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# Optimization of scarf patch stacking sequences using the design of experiments method

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**Abstract.** In this study, The Von Mises stresses in composite plate loaded in tension and repaired by a boron/epoxy scarf patch were analyzed using the finite element method. The performance of the repairs depends on several parameters: the dimensions and the intrinsic properties of the patch and the adhesive which are dependent on each other. Therefore, the method of experiment designs is used to determine the interaction effect of different parameters (patch folds), their optimum and the most influential parameter. The optimum of stacking sequences allows reducing stresses significantly, and thus permits designers to improve the quality of repairs.

**Keywords:** adhesive; optimization; repair; scarf patch; stacking sequence

## 1. Introduction

Composite materials were seen in the early 1930s in some industrial fields regarding their diversity, resistance, lightness with respect to metallic materials. Later on their application extended to different sectors: nuclear, medical, sports, maritime, automotive and aeronautics. Composite materials are more widely used in the aeronautical field for the manufacture of primary and secondary structures. These structures are often in an environment that is detrimental to them in terms of strength reduction and the creation and propagation of cracks. Due to strict safety requirements recommended in this sector in terms of safety, the study of the behavior of these materials is essential. Several research works have been undertaken in this field in order to study their behavior towards cracking and impact (Bakhshi *et al.* 2019, Tahar *et al.* 2022, Ramdoun *et al.* 2018, Achache *et al.* 2013).

The damage that the structures can suffer during their operation forces manufacturers to replace them for safety reasons, regarding the high cost of replacing them, it is recommended to look for other solutions. The development of maintenance or repair techniques is the most suitable solution to reduce the time of immobility of the devices and the loss of money. Several repair techniques have been developed, except that the bonding repair is the most efficient because of the many advantages it provides. The most common types of bonding repair are: scarf and external patch repair. External patch repair consists of bonding layers of composite in areas subject to high stress concentrations. It makes it possible either to slow down the cracks or the shells appearing on the

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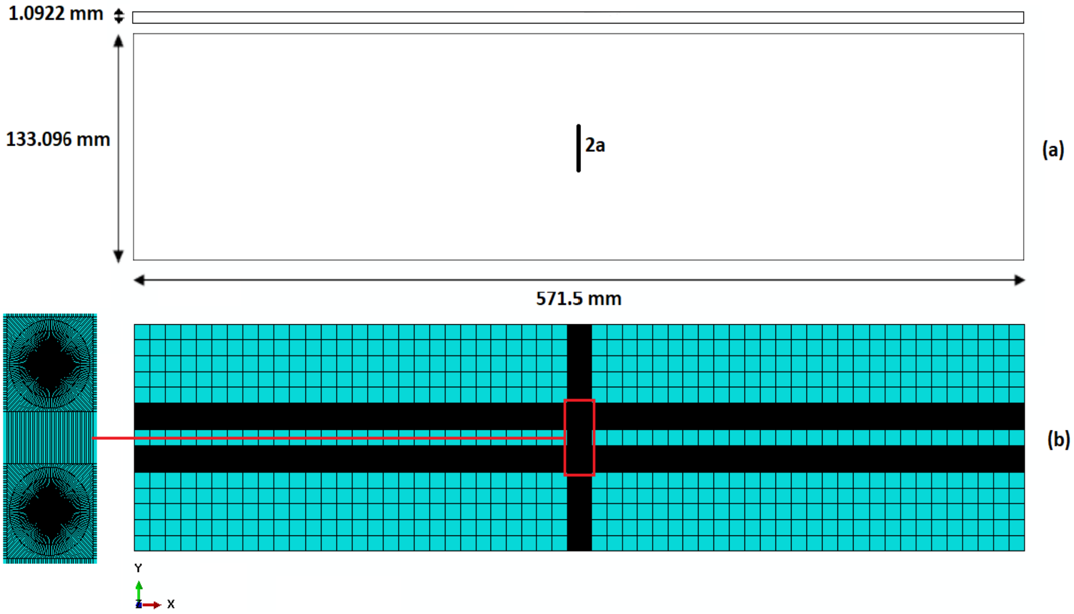


Fig. 1 Model of the unrepaired cracked plate

Table 1 Mechanical properties of the composite material (boron/epoxy) (Fekih *et al.* 2012)

| Young's modulus (GPa) | Poisson's ratio | Shear modulus (GPa) |
|---|---|---|
| $E_{11}$=208 | $\upsilon_{12}$=0.1677 | $G_{12}$=7.2 |
| $E_{22}$=25.4 | $\upsilon_{13}$=0.1677 | $G_{13}$=7.2 |
| $E_{33}$=25.4 | $\upsilon_{23}$=0.035 | $G_{23}$=4.9 |

plates, or delay their appearance in the case of preventive reinforcement. Many studies have been conducted to determinate the effect of external patch repairs (Benkheira *et al.* 2018, Cheng *et al.* 2011).

Scarf repair consists on removing the damaged area with an inclined manner using drilling tools and replacing it by bonding a composite laminate piece. The advantages - absence of the bending effect, absence of resistance to aerodynamic flows, etc. - that are provided by the scarf compared to the external patch, which allowed to carry out several studies to determinate the features and performance of the scarf (Cheng *et al.* 2014, Caminero *et al.* 2013, Yoo *et al.* 2016, Campilho *et al.* 2007, Pierce *et al.* 2019, Moreira *et al.* 2020, Breitzman *et al.* 2009, Psarras *et al.* 2020). Scarf repair is considered the most efficient repair technique except that it requires meticulous manufacturing of surfaces' pieces (Cheng *et al.* 2014) and the right choice of the scarf ratio that ensures the recovery of rigidity and resistance. The decrease in the scarf ratio increases the contact surface between adhesive-plate and adhesive-scarf and consequently induces an increase in resistance (Psarras *et al.* 2020). On the other hand, there is an optimal value of the scarf ratio (1:20) beyond which the resistance varies weakly, according to Yoo *et al.* (2016). In addition, stacking sequences have an important influence on repair. Breitzman *et al.* (2009) found that the optimal stacking sequences allow substantially the reduction of the stress levels and restore's resistance estimated between 85% and 90% from the resistance's virgin pieces.

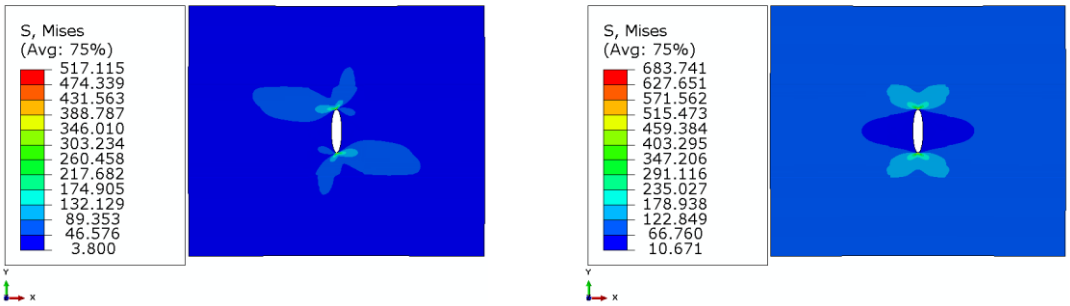
Our numerical study aims to work on the tensile behavior of a cracked laminated composite plate and on the effect of repair by internal patch where the experimental design method is used to optimize composite patch stacking sequences.

## 2. Unrepaired cracked plate

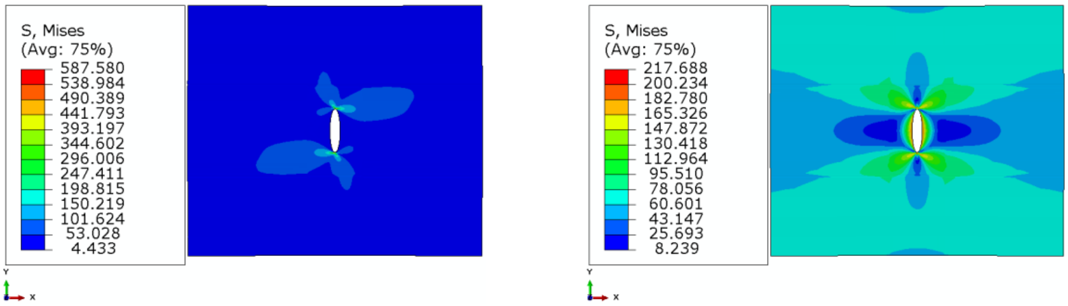
Fig. 1(a) illustrates a laminated boron/epoxy fissured composite plate of length, width and thickness respectively equal to 571.5 mm, 133.096 mm and 1.0922 mm (Breitzman *et al.* 2009). The panel is composed of eight folds with a $[45/0/-45/90]_s$ stack. The crack of length $2a$=25.4 mm, is central and perpendicular to the loading direction. The plate composite material is considered as an orthotropic material with a revolution axis (unidirectional material) whose behavior is linear elastic and its properties are mentioned in Table 1. One of the plate edges is embedded and the other is subjected to a 0.2 mm displacement in the direction of the x-axis. The structure is modeled by hexahedral linear elements of the C3D8R type. The mesh of 59648 elements is used for the whole structure with a refinement around the crack to account for stress concentration (Fig. 1(b)).

Composite materials are subject to various types of degradation resulting from local damage to the matrix, the fibers and the matrix-fiber interface under the effect of external stresses. Failure of composite laminates can occur in several complex ways. For this reason, a preliminary study was carried out to determinate the behaviour of the laminates towards cracking.

It is very beneficial, in terms of strength, to manufacture a unidirectional composite material whose plies are oriented in the direction of loading. However, the materials are generally subjected to multiaxial loads, so it is essential to provide transverse and/or shear reinforcements. These



Ply 1 (45°) Ply 2 (0°)



Ply 3 (-45°) Ply 4 (90°)

Fig. 2 Stress contour of unrepaired cracked plate

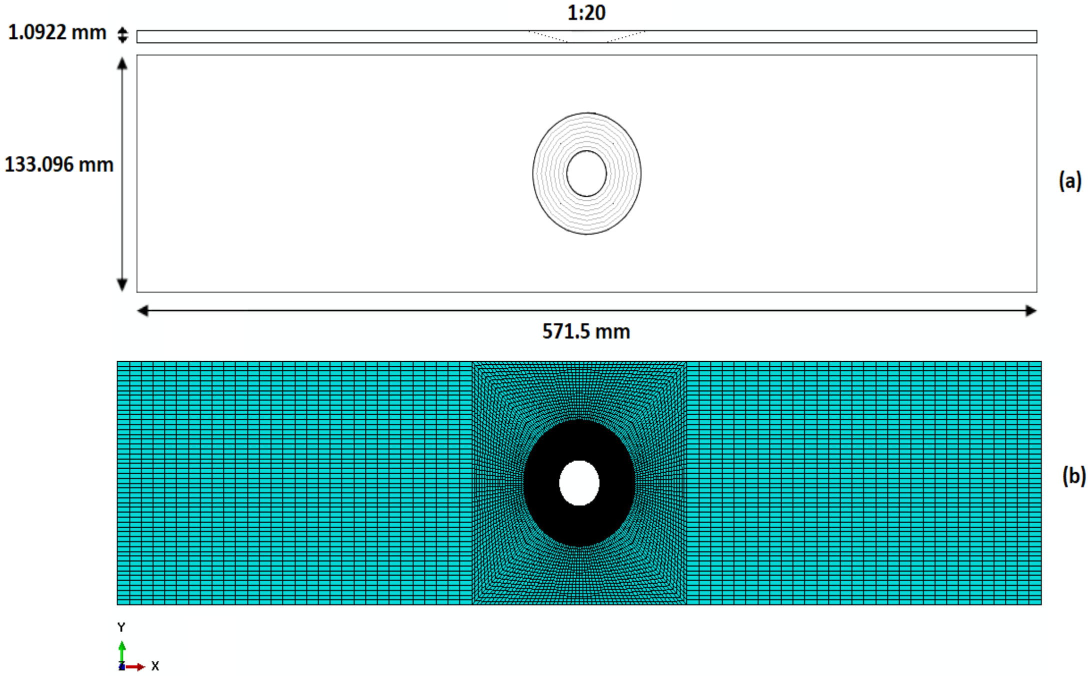


Fig. 3 Model of the perforated plate with inclined angle

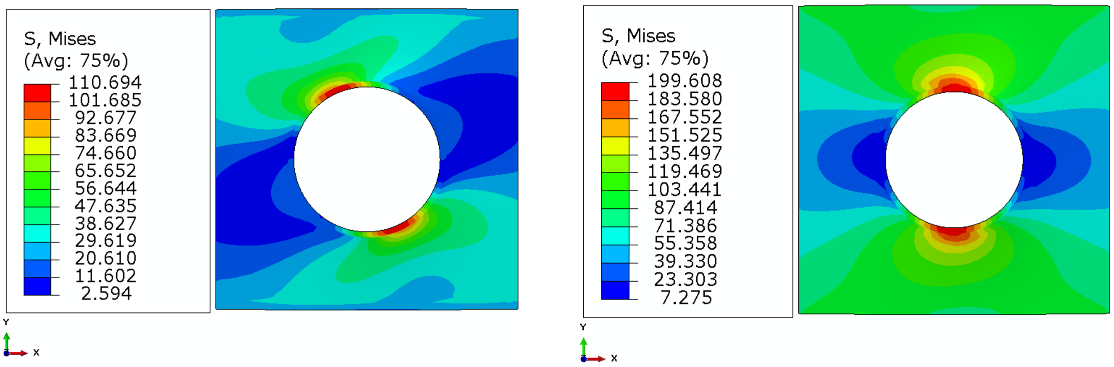
reinforcements can be achieved by making a laminate with different orientation plies (-45, 0, 45, 90).

Fig. 2 represents the Von Mises stress contour for four different orientation layers of the cracked laminate where we perceive that the highest stress is concentrated at the crack's tip and it varies along the fibers orientation angle. The maximum value of this constraint corresponds to the 0° orientation layer and its minimum value at the 90° orientation layer. This shows that the strength of a composite depends on the orientation of the fibers; they do indeed support the applied load, while the role of the matrix is to transmit external mechanical stresses to the fibers and to protect the latter against external aggressions.

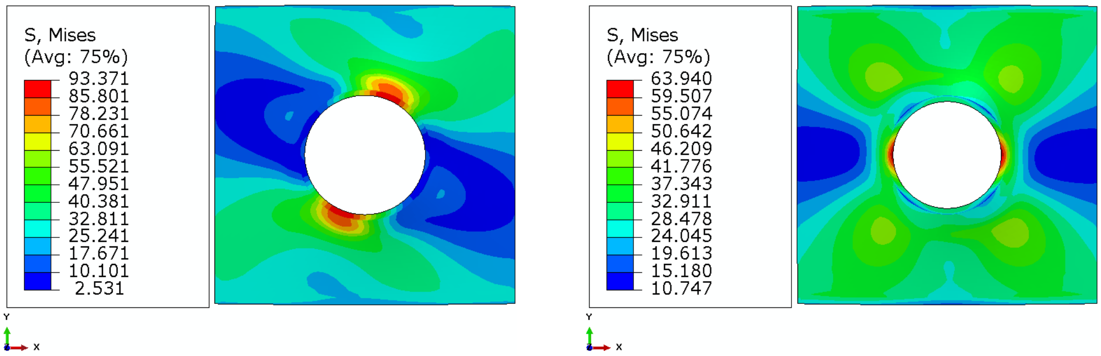
## 3. Unrepaired perforated plate

Before studying the effect of the scarf repair, an analysis was performed on the laminate after removing the damaged area (the cracked area) with an inclined hole whose diameter is equal to 25.4 mm and scarf ratio to 1:20 (Fig. 3(a)). The dimensions, stacking, mechanical properties and boundary conditions of the perforated model with an inclined angle are those of the cracked plate. As for the mesh, linear hexahedral elements of the C3D8R type are used with a refinement near the hole where stress concentration is high. A mesh of 115200 elements is carried out for the whole structure (Fig. 3(b)).

The stress contour in the perforated plate with an inclined angle is shown in Fig. 4, where the layers are numbered from front surface to rear surface. We observe two concentrations of Von Mises stress zones' which are diametrically opposed. These zones are located on the direction



Ply 1 (45°) Ply 2 (0°)



Ply 3 (-45°) Ply 4 (90°)

Fig. 4 Stress contour of perforated plate with inclined angle

Table 2 Mechanical properties of the adhesive (ADEKIT A140) (Madani *et al.* 2010)

| Young's modulus (GPa) | Poisson's ratio |
|---|---|
| $E$=208 | $\upsilon$=0.1677 |

perpendicular to that of the fibers. We also observe that the plies oriented to 0° (ply 2 and ply 7) are the most loaded regarding their high stiffness compared to the other plies. The composite strength decreases with increasing fiber orientation; indeed, the rupture of the layer oriented at 90° occurs first, followed by those of orientation ±45 then 0°, thus causing the total rupture of the laminate in the transverse plane of the medium.

After removal of the material in the area damaged by cracking, the void in the plate with inclined hole is filled by a repair patch adhered to it by a layer of ADEKIT A140 adhesive - 0.127 mm thick - where the properties are listed in Table 2. The repair part is made of a boron/epoxy laminate whose mechanical properties, stacking and boundary conditions are the same as those of the cracked plate (Fig. 5(a)). The mesh of the plate is the same as the perforated plate, however for the adhesive and the patch, the adapted mesh is linear prismatic of type C3D6 (Fig. 5(b)). To have an optimal refinement, it is necessary to study the convergence of the numerical solution. Fig. 6 illustrates the convergence curve of the numerical model studied. This mesh, 285600 elements, is carried out throughout the computation. The boundary conditions remain the same for the cracked plate.

Fig. 7 shows the histogram of maximum Von Mises stresses in plies 1 to 8 for cracked, notched

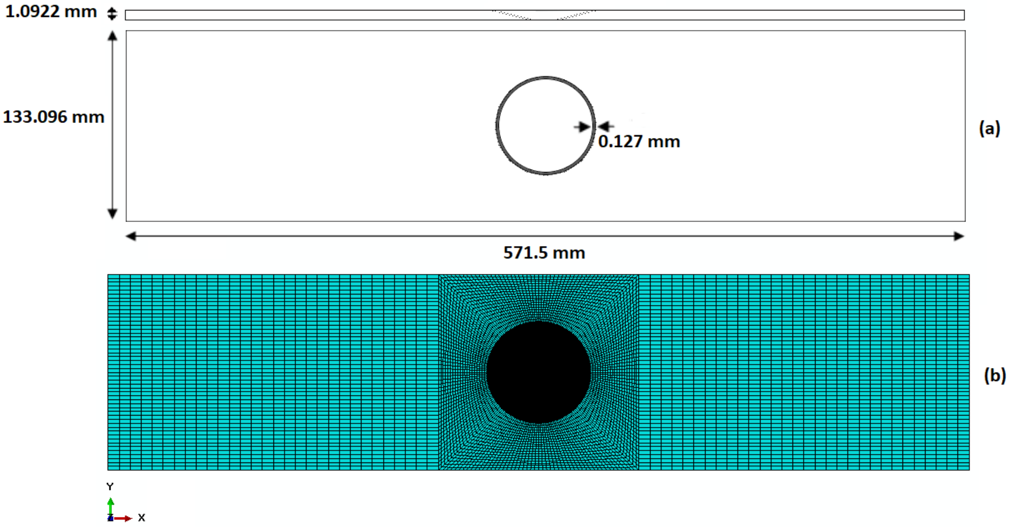


Fig. 5 Model of the plate repaired by scarf

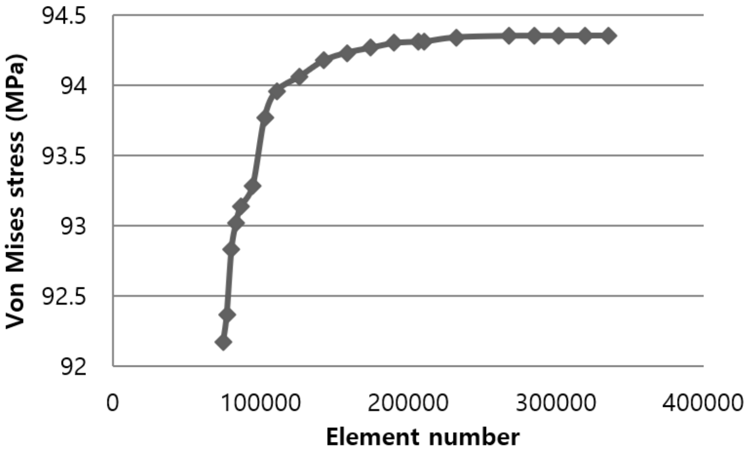


Fig. 6 Convergence curve

and scarf-repaired plates. It can be seen that the highest of these stresses are obtained for the 0° orientation and the lowest values for the 90° orientation. The stresses in the 3 plates vary in a similar way according to the number of plies. For the same orientation, the maximum stress at the edge of the hole is much lower than that at the crack's tip and is close to twice the stress in the repaired plate. Indeed, the stresses at the edge of the hole are perfectly reduced by the addition of the repair piece, especially for the most rigid plies (ply 2 and ply 7), it is due to the transfer of loads from the plate to the patch through the adhesive.

## 4. Optimization of scarf stacking sequences

The repair of damaged structures involves several ones which depend on each other parameters

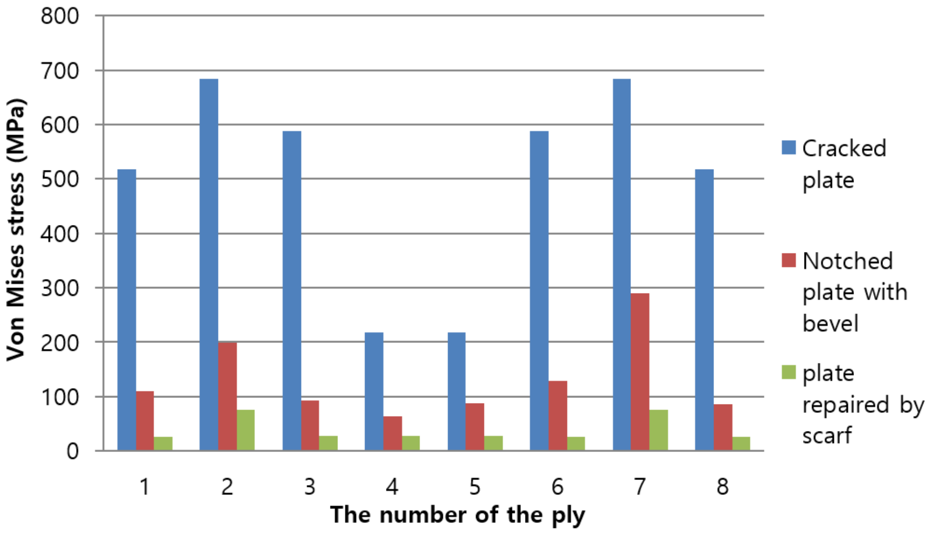


Fig. 7 Comparison of Von Mises stresses

Table 3 Results of D-optimal experiments

| Exp. N° | Ply1 | Ply2 | Ply3 | Ply4 | $\sigma_{Von\ Mises}$ plate |
|---|---|---|---|---|---|
| 1 | 90 | -45 | -45 | -45 | 139,706 |
| 2 | -45 | 0 | -45 | -45 | 95,165 |
| 3 | 0 | 90 | -45 | -45 | 163,965 |
| 4 | 0 | -45 | 0 | -45 | 107,357 |
| 5 | 90 | 90 | 0 | -45 | 186,795 |
| 6 | -45 | -45 | 90 | -45 | 132,4 |
| 7 | -45 | 45 | 0 | 0 | 149,332 |
| 8 | 90 | -45 | 45 | 0 | 171,331 |
| 9 | 45 | 0 | 90 | 0 | 88,917 |
| 10 | 45 | -45 | -45 | 45 | 157,053 |
| 11 | 0 | 0 | 45 | 45 | 105,142 |
| 12 | -45 | -45 | -45 | 90 | 159,371 |
| 13 | 90 | 45 | -45 | 90 | 137,222 |
| 14 | -45 | 90 | -45 | 90 | 161,823 |
| 15 | -45 | -45 | 90 | 90 | 158,073 |
| 16 | -45 | 90 | 90 | 90 | 185,923 |
| 17 | 90 | 90 | 90 | 90 | 162,916 |

that make the analysis of the results difficult. To overcome this difficulty, it is necessary to seek the maximum of parameters that have a great influence on the repair.

In this study, we consider the orientation of 8 stacking sequences of the patch as variable parameters between -45° and 90° while we keep constant the geometrical properties of the patch, i.e., the geometrical and mechanical properties of the adhesive.

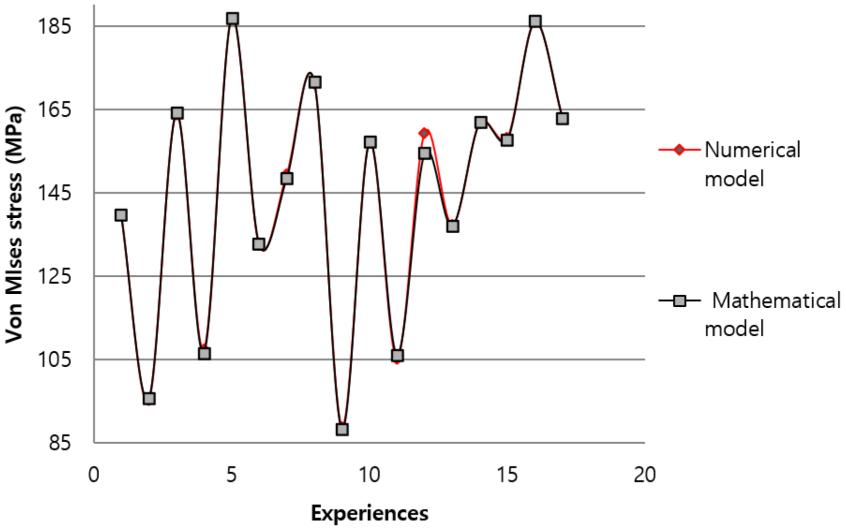


Fig. 8 Mathematical model validation

The optimization analysis is carried out using the experimental design method where the MODDE software (MODDE 6.0 2001) was used. For 4 factors at 4 levels, 256 experiments are generated. However, the use of the D-optimal design allows us to reduce the number of experiments necessary for the investigation and to find the most important factors with their interactions by using a quadratic model that offers response surface modeling (RSM). The results of 17 experiments performed according to the D-Optimal design are reported in Table 3.

MODDE 6.0 software allows the development of a mathematical model based on the experiments shown in Table 3, which expresses the value of the Von Mises stress of any stacking sequence. The mathematical model proposed is represented by Eq. (1)

$$\begin{gathered}\sigma_{VonMises} = 98{,}3836347 - 0{,}27991033 * ply_1 - 0{,}19398064 * ply_2 + 0{,}17253333 * \\ ply_3 + 0{,}26063477 * ply_4 + 0{,}0074062 * ply_1^2 + 0{,}01249675 * ply_2^2 - 0{,}00256676 * \\ ply_3^2 - 0{,}00225762 * ply_4^2 - 0{,}00292256 * ply_1 * ply_2 - 0{,}00175957 * ply_1 * ply_3 + \\ 0{,}0021792 * ply_1 * ply_4 + 0{,}00141884 * ply_2 * ply_3 - 0{,}00464112 * ply_2 * ply_4 - \\ 0{,}00094125 * ply_3 * ply_4\end{gathered} \tag{1}$$

To validate this mathematical model, its results were compared with those obtained by the finite element method. These two types of results illustrated in Fig. 8, are in very good agreement. Therefore, this mathematical model is validated and its prediction of Von Mises stress values in studied plate is reliable and accurate.

### *4.1 Interaction's effects of Von Mises stress in the plate*

This analysis focuses on the minimization of the Von Mises stress in the plate (output parameter) and particularly in the layers at the 0° orientation. Since these layers support the highest stresses they generate high stresses in the ply-adhesive interface which could cause the adhesive's debonding.

Given the large number of interactions between stacking sequences, only those that lead to low

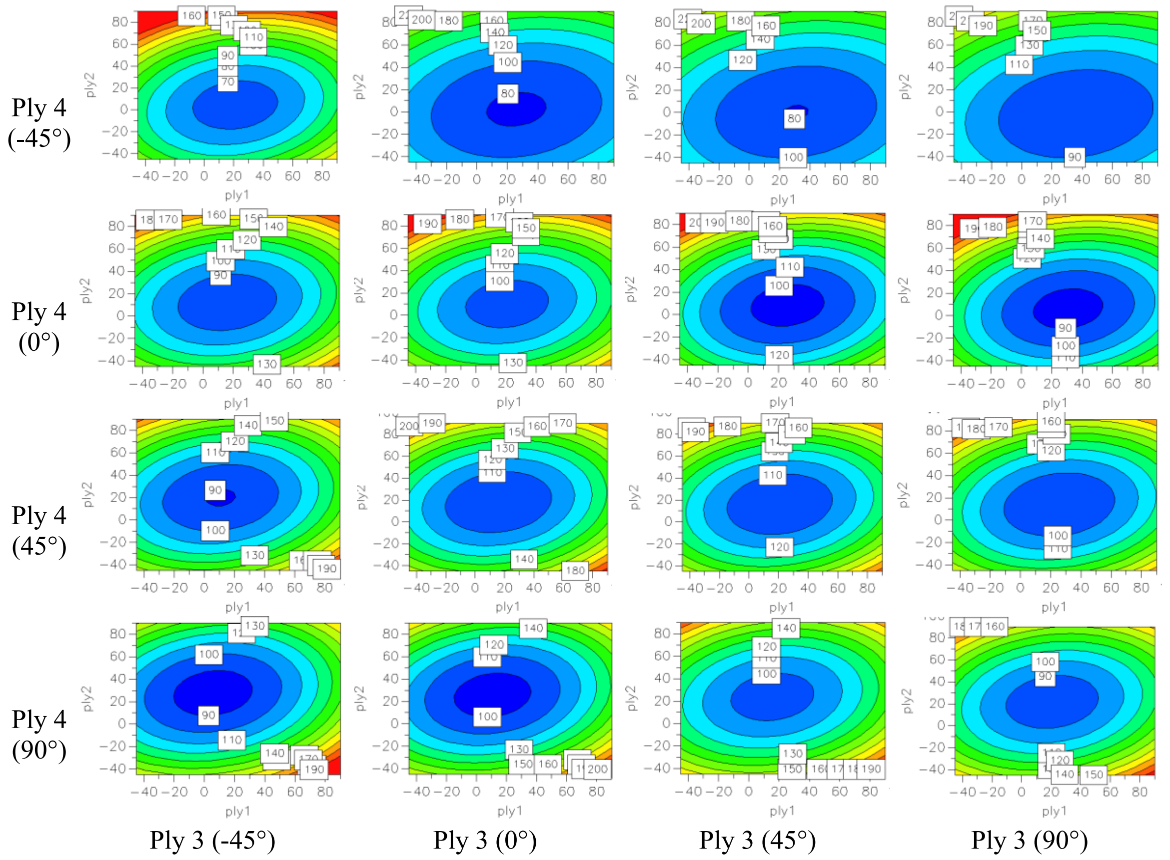
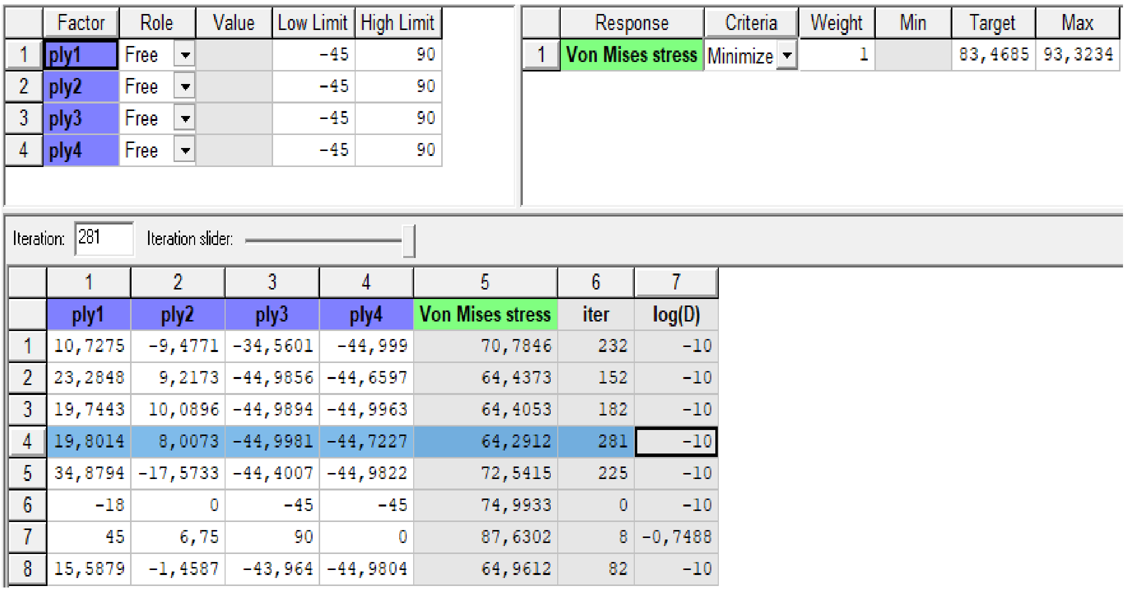


Fig. 9 Effect of 4-ply interaction on $\sigma_{Von\text{-}Mises}$ in the plate



|  | Factor | Role | Value | Low Limit | High Limit |
|---|---|---|---|---|---|
| 1 | ply1 | Free |  | -45 | 90 |
| 2 | ply2 | Free |  | -45 | 90 |
| 3 | ply3 | Free |  | -45 | 90 |
| 4 | ply4 | Free |  | -45 | 90 |

|  | Response | Criteria | Weight | Min | Target | Max |
|---|---|---|---|---|---|---|
| 1 | Von Mises stress | Minimize | 1 |  | 83,4685 | 93,3234 |

Iteration: 281 Iteration slider:

|  | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
|  | ply1 | ply2 | ply3 | ply4 | Von Mises stress | iter | log(D) |
| 1 | 10,7275 | -9,4771 | -34,5601 | -44,999 | 70,7846 | 232 | -10 |
| 2 | 23,2848 | 9,2173 | -44,9856 | -44,6597 | 64,4373 | 152 | -10 |
| 3 | 19,7443 | 10,0896 | -44,9894 | -44,9963 | 64,4053 | 182 | -10 |
| 4 | 19,8014 | 8,0073 | -44,9981 | -44,7227 | 64,2912 | 281 | -10 |
| 5 | 34,8794 | -17,5733 | -44,4007 | -44,9822 | 72,5415 | 225 | -10 |
| 6 | -18 | 0 | -45 | -45 | 74,9933 | 0 | -10 |
| 7 | 45 | 6,75 | 90 | 0 | 87,6302 | 8 | -0,7488 |
| 8 | 15,5879 | -1,4587 | -43,964 | -44,9804 | 64,9612 | 82 | -10 |

Fig. 10 The optimal values for the minimum value of $\sigma_{Von\text{-}Mises}$ in the plate

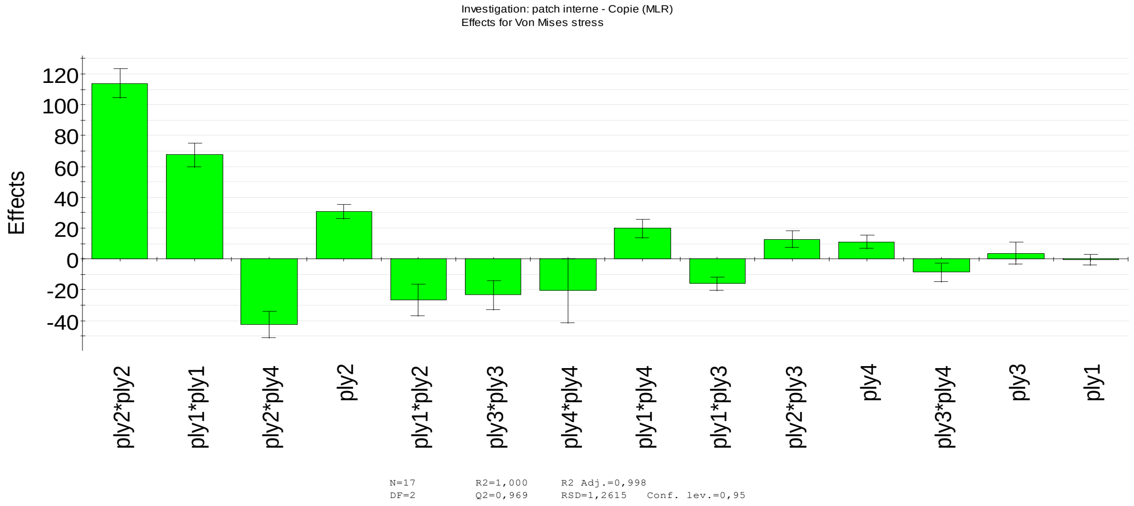


Fig. 11 The optimal values for the minimum value of $\sigma_{Von\text{-}Mises}$ in the plate

output parameters have been considered. Fig. 9 illustrates the effects of the interactions of the orientations of the 4 plies (Von Mises stresses) in the plate. For each pair (ply 3, ply 4) are represented in contour by the combined effects of the orientations of ply 1 and ply 2 on the Von Mises constraints. The orientations of ply 3 and ply 4 take the values (-45°, 0°, 45°, 90°). Among the contours illustrated in Fig. 9, corresponding to ply 4 and ply 3 oriented, -45° has the lowest Von Mises stress levels. The minimum of this constraint is obtained for the orientations of ply 1 and ply 2 comprised respectively between (-8°, 50°) and (-18°, 28°).

### *4.2 Checking the optimum point*

In order to determinate the optimal point, the MODDE 6.0 software seeks the lowest value of the Von Mises stress using a mathematical model developed from the experiments carried out. The optimum point in this analysis corresponds to a Von mises stress value equal to $\sigma_{Von\text{-}Mises}$=64.2912 MPa and a stack of $[19.8014/8.0073/-44.9981/-44.7227]_s$. This optimal point is illustrated in Fig. 10.

### *4.3 Effect of different factors*

Along what has been calculated so far, study the effect of different factors on the scarf repair's performance is also important. Firstly, it is necessary to determinate the most influencing factors, then observe how the measured value behaves with these factors. These effects are represented by a histogram (Fig. 11). The analysis of these diagrams shows that the most important orientation in the patch is the orientation of ply 2, which is in contact with the structure's ply oriented at 0°.

## 5. Conclusions

The work presented aims to establish a numerical model to simulate the tensile behavior of a laminated composite repaired by bonding scarf in laminated composite. We started by studying the distribution of stresses in a cracked plate and a plate with an inclined hole in order to compare the results obtained with those of the plate repaired by scarf.

At the end of this numerical investigation, we were able to draw the following conclusions:

- The orientations of the folds of the plates have an important influence on the stresses' distribution from where it is essential to use the stacking rules (The rule of mirror symmetry, balancing, grouping, disorientation, 10%, damage tolerance).
- The damage is generally initiated in the less rigid layers, then propagates towards the more rigid ones, which are the most loaded causing the total failure of the laminate.
- Von Mises stresses are high near the defects. However, removal of the cracked area by an inclined notch leads to a significant decrease in it.
- The addition of repair patches by scarf causes a redistribution of the stresses in the plate therefore it improves the resistance in this one for any stacking sequence. On the other hand, the best repair performance is obtained with the optimal stacking.
- The outcome of this study given by the optimization analysis is that the orientation of the ply in which the fibers are oriented in the direction of the loading constitutes the main parameter to be modified to obtain an optimal repair.

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