Failure behavior of a notched plate repaired by a hybrid repair technique (Stop hole bonded composite

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Research Article

Keywords: Bonded composite, Stop-hole, Hybrid technic, volumetric method, PLL, NSIF.

Posted Date: July 11th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-2994646/v1

Failure behavior of a notched plate repaired by a hybrid repair technique (Stop hole bonded composite

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Abstract

Generally, bonded repairs are only approved if the primary aircraft structure is cracked and the residual strength significantly exceeds the design limit charge before the bonded repair can be applied.. In order to improve the maintenance effect of the stop hole approach for cracks, a solution of using both techniques (stop hole / bonded composite repairs) are proposed and investigated by finite element analysis. This work presents a study on the effectiveness of the hybrid repair technique in notched panels using both stop drilling hole and bonded composite repair techniques. Several parameters are taken into account: the diameter of the size of hole drilling, the width and the thickness of the composite patch and other parameters are modeled with a elastoplastic behavior of the plate using Abaqus software. A limit-load analysis determines a lower bound to the limit charge of a component and provides an alternative way to estimate plastic collapse for the limit loads. In addition, the limit load analysis had helped to provide an evaluation of the behaviors of structures or components for other failures. The plastic limit load (PLL) was evaluated by a convergent load increment in a well-configured finite element analysis with a load of a sufficiently small increment for an elastic-perfectly plastic behavior of the structure. The allowable limit stress on the aircraft is calculated by applying design factors to the plastic limit load (PLL) so that the onset of plastic collapse does not occur. The results proved that the hybrid repair provided the largest percentage in terms of maintenance and the smallest values for the notch stress intensity factor (NSIF) and von Mises stress for most of the hybrid configuration compared to the single repair technique.

Keywords: Bonded composite, Stop-hole, Hybrid technic, volumetric method, PLL, NSIF.

1 Introduction

Bonded composite repairs for cracked aircraft primary structures have long been successfully applied, although they have drawbacks compared to conventional mechanical repairs [1], [2]. Another alternative calls for the combination of two or more repair techniques in a single configuration with the aim of finding a physical complementarity between these techniques. J. Wang et al [3], investigate certification requirements for composite repair applications bonded to primary structures in combination with other methods to improve the tensile strength of damaged structures, such as optimal defect elimination and the addition of a variable load path. The results of this research indicated that hybrid repair methods hold promise for repair applications on primary structures. It has been shown that also in hybrid repairs the adhesive provides a significant advantage in improving the static strength and fatigue resistance of the damaged structure.. N. Chowdhury et al [4], in this study, three configurations are proposed by N. Chowdhury namely, a hybrid joint composed of both bonding and riveting, a purely riveted joint and a purely bonding joint . Researchers compare static strength and fatigue strength for these case studies. The influence of various parameters was studied, such as the configuration of the network of mechanical fasteners, the clamping pressure of the rivets, the bond strength, the initial defects and the hardening conditions. Y.Yo et al [5], this study analyzes the application of drill-hole repair for cracks locating in weld joints in diaphragm-to-rib and propagating to the diaphragm. The optimization of the hole drilling protocol such as the position and diameter of the stop hole in real bridges is based on the combination of fatigue tests and FEM analysis. Gu et al [6], investigates the failure behavior of a single notch plate (SEN) repaired by a unidirectional bonded composite with acoustic emission (AE) measurements. Resin failure, patch repair region failure, and finally base metal failure may occur sequentially during the loading step. The examination of the individual fracture process in association with the AE characteristics of the resin, the patch and the base metal as well as their interfaces are based on observations by the scanning electron microscope and by the ultrasonic C-scan imaging.

The demanding requests of the different branches of engineering, especially in aeronautics, require the application of new materials and new multi-component structural systems. Appropriate choice of hybrid repair techniques can offer significant improvement in structural performance in terms of stiffness and robustness, in this context, we can cite the work of Toshiyuki Ishikawa et al [7] who propose a technique for reducing the concentration of stresses for a stop hole by bolting the fatigue crack between the stop holes. The study is based on tensile and bending tests on cracked specimens and finite element analysis. As a conclusion it was determined that the stress concentration of the stop hole was significantly reduced by bolting a crack in the condition before the bolts slipped.
The aim of this work is to evaluate the effectiveness of the combination of two techniques for repairing cracked structures, here the repair by bonded composite and the drilling of holes at the crack front are chosen. A three-dimensional finite element elastic-plastic analysis are performed to compare the efficiency of the hybrid repair method with bonded composite patches and stop drilled hole method for a repaired aluminum plates containing lateral U- notches. The Volumetric method criterion is developed to obtain the notch stress intensity factor $K_p$in mode I of fracture and the plastic limit load criteria from the ASME Boiler Pressure Vessel Code are chosen to describe the failure behavior of the repaired structures.

2 Concept of notch stress intensity factor (NSIF)

In theory stresses have a finite value at the notch-tip, which requires a physical value called fracture process volume, depends on the notch radius, geometry and loading mode [8]. This volume is assumed to be cylindrical by analogy with a notch plastic zone, the diameter of this cylinder is called "effective distance" X_{eff} wherefore an effective stress σ_{eff} can be estimated.

This leads to the notch stress intensity factor NSIF based on these two parameters. NSIF is used as fracture criterion using this equation:

$$\mathrm{K}_p = \sigma_{eff}(2\pi X_{eff})^{\alpha}$$

Where K_p:notch stress intensity factor
σ_{eff} :effective stress
X_{eff} effective distance
The exponent depends on the angle of the notch and whether the sides of the notch are parallel $\alpha = 0.5$. Fig 1 represents the criterion of the volumetric method.

3 Concept of plastic limit load analysis (PLL)

Limit load analysis of a structure containing defects is one of the most effective methods when performing a structural integrity assessment. Used by the ASME code

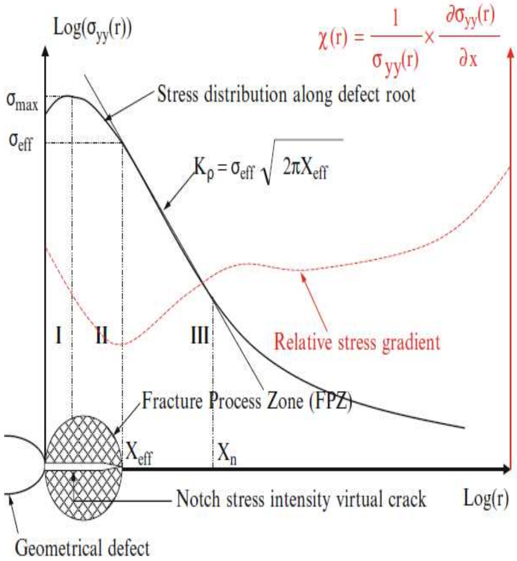

Fig. 1 Schematic of the notch stress intensity virtual crack concept and elastic-plastic stress distribution along the notch ligament. [8]

several searches are made, in fact Miller [9] listed the limit load expressions for several cracked structures under various types of loadings. Gangsi Cai. [10] Compared the limit load solutions with finite element method FEM results, for thick cracked pipelines with circumferential cracks under combined loadings internal pressure and axial tension.
The limit load analysis for plates with semi-elliptical crack has been used by Dilistrom et al [11] by finite element calculations and limit load results for plates with rectangular cracks embedded in the net collapse section have been obtained by Lei et al [12]. The development of finite element methods and calculation tools has stimulated limit load analysis for structures. This method estimates the plastic collapse for the given loads and determines the plastic limit load (PLL) so that the onset of plastic collapse does not occur for elastic perfectly plastic behaviour.

4 Geometry and materials properties

Figure 2 illustrates the geometries of a notched $2024-T3$ aluminum plate repaired with a thin layer of FM73 adhesive superimposed by a composite (Boron/Epoxy), the aluminum plate is subjected to a uniaxial tensile load of $\sigma 65$ MPa .
The dimensions are: $W_{pl} = 39$ mm, $L_{pl} = 160$mm and $e_{pl} = 3$ mm, the notch radius $\rho = 0.25$ mm and the crack length a $= 9.75 + \alpha = 10$mm. The geometry of the composite is assumed to be a square with one side $W_{comp} = 25$ mm and its thickness is$e_{comp} = 1.5$ mm, the thickness of the adhesive is 0.1mm.

The plate and the adhesive are considered as isotropic while the composite patch is orthotropic modeled by the "engineering constants" model [13], [14]. The dimensions of the studied model are based on the standard ASTM E-647 [13]. Standard tensile tests were performed on Aluminum $2024-T3$ and the stress-strain curve obtained is shown in Fig 2

The mechanical properties of the aluminum plate, the adhesive and the composite patch are given in tables 1 and 2 .

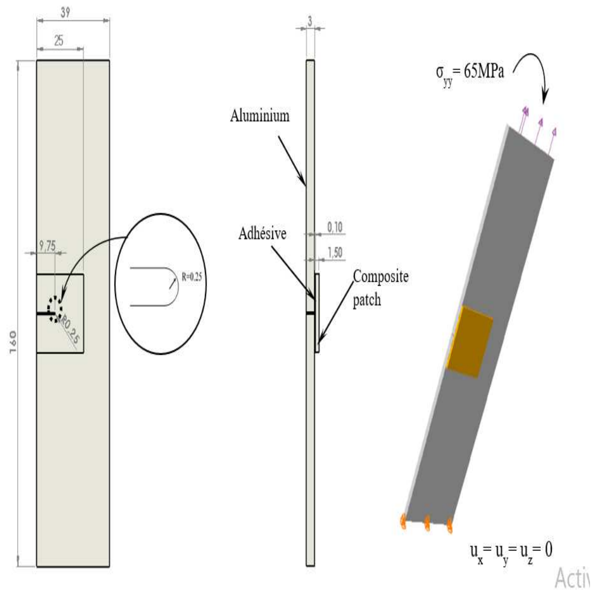

Fig. 2 Geometry and boundary condition of the repaired model.

Parameters	Aluminum alloy 2024T3	Adhesive FM73
E (GPa)	72	2.21
υ	0.3	0.43

Table 1 Material properties of 2024-T3 aluminum alloy and FM 73 Adhesive

Elasticity modulus (GPa)		Shear modulus (GPa)			Poisson's ratio
E_{11}	200	G_{12}	7.2	υ_{12}	0.21
E_{22}	25	G_{13}	5.5	υ_{13}	0.21
E_{33}	25	G_{23}	5.5	υ_{23}	0.21

Table 2 Material properties of composite patch boron/epoxy

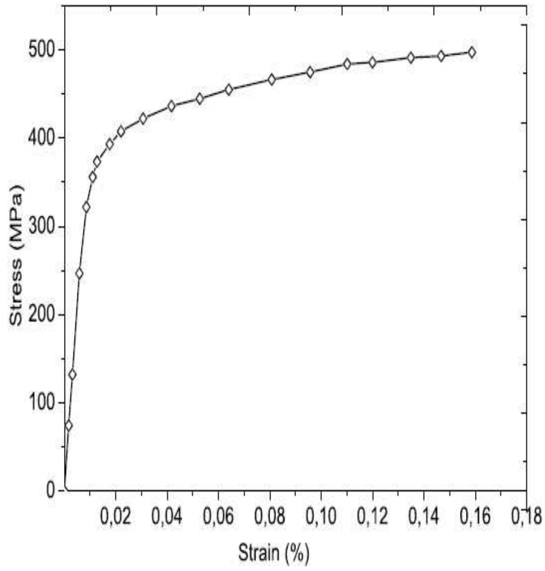

Fig. 3 Stress–strain curve of aluminum alloy $2024-T3$.

5 Finite element model

The studied model is a notched plate modeled by the finite element method (FEM) with the ABAQUS software, the geometry with a typical mesh of a repaired notched plate is illustrated in Fig. 4

The assembly of the model composed of the drilled plate, the composite and the adhesive is subjected to a uniaxial tension in the Y direction, sig = 65MPa. as Limit Condition the base section is clamped for the displacements (x = y = z = 0)Fig 2

The mesh is modeled by three-dimensional 3D elements with quadratic brick element with 20 nodes and hexagonal shape C3D20R. To increase the accuracy of the results a refined mesh was generated close to the notch tip region with an element size of 0.05 mm (Fig.3).

the finite element analysis used in the ABAQUS computer code is structured as follows: (i) application of tensile stress on the specimen; (ii) the ABAQUS software uses the "STEP" module with "general static" as sub-model; (iii) an automatic step increment is used with a maximum number of increments of 100.

The minimal value of increment is of 105 and the maximum increment is 1. Nevertheless, in the option of "STEP" the solver of the ABAQUS code could replace the choice of the matrix solver.
In an assembled model it is imperative to define the type of contact between the

interface regions and between the assembled structures because Abaqus does not recognize the mechanical contact between the parts or the regions of an assembly. For this, the "TIE" option in ABAQUS is used to define as a type of interactions between the plate/adhesive and patch/adhesive, hence a fusion of the two regions by a link constraint even if a dissimilar mesh is created on the surfaces of the regions in contact. Abaqus can use the default mesh techniques and automatically generate binding constraints on incompatible interfaces.

Abaqus code can automatically generate attachment constraints on incompatible interfaces by automatically choosing one side of the interface as the slave surface and the other as the master surface, while creating common (merged) nodes on the incompatible perimeter of the interface a surface with the finest mesh is generally considered as a slave surface for Abaqus code. The calculation of the size of the fit zone for a slave node for a bonding constraint is based on the bounding dimensions of the interface regions; in the "tolerance" position, the default value was used.

Rotational degrees of freedom (DOF) have been linked together for the nodes of the different subsections of the model.

Finally, the plastic deformation is predicted by the criterion of Von Misses elasticity and the non-linearity of materials is modeled by the theory of incremental plasticity. To solve nonlinear finite element equations the iterative Newton-Raphson approach is used [15].

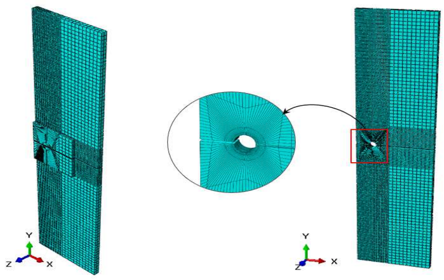

Fig. 4 Detailed mesh of the model.

6 Effect of drilling hole diameter(ρ)

One of the most accessible crack arresting methods is the drilling or crack stop hole, the principle of the stop-hole drilling technique is to drill the crack tip in order to eliminate the stress concentration zone at this location. Drilling a stop hole could delay the onset of crack propagation and provide additional time for subsequent reinforcement or replacement work. [[16] [17]. Many researchers have been conducted regarding the

efficiency of stop hole, Fu et al [18] used this method on steel bridge decks; they compared the stress concentration and stress gradient before and after the drilling. The analysis of different locations and several diameters of drilling was carried out to determine the optimal diameter and its location. Goto et al [19] have shown that drilling a hole near the crack tip has an influence on the direction of crack propagation and can increase the fatigue life of the cracked structure.Thomas et al [20]have studied the inflence of the drilling distance of a hole from the crack tip.
A combination of drilled hole method and composite patch was carried out in this work, the hybrid repair (stop hole/bonded composite) was applied to the notched plates where the stop hole center is located on the notch-tip. Fig.5 shows two repair technics comparing the stop hole technics with a hybrid one (stop hole + bonded patch) according to the drilled radius sizeρ. Indeed, for both techniques the stress σ_{yy-max} decreases with the increase of the drilled radius. The reduction stresses σ_{yy-max} between the two techniques presents an average of 40%whatever the radius of the hole. In this case the hybrid repair carries out reduced rate of 60% for radius 1mm, 67% for 2mm and 72% for radius 4mm compered by stop hole technique.
The stress concentration decreases with the size of the drilled radius and is more absorbed when using the hybrid technique compared to the drill-only technique. This reduction in concentration at the front of the notch is due to the beneficial effect of the composite for its quality of absorption of the stresses near the tip of the notch, which improves the fatigue resistance of the structure.

This analysis with the local failure stress criterion is provided to estimate the notch

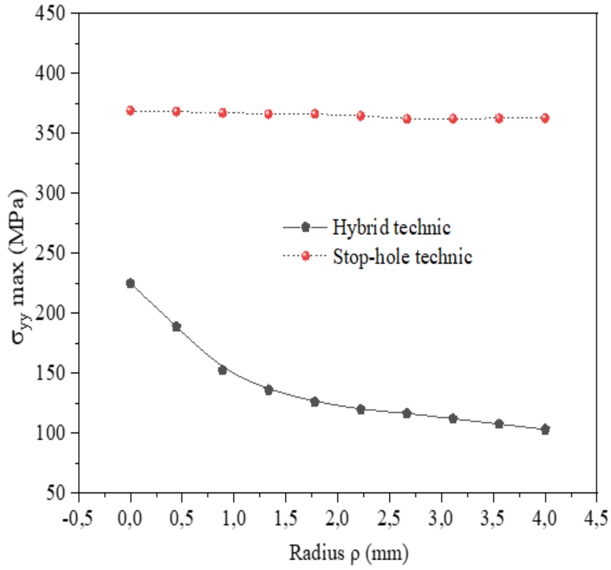

Fig. 5 Distribution of the maximum stress σ_{yy} according to the drilled radius ρ size.

stress intensity factor (NSIF) at the bottom of the notch for the two techniques stop hole only and hybrid technique. Fig.6 shows the evolution of the NSIF as a function of the drilling diameter radius for the two configurations.

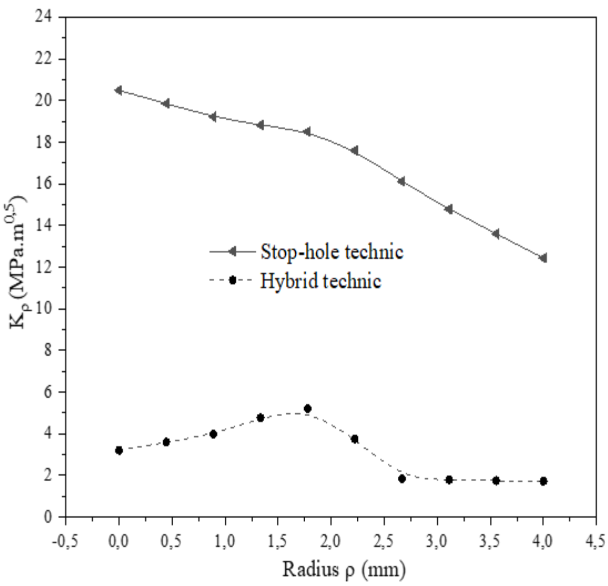

Fig. 6 Distribution of notch stress intensity factor (NSIF) according to the size drilled radius .

The NSIF shows an increasing behavior from 0 to 2mm for hybrid repair compared to drilling technic but hybrid repair technique is still inferior compared to the drilled repair technique only with an average reduction of the NSIF (Kp) of 70%. It can be noted in this case, that the hybrid repair reaches a reduction rate of 69% for the 1mm radius, 61% for the 2mm radius, while for the 4mm radius the reduction decreases to 47%. Likewise the NSIF (Kp) also decreases for the drilling repair confirmed by the researches of [5] [17][[18].

6.1 Effect of composite geometry

In recent years, the reinforcement of a composite patch on cracked plates was analyzed by the finite element method. Ramji et al [21] . Study the effectiveness of repair by patch on a cracked structure subjected to thermomechanical loads to determine the thickness and the optimal shape of the patch, as well as the appropriate adhesive. Oudad et al [14], this paper used the nonlinear three-dimensional finite element method to calculate the contour integral and size of the plastic zone at the tip of the crack repaired by a bonded composite patch. The effects of composite patch geometry and adhesive properties on plastic zone surface size has been demonstrated.

In this configuration the bonding of a single simple composite for one side of the repaired plate is applied for the hybrid repair (stop hole, drilling hole ρ = 2mm + bonded patch) and a repair by a single composite. The behavior of both techniques is followed by increasing the width of the composite W_{comp} for the report W_{comp}/a, with "a" corresponding to the crack length (W_{comp}/a = 0.5, 1, 1.5, 2, 2.5). Fig7 illustrates the effect of varying the width of the composite as a function of the maximum stress displayed at the bottom of the notch.
It can be seen that for both techniques, the normal stress σ_{yy-max} is partially independent of the width of the composite for the simple patch repair , whereas it is very sensitive for the hybrid repair because it strongly decrease until W_{comp}/a =2 i.e. a reduction of 83% compared to a repair by simple patch. Beyond this ratio, the stress σ_{yy-max} resumes its increase. This behavior is because the field of shear stresses at the bottom of the notch under the effect of absorption of the composite becomes smaller and it contributes to minimizing the creation of plastic deformation as well as small plastic zones at the front of the notch. Hence the use of a larger composite patch is recommended, twice the size of the length of the crack, in order to improve the repair performance and therefore increase the service life. It is therefore clear that the application of the hybrid repair technique is very beneficial for cracked structures.

The effect of the thickness is taken into account in figure 8. In this configuration, the maximum normal stresses σ_{yy} resulting from the hybrid repair for a drilling of a hole of 2 mm are compared to a repair by a simple patch. The thickness varies according to the ratio e_{comp}/epl for 1/4; 1/3; 1/2; 3/4; 1; 5/4,
Fig.8 affirms the independence of the maximum values of the stress σ_{yy-max} from the thickness of the composite, which remains practically constant at an average of 120 MPa for a hybrid repair. In Fig. 8, therefore, the stress σ_{yy-max} for the simple patch

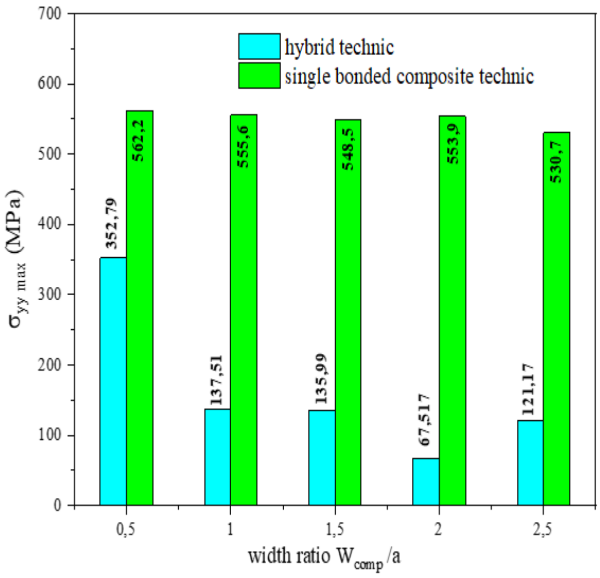

Fig. 7 variation of σ_{yy-max} with increasing composite width.

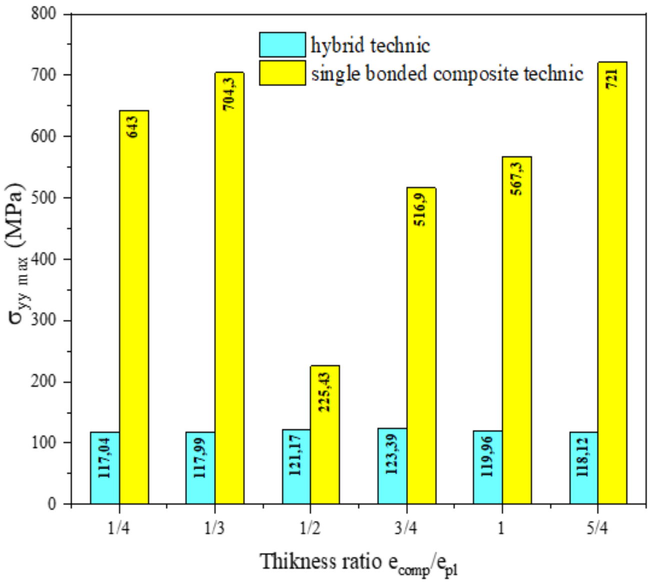

Fig. 8 variation of σ_{yy-max} with increasing thickness of the patch composite.

repair presents ups and downs, which reflects the presence of the singularity zone at the notch tip, which generates significant stress concentrations and we can also notice that the repair by simple patch only is very affected by the variation in thickness of

the composite. This result is also confirmed by Oudad et al and Kaddouri et al [14], [22]. The σ_{yy-max} stress is minimal for a ratio 2 for the both configurations, but a hybrid repair offers an additional reduction of 46% for this optimized thickness.
The beneficial effect offered by the hybrid configuration, which reduces the normal stress σ_{yy-max} in a distinctive way is very interesting from the point of view of reducing the mass for an aircraft, which will reduce the fuel bill and the operating costs.

6.2 Fiber orientation:

Fig.8 affirms the independence of the maximum values of the stress σ_{yy-max} from the thickness of the composite, which remains practically constant at an average of 120 MPa for a hybrid repair. In Fig. 8, therefore, the stress σ_{yy-max} for the simple patch repair presents ups and downs, which reflects the presence of the singularity zone at the notch tip, which generates significant stress concentrations and we can also notice that the repair by simple patch only is very affected by the variation in thickness of the composite. This result is also confirmed by Oudad et al and Kaddouri et al [14], [22]. The σ_{yy-max} stress is minimal for a ratio 2 for the both configurations, but a hybrid repair offers an additional reduction of 46% for this optimized thickness.
The beneficial effect offered by the hybrid configuration, which reduces the normal stress σ_{yy-max} in a distinctive way is very interesting from the point of view of reducing the mass for an aircraft, which will reduce the fuel bill and the operating costs.

6.3 Fiber orientation

In a cracked and repaired structure stressed in mixed mode, the orientation of the fibers of the composite according to the direction of the crack is an important factor to ensure the good absorption of the stresses in the tip of the crack as shown Khodja et al. [23] . In fig.9, the effect of composite fiber orientation is showed for to configurations repair. The hybrid repair with a hole diameter of 2 mm and patch width of 25 mm, thickness of 1.5mm is considered in figure 9, compared with bounding simple patch and stop hole technic of the notched plate in term of maximum opening stress σ_{yy-max} close to the notch-tip.

Figure 9 shows that hybrid repair significantly reduces peak stresses σ_{yy-max} compared to single patch repair. It can be seen that for all the chosen orientations the hybrid repair corresponds to the low values of the normal stress σ_{yy-max} . Which confirms the reliability of this combination of repair techniques. However, when the orientation of the fibers takes 90°, the two configurations record the lowest values, with an additional reduction rate for the hybrid repair of 72.7% compared to the simple patch. The most effective fiber orientations for optimized hybrid repair performance are 45° and 90°.

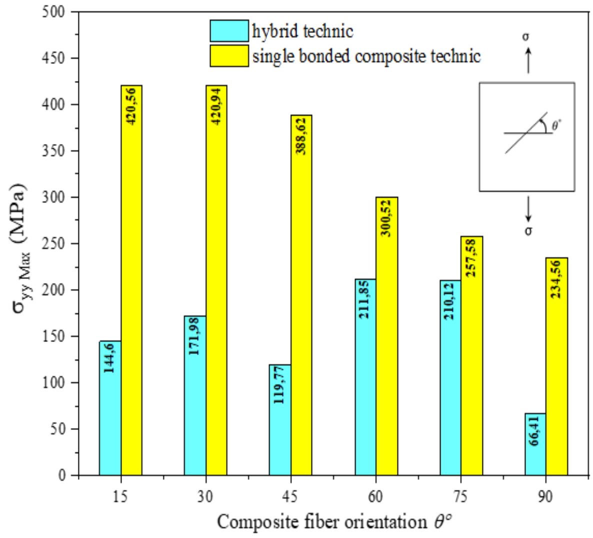

Fig. 9 Distribution of σ_{yy-max} for different fiber composite orientation.

6.4 Double and single bonded side

To improve the fracture toughness of a notched structure, reduce the notch point stress concentrations, for patch repair, and increase repair performance, we bonded the two sides of the plate with the same composite we will call double patch repair and repair on one side single repair.
To examine the effectiveness of double bonded patch application.Fig10 shows the normal stress variation σ_{yy-max} according to the types of repair in double or with single bonded composite. Knowing that the application of a double repair requires accessibility and presents a major inconvenient that prevents the follow-up of the propagation of the crack after repair. Even with these circumstances figure 9 indicates that the use of a double repair is the best, compared to a single composite repair and for both configurations. However, for the hybrid repair only the application of a double patch gives an additional reduction of 57% compared to the repair by a single composite. Whereas for a double repair without drilling the double hybrid repair offers a gain of 77% which is very beneficial from the point of view of reducing the concentration of the maximum stress at the tip of the notch.

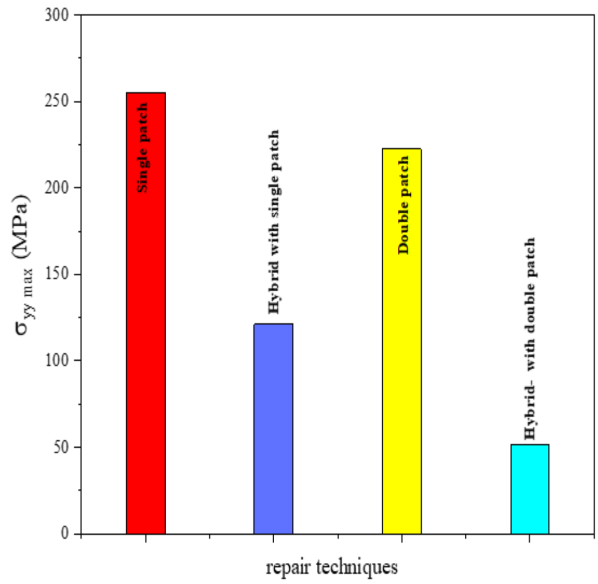

Fig. 10 Distribution of σ_{yy} for one side and double side patch configuration.

6.5 The plastic limit load for different repair technics

Conventional limit load analysis calculates the overall or limit stress of net section collapse, at which the displacements become irreversible. This corresponds to the maximum stress that a cracked structure can support. A global limit load solution can be used to assess the integrity of plates containing through-thickness cracks.

For partial-thickness cracks, the limit load can be considered conservative as a local limit load necessary to cause plasticity on the ligament of the plane of the crack.. The development of plasticity at the front of cracks is influenced mainly by the geometry of the crack, the type of loading and the imposed boundary conditions. Conventional limit load analysis calculates the overall or net limit load of the section, at which displacements become irreversible. This corresponds to the maximum load that a cracked structure can support. A global limit load solution can be used for the evaluation of plates containing through-thickness cracks. For partial-thickness cracks, the limit load can be conservatively thought of as a local limit load necessary to cause plasticity on the remaining ligament of the plane of the crack. The development of plasticity in a cracked plate depends mainly on the geometry of the crack, the type of loading and the boundary conditions imposed [11].
"The limit load is defined as the load needed to cause a local through-ligament plasticity somewhere along the crack front." [11]
To predict the nonlinear collapse of the structure and to estimate the plastic limit load of the notched plate under uniaxial tensile load, the "Step Riks" module is used, incorporated into the ABAQUS calculation code.
The "Riks step" uses the magnitude of the load as an additional unknown; it solves

loads and displacements simultaneously. Therefore, another quantity must be used to measure the progress of the solution; Abaqus/Standard uses ”arc length”, along the path of static equilibrium in load-displacement space. This approach provides solutions regardless of whether the response is stable or unstable [15].
The behavior of the elastoplastic material for the stress-strain relationship was modeled as rigid-perfectly plastic.
Fig.11 shows the evolution of the plastic limit load of the notched plate as a function of the length of the notch. It is clearly distinguished that the increase in the length of the notch causes a marked reduction in the plastic limit load resulting in a considerable reduction in the stiffness of the structure. This is mainly due to the generation of a high stress concentration at the tip of the notch, thus causing larger plastic zones. Oudad et al also confirm this result.

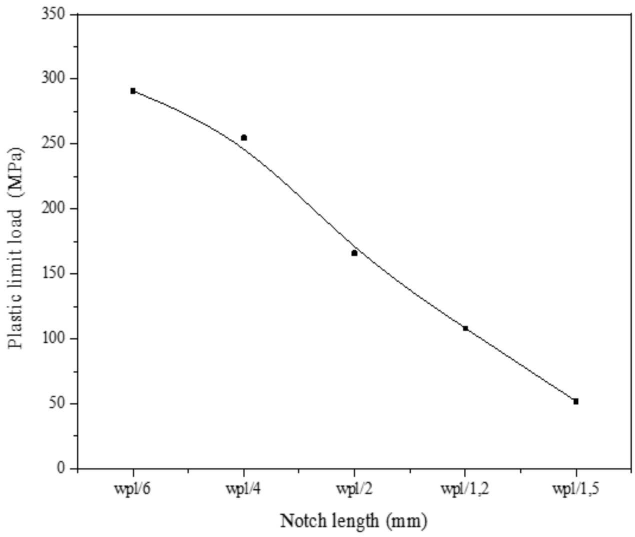

Fig. 11 The variation of the plastic limit load for different notch lengths.

The fig 12 shows the plastic limit load for different repair techniques. Figure 12 denotes the variation in plastic limit loading for different repair configurations. The figure shows that the notched structure and that repaired by drilling lose 30% of their rigidity compared to the elastic limit of the aluminum fixed at 350 MPa. Therefore, even with a repair by drilling a hole the plate loses some of its stiffness. The plastic limit loading increases with the two repair techniques, by bonded patch and the hybrid repair where the structure recovers 100% of its rigidity, however it should be noted that the two techniques record the same values of the limit loads, that is to say 350Mpa.

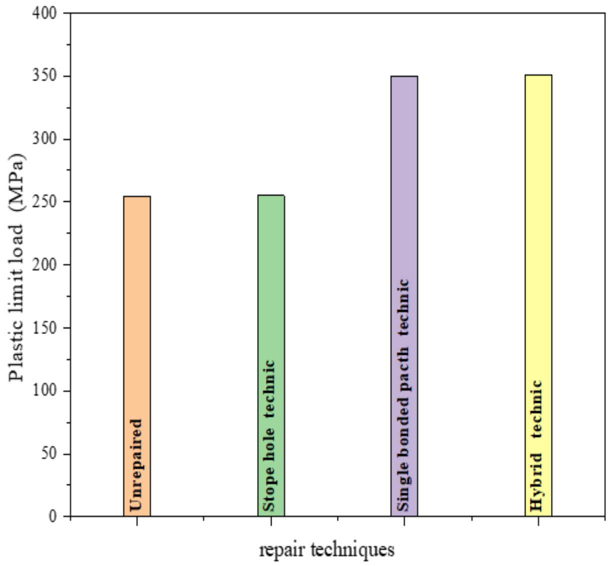

Fig. 12 The plastic limit loading for different technics repair.

We can therefore confirm that the use of a hybrid repair has a great advantage in repairing cracked structures and recovering their robustness and consequently increasing their lifespan.

7 Conclusion

In this paper, the authors proposed the combination of two repair techniques (stop hole / bonded composite repairs) for notched structures, using the concept of the volumetric method and the concept of limit load analysis. The study is based on a three-dimensional analysis by FEM of a notched aluminum plate subjected to a unidirectional tension and for an elastoplastic behavior. The main conclusions of this study are as follows:

- The stress concentration in notch-tip decreases with the size of the drilled radius and it is more absorbed when using the hybrid technique compared to the drilled repair technique only.
- The NSIF Kp shows an increasing behavior from 0 to 2mm for hybrid repair compared to drilling technic but hybrid repair technique is still inferior compared to the drilled repair technique only with an average reduction of the NSIF (Kp) of 70%.
- It is very desirable to use a larger composite, i.e. twice the size of the crack length in order to increase the effectiveness of repairs and thus prolong the life of damaged structures.

- The σ_{yy-max} stress is minimal for a ratio 2 for the both configurations, but a hybrid repair offers an additional reduction of 46% for this optimized thickness.
- The beneficial effect offered by the hybrid configuration, which reduces the normal stress σ_{yy-max} in a distinctive way is very interesting from the point of view of reducing the mass for an aircraft, which will reduce the fuel bill and the operating costs.
- For the hybrid repair only, the application of a double patch gives an additional reduction of 57% compared to the repair by a single composite. Whereas for a double repair without drilling the double hybrid repair offers a gain of 77% which is very beneficial from the point of view of reducing the concentration of the maximum stress at the tip of the notch.
- The increase in the notch length causes a noticeable reduction in the plastic limit load resulting in a considerable reduction in the stiffness of the notched structure.
- The plastic limit loading increases with the two repair techniques, by bonded patch and the hybrid repair where the structure recovers 100 % of its rigidity.

Author's contributions Dr. M. Belhamiani and Dr. N. Djebbar designed the geometric model and contributed to the design and implementation of the research, to the analysis of the results and to the writing of the manuscript, Dr. W. N. Bouzitouna developed the theoretical formalism, performed the numerical simulations with Abaqus software, Dr. M. Belhamiani and Dr. N. Djebbar interpreted the results and planned and carried out the simulations. All authors discussed the results and contributed to the final version of the manuscript. **Funding** Any organization or university did not fund the research.
Availability of data and materials Not Applicable.

Declarations
Conflict of interest All authors declare that they have no conflict of interest.
Ethical approval Not Applicable.
Consent to participate Not Applicable.
Consent for publication Not Applicable.

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