Representativity of thermal stresses in designing composite joints based on singular stress states at multimaterial corners.

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Abstract: Using adhesives curing at temperature in bonded joints between dissimilar materials (composites and metals) gives rise to residual stresses due to the difference in the value of the thermal expansion coefficients of the adherents. The presence of multimaterial corners in these adhesive joints originates critical points where failure is likely to occur. Numerical results of several double-lap joints of aluminium to different carbon fibre laminates including the thermal stresses during curing are presented. The uniform temperature variation (from curing to room temperature) has been shown, numerically, to have a significant influence on the local stress field in the neighbourhood of these corners. Due to the fact that high stress gradients are developed at these corners in the curing process and stress relaxation effects may occur due to the viscoelastic behaviour of the polymeric adhesive at room temperature, experimental tests have also been carried out to study the influence of uniform temperature fields on the strength of these joints based on the parameters which define the singular stress state at these multimaterial corners. The experiments show that the thermal stresses during curing do not significantly alter the behaviour, type and load failures of the joint.

Keywords: thermal stresses, adhesive joint, stress singularity.

1. Introduction

The use of structural adhesives curing at temperature (higher than room temperature) for joining dissimilar materials (e.g. metals and composites) gives rise to residual thermal stresses associated to the geometry of the joint and the high difference in the values of thermal expansion coefficients of these materials, in conjunction with their lack of thermoelastic isotropy. The importance of these thermal residual stresses in adhesively bonded joints has been widely reported in the literature [1, 2]. A comprehensive analysis of the influence of these thermal effects on the efficiency of adhesively bonded lap joints was presented by Hart-Smith [3]. Thermal residual stresses increase with the curing temperature of the adhesive and also with the difference in the thermal expansion coefficient of the materials. If these values (adhesive curing temperature and the difference in the thermal expansion coefficients) are high enough, the joint may fail even before reaching room temperature [3].

Unlike the nominal stress state approach to failure by Hart-Smith, there are other alternative approaches to failure initiation in adhesive joints based on the local stress state in the neighbourhood of the multimaterial corners which typically appear in these joints [4-14]. In fact, there are experimental evidences, in particular geometrical and material combinations, showing that failure can be controlled by the parameters which define the singularity stress state at these corners [4,6-8,10].

In these previous works [4,6-8,10] the effect of residual stresses arising from the curing process was not included. It is well known that the thermal stresses in these multimaterial corners with singular stresses play an important role in the asymptotic stress state, see Yang and Munz [15], Lee [16] and Qian *et al.* [17] among others.

Nevertheless, the presence of high stress gradients, in combination with the known viscoelastic behaviour of polymeric adhesives, may lead (even at room temperature [18]), at least in the neighbourhood of these highly stressed corners, to an important stress relaxation, as pointed out by Lee [16], Qian *et al*. [17], Yadagiri [19] , Feldstein [20] or Atkinson and Bourne [21]. In particular, Yadagiri [19] predicts, numerically, a relaxation of 40% of the peak stress values developed at the ends of the overlap in the first few hours after the curing process. Feldstein [20] reports stress relaxations for polymeric adhesives within a time range of 800 s (<15 minutes) in a wide range of polymeric materials. Lee [16] obtained a relaxation effect of the edge stress intensity factor values and an increment of the order of stress singularities. Qian et al. [17] calculated also a relaxation effect (in the $\sigma_{\theta\theta}$ stress component) in an elastic/viscoelastic adhesive joint if the load is applied in the elastic material (the outer adherent), and not in the viscoelastic material (the inner adhesive). Atkinson and Bourne [21] computed numerically, from analytical expressions, the short and long term variation of singularity stresses in angular sectors of viscoelastic media. Kay et al [22] found significant relaxation effects in bimaterial joints considering the viscoelastic behaviour of the materials.

All these previous considerations on whether or not the thermal stresses play a role in the asymptotic stress field, at the multimaterial corners which have been shown to control the initiation of failure of these adhesively bonded joints, are the reason for the present work. Although it is well known that thermal residual stresses may have a long term effect, as observed in the permanent curvature of a 0/90 cross-ply laminate, part of the interest of the present work is focused on the local stress relaxation at these highly stressed corners.

Among the various complex processes affecting the generation of thermally induced residual stresses in polymer composites [23-28], in the present work the different thermal contraction values of the materials and the temperature dependent mechanical properties have been included in the numerical analyses. Thus, viscoelastic behaviour and volume shrinkage of the adhesive layer during isothermal curing have not been considered in the numerical evaluation but experiments have been conducted to see their effect.

The presence of singular stress states at multimaterial corners makes the Boundary Element Method [29] an efficient tool for a detailed analysis of problems of this kind [8, 16]. In the present paper, a BEM code by Graciani [30] has been used to study the influence of the residual thermal stresses in the asymptotic stress state at corners in Aluminium-CFRP double lap joints loaded in shear by tension. In Section 2, details of the BEM model and of the analysis carried out are presented, while numerical results with and without thermal effects are compared in Section 3 (3.1 for a Al-CFRP$[0]_8$ configuration and 3.2 for a Al-CFRP$[0_4/90_4]_s$ configuration). Section 4 describes the experimental tests carried out, including the analysis of the influence of uniform temperature fields on the strength of adhesive joints containing thermal residual stresses, and covering the study of the role of possible residual stress relaxation over time on the strength of the joints.

The final objective of the research work by the authors is the proposal of a failure criterion based on the generalized stress intensity factors at the corner tip. The aim of the present paper being only a previous analysis of the role of the thermal effects on the asymptotic stress and displacement fields at the neighbourhood of the corner tip.

The structure of the paper follows the chronological sequence of the research carried out: the experimental tests were performed to verify the numerical predictions.

2. Problem configuration and numerical BEM model

The problems under analysis are depicted in Fig. 1, in which, due to symmetry, only one half of the joints are considered.
Fig. 1a) A double-lap joint between an aluminium plate (3.2 mm thickness) and a unidirectional carbon fibre reinforced plastic, CFRP $[0]_8$ (1.6 mm thickness). The adhesive layer has a final thickness (after the curing cycle: 2 hours at 115ºC and 6 MPa) of 0.1 mm, measured, using optical microscopy, from a real adhesive joint. The average thickness per ply (for the AS4/8552 unidirectional tape supplied by Hexcel) is around 0.2 mm.
Fig. 1b) A lap joint between an aluminium plate (3.2 mm thickness) and a cross-ply laminate $[0_4/90_4]_s$ (1.6 mm total thickness). The thickness of the adhesive layer is 0.15 mm.
In Fig. 1 a and b, for the sake of clarity, the scales in the horizontal and vertical directions are not equal.

In the configuration of Fig. 1a) the right-hand side of the carbon laminate has been modelled as clamped while symmetry has been imposed in the configuration of Fig. 1b). A tensile stress of 125 MPa is applied at the left-hand side of the aluminium plates for both configurations. The resultant load of this tensile stress, for the complete specimen, is $F=\sigma_0\times A$=125MPa·(25×3.2 mm^2)=10^4 N, which is very close to the failure load obtained in the tensile testing of the samples (Fig. 1a).

A linear elastic analysis, assuming plane strain state, has been carried out using the Boundary Element Method (BEM) [29, 31]. A BEM software by Graciani [30] has been used, including the capability to consider uniform temperature effects in orthotropic materials. A 3D Finite Element analysis of the joint was additionally carried out to confirm the validity of the plane strain assumption (Barroso *et al.* [32]). In this study it was obtained that the 3D solution is almost coincident with the 2D plane strain solution in almost 97% of the width of the sample and only different at the free edges of the sample). Thus the 2D plane strain state assumption is considered to be valid for this problem.

The thermo-elastic properties for the carbon/epoxy unidirectional lamina (AS4/8552), modelled as for an orthotropic material, are: E_{11}=141.3 GPa, $E_{22}=E_{33}$=9.58 GPa, $G_{12}=G_{13}$=5.0 GPa, G_{23}=3.5 GPa, $\nu_{12}=\nu_{13}$=0.3, ν_{23}=0.32, α_1=-1·10^{-6} ºC^{-1}, $\alpha_2=\alpha_3$=26·10^{-6} ºC^{-1}, whereas the isotropic elastic properties of the epoxy adhesive (FM-73M.06) and aluminium (L3140)are, respectively, E=3.0 GPa, ν=0.35, α=45·10^{-6} ºC^{-1} and E=68.67 GPa, ν=0.33, α_1=24.5·10^{-6} ºC^{-1}.

Although during the cooling process the mechanical properties, mainly those associated to the adhesive and composite resin, are temperature-dependent, the final stress and displacement states at room temperature only depend on the final stiffnesses (at room temperature) and the mean value of the variation of the thermal expansion coefficient from the curing to room temperature [33-35]. In the particular case of the adhesive used in this work, the difference of the thermal expansion coefficient at room temperature and its mean value (over the range of temperatures from 115ºC to 25ºC) is less than a 10%. Results including the temperature dependent properties of the adhesive layer have also been computed, the relevant results being also below a 10% difference with the results computed using constant values at room temperature. Thus, the latter results (considering all the mechanical properties at room temperature) will be used in what follows.

3. Analysis of numerical results

Using a BEM code, the problem shown in Fig.1a) has been analyzed. In particular, the stress and displacement fields have been evaluated, including the thermal effects in the curing process. The corner under analysis is the corner between the 0º laminate and the adhesive layer and fillet, at the left-hand side of the overlap.

Both the mechanical loading (σ_0=125 MPa) and the thermal loading (ΔT=-90ºC, from the curing temperature 115ºC to the room temperature 25ºC) have been considered (Section 3.1), as well as other intermediate values of the temperature decrement (ΔT=-60ºC, ΔT=-45ºC, ΔT=0ºC). Displacements and stresses, from the linear elastic solution, have been evaluated at internal points located on a circumference with r=0.0194 mm from the corner tip, and separated 10º from each other.

In Section 3.2 the double-lap joint Al-CFRP$[0_4/90_4]_s$ (Fig. 1b) has also been analyzed. In this case a different multimaterial corner configuration appears at the end of the laminate, where three laminas with different fibre orientation meet the adhesive fillet. Internal points around the two corners (corners 1 and 2 in Fig. 5) at r=0.04 mm have been used to compare the stress state with and without thermal effects. Although it is well known that there is a radial dependency of the stresses and displacements, in Barroso [7-8] it was shown that in the range 10μm<r<33μm no significant changes appear in the qualitative stress and displacement distributions along the circumferential coordinate and the failure path was in good agreement with the experimental evidences.

3.1. Al-CFRP$[0]_8$ under mechanical and thermal loading

The BEM model includes three materials (aluminium, adhesive and the CFRP laminate) and perfect adhesion is considered along the common boundaries. Symmetry conditions are applied at the bottom side of the aluminium plate, while clamped conditions (u_α=0, α=1,2) and uniform tensile stress are respectively applied at right and left ends of the joint, as shown in Fig. 1a). The model has 1364 linear elements and for an accurate evaluation of the stress field at the neighbourhood of the CFRP-Adhesive corner, a progressive refinement towards the corners has been carried out with a final element length of 10^{-6} mm at the corner tip. This size, out of physical meaning, is required to achieve satisfactory results in presence of a singular stress field and avoid the typical numerical errors associated to the discretization to appear at the characteristic distance of interest (r~0.02 mm). None result is obtained at such small distance (10^{-6} mm). A detail of the BEM model of the overlap zone is shown in Fig. 2.

Taking into account both the mechanical (σ_0=125 MPa) and thermal loading, displacements (u_r, u_θ) and stresses (σ_r, σ_θ, $\sigma_{r\theta}$) have been evaluated around the corner notch at a distance of r=0.0194 mm from the corner tip.

Displacements (u_r, u_θ) around the corner, at r=0.0194 mm, are shown in Fig. 3 for the four cases. From Fig. 3 almost the completely opposite behaviour can be observed between the cases with only mechanical loading and the actual case with ΔT=-90ºC plus mechanical loading. The cases with mechanical and intermediate temperature decrements ΔT=-60ºC and ΔT=-45ºC give rise to intermediate results. Previous experimental experience, by the same authors, in the failure analysis of specimens of this type, see [7-8], has demonstrated that the local stress field is influencing the failure of these specimens, thus, figures 3, 4 and 6, show the elastic variables (stresses and displacements) at the close neighbourhood of the corner tip.

The three components of the stresses (σ_θ, σ_r, $\sigma_{r\theta}$) around the corner at r=0.0194 mm are shown, for the same four cases considered above, in Fig. 4.

The angular behaviour of the stresses is, as in the case of the displacements, roughly opposite depending on whether or not the thermal effect of ΔT=-90ºC is included. For the intermediate cases ΔT=-60ºC and ΔT=-45ºC it is important to observe that the computed stresses around the corner are very low (in absolute values) if compared with the cases with ΔT=0ºC, which would correspond to an adhesive curing at room temperature, and ΔT=-90ºC which corresponds to the real case. This fact opens up a future line of work in which the effects of the thermal effects during curing may be used to compensate mechanical stresses caused by nominal loads. All this in the context clearly clarified in the introduction, that the unique source of residual stresses considered in this paper is the thermal stress.

If the stress field in the neighbourhood of the corner is controlling the initiation of failure, as suggested by [7,10-14], the results shown in Fig. 4 would imply, for instance, a higher static strength, or fatigue life, in adhesively bonded double-lap joints under the configuration analyzed between aluminium and CFRP 0º laminates with adhesives curing at temperatures between 70ºC and 85ºC (which correspond to cooling stages of ΔT=-45ºC and ΔT=-60ºC respectively). All this assuming that the initiation of failure is controlled by the asymptotic linear elastic solution. The previous comments would be questionable in presence, for instance, of gross yielding zones [36-38].

3.2. Al-CFRP[$0_4/90_4$]$_s$ under mechanical and mechanical + uniform thermal loading

When more complex laminates are involved, other corner configurations appear in the adhesive joints where failure can initiate as well. As an example, a double-lap joint between Aluminium and a CFRP[$0_4/90_4$]$_s$ laminate has been analyzed (Fig. 1b). In this configuration three-material corners appear at the end of the laminate, where two laminas with different fibre orientation (0º and 90º) are bonded to the adhesive fillet.

The same material properties are used in this analysis, and only the extreme cases with ΔT=0ºC and ΔT=-90ºC are presented for the sake of brevity. The details of the left side of the overlap zone are shown in Fig. 5 for the two cases considered. In both cases (figure 5a and b) magnification factors of ×100 and ×25, respectively, have been used in the deformed shape geometries. The three multimaterial corners appearing at the end of the laminate are shown in the deformed shape corresponding to mechanical loading and mechanical plus thermal loading (corner 1: the same bimaterial corner as in the previous case in Section 3.1, corner 2 and 3 are three-material corners with laminas of 0º and 90º in contact with the adhesive fillet).

A completely different local deformed configuration can be observed in Fig. 5 corresponding to the two cases studied. The influence of the thermal stresses on the asymptotic stress field can be clearly observed in the results shown in Fig. 6, where $\sigma_{\theta\theta}$ is evaluated at a distance of r=0.04 mm from the corner tip 1 (Fig. 6 a) and 2 (Fig. 6 b).

As in the previous case, with the 0º laminate (Section 3.1), the presence of the uniform thermal loading (ΔT=-90ºC) in addition to the mechanical loading, makes the $\sigma_{\theta\theta}$ stress component at corner 1 to be completely different, in fact approximately opposite, from the $\sigma_{\theta\theta}$ distribution without temperature, as shown in Fig. 6 (a). Also, as in the previous case see Fig. 4, intermediate temperature values would imply, in general, lower absolute values of $\sigma_{\theta\theta}$ in almost all angular values.

In the three-material corner 2, Fig. 5, placed between the 0º and 90º layers and the adhesive fillet, the incorporation of the thermal loading (ΔT=-90ºC) has also an important influence on the $\sigma_{\theta\theta}$ stress distribution, which is shown in Fig. 6 (b) for the adhesive zone (90º<θ<270), θ being measured from the interface between the 0º and 90º layers, as indicated in the figure.

Corner 3 is locally equal to corner 2 (90º sector of 0º layer, 90º sector of 90º layer and 180º sector of adhesive). No particular failure mode involving this corner was observed experimentally in [6-8]. Thus no different results, from those already mentioned for corner 2, can be added.

4. Experimental results

The numerical results obtained in Section 3, have shown the significant influence of the thermal stresses in joints of this kind, changing completely the predicted local stress (and displacement) distribution depending on whether or not, the thermal effects during the cooling stage of the curing cycle are taken into account.

As mentioned in the introduction, previous experimental results [7] show that failure paths in the configuration analyzed in Section 3.1 are properly predicted considering only the mechanical loading and the maximum circumferential stress criterion, without taking into account the thermal loading. The satisfactory agreement between experimental and numerical results in [7] prompts the question of whether the local residual stresses due to temperature (obtained numerically) really were present in the joint at the time the tests were carried out or, on the contrary, they progressively relax and disappear with time, as pointed out by [16,17,19-21]. For this reason, and in order to further investigate the presence or not of these local residual stress fields, two different experiments have been carried out using the configuration described in Section 3.1. The first one consists of double-lap joints subjected to shear by tension at different temperatures, and the second one has the same configuration but is tested at different times from the end of the curing cycle. Both experiments are detailed in Sections 4.1 and 4.2 respectively.

All the specimens for both tests were manufactured by bonding the composite laminate with the aluminium plate in a hot plate press, the curing cycle recommended by the manufacturer of the adhesive was used in the bonding process (90 minutes at 115ºC and 0.28 MPa). For each type of test (Section 4.1 and 4.2), all the specimens were obtained from a single batch of samples to reduce uncertainty associated to the curing process.

4.1. Double-lap joints at different temperatures

The results in Fig. 4, showing completely different stress distributions for all stress components depending on whether or not the ΔT=-90ºC is considered, suggest that, if failure is controlled by the stress state at the neighbourhood of the corner, failure initiation in these joints, using adhesives curing at lower temperatures, would occur at higher mechanical load values. In Fig. 4, the mechanical load is the same for all values of ΔT. Thus, failure should occur at a higher value of the applied mechanical loading for adhesives curing at ΔT=-60ºC or ΔT=-45ºC than that observed for the configuration with ΔT=-90ºC, if the same value of any of the stress components is to be obtained at failure. In any case the failure mechanism, including the thermal loading, may vary from that obtained without thermal loading due to the fact that the stress state is different.

Curing the joints at a different temperature than the one recommended by the manufacturer can greatly affect the mechanical properties of the adhesive. For this reason, a different strategy has been used, as the simplest approach, to try to observe the influence of different curing temperatures on the residual stress field developed at the joint, which may be considered as an alternative to analyze this effect. The samples bonded with the adhesive curing at T=115ºC tested at a temperature T_0, higher than room temperature, could be considered to have a similar stress state to that developed with an adhesive curing with ΔT=-(115-T_0)ºC. In particular, testing at T_0=65ºC, which is 40ºC over room temperature, would be similar to having an adhesive curing with a cooling jump of ΔT=-50ºC, 40ºC lower than the reference value of ΔT=-90ºC. The previous arguments are only a rough approximation of both situations, as the mechanical properties of the adhesive change at T=65ºC, although this is only 40ºC above room temperature, but they can help in a preliminary attempt to analyze the influence of the temperature on the residual stress field.

The suggested tests have been carried out from room temperature, 25ºC, to 65ºC, at intervals of 10ºC, using two samples at each temperature level. The tests were done after letting the samples stabilize at the test temperature (~25 minutes). The temperature was monitored by means of a thermocouple located close dto the centre of the specimen. For each pair of samples to be tested at the same temperature, the procedure was the same; while the first specimen was being tested, the second was inside the oven at the prescribed temperature to avid a temperature change. The time between the first and second test at each temperature level was only one or two minutes. The results for all the tests are shown in Fig. 7, where the apparent shear strength (the failure load divided by the bonding area $\tau = F_{\max}/(2bh)$ where F_{max} is the failure load and b and h are the width and length of the overlap area) is plotted versus the temperature in the test chamber.

Results in Fig. 7 show a decrement of the apparent shear strength with temperature. In the range 25ºC<T<45ºC the shear strength obtained in the tensile tests is quite constant and then decreases for T≥55ºC. No increment of the failure load is observed even for moderate temperatures, where adhesive mechanical properties are expected not to change significantly. In fact, it seems that due to the drop in the adhesive mechanical properties with temperature (although ΔT is moderate with respect to room temperature), the apparent shear strength also decreases.

Pictures of the failure path were taken after failure. Figure 8 shows the failure details of the adhesive fillet at the end of the overlap (magnification ×50) for tests carried out at T=25ºC, 55ºC and 65ºC respectively.

Failure path orientation was observed to be quite similar in the three samples, showing failure angles in the range 32º<θ<36º, measured from the vertical adhesive-composite interface. Results in Fig. 8 show a significant independency of the failure path orientation with respect to the test temperature, in contrast with the numerical results obtained in Fig. 4.

4.2. Double-lap joints at different times (stress relaxation)

The residual stresses developed in the adhesive layer during the cooling stage of the curing cycle could decrease over time due to stress relaxation effects, as pointed out in the introduction [16-21]. This relaxation effect is more intensive at highly stressed areas such as those considered in this work with singularity stress fields. In such a case, the discrepancies observed between the experimental [7] and numerical predictions obtained in this work would be justified, as the tests carried out in [7] were done several weeks after curing the samples, and the residual stresses due to the bonding process could therefore be less significant.

For this reason a new experiment was also conducted curing 24 identical samples of the double-lap joint, shown in Fig. 1a and analyzed in Section 3.1. The samples were tested at different times from the end of the bonding process. The first test was performed only 15 minutes after the bonding was done, the minimum time required to prepare the sample, which is above the relaxation time reported by Feldstein [20] for stress relaxation. The second pair of tests were done one hour after the first one, and then each pair of tests were separated from the previous ones by a factor of 2.2^n (n=1, 2, 3, ...) with a final time schedule (in hours) of: (1, 3.2=1+2.2, 8=3.2+2.2^2, 18.7=8+2.2^3...). This allows tests to be carried out from 15 minutes to 203 days (≈ 7 months), equally spaced in time, in a logarithmic scale in the time axis (see Fig. 9). The samples were stored at 23±3ºC and 50±10%RH. Each test was done using two samples, thus producing 12 pairs of results. Each pair of samples was tested with a delay of just one or two minutes between each specimen, the typical testing time to failure. A picture of some of the tested specimens, and the complete data for the 24 samples, is shown in Fig.9, including the apparent shear strength obtained from the tests.

The results shown in Fig. 9 do not show a clear variation, or trend, in the apparent shear strength over time. In fact the average value for the 24 tests is 19.3 MPa, with a standard deviation of 2.6 MPa (a variation coefficient of 13.3 %) which is a usual deviation value reported for this type of test (see for example ASTM D3528 [39]).

The fact that the geometry of the samples has a relatively short overlap length (12.5 mm) makes the whole overlap area highly stressed, and the relaxation effects may possibly affect not only the edge zones of the overlap but also the central part. Double-lap joints with a higher "overlap_length to thickness" ratio would have the central part of the overlap much less loaded than the one analyzed and tested in the present work.

5. Conclusions

Previous experimental results on composite-to-metal adhesively bonded double-lap joints have shown that the local stress field at the multimaterial corners at the ends of the overlap may play an important role in the prediction of failure initiation [6-8]. These previous studies did not include the residual stress field which appears in the curing cycle due to the difference in the thermal expansion coefficients of the materials. The importance, for design, of this residual stress field is widely reported in the literature.

To analyze the influence of these thermal stresses between dissimilar materials (Al-CFRP double lap joints) on the asymptotic stress state in the neighbourhood of multimaterial corners (involving isotropic and orthotropic materials) detailed numerical analyses have been performed, including examples of adhesively bonded double-lap joints (Al-CFRP$[0]_8$) and (Al-CFRP$[0_4/90_4]_s$). The attention in these numerical analyses has been focused on the residual stress field in the neighbourhood of the multimaterial corners, which are potential points for failure initiation. Assuming the presence of significant thermal stresses during curing, it has been proved in this work that they might have a great influence on the nominal local stress state at these corners, changing completely (qualitatively) the stress distribution, and in fact reaching approximately the opposite distribution of the stresses around the corner. For the two configurations which have been analyzed, it has been observed, numerically, that locally (close to the corner), the temperature effect generates a stress field which tends to compensate (almost the same angular shape functions, with opposite sign) the stresses generated by the mechanical loading. This fact might imply the re-evaluation of the numerical and experimental agreement observed in the previous works mentioned [6-8].

However, many researchers have reported relaxation effects on the stress state of polymeric materials (due to their viscoelastic behaviour, even at room temperature) mainly at highly stressed areas. Thus, the satisfactory agreement observed in [7] between numerical and experimental results without incorporating the thermal stresses, raises the question of whether these thermal stresses really affect the local stress field at the multimaterial corner or, on the contrary, they do not play any significant role due to relaxation effects.

For this reason two preliminary experimental tests have been carried out in the present work, the first one testing the adhesive joints at different temperatures (moderate temperatures over room temperature), which can be assumed to simulate adhesives curing at temperatures lower than the real curing temperature. Adhesives curing at lower temperatures have been shown in the numerical analyses carried out in this work to develop lower residual stresses, which could influence initiation of failure. The second one tests the adhesive joints at room temperature but at different times from the end of the bonding process, to try to see if there is any stress relaxation effect over time, especially at highly stressed areas.

Assuming that the local singularity stress field is controlling failure initiation in joints of this type, none test has shown a significant influence of the thermal stresses during curing on the failure load. Thus, the numerical results together with the experimental evidences seem to indicate that for prediction of failure initiation, based on the singularity stress field at the multimaterial corners, the evaluation of the parameters which define the asymptotic singularity stress field can be computed without including the thermal stresses during curing.

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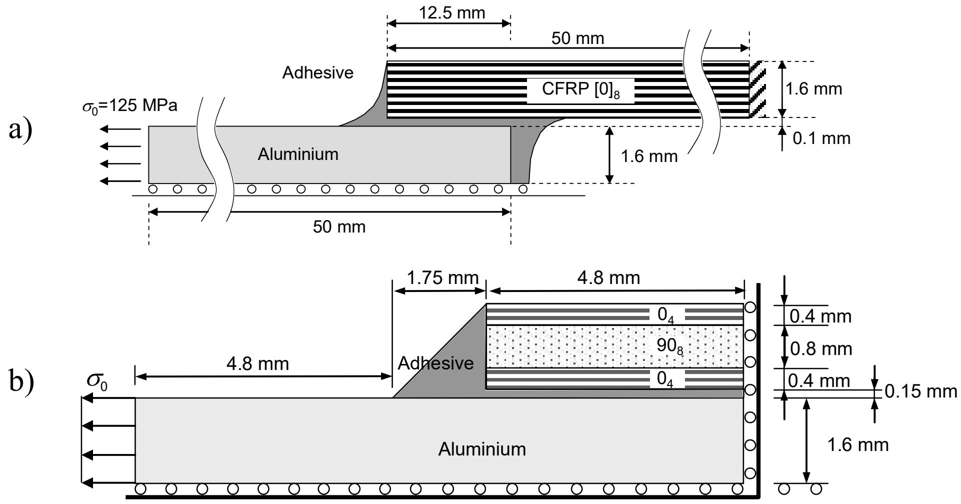


Fig. 1. Schemes of a) Al-CFRP $[0]_8$ double lap joint and b) Al-CFRP$[0_4/90_4]_s$.

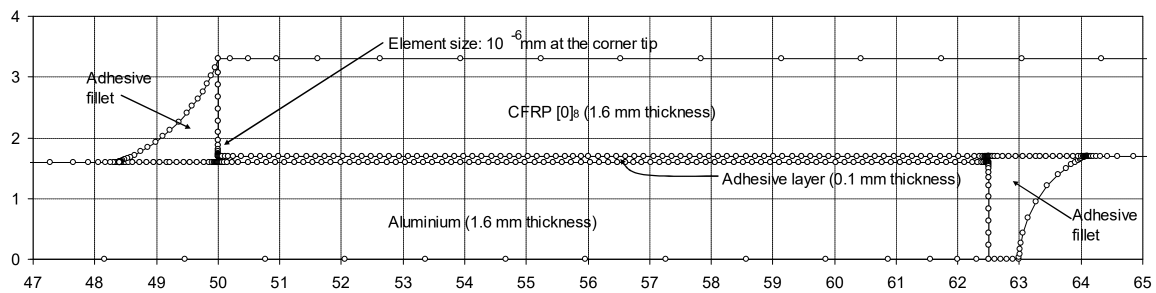
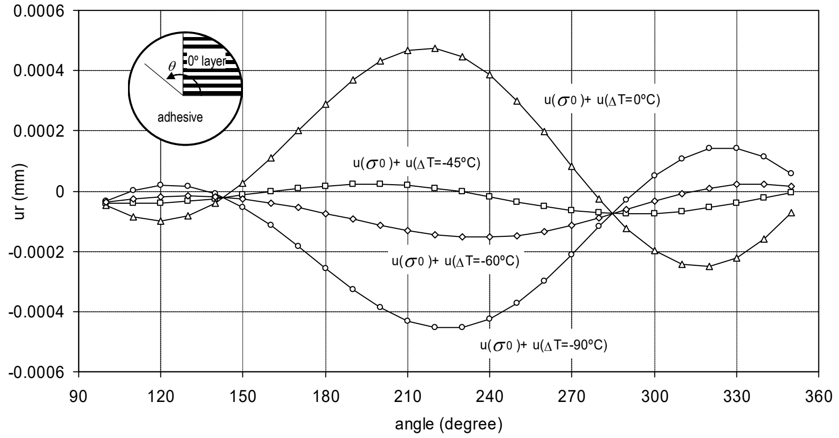


Fig. 2. BEM model, detail of the overlap zone.

a)



b)

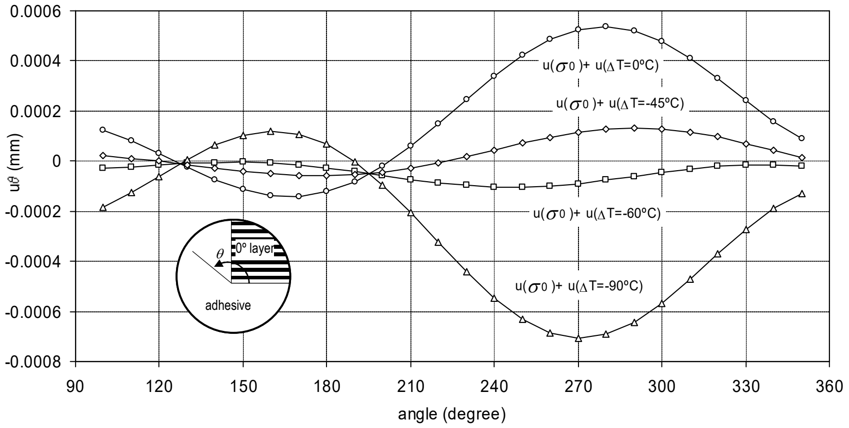


Fig. 3. Displacements inside the adhesive u_r (a) and u_θ (b) at r=0.0194 mm under mechanical and different thermal loadings.

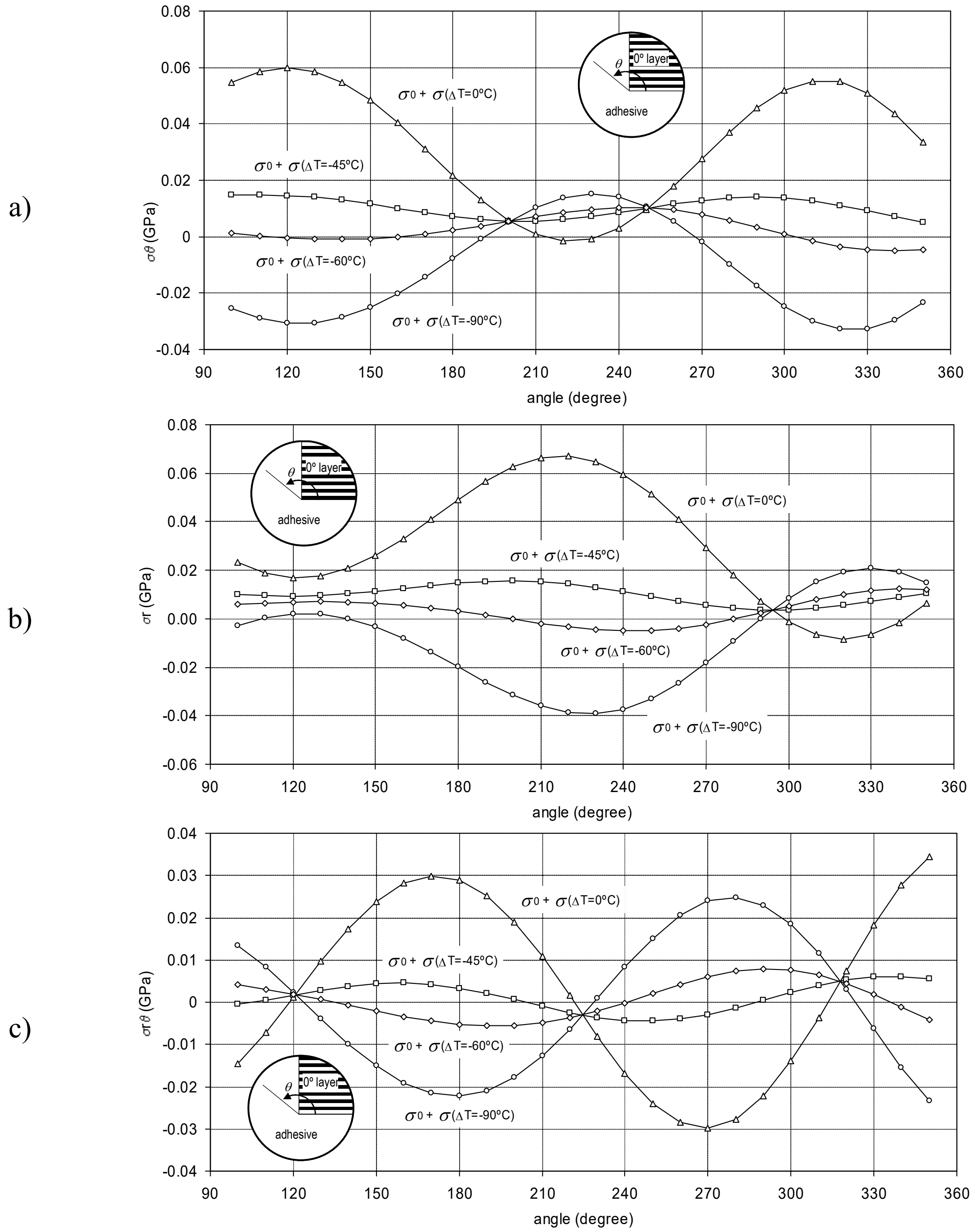
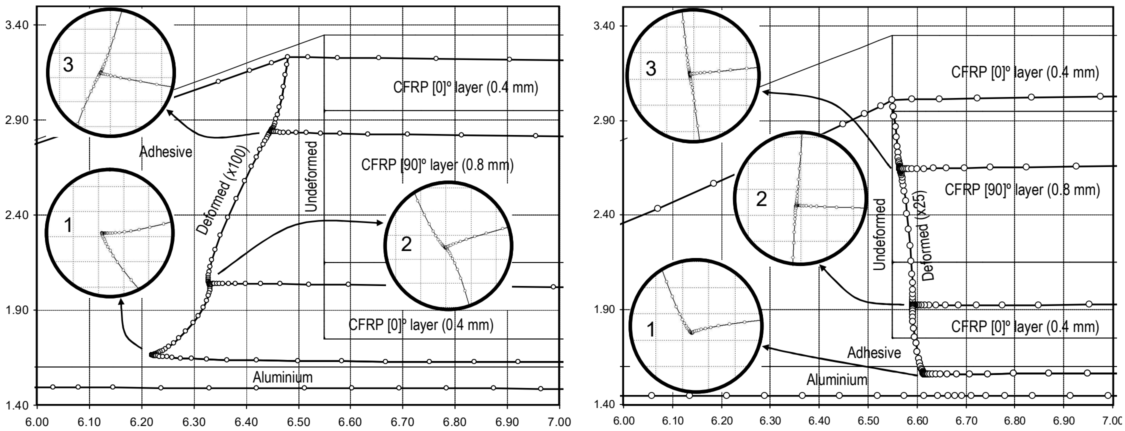


Fig. 4. Stresses inside the adhesive, (a) σ_θ, (b) σ_r and (c) $\sigma_{r\theta}$ at r=0.0194 mm under mechanical and different thermal loadings.



a) Mechanical and ΔT=0ºC b) Mechanical and ΔT=-90ºC

Fig. 5. Detail of the BEM models of Al-CFRP[0_4/90_4]$_s$ under (a) mechanical, (b) mechanical plus thermal loading ΔT=-90ºC.

a)

b)

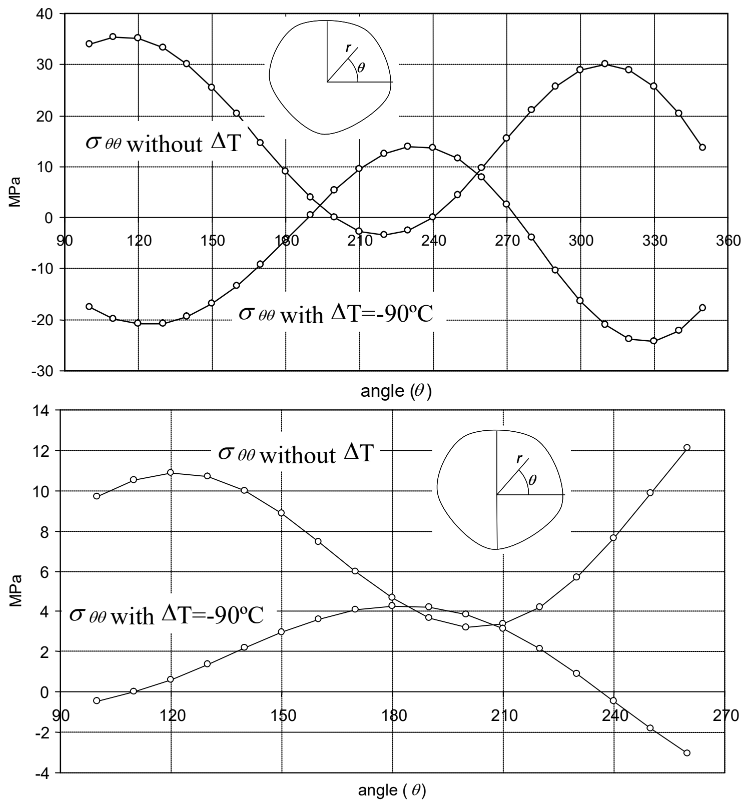
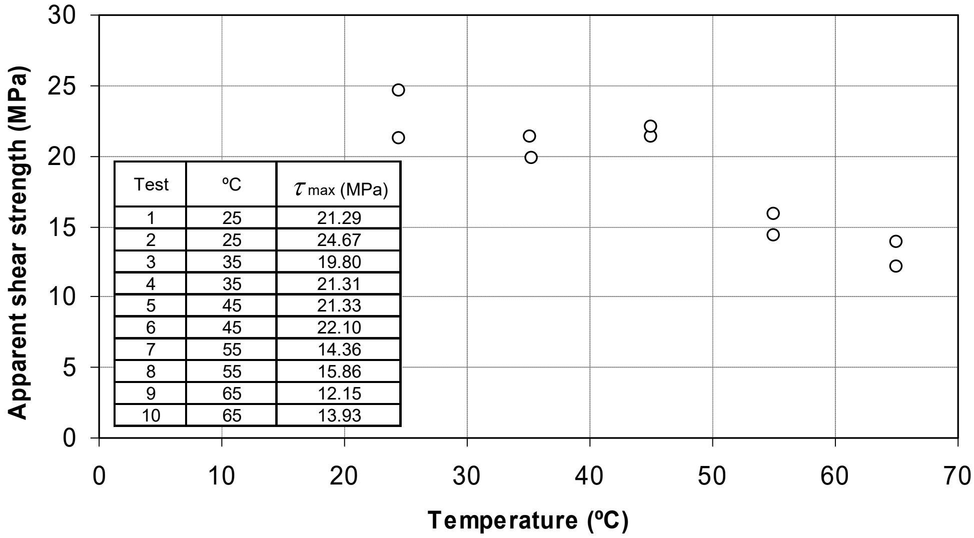


Fig. 6. $\sigma_{\theta\theta}$ inside the adhesive in corners 1 (a) and 2 (b) with and without thermal effects.



Test	ºC	τ_{max} (MPa)
1	25	21.29
2	25	24.67
3	35	19.80
4	35	21.31
5	45	21.33
6	45	22.10
7	55	14.36
8	55	15.86
9	65	12.15
10	65	13.93

Fig. 7. Apparent shear strength at different temperatures.

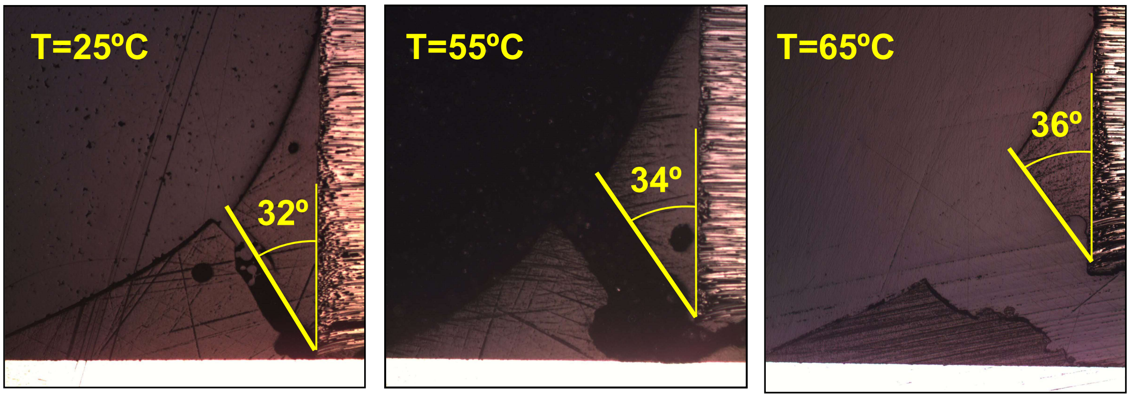
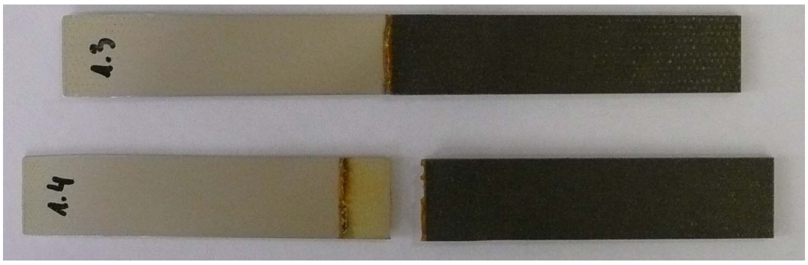
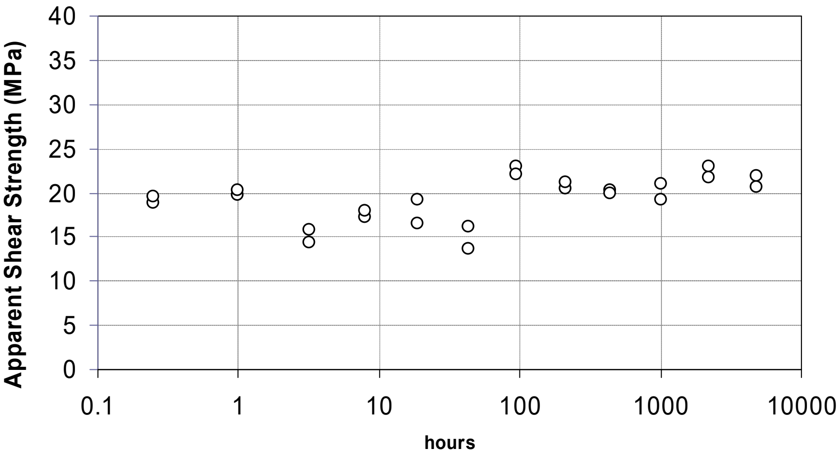


Fig. 8. Failure path orientations for specimens tested at 25ºC, 55ºC and 65ºC.





test	days		hours
1	0	+	0.0
2	0	+	1.0
3	0	+	3.2
4	0	+	8.0
5	1	+	18.7
6	2	+	18.1
7	4	+	21.6
8	9	+	15.0
9	19	+	0.5
10	42	+	21.2
11	92	+	4.5
12	203	+	20.5

Fig. 9. Tested specimens and apparent shear strength at different times.