Visual Abstract

Numerical analysis of bonded composite patch efficiency in the case of lateral U and V-notched aluminium panels

Bouchelarm Mohammed A., Boulenouar Abdelkader, Chafi Meriem
Laboratoire de Matériaux et Systèmes Réactifs- LMSR, Djillali Liabes University of Sidi Bel-Abbes- 22000, Algeria
m.bouchelarm@yahoo.com, aek_boulenouar@yahoo.fr, chafi.meriem@yahoo.com

ABSTRACT. In this study, the finite element method is applied to investigate the mechanical behavior of aluminium notched structures reinforced by composite patch. In order to evaluate the efficiency of patches in the case of lateral U and V-notches repaired with a semi-circular patch shape, it is very important to analyze the stress distribution at the notch tip and to take in consideration the influence of the geometrical and mechanical properties of the patch and the adhesive. The effect of the patch size, thickness and type was highlighted. Furthermore, the effect of the adhesive thickness on the normal stress distribution was investigated. Simple and double patch were used as reinforcement techniques. Results showed that the increase of the contact area between the plate and the patch contributes to the normal stress reduction in the ligament of the plate. The adhesive thickness must be chosen carefully to keep the positive effects of the patch. The normal stress as well as the stress concentration factor are reduced at the notch tip by using a double patch reinforcement. This reduction becomes more noticeable when the patch thickness increases.

KEYWORDS. Bonded composite patch; Adhesive; Stress concentration factor; Finite element method; Notch.

Citation: Bouchelarm, M. A., Boulenouar, A., Chafi, M., Numerical analysis of bonded composite patch efficiency in the case of lateral U and V-notched aluminium panels, Frattura ed Integrità Strutturale, 60 (2022) 62-72.

Received: 23.11.2021
Accepted: 28.12.2021
Online first: 27.01.2022
Published: 01.04.2022

INTRODUCTION

Considerable attention is given through composite repair and reinforcement to enhance the life cycle of damaged structures, which is a primary focus from an economic perspective. The high level of durability under operating conditions provided by adhesively bonded composite patches approves their use as a reinforcement of mechanical structures. Baker [1] pioneered repair of aircraft structures by bonded adhesives in the 1970s, since, considerable work has been achieved to develop the technique of using the composite patches on different structures [2-7].

To understand the mechanical behavior of defects reinforced by patches, several authors used finite element method [8-14] The focus of these studies was repairing cracks in thin plates. In the case of three-dimensional problems, Boulenouar et al. [15] used finite element method for the repair of semicircular cracks in a finite-thickness plate. Merzoug et al. [16] carried out simulations to analyze the behaviour of repaired surface cracks with a bonded composite patch. Meran and Samanci

[17] studied a various composite patches effect on mechanical properties of notched Al-Mg plate. Cetisli and Kaman [18] investigated the stress intensity factors for an interfacial edge crack between two dissimilar composite plates jointed with a single side composite patch. A three-dimensional finite element approach was used by Maligno et al. [19] to investigate the behaviour of fatigue crack growth in a thick aluminium alloy plate repaired with a bonded composite patch. The ultimate failure pressure of corroded pipes reinforced with composite repair systems was investigated by Chen et al. [20], a numerical model of the ultimate failure in a repaired pipe was established. Saffar et al. [21] studied the prediction of failure pressure in pipelines with localized defects repaired by composite patches. El-Sagheer et al. [22] analyzed the multi-effects of the glass fiber reinforced polymer (GFRP) composite patch to repair the inclined cracked 2420-T3 aluminum plate.
In this paper, a three-dimensional finite element modeling is carried out using Ansys APDL program; the aim of this study is to examine the efficiency of bonded composite patches in the case of lateral U and V-notched aluminium panels repaired with a semicircular patch shape. The effect of the patch size, thickness and type is investigated. In addition, the effect of the adhesive thickness on the normal stress distribution is investigated. Two types of repair are used as reinforcements, the simple and double patch. Their effect on the variation of normal stresses and on the stress concentration factor (K_t) at the front of U-notches and V-notches with different angles will be considered.

NUMERICAL MODELING OF LATERAL U-NOTCHES

Consider a thin plate made of a 2024-T3 aluminium alloy with a lateral U-notch having the following dimensions: height H = 203.2 mm, width 2W = 152.4 mm, thickness ep = 1 mm and notch radius ρ = 12.7 mm. The mechanical properties of the plate, the patch and the adhesive are given in table 1. The plate is subjected to uniaxial tensile load giving a remote stress state of σ = 100 MPa. Fig. 1 presents the geometrical model of a simple and double composite patch bonded to the plate. The plate was reinforced with semi-circular patches. The patch dimensions were chosen according to the notch: the radius $\rho_p = 3.\rho$ et and the thickness er = 1 mm.

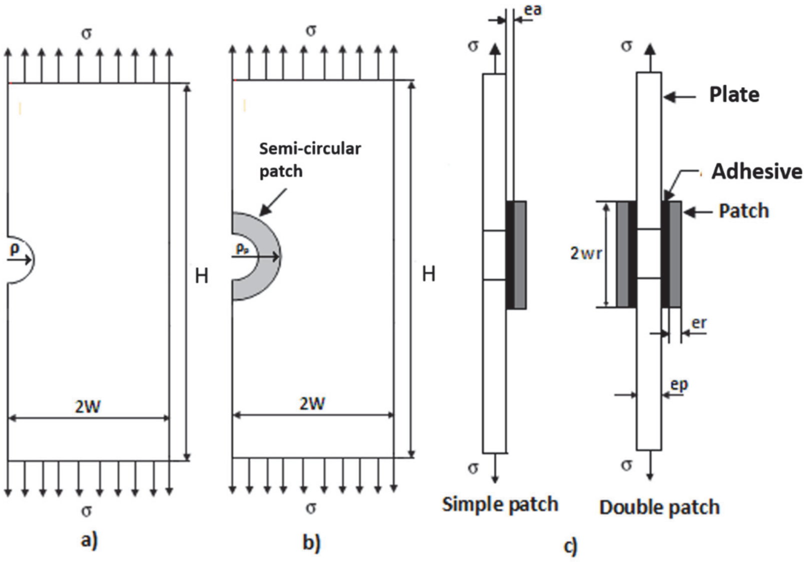

Figure 1: Geometrical model of the plate with lateral U-notch. a) non-reinforced, b) reinforcement with semi-circular patch, c) reinforcement technique configurations.

The notched plate is represented in fig. 2 by a 3D meshing. The finite element model consists of three subsections to model the notched plate, the adhesive, and the composite patch, the considered volumes are then combined and overlapped into one volume. For symmetrical considerations, only one half of the structure was modeled by three dimensional elements with an applied load σ in the y axis. A total number of 4440 elements was considered to model the structure. A solid186 element is considered for the simulation, it is defined by 20 nodes having three degrees of freedom per node: translations in the nodal x, y, and z directions. The mesh size close to the notch tip is considered small enough to accurately describe the deformation and stress gradients. However, for the remaining regions coarse mesh is used in order to reduce the computational costs. Note that the mesh size has the same dimensions in the common part of materials.

Properties	Aluminium 2024-T3	Boron/Epoxy	Graphite/Epoxy	Glaxy/Epoxy	Adhesive
E_1 (GPa)	72	200	134	50	2.21
E_2 (GPa)		19.6	10.3	14.5	
υ_{12}	0.33	0.33	0.1677	0.33	0.43
G_{12} (GPa)		7.2	5.5	2.56	
G_{13}(GPa)		5.5	5.5	2.56	
G_{23}(GPa)		5.5	3.2	2.24	

Table 1: Mechanical properties of the different materials.

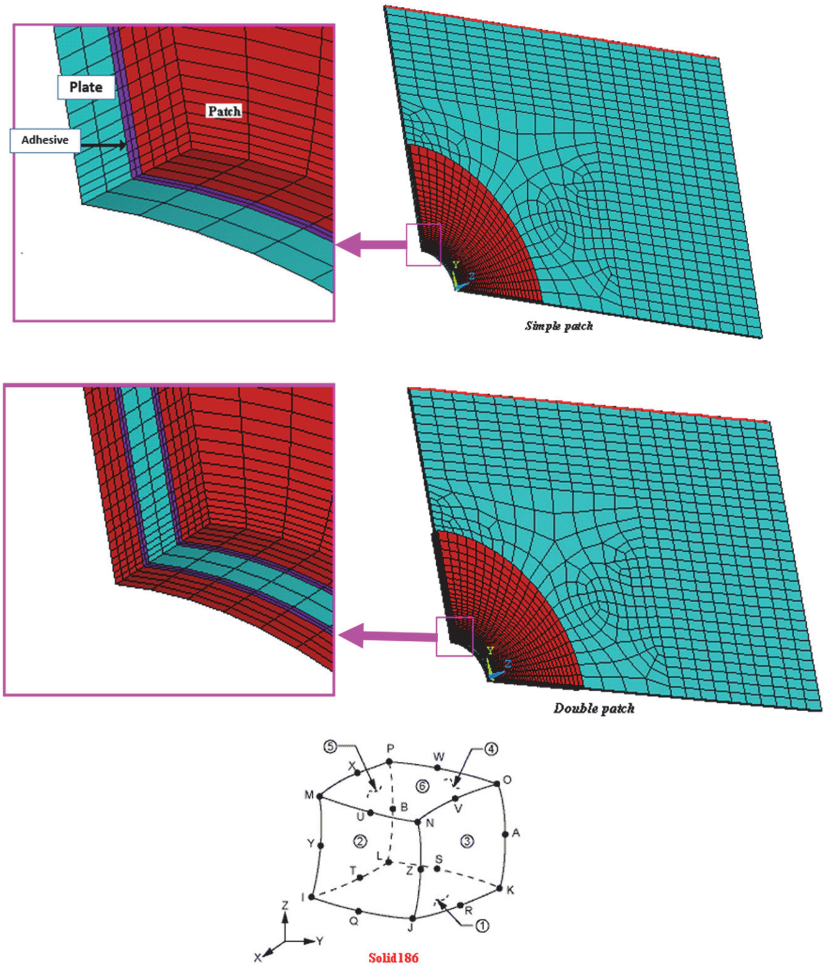

Figure 2: Typical 3D finite element mesh for simple and double patch reinforcement

Normal stress reduction at the notch tip

Fig. 3 illustrates the distribution of normal stresses along the ligament of the plate. The stress distribution taken from the middle point along the plate thickness is compared for an unpatched plate, a plate reinforced with simple patch and another plate reinforced with double patch. It can be seen that the presence of the patch contributes to the stress reduction at the notch tip especially in the case of a double patch reinforcement. This reduction is seen because of a transfer of stresses through the adhesive towards the Boron-Epoxy patch.

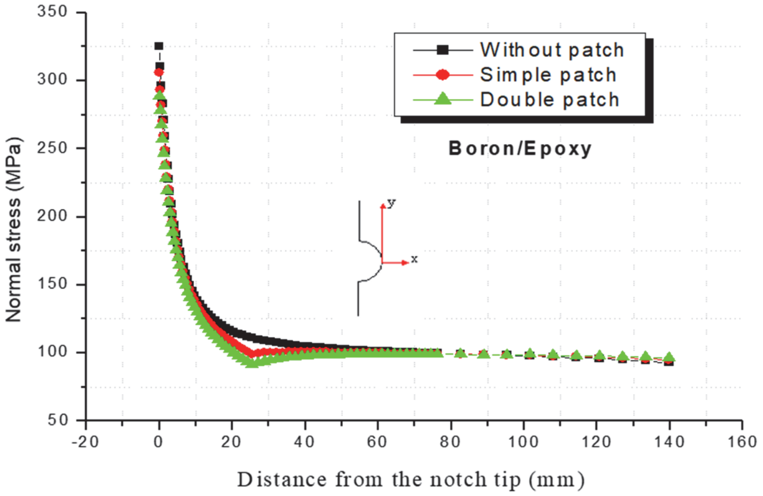

Figure 3: Distribution of the normal stresses along the ligament of the plate.

Effect of patch size

Using the first technique of reinforcement (simple patch), the effect of different patch sizes on the normal stress distribution along the ligament of the plate, is presented in fig. 4. This effect is investigated for three different patch types: Boron/epoxy, Graphite/Epoxy and Glass/Epoxy. One can notice that whatever is the patch type, the contact area between the plate and the patch plays an important role in the normal stress distribution. In fact, the increase of this area contributes to the normal stress reduction in the ligament of the plate, which also reduces the stress concentration.

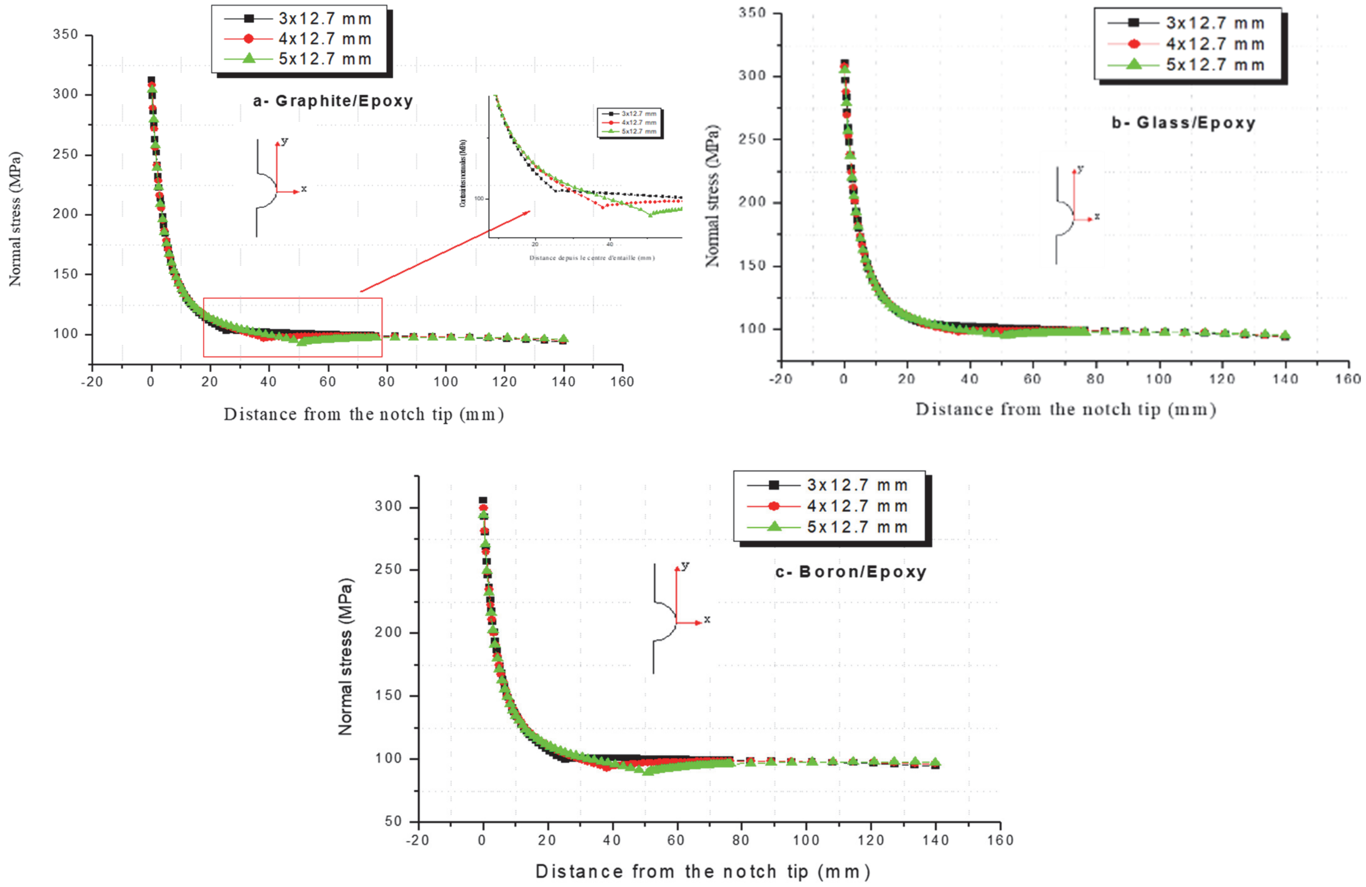

Figure 4: Effect of the patch size on the distribution of normal stresses along the ligament of the plate: a) Graphite/Epoxy, b) Glass/Epoxy and c) Boron/Epoxy.

Effect of the adhesive thickness

In the notched plates, the adhesive thickness is a key parameter for the transfer of the loads towards the patch and to prevent the adhesive failure. In this section, we have analyzed the effect of the adhesive thickness on the normal stress distribution in plates reinforced by simple and double Boron/Epoxy patches. From fig. 5, one can observe that for an adhesive thickness from 0.10 mm to 0.30 mm, the influence on the stress distribution is almost the same. However, the thickness must be chosen carefully, because a thicker adhesive reinforces adhesion, but minimizes the transfer of the loads into the patch, which cancels all the positive effects of the patch.

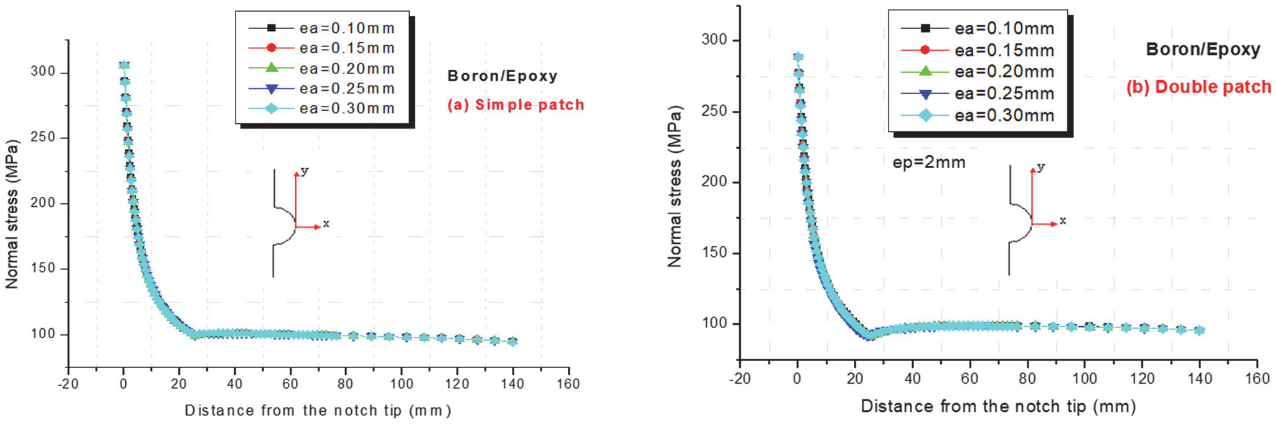

Figure 5: Effect of the adhesive thickness on the distribution of normal stresses along the ligament of the plate: a) simple patch, b) double patch

Effect of the patch thickness

In order to exhibit the effect of the patch thickness on the mechanical behavior of a notched structure, fig. 6 shows the evolution of the normal stress along the ligament of the plate. The results are plotted for the two reinforcement techniques (simple and double Boron/Epoxy patch). It can be observed that the increase in the patch thickness leads to a decrease of the maximum stresses at the notch tip. This behavior is noted whatever the reinforcement technique is.

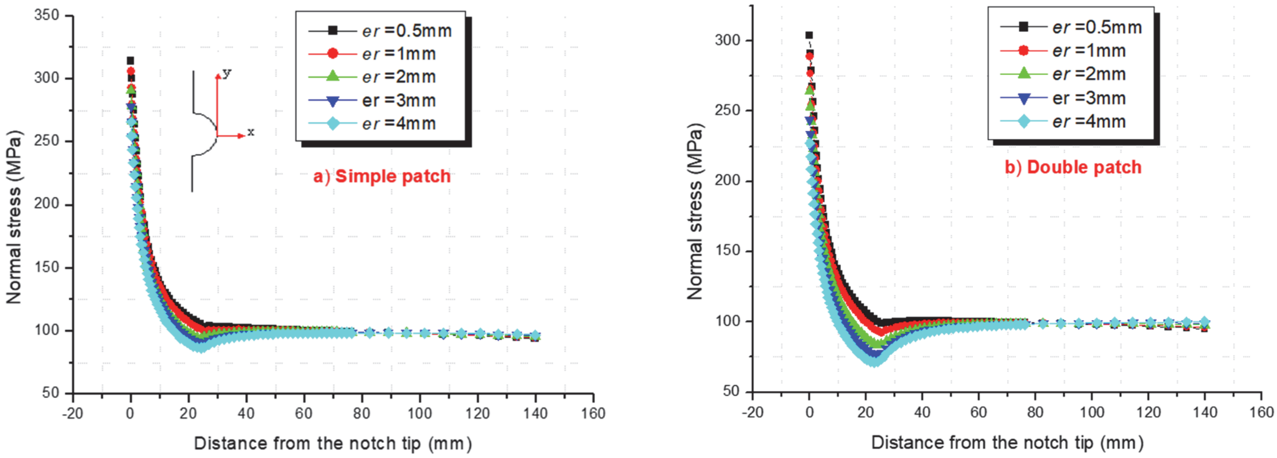

Figure 6: Effect of the patch thickness on the evolution of the normal stress along the ligament of the plate. a) Simple patch, b) Double patch.

The patch thickness have an important role on the stress variation in the contact area between the patch and the plate. In fact, a higher patch thickness reduces the stresses in the contact area. This is illustrated in fig. 7 for 2 and 4 mm patch thicknesses respectively, where the reduction of the stresses is about 18 % for the 4 mm simple patch and about 30% for the 4 mm double patch. One can conclude that the choice of the patch thickness is one of the best ways for a better efficiency of the patch repair.

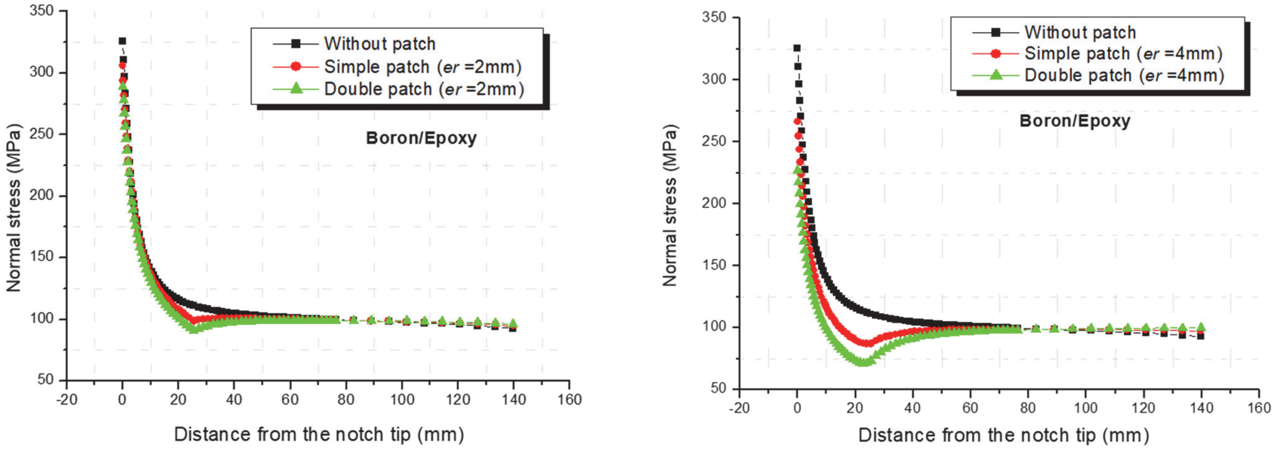

Figure 7: Effect of the patch thickness on the evolution of the normal stress along the ligament of the plate. a) er = 2mm, b) er = 4mm

In a notched plate, the stress field around the notch tip is dominated by the normal stress. Increasing the normal stress leads to a higher stress concentration, which can cause the adhesive failure. The variation of the stress concentration factor defined by ($K_t = \sigma_{max} / \sigma_0$) is plotted as a function of the patch thickness in fig. 8. As can be seen, the increase of the patch thickness decreases the stress concentration factor (SCF) at the notch tip. In addition, the double patch reinforcement technique presents more reduction of the stress concentration factor than the simple patch. This reduction is remarkably observed when the patch thickness becomes higher, with 27% reduction versus 15% reduction for the double and the simple patch, respectively.

Note that the SCF reduction is calculated by the following relation:

$$K_{reduction} = 1 - \left(K_{repaired} / K_{unrepaired} \right) \qquad (1)$$

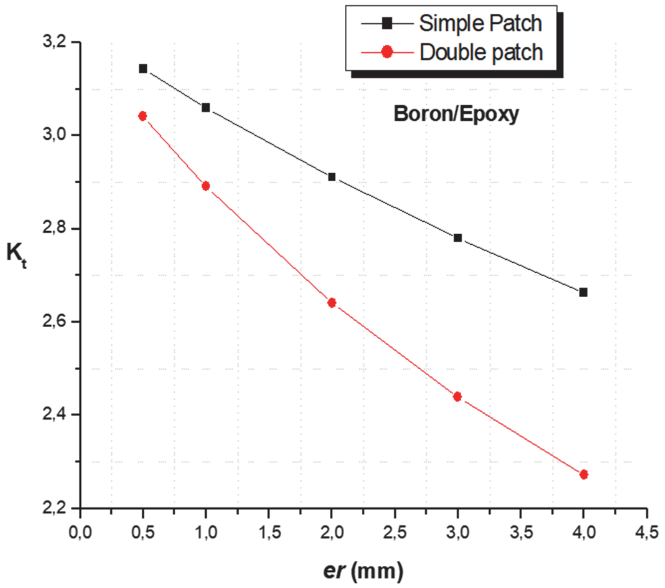

Figure 8: Effect of the patch thickness on the stress concentration factor.

Fig. 9 illustrates the evolution of stress concentration factor as a function of the patch thickness. The results are presented for different patch types: Boron/Epoxy, Graphite/Epoxy and Glass/epoxy. One can notice that the values of stress concentration factor are strongly affected by the patch type. Indeed, the maximum reduction is observed with the Boron/Epoxy patch when compared with Graphite/Epoxy and Glass/Epoxy patches. To reach a reduction of K_t similar of that obtained with Boron/Epoxy, the patch thickness must be more than 4 mm for the other types. So, it can be concluded that the Boron/Epoxy patch allows a better absorption of the stress transmitted by the notch than the other patch types. From a 0.5 to 4 mm patch thickness, the drop of the stress concentration factor is 16.7%, 21 % and 27% for Graphite/Epoxy, Glass/Epoxy and Boron/Epoxy double patch respectively.

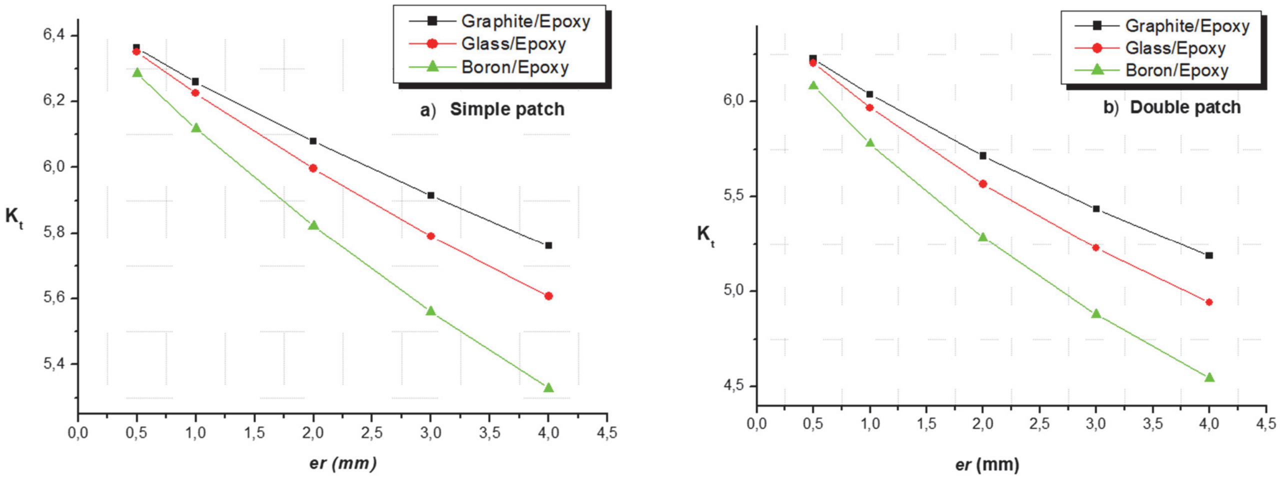

Figure 9: Effect of the patch thickness on the stress concentration factor for different patch types. a) Simple patch, b) Double patch.

NUMERICAL MODELING OF LATERAL V-NOTCHES

Sharp V-notches present a danger of crack initiation and propagation because of the high stress concentration at the notch tip. To evaluate the behavior of these notches, we consider a thin plate made of 2024-T3 aluminium alloy with a lateral V-notch having the following dimensions: height H = 203.2 mm, width 2W = 152.4 mm, thickness ep = 1 mm. The mechanical properties of the plate, the patch and the adhesive have already been given in table 1. It is noted that only the Boron/Epoxy patch will be used in this section.

The geometrical model is shown in fig. 10, the notched plate is reinforced with simple and double bonded composite patch with a semicircular form. The plate is subjected to uniaxial tensile load giving a remote stress state of σ = 50 MPa.

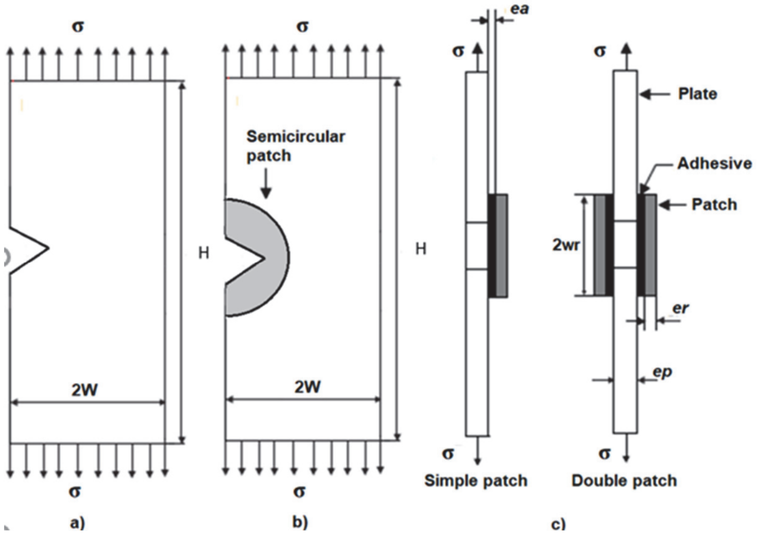

Figure 10: Geometrical model of the plate with lateral V-notch. a) non-reinforced, b) reinforcement with semi-circular patch, c) reinforcement technique configurations.

Effect of the V-notch angle

Fig. 11 shows the distribution of the normal stress along the plate ligament. The results are presented for different V-notch angles α (30°, 75°et 120°). It can be observed that the maximum stresses in plates with V-notches plates are higher than those of the U-notches, which means that the values of the stress concentration factor for sharp V-notches are also higher than the U-notches. The stress levels for a low notch angle are bigger than those obtained for a high notch angle. These values are generally sufficient for the crack initiation and propagation.

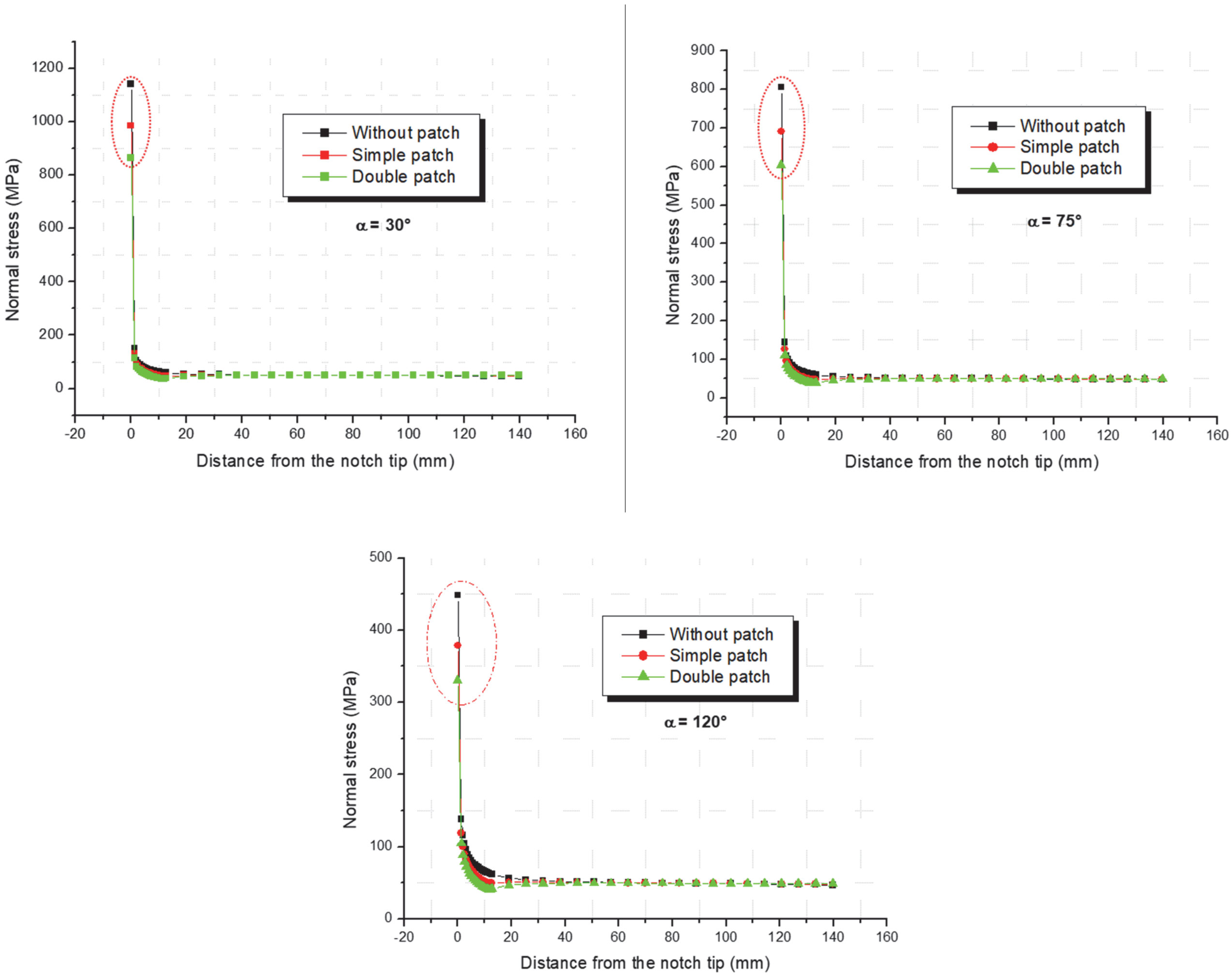

Figure 11: Distribution of the normal stress along the plate ligament for different V-notch angles. a) α = 30°, b) α = 75°, c) α = 120°.

The stress concentration factor is affected by the notch geometry. In the fig. 12 the K_t variation as a function of the V-notch angle α is presented for reinforced and non-reinforced plate. In this figure, the stress concentration factor decreases by increasing the notch angle which leads to a stress reduction. One can say that for the small angles, the risk for the failure becomes higher.

The plotted results show that the variation of K_t presents a linear evolution expressed by the relation:

$$K_t = A + B.\alpha \tag{2}$$

where: A and B are constants to determine

The coefficients A and B are parameters dependent to the applied load and the mechanical and geometrical properties of the reinforced plate, the patch and the adhesive. Table 2 presents the values of A and B identified from the curves.

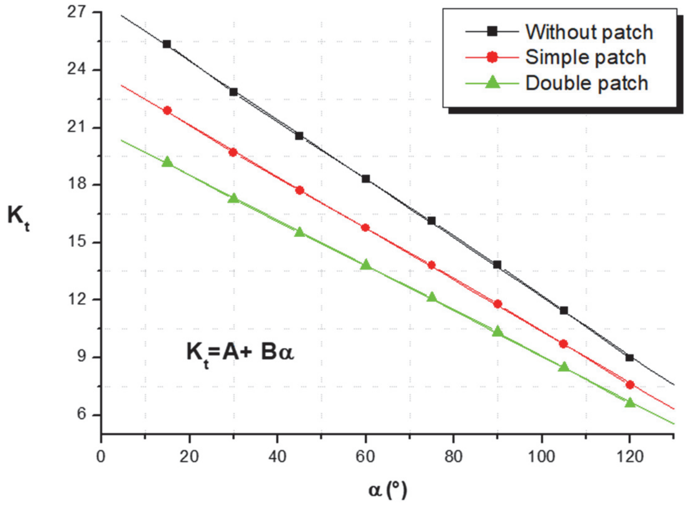

Figure 12: Variations of the stress concentration factor as a function of the V-notch angle.

Coefficient	Without patch	Simple patch	Double patch
A	27.56367	23.83085	20.91013
B	-0.15392	-0.13467	-0.11846

Table 2: Values of the coefficients *A* and *B* identified from the curves.

Effect of the patch thickness

We have analyzed in fig. 13 the effect of the patch thickness on the stress concentration factor for different notch angles α (30°, 75°et 120°). One can observe that the increase in the patch thickness leads to a decrease of the stress concentration factor at the notch tip. This behavior is noted whatever the reinforcement technique is. The reduction of K_t values is more noticeable for the double patch than the simple patch reinforcement technique. It can also be observed that the low notch angles presents a higher stress concentration at the notch tip.

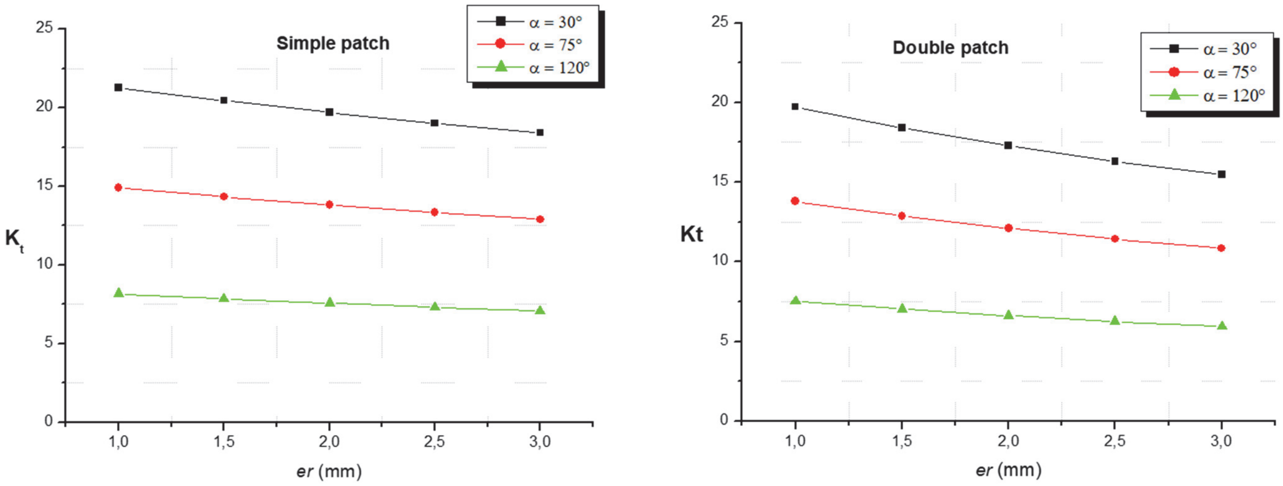

Figure 13: Effect of the patch thickness on the stress concentration factor for different notch angles α (30°, 75°et 120°). a) Simple patch, b) Double patch.

All the variables considered in this study are summarized in Table 3.

	U-notch	V-notch
Patch size	3 x 12.7 mm 4 x 12.7 mm 5 x 12.7 mm	-
Adhesive thickness	From 0.1 to 0.3 mm	-
Patch thickness	From 0.5 to 4 mm	From 1 to 3 mm
Notch angle	-	30° 75° 120°

Table 3: Considered variables with the relevant values.

It is noted that the drop of the stress concentration factor values in the reinforced U-notches is more important than that observed for the reinforced V-notches. This is due to the higher stress concentration at the V-notch tip. This problem can be attenuated by increasing further the patch thicknesses.

CONCLUSION

Using a three dimensional finite element analysis, we have investigated the performance of bonded composite patches used as reinforcements of aluminium panels in the case of U and V-notches. A semicircular patch shape was used in both cases. The stress distribution at the notch tip was investigated by taking in consideration the effect of various parameters. The effect of the patch size, type as well as the patch and the adhesive thickness was explored. The simple and the double patches were used to reinforce the aluminium panels. The important findings can be summarized as follows:

- ✓ The presence of the patch contributes to the stress reduction at the notch tip because of a transfer of stresses through the adhesive towards the patch.
- ✓ The increase of the contact area between the patch and the plate contributes to the normal stress reduction in the ligament of the plate.
- ✓ The increase in the patch thickness leads to a decrease of the maximum stresses as well as the stress concentration factor at the notch tip.
- ✓ The double patch reinforcement presents more reduction of the stress concentration factor (about 27%) compared to the simple patch reinforcement.
- ✓ The use of Boron/Epoxy patch leads to an improved absorption of the stress transmitted by the notch than Graphite/Epoxy and Glass/Epoxy patches.
- ✓ The drop of the stress concentration factor in the reinforced U-notches is more important than that observed for the reinforced V-notches.
- ✓ As a conclusion, we can say that the use of a Boron/Epoxy double patch with an optimized patch thickness can be one of the most efficient ways to increase the performance of the patch reinforcement.

REFERENCES

[1] Baker, A. A. (1984). Repair of cracked or defective metallic aircraft components with advanced fibre composites—an overview of Australian work, Composite Structures, 2(2), 153-181. DOI: 10.1016/0263-8223(84)90025-4.

[2] Baker, A. A. and Chester, R. J. (1993). Recent advances in bonded composite repair technology for metallic aircraft components, In: Proceeding of the international conference on advanced composite materials, Wollongong, Australia. pp. 45-49.

[3] Callinan, R. J., Sanderson, S. and Keeley, D. (1997). Finite Element Analysis of an F-111 Lower Wing Skin Fatigue Crack Repair, Defence Science and Technology Organization Canberra (Australia).

[4] Jones, R. and Chiu, W. K. (1999). Composite repairs to cracks in thick metallic components, Composite Structures, 44(1), 17-29. DOI: 10.1016/S0263-8223(98)00108-1

[5] Ghasemi, F. A., Vanani, L. M. and Anaraki, A. P. (2016). A study on the Charpy impact response of the cracked aluminum plates repaired with FML composite patches, Journal of Failure Analysis and Prevention, 16(4), pp. 594-600. DOI: 10.1007/s11668-016-0123-0

[6] de Barros, S., Budhe, S., Banea, M. D., Rohen, N. R., Sampaio, E. M., Perrut, V. A. and Lana, L. D. (2018). An assessment of composite repair system in offshore platform for corroded circumferential welds in super duplex steel pipe, Frattura ed Integrità Strutturale, 12(44), pp. 151-160. DOI: 10.3221/IGF-ESIS.44.12

[7] Carta, F. and Pirondi, A. (2011). Damage tolerance analysis of aircraft reinforced panels, Frattura ed Integrità Strutturale, 5(16), pp. 34-42. DOI: 10.3221/IGF-ESIS.16.04

[8] Bouiadjra, B. B., Oudad, W., Albedah, A., Benyahia, F. and Belhouari, M. (2012). Effects of the adhesive disband on the performances of bonded composite repairs in aircraft structures, Materials & Design, 37, pp. 89-95. DOI: 10.1016/j.matdes.2011.12.028

[9] Gu, L., Kasavajhala, A. R. M. and Zhao, S. (2011). Finite element analysis of cracks in aging aircraft structures with bonded composite-patch repairs, Composites Part B: Engineering, 42(3), pp. 505-510. DOI: 10.1016/j.compositesb.2010.11.014

[10] Ramji, M., Srilakshmi, R. and Prakash, M. B. (2013). Towards optimization of patch shape on the performance of bonded composite repair using FEM, Composites Part B: Engineering, 45(1), pp. 710-720. DOI: 10.1016/j.compositesb.2012.07.049

[11] Belhouari, M., Bouiadjra, B. B., Megueni, A. and Kaddouri, K. (2004). Comparison of double and single bonded repairs to symmetric composite structures: a numerical analysis, Composite Structures, 65(1), pp. 47-53. DOI: 10.1016/j.compstruct.2003.10.005

[12] Umamaheswar, T. V. and Singh, R. (1999). Modelling of a patch repair to a thin cracked sheet, Engineering Fracture Mechanics, 62(2-3), pp. 267-289. DOI: 10.1016/S0013-7944(98)00088-5

[13] Rasane, A. R., Kumar, P. and Khond, M. P. (2017). Optimizing the size of a CFRP patch to repair a crack in a thin sheet, The Journal of Adhesion, 93(13), pp. 1064-1080. DOI: 10.1080/00218464.2016.1204236

[14] Shinde, P. S., Kumar, P., Singh, K. K., Tripathi, V. K., Aradhi, S. and Sarkar, P. K. (2017). The role of yield stress on cracked thin panels of aluminum alloys repaired with a fRP patch, The Journal of Adhesion, 93(5), pp. 412-429. DOI: 10.1080/00218464.2015.1078243

[15] Boulenouar, A., Aminallah, M., & Benamara, N. (2013). Computation of the SIF for repaired semi-circular surface cracks in finite-thickness plates with bonded composite patch, Journal of Materials, Processes and Environment, 1(2), pp. 121-127.

[16] Merzoug, M., Boulenouar, A. and Benguediab, M. (2017). Numerical analysis of the behaviour of repaired surface cracks with bonded composite patch, Steel and Composite Structures, 25(2), pp. 209-216. DOI: 10.12989/scs.2017.25.2.209

[17] Meran, A. P. and Samanci, A. (2017). Analysis of various composite patches effect on mechanical properties of notched Al-Mg plate, Steel Compos. Struct, 25(6), pp. 685-692. DOI: 10.12989/scs.2017.25.6.685

[18] Cetisli, F. and Kaman, M. O. (2014). Numerical analysis of interface crack problem in composite plates jointed with composite patch, Steel and Composite Structures, 16(2), 203-220. DOI: 10.12989/scs.2014.16.2.203

[19] Maligno, A. R., Soutis, C. and Silberschmidt, V. V. (2013). An advanced numerical tool to study fatigue crack propagation in aluminium plates repaired with a composite patch, Engineering Fracture Mechanics, 99, pp. 62-78. DOI: 10.1016/j.engfracmech.2013.01.006

[20] Chen, R., Qiu, J., Liu, B., & Ren, G. (2019). Ultimate failure of defective pipelines reinforced with composite repair systems. Journal of Failure Analysis and Prevention, 19(2), pp. 581-589. DOI: 10.1007/s11668-019-00636-8

[21] Saffar, A., Darvizeh, A., Ansari, R., Kazemi, A. and Alitavoli, M. (2019). Prediction of failure pressure in pipelines with localized defects repaired by composite patches. Journal of Failure Analysis and Prevention, 19(6), pp. 1801-1814. DOI: 10.1007/s11668-019-00781-0

[22] El-Sagheer, I., Taimour, M., Mobtasem, M., Abd-Elhady, A. and Sallam, H. E. D. M. (2020). Finite Element analysis of the behavior of bonded composite patches repair in aircraft structures, Frattura ed Integrità Strutturale, 14(54), pp. 128-138. DOI: 10.3221/IGF-ESIS.54.09.