International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 2 Issue 3, March - 2013

Effect Of The Repair Parameter On The Lifetime Of Bonded Composite Repair In Aircraft Structure

Miloudi Abdelkader[1,2], Laid Aminallah[1],Benguediab Mohamed[2] and Amrouche Abdewaheb[3]
1- Department of Engineering Mechanics- University of Mascara (Algeria)
2-Laboratory of Materials and Reactive System- University of Sidi Bel Abbes (Algeria)
3- LGCgE- Faculty of Applied Science- Bethume, University of Artois (France)

Abstract

Aircraft repair is gaining importance for extending the fatigue life of aging aircrafts and also for improving its structural integrity. Among various repair techniques, bonded composite patch repair is mostly preferred. The aim of this work is to formulate a set of recommendations for the selection of the various factors that may affect the repair process of damaged structures by fatigue and find a mathematical model that can link these different factors chosen. The experimental design method is used for predicting the service lifetime and optimisation of the patch size. It has been shown that the most influential parameters are in order: the length of the patch, the patch thickness and width of the patch.
The interaction study has found different combinations of factors for a number of important cycles.

1. Introduction

Bonded composite repair has been recognized as an efficient and economical method to extend the service life of cracked aircraft structures. The ideal patch design is the one that maximizes the repair efficiency while minimizing the risks of in-service failure. It is practically impossible to design a standard "optimal patch" for a wide range of different cases because of the interaction of the effects of several parameters in the repair design. Several design parameters play important roles in bonded composite patches; These parameters include:
patch size, patch shape, materials selection,
patch taper, ply fibre orientation, curing temperature and heating zone size…etc. Several studies [1-2] have been made in order to evaluate the importance and the effects of some of the above mentioned design parameters.
The analysis of the effects of the composite geometrical properties on the repair performance got great interest in the literature. Heller and Kaye [3] used the genetic algorithm to optimize the patch shape. Bachir Bouiadjra et al [4], Ouinas et al [5-6] analyzed numerically the performance of the octagonal, circular and elliptical shapes of the patches. They showed that the patch shape has a significant effect on the value of the stress intensity factor at the crack tip. In addition, the use of appropriate patch shapes can reduce the level of the thermal residual stresses due to the adhesive curing. Bachir Bouiadjra et al [7] analyzed the effect of the patch thickness. They showed that the patch thickness must be optimized.
Miloudi et al [8], studied the effects of patch size on the variation of the J integral for repaired cracks and analysed using the finite element nonlinear, the experimental design method was applied to optimize the patch size and to determine the most influencing dimension on the repair efficiency. They showed that, the width of the patch must be very larger than the crack length in order to include the crack propagation under the composite patch. The increase of the length or width of the patch leads to increase the total strength of the assembly. The increase of the patch dimensions reduces the J integral at the crack tip.
The method of experimental design has been widely used in industry for determining factors that are most important in achieving useful goals in a manufacturing process [9-10-11]. These factors, under the designer's control, are varied over two or more levels in a systematic manner. Experiments are then performed, according to an orthogonal array to show the effects of each potential primary factor; thus allowing us to perform an analysis that will reveal which of the factors are most effective in reaching our objective and how these factors should be adjusted to optimise it.
In this work, we apply the experimental design method for predicting the service life of structures damaged by fatigue and optimization of the patch size and to determine the most influencing dimension on the repair efficiency.

2. Selection of influential factors

The difficulty of repairing damaged structures by fatigue is the fact that this technique is a multifactorial

process interdependent. It is very important to make all the parameters that have a great influence on the latter (geometric and mechanical parameters of the patch and the adhesive).
For a good understanding of the repair process, and the interdependence between these parameters, it is interesting to study the maximum parameters at once. For our study, we considered four variable parameters, length of the patch, the thickness of the patch, the patch width and the shear modulus of the adhesive.
Intervals for the Study of various factors were chosen following the responses obtained from preliminary tests.

According to table initial experiments (Table 1), we chose the intervals of study for the four factors as follows:

$0.92mm \leq ep \leq 1.71mm$ (Thickness of the patch)
$0.6mm \leq Wp \leq 25mm$ (Width of the patch)
$03mm \leq Lp \leq 13mm$ (Length of the patch)
$482MPa \leq G \leq 6$ (Shear modulus of the adhesive)

The parameter that was held constant is the thickness of the adhesive.

3. Geometric model

An aluminum plate with a central circular notch 300 length, 25 mm width and 1.30 mm thickness. A central crack of length 3 mm perpendicular to the loading direction exists in the plate. This crack is repaired with a bonded graphite/epoxy unidirectional composite patch with the following mechanical properties (Figure 1).
E_1 = 172,400 MPa; $E_2 = E_3$ = 10,300 MPa; G = 4800 MPa; $\nu_{12} = \nu_{13}$ = 0.3; ν23 = 0.02.
The maximum stress is 15 MPa is applied to the plate perpendicular to the direction of the crack; the charge ratio used in this study (R) is 0.1.

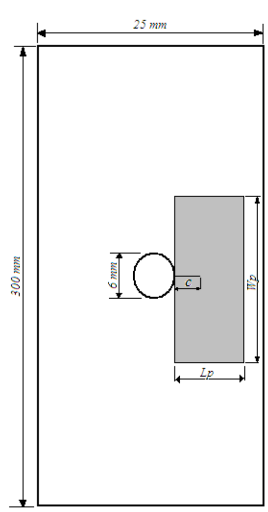

Figure 1. Geometric model

Table 1: Results of different program execution

3. Choice of experimental

Exp. No	Length (mm)	Width (mm)	Thickness (mm)	G adhesive (MPa)	Lifetime (cycles)
1	3	0,6	0,92	482	108055
2	3	0,6	1,71	482	159196
3	3	25	0,92	482	109055
4	3	25	1,71	482	160196
5	13	0, 6	0,92	482	557034
6	13	0, 6	1,71	482	929061
7	13	25	0,92	482	616556
8	13	25	1,71	482	930071
9	3	0, 6	0,92	620	75000
10	3	0, 6	1,71	620	110496
11	3	25	0,92	620	75010
12	3	25	1,71	620	110496
13	13	0, 6	0,92	620	390118
14	13	0, 6	1,71	620	640551
15	13	25	0,92	620	390118
16	13	25	1,71	620	640551
17	8	12.8	0,92	551	373987
18	8	12,8	1,71	551	658859
19	8	0, 6	1,315	551	519028
20	8	25	1,315	551	520030
21	3	12,8	1,315	551	165747
22	13	12,8	1,315	551	859842
23	8	12,8	1,315	482	588972
24	8	12,8	1,315	620	524511
25	8	12,8	1,315	551	530520
26	8	12,8	1,315	551	530520
27	8	12,8	1,315	551	530520

The experimental design used in this study is a comprehensive quadratic plan, which deals with a mathematical model of second order and has the following form:

$$y = a_0 + \sum_{i=1}^{4} a_i x_i + \sum_{1 \le i < j \le 4} a_{ij} x_j + \sum_{i=1}^{4} a_{ii} x_i^2 + e \qquad (1)$$

where y is the response of the process (i.e., the life in the plate) and x_i is the normalized centered value for each factor u_i:

$$x_i = (u_i - u_{ic})/\Delta u_i = u_i^*,$$

$$u_{ic} = (u_{imax} + u_{imin})/2 \ ; \ \Delta u_i = (u_{imax} - u_{imin})/2$$

For the considered factors in the present study, i.e. the length (L_p), the width (W_p), thickness (e_p) of the patch, and the Shear modulus of the adhesive (G) quadratic model of the response (N lifetime) will take the following form:

$$N = a_0 + a_1 L_p^* + a_2 W_p^* + a_3 e_p^* + a_3 e_p^* + a_3 G^* + a_{12} L_p^* W_p^* + a_{13} L_p^* e_p^* + a_{14} L_p^* G^* + a_{23} W_p^* e_p^* + a_{24} W_p^* G^* + a_{34} e_p^* G^* + a_{11} L_p^{*2} + a_{22} W_p^{*2} + a_{33} e_p^{*2} + a_{44} G^{*2} \qquad (2)$$

Using software MODDE 5.0 (Modeling and Design) [12] to the various statistical calculations. There are two methods for regression in MODDE: regression, PLS '(Partial Least Squares) is used when data are missing and regression' MLR '(Multiple Linear Regression). MLR is the method chosen; least square's regressions on several factors.

After an initial study of the various factors that influence the lifetime, we will now try to establish a relationship between input variables and output variables.

For this we propose a plan of second degree called "composite face-centered plan" which provides a modeling response surface (RSM).

The numerical results obtained by the fatigue calculation software (Afgrow) [13], the results of 27 experiments according to the experimental design are shown in Table 1.

3. Results

3.1. Analysis with a single effect

To study the influence of variables (length "LP" - width "Wp" - Thickness "ep" - shear modulus "G"), we must fix three parameters and vary the fourth parameter, we will see later that each factor has a significant influence on the performance criteria of the patch.

From the mathematical models obtained, we can determine the influence of each factor on each response, by plotting the variation of responses based on these selected factors. If we want to determine, for example, the influence of a factor (x_i) on the lifetime, we represent the variation for the three levels of the factor chosen.

3.1.1. Effect of patch thickness.

The objective of this study is to analyze the influence of the thickness of the patch on the life of structures damaged by initially cracking and repaired by composite patch. Extending the life of these structures is analyzed in terms of increasing the number of cycle. In this study, we considered several thickness of the patch that varies between 0.9 mm and 1.7 mm, a length of 12.8 mm of the patch and a width of 8 mm.

A study by the method of experimental design was conducted to analyze the effect of the thickness of the patch on the life of the repaired structures (Figure 2). The analysis of this figure shows an increase in the thickness of the patch results in an increase in the lifetime of these structures. Indeed, over the thick patch is used as the level of the stress field at crack tips of the repaired area is low. Our results show that the patch repair of composite material significantly reduces the mechanical energy with high concentrations of crack heads, and therefore, slowed the kinetics of propagation of these defects. This reduction is even stronger when the repair material is thick. From these results, one can also say that there is a critical thickness of the repair material (patch thickness = 1.3 mm) beyond which the life of the repaired structures is almost independent of the geometrical parameter.

Figure 2. Changes in the number of cycles, depending on the thickness of the patch

3.1.2. Effect of patch length.

In this section, we studied the influence of the length of the patch on the life of the repaired structures. This study was conducted for the patch lengths ranging from 3 to 13 mm, the other two geometric parameters for the repair material used in this analysis have the following dimensions: width = 12.8 mm, thickness = 1315 mm.

Figure 3 illustrates this influence, from this figure; we see an increase in the length of the patch causes an increase in the lifetime of the repaired plate. This clearly shows that the repair of damaged areas with patches composite longer causes a stress relaxation at the crack tip repaired. This fundamental characteristic length of the repair determines the area of recovery and therefore, the reliability of the repair. Its optimization is very useful for performance and durability of the repair. In other words, the length of the patch affects the level of these constraints, which agrees well with results obtained by Megueni et al. [14].

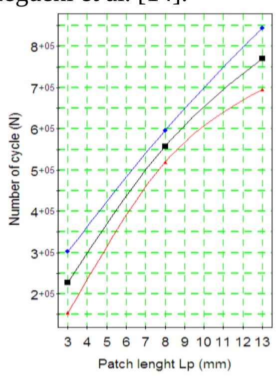

Figure 3 Changes in the number of cycles, depending on the length of the patch

3.1.3. Effect of shear modulus of adhesive

The mechanical properties of the adhesive determine the degree of charge transfer from defects to patch. If the adhesive is regarded as an elastic material, its mechanical properties, especially its shear modulus determines the performance and durability of structures repaired with a composite patch.

In this study, the effect of adhesive properties on the variation of the lifetime is analyzed. The geometric characteristics of the patch used in this part of study are: length = 8 mm, width = 12.8 mm and thickness = 1315 mm.

Figure 4 shows the effect of the shear modulus of the adhesive on the parameter N (number of cycles). This figure shows a crack repaired with an adhesive having high shear modulus results in a decrease in the number of cycle, in other words, an increase in the level of this module leads to a drop in the lifetime of the structural repairs, this conclusion was stated by , Bouiadjra Bachir and al [15-16]. So we can conclude that the better adhesives are characterized by low shear modulus allowing them to resist shear stresses

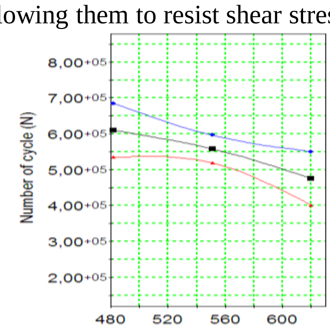

Figure 4. Changes in the number of cycles depending on the shear modulus of adhesive

3.1.4. Effect of patch width.

This effect is illustrated by Figure 5 for the patch widths ranging from 0.6 to 25 mm. The length and the thickness of the repair material used in this section are the following dimensions: 8 mm and 1.315 mm, the shear modulus of the adhesive G is 551 MPa.

We observe that this increase in width leads to an increase in the life plate repaired. This effect is more marked for the patch width equal to 13 mm. In fact, an increase of 60% of the thickness of the patch leads to an increase of order 8% of the duration of life. So we can say that there is a critical width (w = 13 mm) beyond which the width of the patch has no influence on the life of structures repaired with a composite patch.

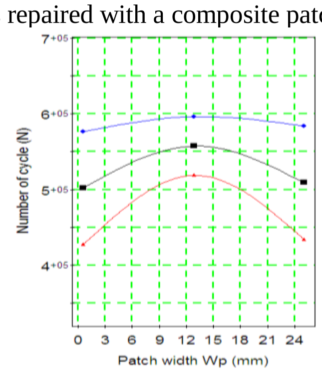

Figure 5. Changes in the number of cycles depending on the width of patch

3.2. Effects of interactions on the response

3.2.1. Interaction thickness - shear modulus.

In this step, we extend our analysis by taking into account comments this time an interaction between two factors while keeping constant the other two this decision allows us to visualize the variation of the number of cycles N by a graph in three (3) dimensions (Figure 6), the latter is a representation of the variation in the number of cycles N as a function of the thickness of the patch and the shear modulus of the adhesive.

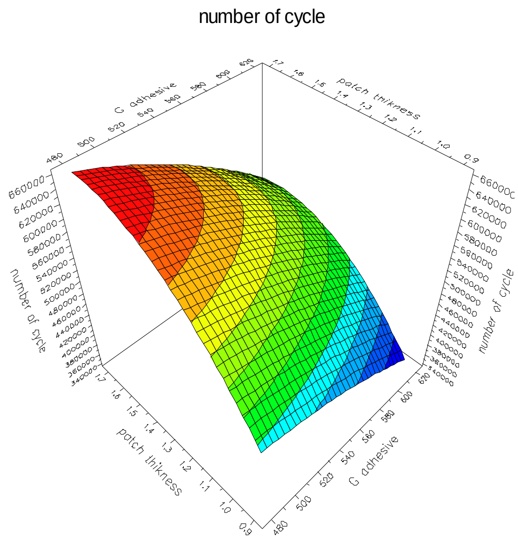

Figure 6. Change in a number of cycles depending on the thickness and G

Figure 07, usually called 'Iso curves' which is the projection of the surface 6 of the plan, the analysis of the curve 07 shows that the more you increase the thickness of the patch lifetime increases to a maximum of 640,000 cycles, but this applies to a G value of less than 508 MPa, beyond this value the shear modulus of the adhesive G has a negative influence on the response (the lifetime). So we can conclude that for a long lifetime, you must use an adhesive having a shear modulus less than 508 MPa and a thickness of the patch that varies between 1.5 and 1.7 mm.

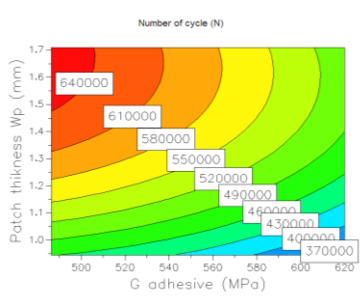

Figure 7. Interaction thickness - shear modulus

3.2.2. Interaction thickness - length.

It is in this case to set the shear modulus of the adhesive (G = 551 MPa) and the width of the patch (Wp = 12.5 mm) and varying the length and thickness of the patch (Figure 8).

In this case interaction, the number of cycles guards these high levels when these two factors are of maximum values.

So to increase the lifetime should increase the thickness and length of the patch.

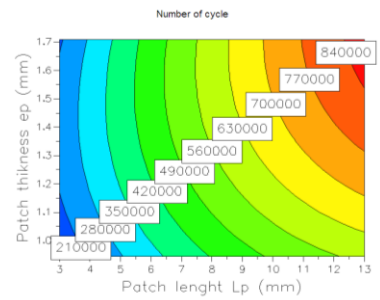

Figure 8. Interaction thickness - length

3.2.3. Interaction width-thickness.

The graph 9 shows the variation in the number of cycles N as a function of thickness and width of the factor's patch with G = 551 MPa and the patch length = 6.5 mm. This time the thickness has no effect on the lifetime against by increasing the thickness increases the lifespan up to a maximum of 550,000 cycles for values between 0.9 and 1.3 mm.

This time we note that beyond a patch of width, Wp = 2mm lifetime remains constant equal to 550,000 cycles, for against lifetime increases with increasing duration of the thickness of the patch. It is concluded that to increase the life you have to keep the thickness of the patch between 1.3 and 1.7 and keep the width of the patch equal to 2 mm.

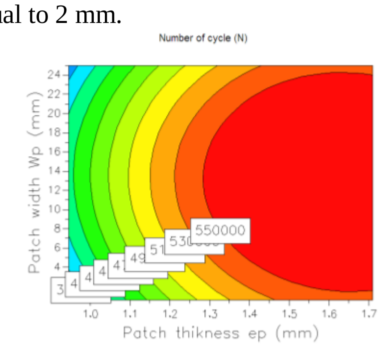

Figure 9. Interaction width-thickness

3.2.4. Interaction length-width.

Figure 10 shows the effect of both length and width factors acting simultaneously in the patch from their minimum to their maximum value, the third and fourth factor was constant (G = 551 MPa and thickness = 0.92 mm patch) on the life N. Analysis of this curve shows that the greater the length of the patch life increases until it reaches a maximum value of 720,000 cycles, for beyond against a width greater than 2 mm life is constant. We conclude that for this analysis for a maximum of life must have a value of (Lp) between 11.5 and 13 mm and keep the value of Wp equal to 2 mm.

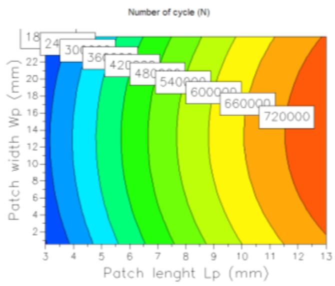

Figure 10. Interaction length-width.

3.3. Effects of patch parameters

It is important to study the effect of different factors on the bonding patch. We must first know which factors have the greatest influence and then how the variables react with these factors. We present the effects of factors using a bar graph. This diagram shows the effects in descending order of their importance in absolute terms.

Figure 11 shows the effects of all the terms of factors (linear, quadratic and cross).

- Patch length (L_p)
- patch thickness (e_p)
- Module of the adhesive shear G
- Patch width (W_p).

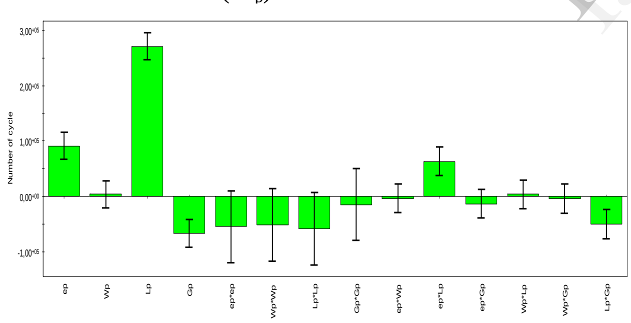

Figure 11. Effects of the factors on the time

3.3.1. Verification of the optimal point.

From the analysis performed by the software "modde5.0" we find that the verification of optimal focus is simple, according to table 2, the values given by the program, we note that maximizing the lifetime can be achieved by the experience that includes the values of the thickness of 1. 6611 mm, the width which is equal to 14.2529 mm, the length of which is equal to 13 mm, and shear modulus, which is equal to 482 MPa.

The method is to maximize thickness, length and width, minimize the shear modulus of the adhesive.

Table 1: Optimal of patch dimensions

	Length (mm)	Width (mm)	Thickness (mm)	G adhesive (MPa)	*N* optimum (cycles)
(1)	1,078	14,3622	13	482	752347
(2)	1,6611	14,2529	13	482	977498
(3)	1,71	24,5945	12,9994	482,005	943837

3.3.2. Realization of the mathematical model.

The experimental design used in this study is a comprehensive plan quadratic, that is to say, that deals with a mathematical model of the second degree, Table 3, presents the coefficients of the different parameters and their interactions.

The mathematical model suggested by MODDE 5.0 is:

$$N = 55751 + 91363.5 * e_p + 3530.25 * W_p + 271147 * L_p - 66741.4 * G_p - 55130.4 * e_p^2 - 52024.3 * W_p^2 - 52024.3 * W_p^2 - 58758.8 * L_p^2 - 14811.7 * G_p^2 - 3657.57 * e_p * W_p + 63321.5 * e_p * L_p - 13498.5 * e_p * G_p + 3657.66 * W_p * L_p - 3907.65 * W_p * G_p - 50367.7 * L_p * G_p \quad (3)$$

Where e_p (thickness of the patch), W_p (width of the patch), L_p (length of the patch) and G_p (shear modulus of the adhesive), are coded values, this forces us to make coding in order to have the factor values in between -1 and +1 terminals; it can handle, and these give the model. The formulas used for encoding are:

$$L^* = \frac{L - (L_{max} + L_{min})/2}{(L_{max} - L_{min})/2} = \frac{L - 70}{50}$$

$$W^* = \frac{W - (W_{max} + W_{min})/2}{(W_{max} - W_{min})/2} = \frac{W - 77{,}5}{42{,}5}$$

$$e^* = \frac{e - (e_{max} + e_{min})/2}{(e_{max} - e_{min})/2} = \frac{e - 1{,}315}{0{,}395}$$

$$G^* = \frac{G - (G_{max} + G_{min})/2}{(G_{max} - G_{min})/2} = \frac{G - 551}{69}$$

3.3.3. Verification of the model.

Figure 12 compares the measured lifetime and that calculated from the proposed model.

Note that the calculated results from the proposed model are in agreement with experimental results. This model allows us to obtain a better prediction of the lifetime of the structure repaired by composite patch.

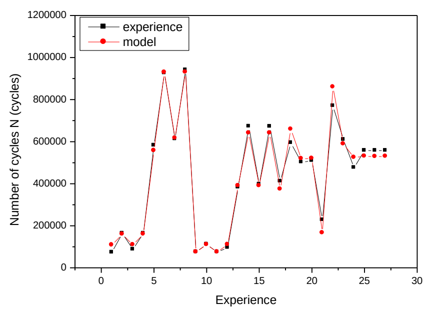

Figure 12. Comparisons between the numerical values of N and those obtained by the mathematical model

3. Conclusions.

This work is focused on the repair of aircraft structures with a composite patch subjected to constant amplitude loading. This study focused primarily on the influence of four factors is the length of the patch, the thickness of the patch, the patch width and the shear modulus of the patch. It is therefore, to understand and explain how to act on them and what is the preponderance of each vis-à-vis the other.

To study the influence of these factors on the number of lifetime use is made of the methodology of experimental design that achieves a better understanding of the phenomena observed by a minimum of tests. The main advantage of this method is rapid and unambiguous interpretation of test results.

This study showed us that the most influential parameters are in order: length, thickness, width and the shear modulus G. The model given by the experimental design allows us to obtain a better prediction of the lifetime of the structure repaired by composite patch.

4. References.

[1] AA. Baker, RJ. Callinan, MJ. Davis, R. Jones, JG. Williams. "Repair of mirage III aircraft using BFRP crack patching technology", Theor Appl Fract Mech , Vol 2, No. 1,pp.1-15,1984.

[2] JQ. Tarn, KL. Shek, "Analysis of Cracked Plates with Bonded Patch", Engineering Fracture Mechanics, Vol 40, No. 6, pp. 1055-1065, 1991.

[3] M. Heller, R. Kaye. "Shape optimisation for bonded repairs",Advances in the bonded composite repair of metallic aircraft structure, Vol. 1, pp. 269–315, 2002.

[4] B. Bachir Bouiadjra, M. Fari Bouanani, A. Albedah, F. Benyahia, M. Es-Saheb, "Comparison between rectangular and trapezoidal bonded composite repairs in aircraft structures: a numerical analysis", Mater Des Vol. 32, No. 6, pp 3161–6, 2011.

[5] D. Ouinas, BB. Bouiadjra, B. Serier. M. Said Bekkouche, "Comparison of the effectiveness of boron/epoxy and graphite/epoxy patches for repaired cracks emanating from a semicircular notch edge", Compos Struct, Vol. 80, No. 4, pp. 514-522, 2007.

[6] D. Ouinas, A. Hebbar, B. Bachir Bouiadjra, M. Belhouari, B. Serier. "Numerical analysis of the stress intensity factors for repaired cracks from a notch with bonded composite semicircular patch", Compos Part B: Eng, Vol 40, No.8, pp. 804–10,2009.

[7] H. Fekirini, B. Bachir Bouiadjra, M. Belhouari, B. Boutabout, B. Serier, "Numerical analysis of the performances of bonded composite repair with two adhesive bands in aircraft structures" Journal of Composite Materials., Vol. 82, No. 1, pp. 84-89, 2008

[8] S.M. Fekih,A. Albedah, F. Benyahia, M. Belhouari, B Bachir Bouiadjra ,A. Miloudi, "Optimisation of the sizes of bonded composite repair in aircraft structures".Materials and Design,Vol 41,No24,pp 171-176,2012.

[9] R.A. Fisher. "Statistical Methods for Research Workers", Oliver & Boyd, Edinburgh,1925. Thirteenth edition, 1958.

[10] DY. Benoist, S. Tourbier, "Experimental design: construction and analyses". Paris: Doc. Lavoisier, 1994.

[11] G. Taguchi, S. Konishi, "Orthogonal arrays and linear graphs: tools for quality engineering", American Supplier Allan Park, MI: ASI; 1987.

[12] MODDE 5.0 (Moeeling and Design) Umetrics AB, Umea, Sweden.

[13] AFGROW users guide and technical manual Afgrow for Windows xp/vista, Version 4.0012.15 afrl-va-wp-tr-2008-xxxx.

[14] A. Ait Yala, A. Megueni "Optimisation of composite patches repairs with the design of experiments method". Materials and Design, vol 30, No. 1, pp. 200–205. 2009.

[15] M. Bezzerrouki, B. Bachir Bouiadjra, "SIF for cracks repaired with single composite patch having two adhesive bands and double symmetric one in aircraft structures", Materials and Design, Vol 44, No. 2, pp. 542–546, 2008.

[16] B. Bachir Bouiadjra, H. Fekirini, "Fracture energy for repaired cracks with bonded composite patch having two adhesive bands in aircraft structures", Materials and Design, vol 44, No. 1, pp. 20–26,2007.