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Analysis of the adhesive damage for different patch shapes in bonded composite repair of corroded aluminum plate

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Abstract. Many military and commercial aging aircrafts flying beyond their design life may experience severe crack and corrosion damage, and thus lead to catastrophic failures. In this paper, were used in a finite element model to evaluate the effect of corrosion on the adhesive damage in bonded composite repair of aircraft structures. The damage zone theory was implemented in the finite element code in order to achieve this objective. In addition, the effect of the corrosion, on the repair efficiency. Four different patch shapes were chosen to analyze the adhesive damage: rectangular, trapezoidal, circular and elliptical. The modified damage zone theory was implemented in the FE code to evaluate the adhesive damage. The obtained results show that the adhesive damage localized on the level of corrosion and in the sides of patch, and the rectangular patch offers high safety it reduces considerably the risk of the adhesive failure.

Keywords: composite repair; corrosion; damage ratio; finite element method (FEM)

1. Introduction

Aging aircraft problem is one of the serious challenges to commercial and military aircraft operators. The high Acquisition costs associated with the purchase of modern aircrafts, coupled with the increased budget cuts in the Acquisition of new aircraft fleets have resulted in the utilization of aircrafts be yond their original design life. Corrosion and fatigue are the major factors that contribute to the aging of aircraft. During its service life, an aircraft is subjected to severe structural and aerodynamic loads which may result from repeated landing sand take-off, fatigue, Ground handling, bird strikes and environmental degradation such as stress corrosion, which cause damage or weakening of the structure. A repair or reinforcement of the structure to restore the structural efficiency and thus assure the continued airworthiness of the aircraft has become an important issue in recent years. Advanced composite material shaves many advantages like high specific strength and stiffness, light weight, resistance to corrosion, directional dependence of the material properties, ability to be formed To conform complex shapes and contour sand to meet variable stiffness requirement. The technique of repairing aircraft

Structures with the corrosion using high strength advanced composite materials. The composite

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reinforcement, also known as a patch, can be attached to the damage do weakened structure either by mechanical fastener or adhesive bonding. Patch repair is a commonly used method for rectifying localized corrosion damage in reinforced concrete members, for a satisfactory patch repair to a concrete structural element the prevention of reinforcement against further corrosion is an important consideration. Therefore, the performance of a repair mortar and reinforcement coating in protecting the reinforcement against further corrosion may need to be considered in the selection of a repair system. Bonded composite repairs provide an efficient method for restoring the ultimate load capability of the structure Bachir Bakuckas *et al.* (2011). These repairs of locally damaged metallic structures have gained considerable interest in aircraft structural maintenance and life extension solution in the last two decades (Baker *et al*. 2011, Ahn *et al*. 2010). Mhamdia (2012) Found that the patch with arrow shape can reduce simultaneously the stress intensity factor at the crack tip and the adhesive shear stresses. Hosseini (2012) established that as the thickness of the composite patch is increased, fatigue crack propagation of repaired stiffened panel is also increased. The corrosion in exposed steel members especially in saline environment may also lead to the reduction of rating factor. Capacity loss in steel girder of a bridge due to corrosion has been studied for static load by Kayeser and Nowak (1987, 1989). We can cite several authors, who discuss this phenomenon of reinforced concrete beam (Fahad *et al*. 2014, Congqi *et al*. 2013, Kurklu *et al*. 2013, Faiz *et al*. 2014), and we notice also (Fournel *et al*. 2015, Dao *et al*. 2012) speaks on the effect of water on the structure.

Recently, several papers describing the damage zone theory were publishing. Fari Bouanani *et al.* (2013) has estimated of the adhesive damage and failure in bonded composite repair of aircraft structures using modified damage zone theory .and there are shows that adhesive damage is principally located at the free edges of the patch and over crack region. Benyahia *et al.* (2014) analyzed four different shapes (rectangular, trapezoidal, circular and elliptical) showed, The rectangular patch offers high safety compared to the other patch shapes but it reduces the repair performances The elliptical patch can be considered as the optimal shape because it simultaneously improves the repair efficiency and the repair durability. Ramji *et al.* (2013) tested several patch shapes and they concluded that the extended octagonal patch shape performs better in case of stress intensity factor reduction. Bachir Bouiadjra *et al.* (2011) compared the repair performance of patches with rectangular and trapezoidal shapes. Benyahia *et al.* (2014) evaluated the effect of water absorption on the adhesive damage in bonded composite repair of aircraft structures, there are shows that, The water absorption accelerates the adhesive damage and The repair durability is affected by the water absorption. We have talked about in this paper on the Effect of the adhesive shear modulus on the adhesive damage and we note that Bachir Bouiadjra *et al.* (2002) showed that an adhesive with high-shear modulus (with bad qualities) gives weak stress intensity factor at repaired crack tips. Hence, they recommended the use if this material for increasing the performance of bonded composite repair. In spite of the fact that higher adhesive shear modulus leads to higher adhesive stresses. This increases the risk of adhesive failure. Albedah *et al.* (2011) used to determine the advantage of the double symmetric patch: it is the determination of the mass gain obtained by the use of the double patch if the two techniques (single and double patches) give the same stress intensity at the crack tip. The obtained results show that the same gain eventually obtained by the use of the double patch can be very significant. In this study the effect of corrosion on the damage of the FM72 epoxy adhesive, in the case of bonded composite repair of aircraft structures, were evaluated using finite element method and the damage zone theory.

This party was carried out in order to determine the evolution of the damage zone in the

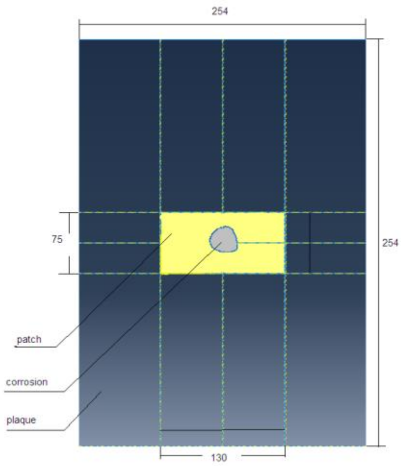


Fig. 1 Geometrical model

Table 1 Elastic properties of the different materials

Properties	Materials		
	Aluminum 2024-T3	carbon/ epoxy	Adhesive (FM73)
Longitudinal Young modulus E1 (GPa)	72	210	4.2
Transversal Young modulus E2 (GPa)		19.6	
Transversal Young modulus E3 (GPa)		19.6	
Longitudinal Poisson ratio υ_{12}	0.33	0.3	0.32
Transversal Poisson ratio υ_{13}		0.3	

adhesive layer of bonded composite patch, for which is used for only repaired corrosion. The theory of damage zone was used to reach the objectives of the analysis. First, the surface of the damage zone was computed for effect of the load with of different forms of patch (rectangular, trapezoidal, circular and elliptical) and a plate with a random form of corrosion and without fissure. The theory of damage zone was used to evaluate the damage progress during the analysis. Ban et al. have shown that the FM 73 adhesive joint fails if the damage ratio reaches the value of 0.2474.

2. Geometrical and FE models

The basic geometry of the structure considered in this study is shown in Fig. 1. Consider a rectangular aluminum 2024-T3 plate with the following dimensions: height H_p=500 mm, width W_p=300 mm, thickness e_p=2.5 mm, with a central corrosion grind-out of random shape. The plies in the patch had unidirectional lay-up where the fibers are oriented along the specimen length direction (parallel to the direction of load). The patch is bonded by 0.15 mm thick film of FM 73 epoxy adhesive (Fig. 1). In order to analyze the effect of the patch shape, four shapes of the composite patch were chosen in this study: rectangular, trapezoidal, circular and elliptical. The sizes of these patches are given in Fig. 2. The elastic properties of the different materials are given

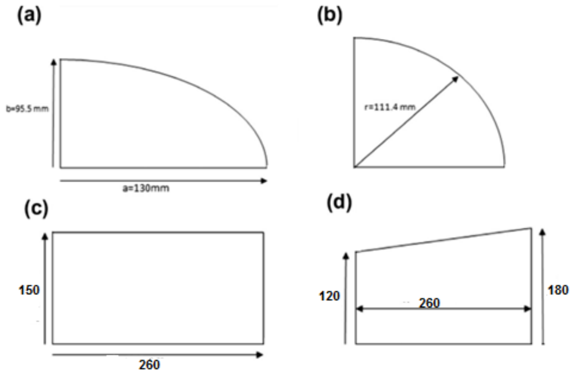


Fig. 2 Patch sizes: (a) elliptical patch, (b) circular patch, (c) rectangular patch, (d) trapezoidal patch

in Table 1, the stress-strain curves of the FM 73 epoxy adhesive is presented in Fig. 4. Presents the multi-linear stress-strain curve of the FM73 adhesive for determining its ultimate strain. The analysis involves a three-dimensional finite element method by using the commercially available finite element code ABAQUS (2007). The finite element model consisted of three subsections to model with corrosion, the adhesive, and the composite patch.

The analysis involves a three-dimensional finite element method by using the commercially available finite element code ABAQUS. The finite element model consisted of three subsections to model with the corrosion, the adhesive, and the composite patch. The plate had four layers of elements in the thickness direction, the adhesive had only one layer of elements through thickness and the patch had two layers of elements through thickness. The mesh was refined near corrosion area with an element dimension of 0.05 mm using at least twenty such fine elements around the corrosion. Fig. 3 shows the overall mesh of the specimen and the mesh refinement in the corrosion region.

The procedure used in the finite element analysis is as follow: the tensile stress was applied to the gripped specimen. General static ‘‘STEP’’-option was used for analysis with ABAQUS. Automatic increment of step was used with maximum number of increments of 200. Minimum increment size was 10^{-5}. Maximum increment size was one. Nevertheless, the ABAQUS solver code could override matrix solver choice according to the ‘‘STEP’’-option.

3. Damage zone model

The theory’s main assumption is that both adhesive and adherend crack initiation in the bonded joints takes place after a damage zone develops. Under low load amplitude, localized damage occurs at the edges of the joint. This damage occurs because the material is locally subjected to strains higher than the ultimate material strain. Under medium load amplitude, the damage zones grow in size and the concentration of points of specific damage increases. As the failure load is reached the damage zone in either the adherend or the adhesive grows to a critical size and the individual components of damage coalesce and form a crack. Numerically, the damage zone is identified by marking the elements for which a failure criterion is exceeded. The adhesive used in the analyzed joints is a hardened ductile adhesive which is expected to fail at yielding. Consequently, the failure criterion used for the cohesive damage of the adhesive layer is the

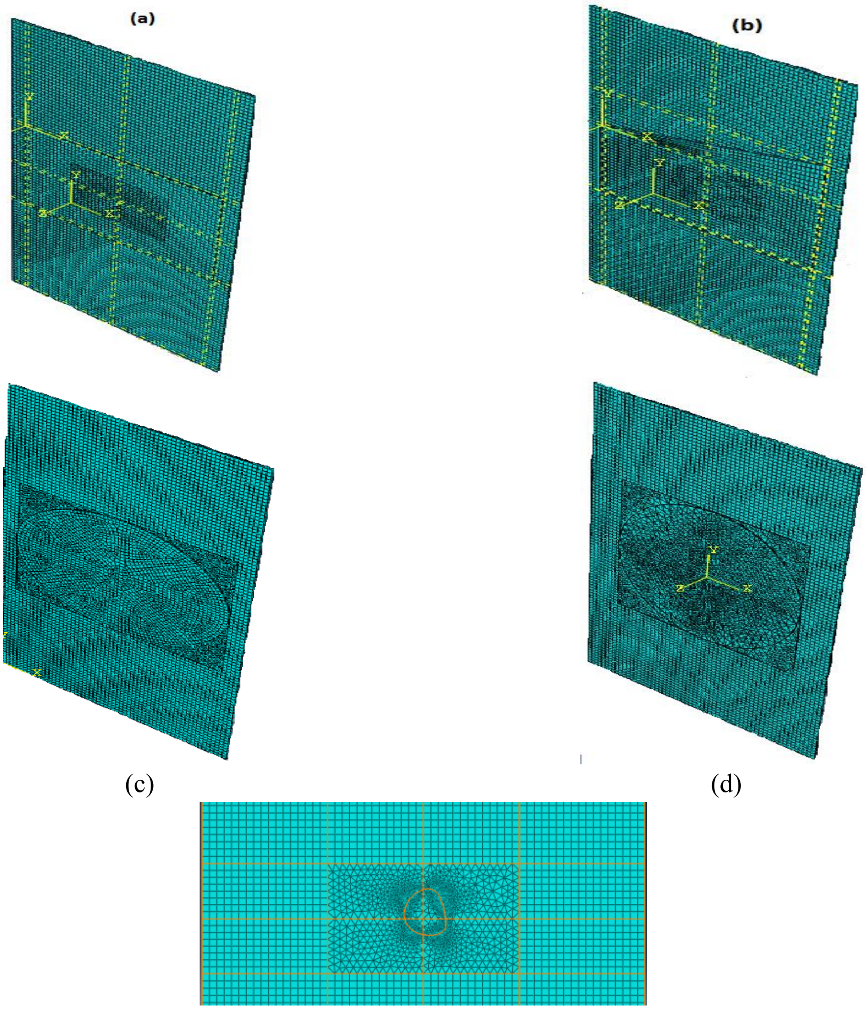


Fig. 3 Typical mesh model: (a) rectangular patch, (b) trapezoidal patch, (c) elliptical patch, (d) circular patch, (e) Near the corrosion

equivalent Von Mises strain criterion

$$\varepsilon_{equuiv} = \frac{1}{\sqrt{2(1+\upsilon)}} X \sqrt{(\varepsilon_{p1} - \varepsilon_{p2})^2 + (\varepsilon_{p2} - \varepsilon_{p3})^2 + (\varepsilon_{p3} - \varepsilon_{p2})^2} \tag{1}$$

Where ε_{equuiv} is the equivalent stain, ε_{pi} are the plastic strains in the different directions and m the Poisson ratio.

This criterion is satisfied when the maximum principal strain in the material reaches the ultimate principal strain. For each failure criterion an ultimate strain will be defined and the corresponding damage zone size at failure is determined. For the FM 73 epoxy adhesive, the damage zone is defined as an area in which the strain exceeded the ultimate strain of 7.87% Ban Chang *et al*. (2008) see Fig. 4.

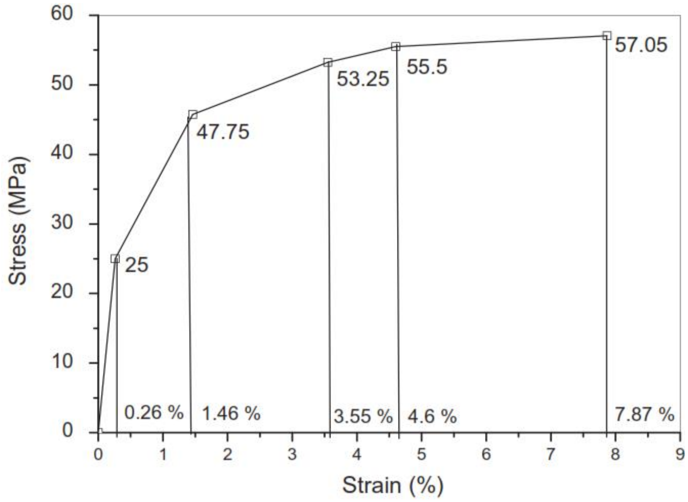


Fig. 4 Multi-linear stress-strain curve of the FM 73 epoxy adhesive Ban Chang *et al*. (2008)

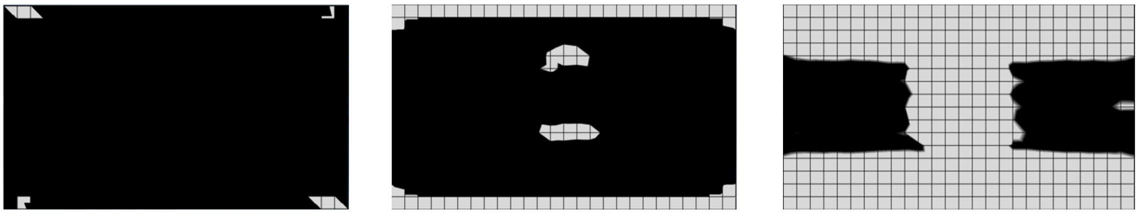
In the damage zone theory, the adhesive joint is assumed to fails when the damage zone reaches a given reference value. The damage zone can be defined by either a stress or a strain criterion. The strain criterion is more appropriate when the adhesive exhibits significant non-linearity. There are two modes of failures of the adhesive joints: interfacial and cohesive failures. In the interfacial mode, the critical failure load of the adhesive joint is related to the interfacial stress between the adhesive and the adherend Ban Chang *et al*. (2008). However, the adhesive fails when the cohesive failure criterion is satisfied in the joint. Knowing that cohesive failures occur in the adhesive joint, the adhesive failure criterion for the damage zone is to be used. For isotropic materials, failure criteria such as the Von-Mises and Tresca criteria can be used to better understand adhesive failures. Moreover, adhesive joints failure can be predicted using the damage zone ratio method.

$$D_R = \frac{\sum A_i}{l.w} \tag{2}$$

D_R is the damage zone ratio, A_i is the area over which the equivalent strain exceeds 7.87%, l is the adhesive length and w is the adhesive width. It has been shown that the FM 73 epoxy adhesive fails when the ratio D_R reaches the value of 0.2474 Ban Chang *et al*. (2008).

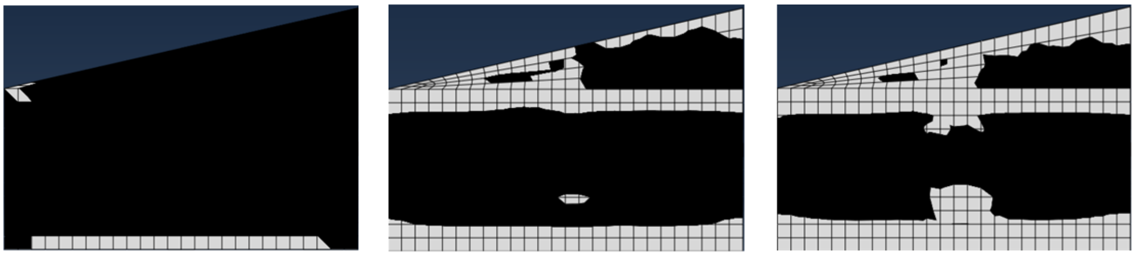
4. Results and discussion

The area of the damage zones in the adhesive layer (in gray) this effect was performed out in order to determine the evolution of the damage zone in the adhesive layer. The majority of the previous studies (Crocombe *et al*. 1995, Sheppard *et al*. 1998) assumed that the adhesive damage reduces significantly the repair durability. First, the area of the damage zone was calculated for different value of load σ=(200,240 and 300 MPA) with an adhesive FM32 of thickness e_a=0.15 mm and of the adhesive shear modulus G_a=4200 MPa, for the different forms of patch. And finally, after the tracing of different graphs of the damage zone ratio can work a comparison



(a) (b) (c)

Fig. 5 Damage zones for rectangular patch shape. (a) σ=200, (b) σ=240 and (c) σ=300 MPa



(a) (b) (c)

Fig. 6 Damage zones for trapezoidal patch shape. (a) σ=200, (b) σ=240 and (c) σ=300 MPa

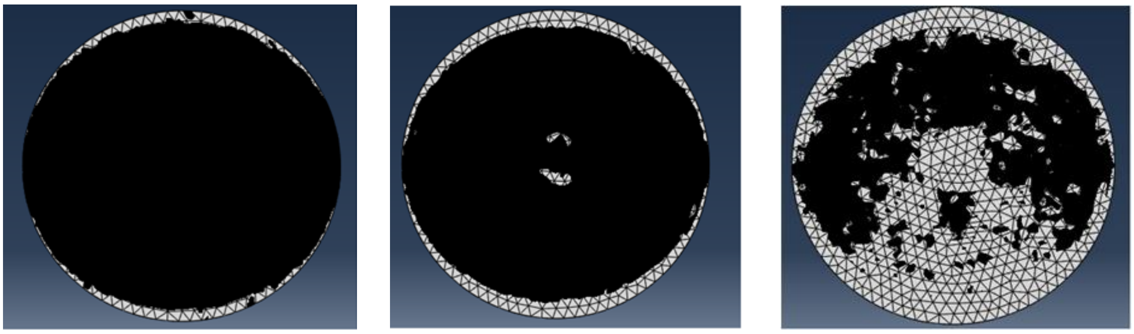
between the different graphs to compare the effect of different forms of patch.

Fig. 5(a), (b) and (c) present the distribution of the damage zone of the adhesive of rectangular patch with a thickness of patch of 0,5 mm and adhesive thickness of 0,15 mm with the adhesive shear modulus G_a=4200 MPa. It is clearly seen from these figures that the size of the adhesive damaged zone increase from the increased load applied on the plate and we also note that the damage zone in the case of 200 MPa to appear at the adhesive angles with a very small area we can be said that it is negligible, and then in the case of 240 MPa is observed that the damage zone is big compared with preceding case it exists in the patch sides (superior and inferior) and also they look at a small damage zone at edge of the corrosion and in the case of the 300 MPa damage zone is very large and it occupies the all surface of the corrosion.

Fig. 6(a), (b) and (c) shows the variation of the damage zone as according to the load σ (200 MPa, 240 MPa and 300 MPa) respectively with the patch of a trapezoid form with the same properties over the case of rectangle, after these Figures it is noted in the case of 200 MPa the damage zone is in the inferior side of trapezoid (low) and a small area on a single angle but any area at the corrosion in the opposite in the case of σ=240 MPa the damage zone is very clear and large. It appears a zone has contour of corrosion, and also to the upper and lower sides of the trapezoid, but in case of the 300 MPa damage zone increases a level of the corrosion area and occupies almost all the lower and upper trapezoidal side.

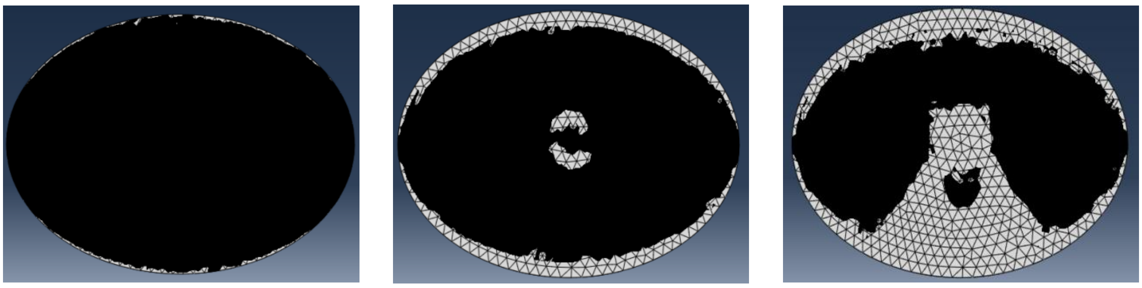
This effect was realized to determine the evolution of the damage zone in the adhesive layer is shown in Fig. 7(a), (b) and (c). Firstly, the damage zone in the entourage of patch but any appearance the damage at the level of corrosion in the case of σ=200 MPa but in case of σ=240 MPa we noticed a small damage zone to the upper edge level and lower the corrosion and damage zone increases at extremity. In the end in case σ=300 MPa is observed that the damage zone occupies all the surface of corrosion and wide on the perimeter of the adhesive.

The variation of the damage zone with use of patch of form ellipse according to different value



(a) (b) (c)

Fig. 7 Damaged zones for circular patch shape. (a) σ=200, (b) σ=240 and (c) σ=300 MPa



(a) (b) (c)

Fig. 8 Damaged zones for elliptical patch shape. (a) σ=200, (b) σ=240 and (c) σ=300 MPa

of loads σ varies between 200 MPa and 300 MPa. Show in the Fig. 8(a), (b) and (c). Below, we see from these figures that the damage zone increases with the increase of the load and also we notice that the damage zone in the case of σ=200 MPa located at the perimeter of the ellipse with a small area but where σ=240 MPa this area develops at the extremity and an appearance at the edge of the corrosion in the extremity if σ=300 MPa the damage zone occupies a big party of the adhesive almost in all direction of the adhesive.

In Fig. 9, if we see the rectangle patch, of the damage zone ratio D_R increased from 0.15 to 0.13 in the interval between the load σ=200 MPa and σ=220 MPa, and then the curve takes a constant value of D_R equal of 0.13 until the load of σ=260 MPa and after this load the curve brutally increases reached the value of 0.37. We can also say that the critical value of the damage zone ratio is reached from load σ=280 MPa which records 0.24. But with a trapezoidal patch the curve remains almost stable with a small change in the damage zone and the other phase between σ=230 MPa and σ=300 MPa the curve is increases progressively, more the load increases more the damage zone ratio increases. And also we see that the critical value of the damage zone ratio (D_R=0.247) is attained after the value of σ=270 MPa. We show also the variation of the damage zone ratio of the circular adhesive according to different load. From this graph we can say that the graph has only one growth phase, more the load increases more the damage zone ratio increases, we could also see that the value of D_R reached after the load value of σ=270 MPa. The results obtained in the case of the patch ellipse notes that D_R increases with the increase of the load and we note that after the load σ=270 MPa the damage zone ratio higher than critical D_R who entrain a degradation of the state of the adhesive which entrain automatically the patch damage.

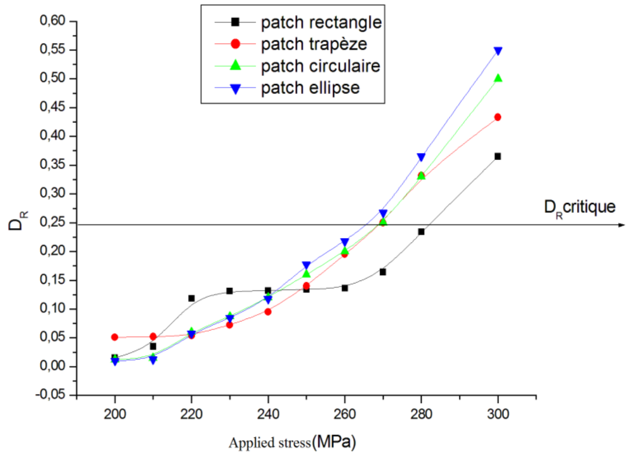


Fig. 9 Damage ratio vs loads for different patch shapes

For better illustration the effect of different patch shapes (rectangular, trapezoidal, circular, elliptical) on the variation of the damage zone of the adhesive we tried to calculate this area according different load values, in order to calculate the damage zone ratio we traced the Fig. 9. Which shows the variation of damage zone ratio we can notice that the increase in the load σ therefore causes an increase in D_R then it is noted that the corrosion repair by the use of rectangle shaped patch useful against other shapes (trapezoid, circular and elliptic) because the critical value of the damage zone ratio will wait before σ=280 MPa contrary to other cases that only reached for σ=270 MPa.

6. Conclusions

In this study, using the damage zone theory for analyzed the adhesive behavior on the repair of corrosion by the materials composite following Effect of the patch shapes. The obtained results show that:

- The adhesive damage localized on the level of corrosion and in the sides of patch, the increase in the load σ therefore causes an increase in the damage zone ratio (D_R).
- The corrosion repair by the use of rectangle shaped patch useful against other shapes (trapezoid, circular and elliptic) thus rectangular patch offers high safety it reduces considerably the risk of the adhesive failure.

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