EXPERIMENTAL ANALYSIS OF THE PERFORMANCE OF COMPOSITE MATERIAL USED AS CRACK FATIGUE REPAIR

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Abstract. *The use of composite materials in structures is becoming more diversified and one of the applications that seem to be quite promising is the repair in damaged metallic structures. One of these lines of research suggests the utilization of composite material bonded to cracked metal plates, instead of the traditional repair using inserted and doubler plates welded or riveted to the structure. This technique not only reduces the weight of the repair but also increases the fatigue life, distributing the stresses around and at the tip crack all over the contact patch area with the cracked plate, which are responsible for the crack growth, without inducing additional stress. In this work, are presented the results of fatigue tests, conducted by Mello (2005), of aluminum specimens (AL5052-H32), 4 and 6.5 mm thick, without and with composite patch, fiber glass and carbon fiber, bonded using a structural adhesive, submitted to cyclic loads with constant amplitude and frequency. It was possible, from the results obtained for the fatigue life, to evaluate the performance of the repairs in the restraint on the crack growth, proving the efficiency of the suggested method.*

Keywords: *composite material, repair, fatigue life*

1. Introduction

The traditional repairing methods, using doubler plates welded or riveted to cracked structure, after stress relief on the crack tip, drilling a hole, can bring changes in the existing stress fields, generating undesirable stress concentration points. In these cases, it is common to have new cracks in areas adjacent to the repairs, where no damage was previously detected. When submitted to cyclic loads during its operative life, machine elements, aircraft structural parts, ships, offshore platform, etc, from a defect often meaningless, can nucleate cracks that lead to a catastrophic fracture of the material during a fatigue process.

Studies concerning the utilization of composite material repairs bonded to the cracked structure, chiefly those made from aluminum have increased. With this technique it is possible to distribute the stress field held on the tip of the existing crack, responsible for its growth over the contact area between the patch and the metal plate.

Recently, Chung and Yang (2003) studied of the effects on fatigue life in aluminum specimen (AL6061-T6), 6 mm thick, pre-cracked, repaired with composite material (fiber glass/epoxy) under a sinusoidal loading condition, has shown that the use of this kind of repair has increased the specimen fatigue life, from 4 to 6 times, in relation to the one without repair.

Analyses on the crack growth front done by Seo and Lee (2002) for thicker (10 mm) aluminum plates (AL7075-T6), repaired with composite material (graphite/epoxy), have shown that the values of the stress on the un-patched surface, are 30% higher than the values found on the patched surface.

The partial patch debonding must be considered, since its occurrence makes the effective repair contact area reduce and, in consequence decreases the stress transfer from damaged structure to the repair. Numerical analysis carried out by Baker (1999) and fatigue tests, conducted by Turaga et al. (1999) and Naboulsi and Mall (1997), prove the fact that the cracks growth speeds are higher where adherence failure happens compared to the opposite situation. Differences in the crack growth, when considered thin or thick specimen attested the effect of partial adherence to be more harmful to the thicker plates than to thinner ones, which was proved by Denney and Mall (1987).

2. Fracture

The failure of the engineering material is always something undesirable, which can, within other consequences, put human lives in danger, cause environmental disasters, economical loses, and it can also make some products and services unavailable. Although the causes of the failures and the materials behavior can be known, their prevention is a condition difficult to keep.

In the fracture process, a solid suffers a division into two or more parts due to the break of atomic liaisons on the fracture surface. There are many possibilities of classifying the fracture. A very used way refers to plastic deformation that happens in the areas bordering the surfaces of the fracture. The ductile fracture is the one in which there is a plastic deformation preceding the fracture, while in the brittle fracture the plastic deformation is very small, even null. In the ductile fracture, the plastic deformation process on the crack front that is growing goes on in a relatively slow way, as its get longer. This kind of crack is frequently called stable, that is, it resists to any additional extension unless there is an increase in the application load (stress). In the brittle fracture, the cracks can scatter in such a very quick way, followed by a small plastic deformation, so they are called unstable and their growth, once initiated, will go on spontaneously with no need to increase the magnitude of the applied load (stress).

These ways of fracture do not depend exclusively on the intrinsic characteristic of the materials, but also on external factors such as temperature, applied load, frequency and environment condition. From the combination of these factors there will be a determined behavior for the metal fracture. The presence of stress concentrator regions (notch, discontinuities, cracks, etc) in the metallic structures and alloy hampers the plastic deformation development, shortening its ductility and toughness, with a weakening effect.

2.1 Principles of Fracture Mechanics

The development of the Linear Elastic Fracture Mechanics (LEFM) provided great advance in the understanding of the cracks and defects effect in the structures fracture, as it suggested a methodology able to compensate the inadequacy of the conventional design criteria, based on resistance, yielding, break load and buckling limits of materials, adequate to many engineering structures, but insufficient when concerning cracks. From that moment, new design philosophies have been created, in which it is assumed that the structure is not a continuous mean; witch can have defects, such as cracks, a natural consequence, for instance, of fabrication processes or any small accident. The structure analysis considering small defects provides answers to the operational security problem, with a quantified estimate of the observed crack behavior or whose existence is under suspicion. From LEFM concepts it is possible to evaluate the meaningful importance of the defects and to compare the toughness of different materials, which allows the designer to decide if a defect detected during the fabrication or in operation can or cannot grow in a stable way, if it needs or needs not repair and also establishes the defects acceptance criteria in the structures.

2.2 Stress Intensity Factor (K)

Studying the stress distribution in the neighboring area of a center crack, $2a$ length, in a linear elastic material infinite plate, under an uniform stress traction s, lead to a stress field on the crack tip defined by a K parameter. This parameter is called *stress intensity factor* and its value for traction load (mode I) in different shapes, orientations and position cracks is given by Eq.(1), where Y is called geometry factor (dimensionless), which depends on the crack proximity to structural element contour or on other cracks, on the crack form and orientation, and also on the contour conditions of the structure that has it. Stress concentration factor is also the measure of the degree according to which a external stress is amplified in the crack tip, being more significant to brittle materials than to ductile ones. The stress intensity factor has $\mathrm{MPa}\sqrt{\mathrm{m}}$, $\mathrm{psi}\sqrt{\mathrm{pol}}$ or $\mathrm{Ksi}\sqrt{\mathrm{pol}}$ units.

$$K = Y\sigma\sqrt{\pi a} \tag{1}$$

In Eq. (1) can be seen that K value depends on s and a value, for a given crack and specimen geometry. When s and/or a values raise, K raises up to the point where the specimen fracture occurs. Keeping the same material, load speed, environment conditions, varying crack and specimen characteristics and raising s and/or a, the fracture will happen an equal K value. So, it is characterized the existence of a critical value for K, called fracture toughness (K_C).

3. Fatigue

Fatigue is a form of failure that occurs in structures exposed to cyclic stress during a period of time (for example bridges, ships and maritime structures, aircraft and machine components). In these circumstances, even if the defects are not present in the beginning of the utilization of these structures, cracks may appear as a consequence of this kind of load. Besides, a failure is possible to occur in a stress level considerably inferior to the material yield limit. The stress intensity factor taken as parameter to describe a stress field on the crack tip growing due to fatigue is widely accept, because in this condition, the plastic zone size on the crack tip is very small. So, the use of K does not imperil the analysis precision.

3.1 Crack Growth Rate

Many experimental techniques can be used to monitor the crack length during stress cycles. In tests usually done under constant amplitude loading, the crack length measurements in determined cycles intervals are registered in a a (crack length) versus N (cycles) graphic. The da/dN crack growth rate is the angular coefficient of this curve at any a point.

In the fatigue cycles there is a minimum variety in the applied stress, from a maximum to a minimum values, which corresponds to a variety in K. It has been observed that the crack length increasing depends on the stress intensity factor amplitude (*DK*), expressed by Eq. (2). In the compressive part of stress cycle with constant amplitude, the crack growth rate does not go on or is despicable and, in this case, s_{min} and K_{min} will be null, making $\Delta K = K_{max}$ and $\Delta s = s_{max}$.

$$\Delta K = K_{máx} - K_{mín} = Y(\sigma_{\max} - \sigma_{\min})\sqrt{\pi a} = Y\Delta\sigma\sqrt{\pi a} \tag{2}$$

Plotting on logarithmic scales of log (ΔK) and log (*da/dN*), the resulting curve presents a sigmoidal format that can be divided into three distinct regions. In region I, for crack of small sizes, there is no noticeable growth of the preexistent cracks. In region II, the curve is essentially linear, given by the expression shown in Eq. (3). In region III, there is a crack accelerated growth and the fatigue life is small, that means, in this region the fracture occurs in few cycles.

$$\log(\frac{da}{dN}) = m\log(\Delta K) + \log(A) \tag{3}$$

In Eq. (3) m is the straight line angular coefficient and log(A) can be determined by using the Eq. (3) at any point of the curve. Equation (3) can also be written in the way given by Eq. (4), which is the expression suggested by Paris:

$$\frac{da}{dN} = A(\Delta K)^m \tag{4}$$

The A and m parameters are constants of the material used and depend on the environment, on the loading frequency and on the ratio between the minimum and maximum stresses (R).

3.2 Fatigue Life

One of the fatigue analysis aims is the determination of the stresses cycles number (N) to which a structural element will have to be submitted so that an initial crack length a_0 reaches the critical length a_C. The integration of Eq. (4), making explicit dN, yields the fatigue life of cracked structure:

$$N = \int_{a_0}^{a_C} dN = \int_{a_0}^{a_C} \frac{da}{A(\Delta K)^m} = \int_{a_0}^{a_C} \frac{da}{A\left(Y\Delta\sigma\sqrt{\pi a}\right)^m} = \frac{1}{A\pi^{m/2}(\Delta\sigma)^m}\int_{a_o}^{a_C} \frac{da}{Y^m a^{m/2}} \tag{5}$$

where a_0 and a_C are initial and final crack lengths, respectively. By using non destructive test it is possible to get the value of a_0 and through toughness fracture test, a_C can be determined. It is considered that Δs is constant and, in general Y (the geometric factor) will depend on the crack length a, thus it will not be able to be removed from integral.

4 Methodologies

For the fatigue tests of the cracked aluminum plates, SEN (Single Edge Notch) specimens have been prepared with 17 mm notch length, see Fig. (1), 5052-H32 aluminum alloy, (E = 70 GPa, σ_{break} = 230 MPa), size of 240 x 80 mm, 6.35 and 4 mm thick, using a fatigue tester INSTRON model 8802, with 25 ton capacity, as shown in Fig. (2).

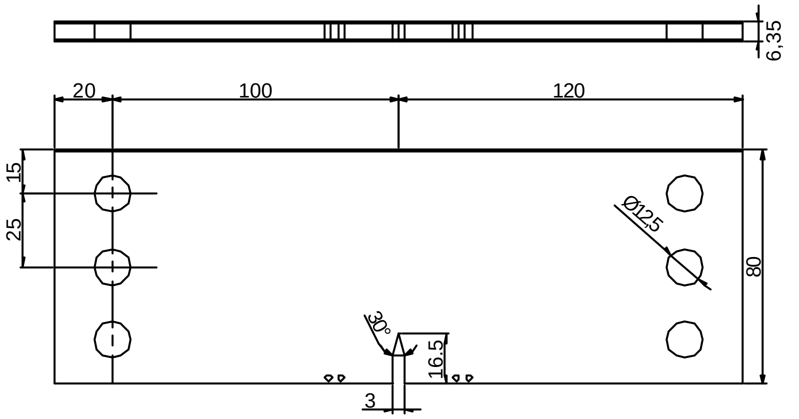

Figure 1 - Specimen Dimensional drawing (units in mm)

A sinusoidal wave form load, with 20 Hz frequency, has been defined intending to keep a maximum stress of 23.62

MPa (10% of AL5052-H32 break limit) and with this, the 6.35 mm thick specimens have been tested at 12 KN, maximum, and 1.2 KN, minimum, amplitudes (R=0.1) and the 4 mm specimens at 7.56 KN and 0.76 KN loads respectively.

Table (1) presents the mechanical properties of patch repairs: carbon fiber (Toray T300) and fiber glass (woven roving 330 g/m^2). The width and the thickness of patch are: 25 x 25 mm and 30 x 25 mm for carbon fiber patch and 25 x 25 mm for fiber glass.

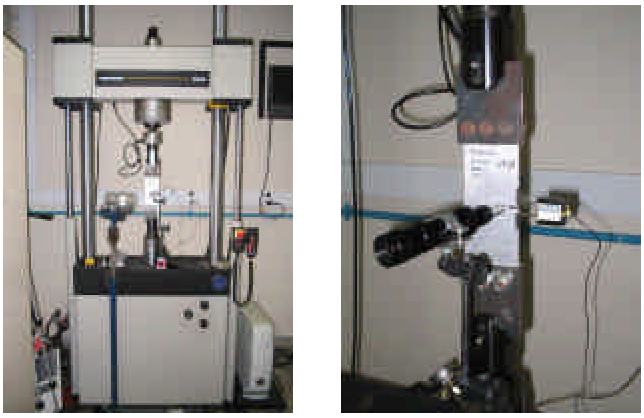

Figure 2 - INSTRON Model 8802 and specimen assembly with COD GAGE and lunette 80x

The patches were bonded on the specimen central region, on the notch, on un-patched surface, as indicated on Fig. (3).For adherence to the specimen, a structural adhesive made from epoxy, DP-460, from 3M Ltd, hardened at room temperature for 96 hours.

Table 1 - Composite material repairs properties

Repair	Thickness (mm)	Young's Modulus (E) (GPA)	Break Limit (MPa)	Volume Fraction	
				Fiber (%)	Resin (%)
Toray 300	1.1	42.9	473.1	54	46
Fiber Glass	1.8	20.4	270.7	67	33

For accurate crack length measurement, a Lunette (80x amplification) and a COD GAGE (Change of Displacement Gage) device connected to specimen were used.

(a) (b)

Figure 3 - Patch bonded to the specimen on one of its surface: (a) carbon fiber and (b) glass fiber

A 3 mm pre-crack was introduced to the specimen, under the same loading condition, in order to relieve the notch machining effects on the crack tip and its initial length becomes to be equal to 20 mm. From that point, the test went on, in a stable growth behavior, until the length reaches the critical value (a_C = 35 mm) that leads the specimen to a unstable fracture. The resulting growth curves, for patch and un-patched specimens, are presented in an a x N graphic from which is possible to get the crack growth rates (da/dN) and ΔK values for the several crack length.

As defined in Eq. (4), the stress intensity factor amplitude (ΔK) depends on the geometric factor Y, which is a function of the crack and other geometric parameters. In this work, the formula proposed by Yang and Chung (2003) was used and is represented on Figure 4 as a function of (*a/w*), where *a* is the crack length and *w* is the specimen wide length (80 mm).

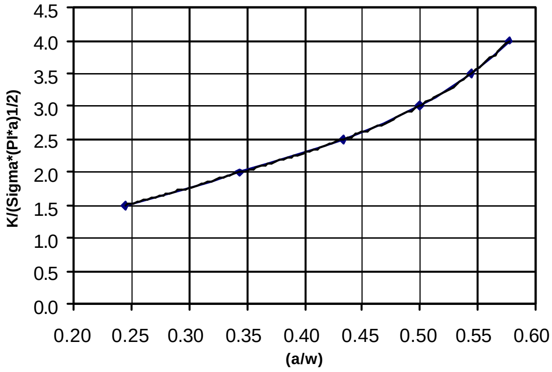

Figure 4 - Geometric factor *Y*

5 Results

This data summarizes the testes carried out in 35 specimens, which total over 12.000.000 cycles, within crack nucleation and growth, which correspond approximately to 170 h of tests.

5.1 Comparative Repairs Performance Analysis

In the comparative graphics of the repair performance, the specimen (SP) type, material thickness, the test configuration and the resulting curve are identified as follows: SP6.35 = 6.35 mm thick specimen; SP4 = 4 mm thick specimen; WR = without repair; CFR25 = 25 x 25 x 1.1 mm carbon fiber repair, CFR30 = carbon fiber 30 x 25 x 1.1 mm repair; GRP25 = 25 x 25 x 1.8 mm repair and LA25 = lack of adhesive in the 25 x 25 x 1.1 mm carbon fiber repair (adhesive only on its extremities, simulating a doubler plate repair, where welding is done only in its contour).

Figure 5 shows the graphic of the growth curves obtained during the SP6.35 fatigue tests. There it is possible to verify that, even, in the worst repair situation, SP6.35-LA25, where the patch is not completely bonded; there is a gain of over 100% of the fatigue life. In the most favorable case, SP6.35-R30, the length of the repair was a preponderant factor that increases the fatigue life, since a bigger contact area between the patch and the plate favors the stress distribution around and on the crack tip front, reducing *K* value.

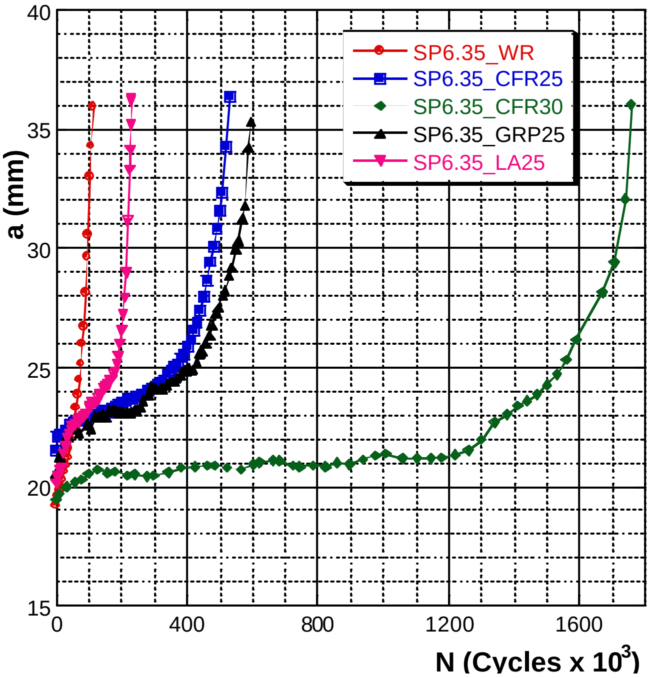

Figure 5 - Comparative graphic *a* x *N*, SP6.35 mm

A similar efficiency was obtained for the same dimension patches (25 x 25 mm) and different materials (SP6.35-CFR25, 1.1 mm thick and SP6.35-GRP25, 1.8 mm thick), raising the material thickness with inferior mechanical properties.

Figure 6 shows the graphic of the growth curve obtained during the SP4 fatigue tests. In this case there is a gain of around 400% of the fatigue life, similar to the one gotten from SP6.35-R25. In the most favorable case, SP6.35-CFR30, the length of the repair was a preponderant factor that increases the fatigue life, since a bigger contact area between the patch and the plate favors stress distribution around and on the crack tip, reducing *K* value.

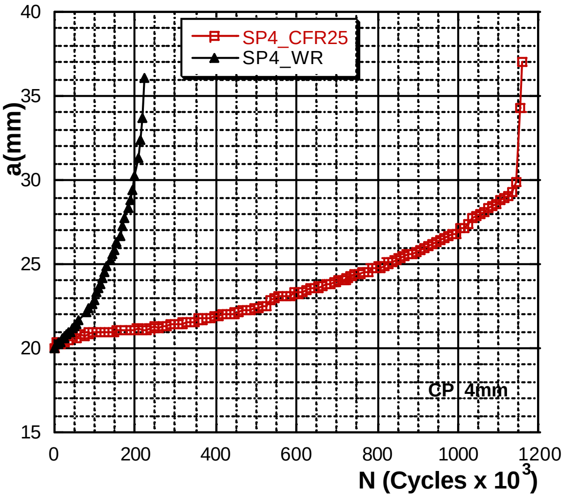

Figure 6 - Comparative graphic *a* x *N*, SP4 mm

On the Table 2, the repair performance evaluation in relation to the fatigue life is achieved by comparing the quantities of cycles from the initial crack length (a_0 = 20 mm) up to the material fracture (a_c = 35 mm).

Table 2 - Comparative table of the fatigue life gain (%)

SP	**SP6.35_WR**	**SP6.35_CFR25**	**SP6.35_CFR30**	**SP6.35_GRP25**	**SP6.35_LA25**	**SP4_WR**	**SP4_CFR25**
Cycles	110.000	530.000	1.700.000	595.000	228.000	220.000	1160.000
Gain%	---	382	1446	441	107	---	427

5.2 Graphics of crack growth rate (da/dN) x stress intensity factor amplitude (ΔK)

Following the procedure previously described, from the *a* x *N* curves, the curves that represent the cracks growth rate of the specimen for the specific conditions adopted on the fatigue tests, were obtained.

Figure 7 represents the SP6.35 curves. Due to the dispersion of obtained points, a special treatment for these results was necessary to prepare the graphics to allow a standard deviation value not superior to 5 % assuring a good adjustment for the interpolated curve (Eq. 4) and consequently for the acquisition of *A* and *m* coefficients (Eq. 3).

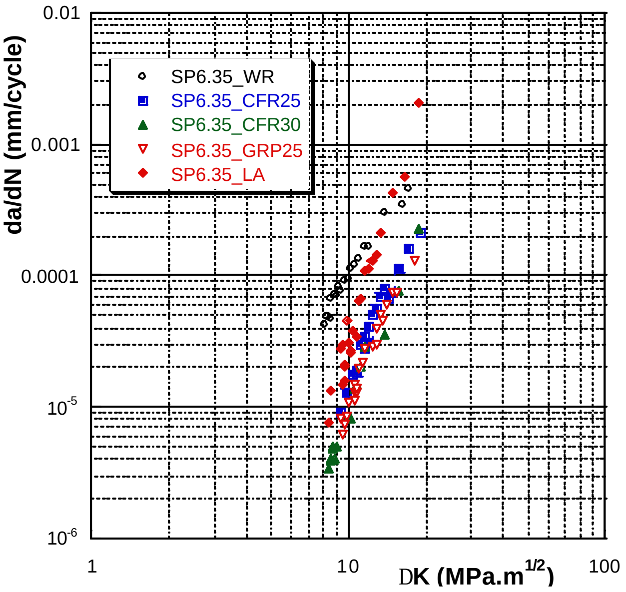

Figure 7 - Comparative graphic Δ*K* x d*a*/d*N*, SP6.35 mm

On Fig. 7, it can be noticed that the bigger crack growth rate are get for the SP6.35-WR, followed by SP6.35-LA, SP6.35-CFR25, SP6.35-GRP25 and SP6.35-CFR30, as it was expected.

Figure 8 represents the SP4 curves and the same treatment for the results was adopted. It could be seen that the SP-WR crack growth rate is bigger than the SP4-CFR25.

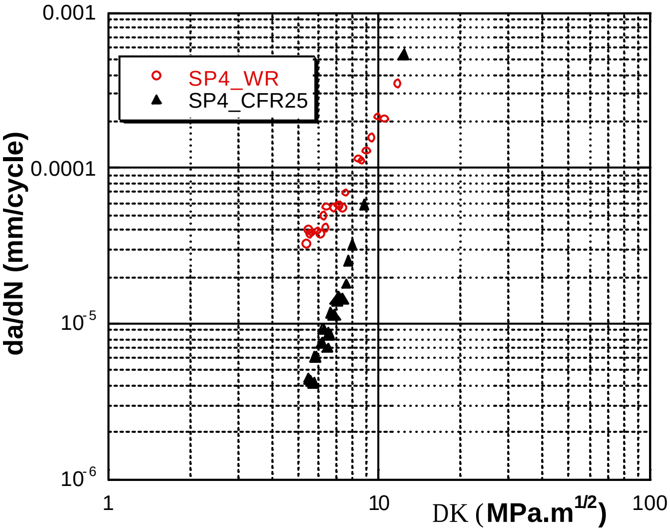

Figure 8 - Comparative graphic ΔK x d*a*/d*N*, SP4 mm

On Table 3 are presented the *A* and *m* coefficients values get through the adjustment of a straight line (Eq. 4) to the whole points get for each test, which can be used for the fatigue life preview, using Eq.5. On the same table is presented the values for ΔK and d*a*/d*N* for each test, considering the crack length equal to 25 mm and ΔK equal to 10 $\text{MPa}\sqrt{\text{m}}$ for the SP6.35 and 7 $\text{MPa}\sqrt{\text{m}}$ for the SP4. On the last column, the d*a*/d*N* values are presented as a percentage of the specimen without a bonded repair. For example, it can be seen that in that column, the SP6.35-CFR30 has the better performance, 9.3 % of the value obtained for the SP6.35-WR

Table 3 - Comparative table of the crack growth speed

SP	*A*	*m*	*DK* (MPa m$^{1/2}$)	*da/dN* (mm/cycle)	Percentual
SP6.35_WR	1.353E-07	2.870	10.0	1.003E-04	100
SP6.35_CFR25	5.845E-10	4.425		1.555E-05	15.5
SP6.35_CFR30	7.892E-11	5.072		9.315E-06	9.3
SP6.35_GRP25	1.686E-10	4.784		1.025E-05	10.2
SP6.35_LA25	1.809E-11	6.223		3.023E-05	30.1
SP4_WR	2.146E-07	2.920	7.0	6.2996E-05	100
SP4_CFR25	2.188E-10	5.724		1.5045E-05	23.9

6. Conclusions

Comparing the performances of the repairs used SP6.35, it is noticed that in the most favorable case, SP6.35-CFR30 (25 x 30 mm carbon fiber repair), where there was an increase of the fatigue life of around 14.5 times as much the value achieved for the one without repair (SP6.35-WR). In the worst situation, SP6.35-LA, simulating a doubler plate repair procedure, with the adhesive only on the repair extremity, there was an increase of 107% in fatigue life. Similar results were gotten for SP4.

These results corroborate that the bigger the contact area between the materials is, the bigger the redistribution of stresses around and ahead the crack tip is and, consequently, the lower K values is, which is responsible for the crack growth.

It is important to emphasize that, considering the tests carried out, the quality of the results achieved also came from the use of a structural adhesive made from epoxy (DP460), with characteristics peculiar to application in fatigue, with high resistance to shear stresses. From the analysis of fractured SP it was possible to verify that the debonding of the patch repair happened due to adhesive not cohesive failure, with no damage to the repair.

Another result observed, which deserves special attention, refers to the fact that it was possible to get a similar efficiency (increase of around 400% of fatigue life) for the same dimensions repairs (25 x 25 mm) and different materials (SP6.35-CFR25, 1.1 mm thick and SP6.35-GRP25, 1.8 mm thick) raising the material thickness with inferior mechanical properties. This is one more factor that must be considered when a repair is under design: it is possible to use other materials, mainly with lower prices, since the thickness of the repair to be used is evaluated. Obviously, the consequences of this procedure will lead to a price reduction of the repair, making it economically more attractive.

Completing the observation related to the cracks growth, the analysis of the growth rate in function of the stress gradient indicates, as it was expected, that the gain of the fatigue life is inversely proportional to the crack growth speed, which can easily be seen on the results obtained for SP6.35-CFR30, where the lowest speed (9% of the SP6.35-WR value) has determined the best performance of this repair (1400%). Similar behavior was achieved for the SP4.

From the study presented it is verified that the utilization of composite material patch repairs, bonded to the cracked specimen has showed to be efficient and promising in relation to the fatigue life increase.

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