The Effect of Thermal Residual Stresses on the Performances of Bonded Composite Repairs in Aircraft Structures

Rachid Mhamdia[1], B. Bachir Bouiadjra[1, 2], B. Serier[1], and M. Belhouari[1]
[1]LMPM, Department of Mechanical Engineering
University of Sidi Bel Abbes
Cité Ben M'hidi, Sidi Bel Abbes, Algeria

B. Bachir Bouiadjra[1, 2]
[2] Mechanical Engineering Department, College of Engineering
King Saud University, Riyadh, Saudi Arabia

Abstract

In this study the finite element method is used to analyse the effect of the thermal residual stresses resulting from adhesive curing on the performances of the bonded composite repair in aircraft structures. The stress-intensity factor at the crack tip is chosen as fracture criterion in order to estimate the repair performances. The obtained results show that the presence of the thermal residual stresses reduces considerably the repair performances and consequently decreases the fatigue life of cracked structures. The effects of the curing temperature, the adhesive properties and the plate thickness on the stress intensity factor (SIF) variation with thermal stresses are also analysed.

Keywords
Bonded composite repair, Thermal stresses, Stress intensity factor, Finite element method.

1. Introduction
Bonded composite repairs can be regarded as a versatile cost-effective method of repairing, strengthening or upgrading inadequate metallic structures. The reinforcements or patches are ideally implemented in situ, avoiding the need for costly disassembly of built-up structures. Currently there are several successful examples of bonded patch repair of thin metallic plates in aerospace structures, such as fuselage skins damaged by fatigue load. The success of these repairs is based on the many studies performed by several researchers over the last two decades [1-4]. The two main composite materials used in this area are boron/epoxy and graphite/epoxy composites. Beside, Kevlar composites are strong and stiff in tension but have relatively poor compression performance [1} . Among the principal criteria influencing the choice of patch materials is the level of the thermal residual stresses due to the adhesive curing. : If a repair (cured at elevated temperature) is likely to see extended service at low temperatures (for example a fuselage repair to a transport aircraft), the best choice may be either a conventional or laminated metallic material where the coefficient of thermal expansion is closer to that of the structure [2] . In this situation, graphite/epoxy repairs and to a lesser extent boron/epoxy repairs will result in higher levels of thermally induced residual stresses.
The process of adhesive bonding using high-strength structural adhesives generally requires curing the adhesive above the ambient temperature. During the first step of bonding, the plate is heated locally to a temperature Ti during the curing process. Due to this non-uniform temperature distribution, thermal stresses develop in the plate, which can be readily derived:

$$\sigma = -\frac{1}{2}\alpha.E\Delta T \qquad (1)$$

The above thermal initial stress is compressive. It should be noted that this thermal stresses arise only in the case of localised heating of a large structure; for the case of a finite size specimen being uniformly heated to Ti, no thermal stress will develop. This stress distribution serves as the initial stress that will be added to the thermal stress induced by cooling the patched region down to the ambient temperature. For the second step of adhesive bonding we assume

that there is no shear stress in the adhesive layer during curing, so that the reinforcing patch expands freely without developing any stresses. After the adhesive is fully cured, the patched plate is then cooled down to the ambient temperature [5].
For instance, in a typical repair applied to aircraft structures the reinforced region is initially heated to a temperature of 120 *°C***,** under pressure, for approximately one hour (the precise curing cycle depends on the adhesive being used). Upon cooling the fully cured, patched structure to the ambient temperature, thermal stress will inevitably develop in both the plate and the reinforcement, due to cooling a locally stiffened structure, especially when the reinforcing patch has a lower coefficient of thermal expansion than the plate being repaired. Thermal stresses may also arise when the patch structure experiences thermal cycling in service. Therefore, thermal residual stresses represent a major concern to the repair efficiency of a repair [1]. This is because the resulting thermal residual stresses post cure in the metal plate are inevitably tensile, owing to the increase in the stiffness of the patched region and the lower coefficient of thermal expansion of the composite patches. This tensile residual stress will increase the maximum stress-intensity factor of the crack after repair, hence may enhance fatigue crack growth rate. In this paragraph, the thermal residual stresses are computed in order to evaluate their intensities. Ii is noted that these thermal residual stresses are computed with linear approach.
It is known that the determination of fracture criteria such as stress intensity factor (SIF) or energy release rate at the crack tip can give a precise idea on the performance of the bonded composite repair. Several authors computed the stress intensity factor (SIF) at the crack tip of repaired cracks under mechanical loading among them: Jones and Chiu [6] Madani et al [7] Bachir Bouiadjra et al. [8-13], Achour et al. [14] Fekirini et al . [15] and Belhouari et al. [16] and Ouinas et al [17-20]. In this study, the effects of the thermal residual stresses on the variation of the stress intensity factor for repaired aluminium crack with Boron/epoxy and graphite epoxy patches are analysed using the finite element method. The effects of curing temperature, adhesive properties and the geometrical properties on the SIF variation under thermo- mechanical loading s are studied.

2. Geometrical and Finite Element Models

The basic geometry of the cracked structure considered in this study is shown in Figure 1. Consider a rectangular elastic aluminium plate with the following dimensions: height $H_{p.}$= 254 mm, width w_p = 254 mm, thickness e_p = 3 mm. The plate is subjected to uniaxial tensile load giving a remote stress state of σ= 1000 MPa. A central crack of length 2a perpendicular to the loading axis is supposed to exist in the plate. This crack is repaired with unidirectional Boron/Epoxy and Graphite/Epoxy composites patches. The ply orientation is parallel to the loading axis. The dimensions of the patch are : height h_r = 127 mm, width W_r= 127 mm and thickness e_r= 2 mm. The adhesive are used to bond the patch on cracked plate : FM73, Epoxy adhesive . The adhesive thickness (e_a) is taken equal to 0.15 mm. The elastic and the thermal properties of the plate, the patch and the adhesives are given in Table 1.
The analysis involved a three-dimensional finite element method by using a commercially available finite element code ABAQUS [21]. The finite element model consists of three subsections to model the cracked plate, the adhesive, and the composite patch. Due to symmetry, only one quarter of the repaired plate was considered. The plate had four layers of elements in the thickness direction, the adhesive had only one layer of elements through thickness and the patch had two layers of elements through thickness. To generate crack front some brick elements are replaced by « crack block ». This crack- block is meshes of brick elements, which are mapped into the original elements space and merged with surrounding mesh. Boundary conditions and loads are transferred to the crack-block elements. The mesh was refined near the crack tip area with an element dimension of 0.067 mm using at least fifteen such fine elements in the front and back of the crack tip. The finite element mesh was generated using brick elements with 20 nodes. The number of element used in this analysis is 49351 and number of degrees of freedom DOF is : 322016. Figure 2 shows the overall mesh of the specimen and mesh refinement in the crack tip region. The Stress intensity factor at the crack front was computed using the virtual crack closure technique (VCCT). This technique was originally proposed in 1977 by Rybicki and Kanninen [22] for bi-dimensional cases. The VCCT is a very attractive SIF extraction technique because of its good accuracy, a relatively easy algorithm of application capability to calculate SIF for all three fracture modes. Other authors [23] have extended the proposed technique. Currently, the three-dimensional virtual crack closure technique (3D VCCT) is often chosen as a tool for SIF calculations [24]. The VCCT is based on the energy balance proposed by Irwin. In this technique, SIF are obtained for three fracture modes from the equation:

$$G_i = \frac{K_i^2}{E} \qquad (2)$$

where *Gi* is the energy release rate for mode *i*, *Ki* the stress intensity factor for mode *i*, *E* the elastic modulus.

3. Results and Discussions

3.1 Effect of curing temperature

In this paragraph, the stress intensity factor is computed with and without presence of the thermal residual stress in order to estimate the effect of these stresses on the repair efficiency. A mechanical tensile loading of magnitude σ = 130 MPa is applied to the aluminium plate in addition with thermal loading due to the adhesive curing process. Figure 3 presents the variation of the SIF variation according to the crack length for two cases of heating: with heating (ΔT = 100 °C) and without heating (ΔT = 0°C), ΔT is the difference between the temperature of heating and the ambient one. The adhesive used for calculation is the FM73 and the thicknesses for the different materials are: plate (ep = 3 mm), patch (er = 2 mm) and adhesive (e_a = 0.2 mm). It can be seen according to Figure 3 that the presence of the residual thermal stresses (due to heating in the bonding process) has a considerable effect on the SIF variation at the crack tip. Indeed, the values of the SIF are highly increased by the thermal residual stresses generated from the cooling process. The relative variation is about 40%. During the cooling, the aluminium, which thermal coefficient of expansion is greater than that of the boron epoxy is subjected to tensile thermal stresses and the composite to compressive one. These stresses would translate into a positive mean stress intensity factor, promoting faster crack growth. Since composite patches generally have a lower thermal expansion coefficient than the metallic component to be repaired, thermal residual stresses would occur upon cooling the fully cured repair from elevated temperature (typically around 80-120 **°C** for structural adhesives) to either the ambient temperature or the operating temperature. In particular, the residual stresses in the metallic plate are generally positive, which may enhance fatigue crack growth rate due to increase of the stress ratio [1].

Figure 4 presents the variation of the SIF according to the difference of temperature ΔT for different plate thicknesses. The applied stress is maintained equal to 130 MPa. With this condition, the SIF is independent to the plate thickness without presence of the bonded composite repair. The results of this figure confirm those of figure 3, the Stress intensity factor increases as the curing temperature increases. Since composite patches generally have a lower thermal expansion coefficient than the metallic component to be repaired, thermal residual stresses would occur upon cooling the fully cured repair from elevated temperature (typically around 80-120 **°C** for structural adhesives) to either the ambient temperature or the operating temperature. In particular, the residual stresses in the metallic plate are generally positive, which may enhance fatigue crack growth rate due to increased stress ratio. According to the plate thickness, one can note that the effect of the curing temperature becomes more significant when the plate thickness decreases. The elevation of the stress intensity factor between T=20°C ((ΔT=0°C and T=100°C (ΔT=80°C)) is about 56% for e_p= 1 mm. This reduction is about 45% for ep=3 mm and 39% for e_p= 5 mm. This behaviour is because the thermal residual stresses due to the adhesive curing are highest when the plate thickness increases. The thermal dilatation of the plate is more significant for weakest plate thicknesses. In what follow and in order to estimate the effect of the thermal residual stresses on the repair performance the ratio R= K_m/K_{tm} is calculated, where K_m is the stress intensity factor under mechanical loading and K_{tm} is the stress intensity with thermo-mechanical loading. It is obvious that the increase of the ratio R proves a reduction of the effect of the thermal residual stresses on the repair performances.

3.2 Effect of the patch thickness

Several authors [14, 8, 10, 17] showed the importance of the effect of the patch thickness on the repair performance in damaged aircraft structures. Bachir Bouiadjra et al [8] showed that, under pur mechanical loading, the increase of the patch thickness with 50% decreases the stress intensity factor at the crack tip in the same order. They concluded that it is useful to use a patch with multiple layers for repairing aircraft structures. In this paragraph, the influence of the patch thickness on the ratio R is analysed. Figure 3 presents the variation of the ratio R according to the patch thickness for different composites. These composites are : Boron/epoxy, Carbon/Epoxy and Glass/Epoxy. The results of figure 3 show that the Boron/Epoxy give highest values of the ratio R It means that the effect of the thermal residual stresses can be reduced by the using the Boron/Epoxy as composite patch This behaviour can be explained by the fact that the Boron/Epoxy have lower coefficients of thermal expansion . The analysis of the results of figure 3 show that the ratio R increases when the patch thickness increases. The effect of the thermal residual stresses can be reduced by using thicker composite patch. This behaviour is due to the fact that thicker patch absorb more stresses from the repaired structure which attenuate the intensity of the thermal residual stresses in the repaired structure. On the other hand, in many researches [8,114,16], it is recommended to use double sided composite patch in order to double the stress absorption from the plate to the composite patch. However, this recommendation is not available for the reduction of the effect of the thermal residual stresses on the repair performances. Indeed, the use double sided composite patch double the intensity of the thermal residual stresses due to the adhesive curing. The heating of the double faces of the repaired plates leads to this increases of the thermal residual stresses.

3.3 Effect of the patch height

It is known that the patch area has not an important effect on the stress intensity factor variation for repaired cracks [12], but its effect on the adhesion is very important. Indeed, if the patch area increases the adhesion between the repaired plate and the composite patch becomes stronger. For rectangular patch, the patch area is characterised by the height and the width of the patch. The effects of these parameters (width and height) on the thermal residual stresses in bonded composite repair did not have important consideration in literature. In this paragraph, the effect of the patch height on the variation of the ratio R is analysed and from this analysis the effect patch width can be deduced. Figure 4 presents the variation of the ratio R according to the patch height. It can be seen that the ratio R increases when the patch height decreases. The increase in the patch height reduces significantly the effect of the thermal residual stresses on the repair performances. This is because higher patches do not permit a great disappearing of the thermal dilatation in the metallic plate, which involve higher tensile residual stresses in the repaired plate. These stresses provoke the increase of the thermo-mechanical stress intensity factor (K_{tm}) and consequently the reduction the ratio R. It is important to note that the patch height affect directly the thermal stress in the y direction (direction of the applied mechanical load). This effect concerns the mode I stress intensity factor (opening mode). Concerning the patch width, it affects the thermal stress in the x direction (perpendicular to the applied stresses). One can thus deduce, that the patch width does not have a significant effect on the mode I stress intensity factor and consequently its effect on the ratio R is also negligible.

3.4 Effect of the adhesive properties

The adhesive shear modulus is the mechanical property, which influences directly on the distribution of the shear stresses in the adhesive layer. Indeed, the shear stresses in the adhesive are related to its shear modulus by the relation:

$$\tau = \frac{G_a}{e_a}\left(u_1 - u_2\right) \qquad (3)$$

Where e_a is the adhesive thickness, u_1 and u_2 are the displacements in the dependent layers (the plate and the patch).
To illustrate the effect of this modulus on the ratio R, the variation of this ratio according to the adhesive shear modulus for various plate thicknesses is plotted in Figure 5. One can note that the ratio R decreases with the decrease of the adhesive shear modulus and exhibits an asymptotic behaviour when the adhesive shear modulus increases indefinitely. This means that effect of the thermal residual stresses on the repair performance is more significant when the adhesive rigidity increases. This behaviour can be explained by the fact that an adhesive with high rigidity allows more important transfer of stresses from the cracked plate to the composite patch, which increases the intensity of the thermal residual stresses in the repaired structures. However, a high rigidity of adhesive leads to significant shear stresses in the adhesive layer, which increases the risk of adhesive failure. One can thus confirm that the mechanical properties of the adhesive must be optimised.

4. Conclusion

Upon cooling the fully cured, patched structure to the ambient temperature, thermal stress will inevitably develop in both the plate and the reinforcement, due to cooling a locally stiffened structure, especially when the reinforcing patch has a lower coefficient of thermal expansion than the plate being repaired. This study was carried out in order to analyse numerically the efficiency of bonded composite repair in aircraft structures under thermo-mechanical loading. The computation of thermo-mechanical and mechanical stress intensity factors showed that thermal residual stresses due to the adhesive curing have a very significant effect on the stress intensity factor at the crack tip. This effect highly reduces the repair efficiency by reducing the fatigue life of the repaired structures. The analysis of the effects of different parameters on the SIF variation allows us to deduce that the effect of the thermal residual stresses can be minimised if the adhesive properties are optimised and if the patch height is reduced

References

[1] Baker A.A. Repair of cracked or defective metallic aircraft components with advanced fibre composites an overview of Australian work. Comput Struct 1984; 2: 153-81.
[2] Baker A.A., Chester R.J. Recent advances in bonded composite repair technology for metallic aircraft components. In: Advanced Composites 93. Chandra T, Dhingra AK, editors. Proceedings of the International Conference on Advanced Composite Materials, . 1993: 45-9.
[3] Jones R, Bridgford N, Wallace G, Molent L. 1991. Bonded repair of multi-site damage. In: Structural Integrity of Aging Airplanes. Atluri SN, Sampath SG, Tong P, editors: 199-212.

[4] Molent L, Jones R. Crack growth and repair of multi-site damage of fuselage lap joints. Engng Fract Mech 1993; 44: 627-37.

[5] Hossein H.T., Bijan M., Thermal residual stresses effects on fatigue crack growth of repaired panels bounded with various composite materials, Composite Structures 2009, 89: 216–223.

[6] Jones R, Chiu WK. Composite repairs to crack in metallic components. Compos Struct 1999; 44:17

[7] K. Madani , S. Touzain , X. Feaugas , M. Benguediab , M. Ratwani, Stress distribution in a 2024-T3 aluminum plate with a circular notch, repaired by a graphite/epoxy composite patch, Int j. adhesion and adhesive, 2009, 29, 225-233.

[8] Bachir Bouiadjra B, Belhouari M, Serier B. Computation of the stress intensity factor for repaired crack with bonded composite patch in mode I and mixed mode. Compos Struct 2002; 56: 401–6.

[9] B. Bachir Bouiadjra, T. Achour, M. Berrahou, D. Ouinas, X. Feaugas, Numerical estimation of the mass gain between double symmetric and single bonded composite repairs in aircraft structures, Materials & Design, 2010,31: 3073-3077.

[10] B. Bachir Bouiadjra, H. Fekirini, B. Serier, M. Benguediab, Numerical analysis of the beneficial effect of the double symmetric patch repair compared to single one in aircraft structures, Computational Materials Science, Volume 38, 2007, pp: 824-829.

[11] B. Bachir Bouiadjra, H. Fekirini, B. Serier, M. Belhouari and M. Benguediab, Energy Release Rate for Repaired Inclined Cracks with Bonded Composite Patch Having Two Adhesive Bands in Aircraft Structures, Journal of Reinforced Plastics and Composites, 27, 2008, 27:1135-1145.

[12] B. Bachir Bouiadjra, H. Fekirini, B. Serier, and M. Benguediab, SIF for Inclined Cracks Repaired with Double and Single Composite Patch, Mechanics of Advanced Materials and Structures, 2007; 14:303–308.

[13] B. Bachir Bouiadjra, H. Fekirini, M. Belhouari, B. Serier, B. Benguediab, and D. Ouinas, SIF for Double- and Single-sided Composite Repair in Mode I and Mixed Mode, Journal of reinforced plastics and composites, In prsess.

[14] Achour T, Bachir Bouiadjra B, Serier B. Numerical analysis of the performances of the bonded composite patch for reducing stress concentration and repairing cracks at notch. Comput Mater Sci, 2003;28:41–8.

[15] Fekirini, H.. Bachir Bouiadjra B., Belhouari M., Boutabout B., Serier B., Numerical analysis of the performances of bonded compositerepair with two adhesive bands in aircraft structures, Compos Struct, 2008; 82:84-89.

[16] Belhouari M, Bachir Bouiadjra B, Megueni M, Kaddouari K.Comparison of double and single bonded repairs to symmetric composite structures: a numerical analysis. Compos Struct, 2004; 65: 47–53.

[17] D. Ouinas, B. Bachir Bouiadjra, B. Achour, N. Benderdouche, Modelling of a cracked aluminium plate repaired with composite octagonal patch in mode I and mixed mode, Materials & Design, Volume 30, 2009, pp: 590-595.

[18] 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, Composites Part B: Engineering, 2009, 40: 804-810.

[19] D. Ouinas, B.B. 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, Composite Structures, 80: 514-522

[20] D. Ouinas, B. Serier, B.B. Bouiadjra, The effects of disbands on the pure mode II stress intensity factor of aluminium plate reinforced with bonded composite materials Computational Materials Science, 2007, 39: 782-787.

[21] ABAQUS/CAE Ver 6.9 User's Manual. Hibbitt, Karlsson &Sorensen, Inc; 2007

[22]. Rybicki., Kanninen E.F, A finite element calculation of stressintensity factors by a modified crack closure integral, Eng. Fract. Mech. 9 (1977) 931–938.

[23]. R. Krueger, The virtual crack closure technique: History, approach and applications. ICASE Report No. 2002-10, Hampton, VA, USA, 2002.

[24]. Leski A., Implementation of the virtual crack closure technique in engineering FE calculations, Finite Elements in Analysis and Design , (2007) , 43: 261 – 268.

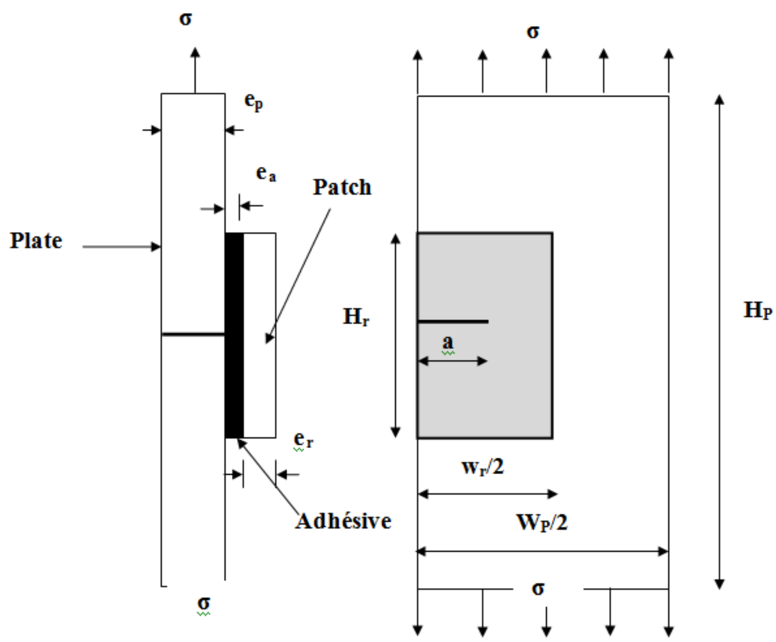

Figure .1 Geometrical model

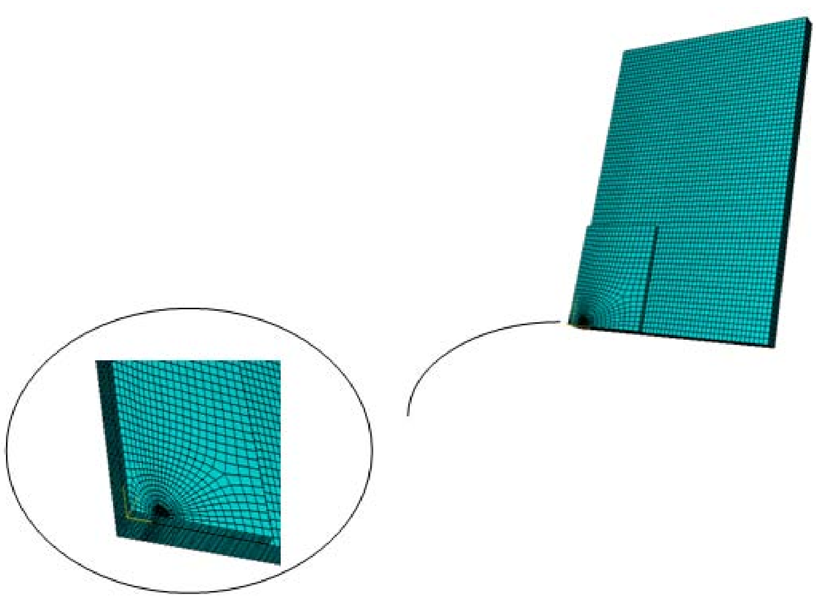

Figure.2 Typical mesh model of the quarter of the structure and near the crack tip

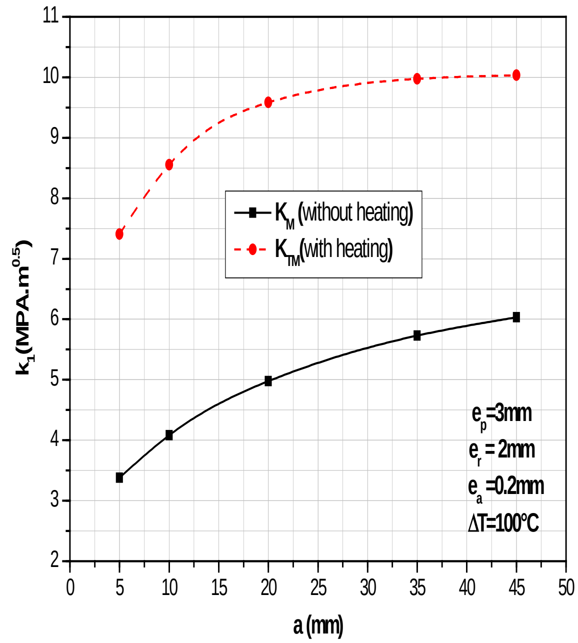

Figure 3: Variation of the stress intensity factor according to the crack length for the cases with and without heating

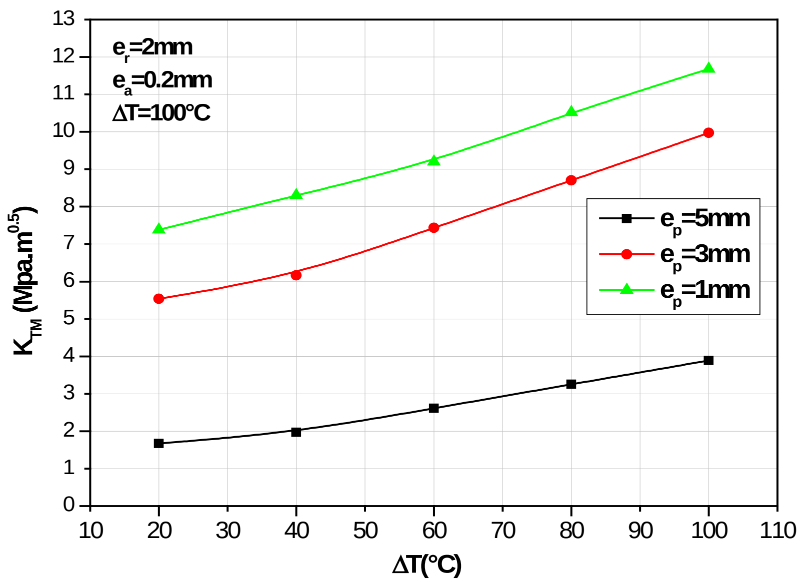

Figure 4: Variation of the thermal stress intensity factor according to ΔT for different plate thicknesses

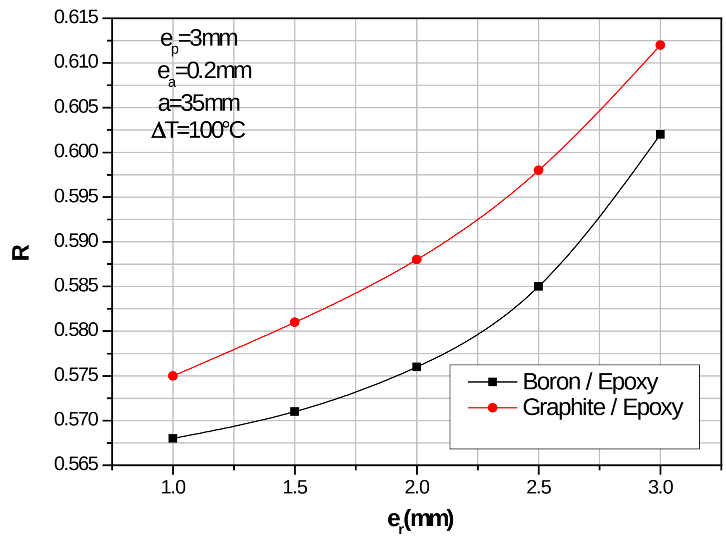

Figure 5: Variation of the ratio R according to the patch thickness for different composites

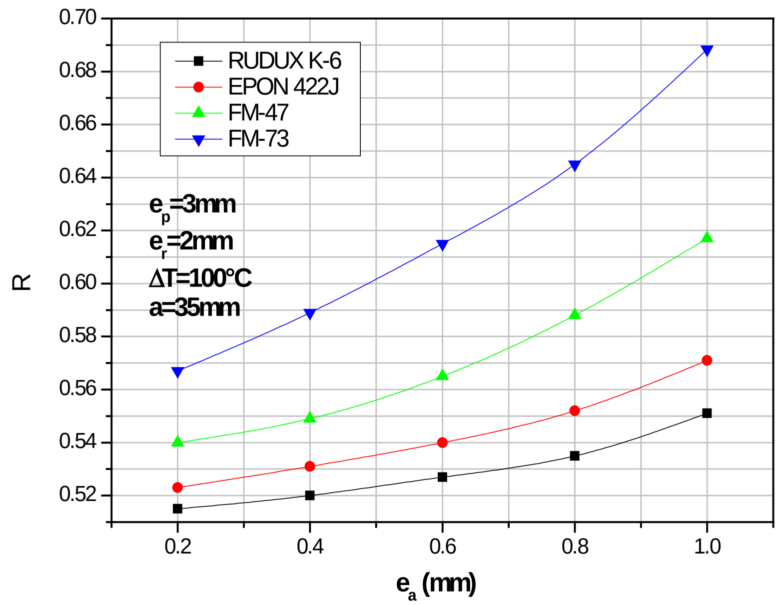

Figure 6: Variation of the thermal stress intensity factor according to ΔT for different Adhesive thicknesses

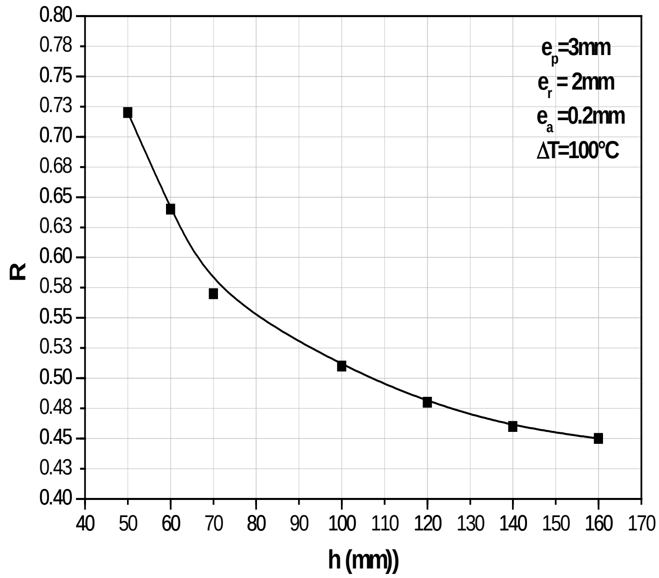

Figure 7: Variation of the ratio R according to the patch height

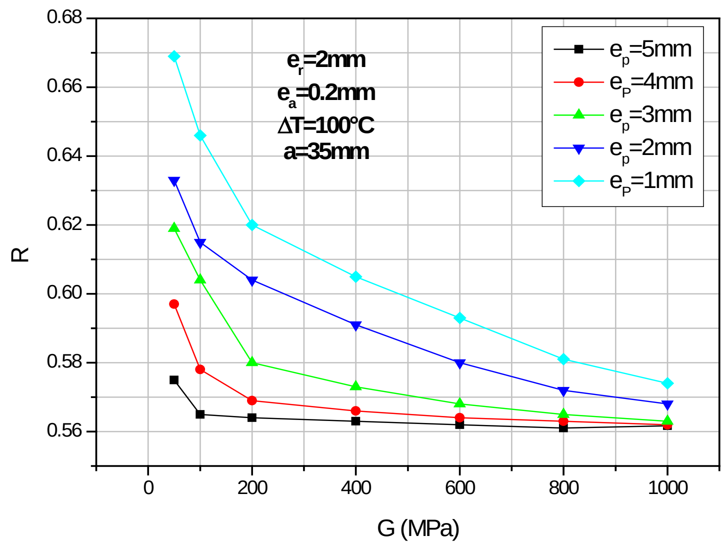

Figure 7: Variation of the ratio R according to the adhesive shear modulus for different plate thicknesses

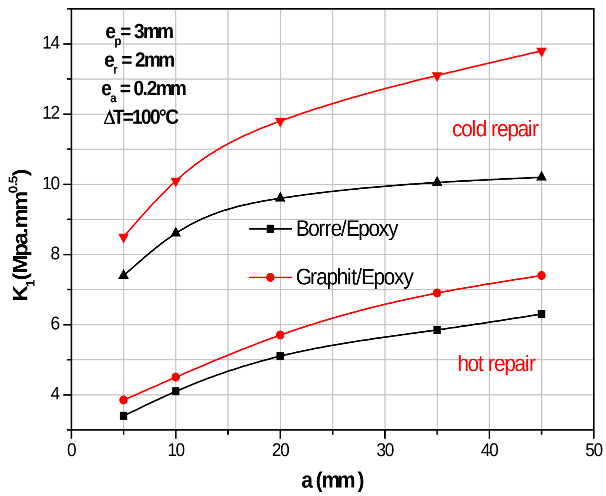

Figure 8: Variation of the stress intensity factor according to the nature of the patch with and without heating