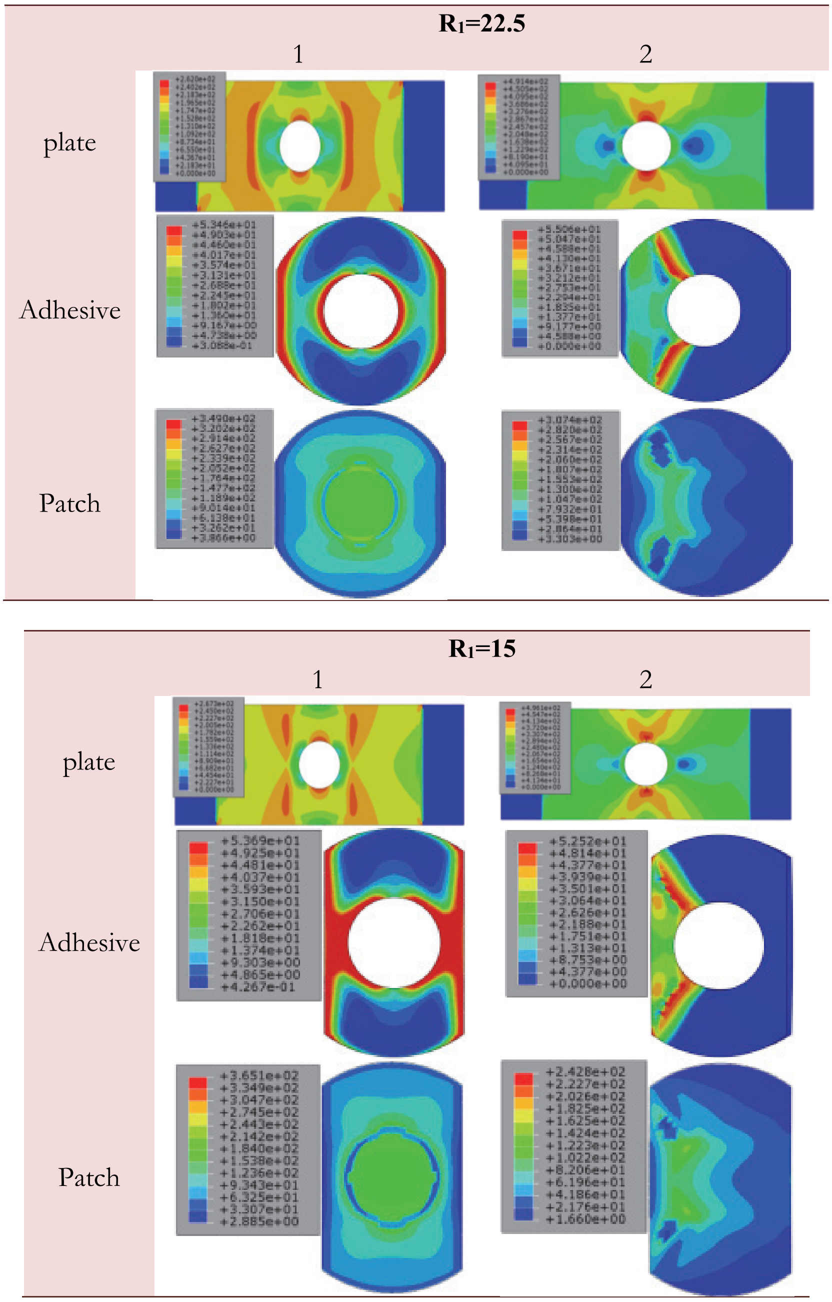
Figure 17: Variation of the maximum tensile force and maximum displacement according to the geometric parameter 'a' of the modification of the edges of the patch.

The stress distribution in the repaired plate is ensured by the load transfer rate through the adhesive (Fig. 18b). The stress level is clearly raised so that if the height of the patch is reduced, a high stress concentration is located in the adhesive layer. The minimum patch size, and the presence of the notch causes a small area covered by the adhesive; this causes high values of stress distributed at the edges and notch.

The representation of the maximum values of the tensile force and displacement of the repaired structure as a function of the variation of the parameter 'R1' is shown in Fig. 19. It is clearly noted that the variation is inversely proportional between the maximum force and the maximum displacement of the structure if the parameter 'R1' of the patch corner modification increases. The maximum force decreases and the elongation increases. For this change, it is noted that if the height 'R1' decreases the width of the patch 'R2' increases which ensures a wide coverage of the damaged area.



a)



b)

Figure 18: a) Traction curves associated with the geometric modification of the patch, and b) Stress levels in different substrates for two applied loads level.

The second modification of the circular patch concerns the variation of the width of the patch, while the height of the patch 'R1' increases (Fig. 20.a). It is clearly noted that if the width 'R2' decreases slightly, the patch ensures always the transfer of stresses (Fig. 20.b). Similar to the structure repaired by the circular patch. If the width 'R2' decreases we will have an elliptical shape that guarantees R1 better resistance of the structure and provides less material for the composite patch.

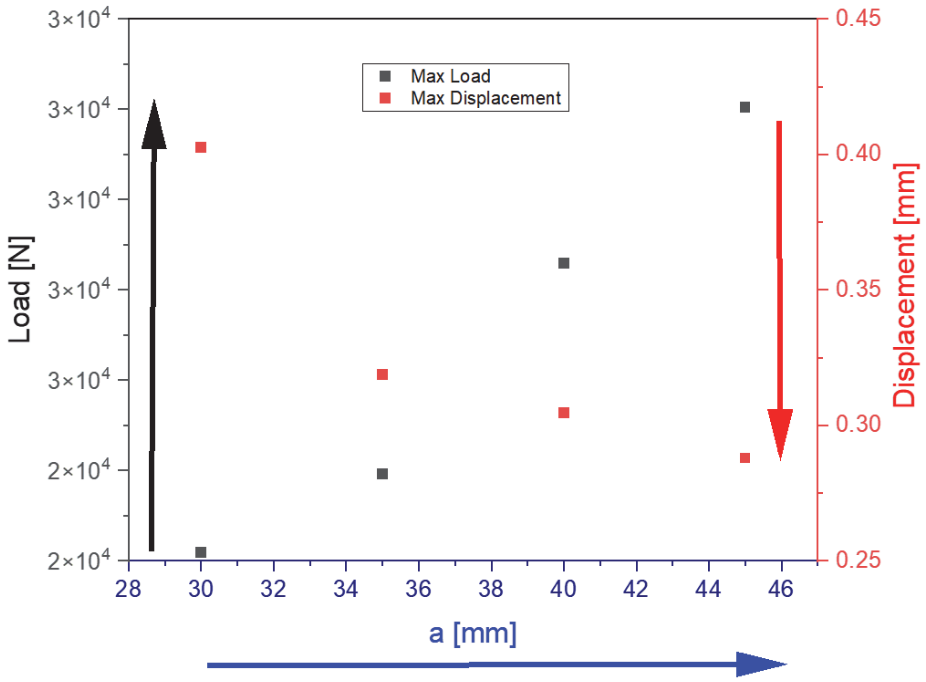
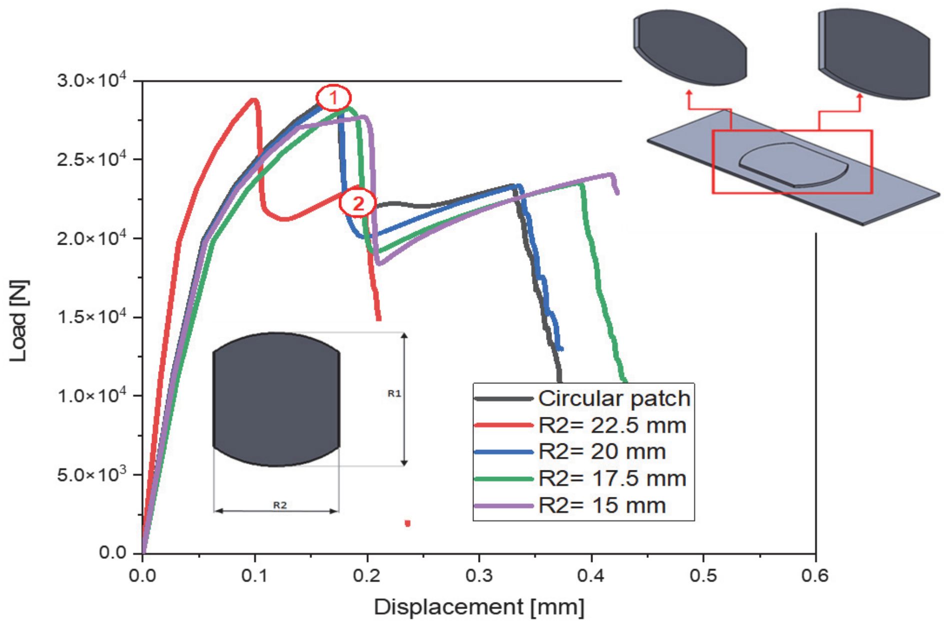


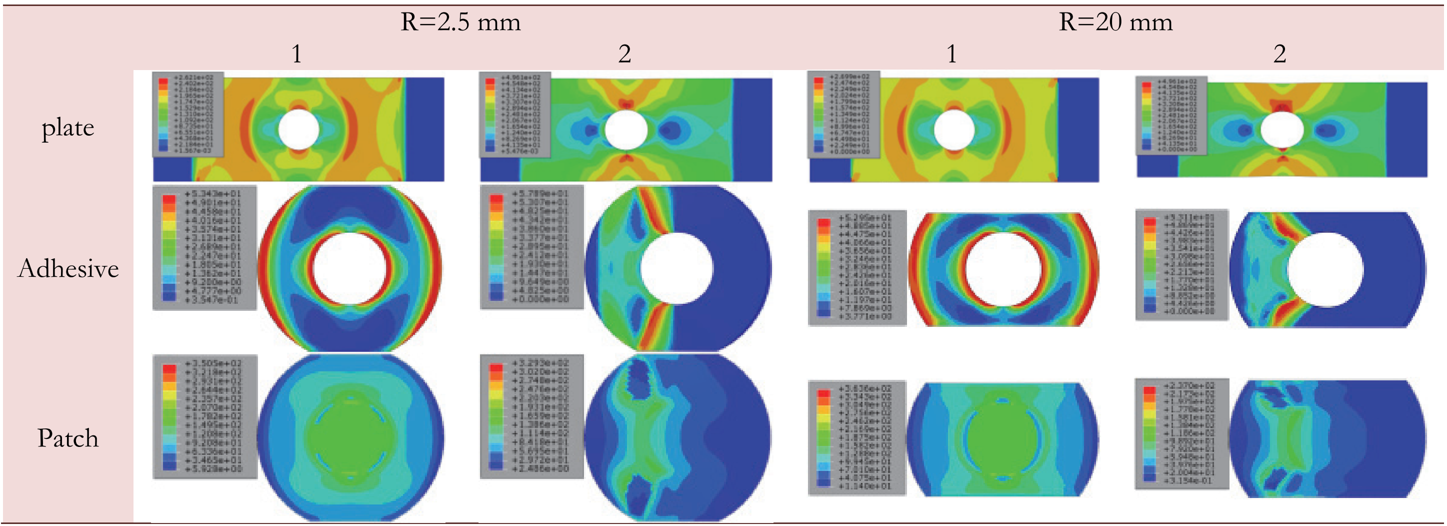
Figure 19: Variation of the maximum tensile force and maximum displacement according to the geometric parameter 'R1' of the change of the edges of the patch.

It is clearly noted that at the level of the damaged area a similar distribution for the two modifications, far from this area, the stress level is not the same and a strong stress concentration area is noted for the case where b is equal to 45mm. As the applied load increases, the stress level changes in the repaired structure and the one with a large width ensures better stress transfer. Once the adhesive damage appears, the structure repaired by large patch width ensures good resistance and the patch continues to transfer stress even after the adhesive damage. The crack appears quickly when the structure is repaired by patch of minimum width.

The stress level in the adhesive is clearly shown that if the patch width is minimal, a high stress concentration is located in the adhesive layer. The adhesive covers a small area of damage and the interaction of the adhesive edges creates high stress values which can exceed the failure limit of the adhesive and the damage of the adhesive begins. If the patch width is minimal the spread of adhesive damage is significant. The failure in the structure appears early only for an area covered by a large patch width.



a)



b)

Figure 20: a) Traction curves associated with the geometric modification of the patch, and b) Stress levels in different substrates for two applied loads level.

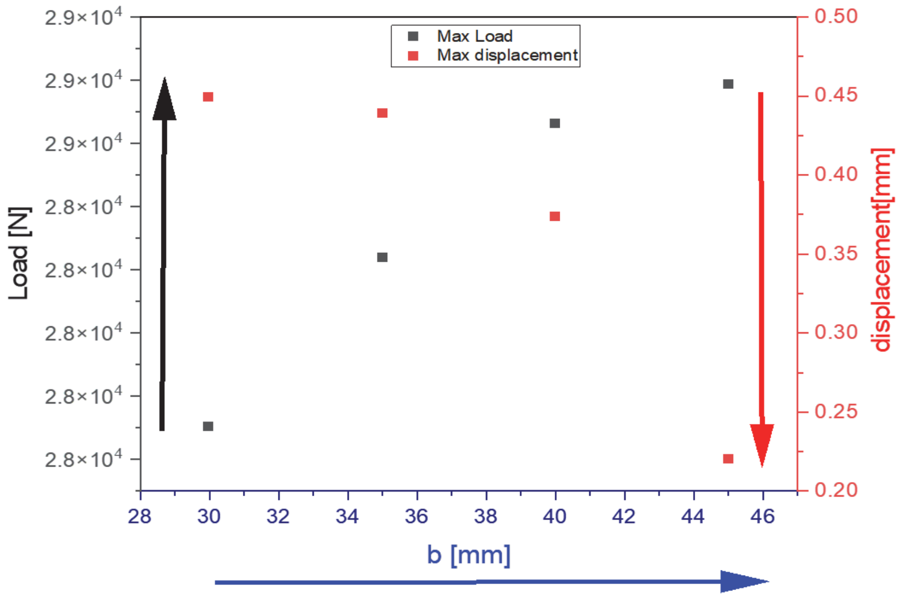


Figure 21: Variation of the maximum tensile force and maximum displacement according to the geometric parameter 'R2' of the modification of the edges of the patch.

For the transfer in the patch, the level of constraints is clearly noted that if the width of the patch decreases the patch always ensures a load transfer that will be distributed over most of its surface. If the applied load increases the patch transmits more stresses which causes damage to the adhesive, unlike the wide patch, the load transfer will be a wider area and ensures lower stresses in the adhesive layer and therefore delays its damage. Once the damage of the adhesive appears it spreads quickly in case the width of the patch is minimal since the free edges of the adhesive are in the vicinity of the notch generating high concentration of stresses.
From the tensile curves shown in Fig. 20.a, the effect of the variation of the width of the patch and therefore its height on the maximum values of tensile force and elongation was analysed (Fig. 21). It is clearly noted that if the width of the patch thus increases the author of the patch also increases thus ensuring a wide open area and therefore gives resistance to the damaged structure. Therefore if the width of the patch decreases, the height of the patch also decreases and therefore a low resistance of the structure repaired by low values of the maximum forces.

CONCLUSION

The study undertaken in this work is based on a numerical analysis by the finite element method of a damaged 2024-T3 aluminum structure repaired by a carbon/epoxy type composite patch through an adhesive AdekitA-140. We were able to analyze the damage of the repaired structure by the automatic propagation of the crack in the plate and the damage of the adhesive by using the combination of the two techniques XFEM (extended finite elements methods) and CZM (cohesive zone model). The results of the analysis allowed the following conclusions to be drawn.

- The validation of the traction curves carried out experimentally on the repaired structures by composite patch has become practical when using these two techniques, XFEM for the automatic propagation of the crack in the plate and CZM for the detachment of the adhesive, while ensuring a good choice of density and type of mesh elements.
- Composite patch of any size and shape provides load transfer and reduces stress concentration in the damaged plate.
- The square-shaped patch ensures a large covered surface and thus provides good structural resistance.
- The reduction of stresses at the edges of the patch is essential in order to avoid its detachment from the structure, especially for the repair by simple patch where the bending of the structure induces additional stresses in the patch.
- The geometry of the edges of the patch is an important parameter that must be optimized to reduce the stress concentration at these edges.
- The square or circular patch has almost the same response in the strength of the damaged plate in terms of tensile strength. Since both patches cover the same width of the plate.
- The modification of the height and width parameters of the patch as well as the geometric shape of the angles of its edges must be optimized in order to ensure a high performance of repair.

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