Experimental study of thermal stresses in a bonded joint

A. Deheeger\textsuperscript{a,}\textsuperscript{*}, C. Badulescu\textsuperscript{a}, J.D. Mathias\textsuperscript{b}, M. Grédiac\textsuperscript{a}

\textsuperscript{a}Laboratoire de Mécanique et Ingénieries, Institut Français de Mécanique Avancée-Université Blaise Pascal Clermont II, Campus des Cézeaux, BP 265, 63175 Aubière Cedex, France

\textsuperscript{b}Laboratoire d'Ingénierie pour les Systèmes Complexes, CEMAGREF, Campus des Cézeaux, 24 avenue des Landais - BP 50085, 63172 Aubière Cedex, France

antoine.deheeger@ifma.fr

Abstract. This paper deals with the assessment of the thermal stress distribution in a composite/aluminium bonded joint. An aluminum specimen symmetrically reinforced with two composite patches is heated while both thermal and displacement fields are measured with an infrared camera and a CCD camera, respectively. The grid method is used to obtain the displacement fields in the composite patch. This displacement field is in good agreement with theoretical expectations. This enables us to deduce the longitudinal strain in the composite patch by fitting the displacement field with a suitable model and differentiating it. The shear stress peak which takes place in the adhesive near the free edge of the patch is finally estimated.

1. Introduction

Composite patches are often used to reinforce damaged aeronautical structures. Such structures are subjected to temperature changes which may cause a thermal stress distribution to appear in the bonded joint between composite and metallic substrate. This phenomenon is due to the difference of Coefficient of Thermal Expansion (CTE) between the two adherends.

The aim of this work is to perform full-field measurements in order to characterize the effect of a temperature change in a metal/composite specimen and to deduce the resulting shear stress distribution in the bonded joint. The patched specimen under study is heated. The temperature change is measured on one side of the specimen with an infrared camera and the displacement distribution is obtained on the other side using a CCD camera and a relevant image processing [1] [2]. It is possible to deduce the thermal shear stress distribution in the adhesive using these two types of measurement if they are processed with a suitable model [3] and if the specimen is assumed to be symmetric with respect to its mid-plane.

The experimental set-up is presented below. The first results obtained are discussed and the effect of temperature changes on the displacement/strain fields is experimentally evidenced.
2. Experimental set-up

2.1. Introduction
The aim of this test is to measure both the thermal and the displacement fields during the same experiment. For this purpose, a CCD camera and an infrared camera are placed in front of each side of the specimen to measure the displacement and temperature fields, respectively (see Figure 1).

2.2. Specimen
The specimen is made of 2024T3 aluminum. Its length, width and thickness are 340 mm, 70 mm and 3 mm, respectively. Aluminum is supposed to be linear isotropic elastic ($E_s = 73.8 \text{ GPa}$, $\nu_s = 0.33$, $\alpha_s = 23.6 \times 10^{-6} \text{ K}^{-1}$). Composite patches are bonded on each side of the specimen. Their length, width and thickness are 70 mm, 70 mm and 0.5 mm, respectively. The composite is assumed to be orthotropic and elastic ($E_x = 181 \text{ GPa}$, $E_y = 10.3 \text{ GPa}$, $\nu_{xy} = 0.28$, $G_{xy} = 7 \text{ GPa}$, $\alpha_x = 0.02 \times 10^{-6} \text{ K}^{-1}$, $\alpha_y = 22.5 \times 10^{-6} \text{ K}^{-1}$). The adhesive used is the Redux 312 supplied by Hexcel. It is assumed to be thermoelastic. Its shear modulus depends on the temperature, as shown in Figure 2 where the real part of the shear modulus $G'$ measured with a suitable rheometer is shown. The thickness of each of the two adhesive layers is 0.15 mm. The composite patches are not tapered near the free edges. This enables us to compare the results observed with some simple analytical models [3] [4].

![Figure 1 - Experimental set-up.](image1)

![Figure 2 - Evolution of the shear modulus $G'$ of the Redux 312 versus temperature.](image2)
2.3. Measurement of the displacement/strain field
The grid method is used to obtain the displacement field on the surface of the patch. This method has been developed by Surrel [2]. It is based on the analysis of the deformation of a grid bonded on the surface of the specimen prior to testing [5]. A camera captures the light intensities on the surface before and after loading. Images are processed by means of an appropriate algorithm [1] [2], which detects very slight variations of the grid pitch caused by the surface deformation. This algorithm calculates the displacement field throughout the surface under investigation. The grid used exhibits a period of 5 lines / mm. The 12 bit camera used exhibits 1376 x 1040 pixels. The distance between the camera and the specimen is adjusted in such a way that 5 pixels are used to discretize one period of the grid. Thus, only the upper-left corner of the patch, corresponding to a 55 mm x 42 mm rectangle, is observed in practice. 9 pixels are used to measure the displacement at a given point. Since one pixel corresponds to 40 µm, spatial resolution is equal to 360 µm.

2.4. Measurement of the temperature field
The second side of the specimen is painted with a black spray to obtain the greatest emissivity as possible and the camera is set to have a global overview of the temperature field on the upper surface of the composite patch. The infrared camera used is a CEDIP Jade. Its sensor exhibits 320 x 240 pixels. The thermal resolution of the camera is 0.02 K. The thermal loading is applied with four Minco 9.8 Ω thermal resistances deposited on each side of the specimen, at each end of the composite patches to obtain a symmetric thermal field.

3. Results

3.1. Temperature field
A typical temperature field on the upper side of the composite is presented in Figure 3(a) and the distribution of the minimum, maximum and average temperatures versus time is presented in Figure 3(b). This is the absolute temperature in °C. The temperature variation is deduced by subtracting the initial temperature which is equal to the room temperature: 20°C.

The temperature field is not strictly homogeneous because the heat flux is transmitted by the four resistances located at the ends of the patch. Hence, there is a variation of about 10°C between the ends and the center of the patch because of the heat exchange with ambient air. For this first approach however, the experimental results will be compared to the analytical results obtained with a constant temperature variation equal to the average temperature variation which is measured.

Figure 3 - (a) Final temperature field measured on the patch. (b) Evolutions of the minimum, maximum and average temperatures on the selected area.
3.2. Displacement and strain fields

A typical displacement field along the x-direction is presented in Figure 4. The results along [AA'] are fitted with a classical shear-lag model suitable for bonded joints [4]. This displacement is described by the following equation

$$u^p(x) = \frac{A}{C} e^{Cx} + \frac{A + B}{C} e^{-Cx} + Bx + D$$

where A, B, C and D are optimized to minimize the distance with the experimental displacements.

Three displacement distributions obtained for ∆T = 10°C, 60°C and 90°C are presented in Figure 5(a). The corresponding shear stresses in the adhesive, presented in Figure 5(b) are deduced with the following equation

$$\tau_{xz}^a = e_p \frac{d\sigma_{xx}^p}{dx} = e_p E_p \frac{d\varepsilon_{xx}^p}{dx} = e_p E_p \frac{d^2 u_x^p}{dx^2} = e_p E_p C\left(A e^{Cx} + (A + B) e^{-Cx}\right)$$

As can be seen in Figure 5(a-b), there is a transfer zone at the free edge since the displacement in the composite patch progressively increases as x increases, whereas the shear stress is maximum in the adhesive near the free edge. This corresponds to a thermal load transfer between the substrate and the adhesive.
composite. The CTE of the substrate is higher than the CTE of the composite which brings about a tensile state in the composite patch. Interestingly, the amplitude of the shear stress peak (at the end of the patch, see Figure 5(b)) is not proportional to the temperature variation. This is due to the fact that the shear modulus of the adhesive is not a constant over the whole temperature variation imposed during the test (20°C to 110°C), as can be seen in Figure 2.

The displacement away from the free edge is linear. This corresponds to a constant value for the strain. This strain obtained at different temperatures at the center of the patch is compared with the strain given by the classical theory for bonded joints [6].

\[
e^p_{ss}(x) = \frac{\chi}{\xi E_p} \left[ \cosh(\sqrt{\xi} l_x) + \frac{1 - \cosh(\sqrt{\xi} l_x)}{\sinh(\sqrt{\xi} l_x)} \cosh(\sqrt{\xi} x) - 1 \right]
\]

with

\[
\begin{align*}
\xi &= \frac{G_a}{e_a e_p E_e} \left( \frac{1}{e_p E_p} + \frac{1}{e_s E_s} \right) \\
\chi &= \frac{G_a}{e_a e_p} (\alpha_p - \alpha_s) \Delta T
\end{align*}
\]

where \(\alpha_p\) and \(\alpha_s\) are the CTE of the patch and the substrate, respectively, \(e_p\), \(e_s\) and \(e_a\) the thicknesses of the patch, the adhesive and the substrate, respectively, \(l_x\) the length of the patch, \(G_a\) the shear modulus of the adhesive, \(E_p\) and \(E_s\) the Young's modulus of the patch and the substrate, respectively, and \(\Delta T\) the temperature variation.

A typical evolution of the composite strain at the center of the patch is shown in Figure 6 when the temperature increases from 20°C to 110°C. The theoretical strain is obtained using Equation 3 for \(x = l_x/2\). The shear modulus \(G_a\) varies with the temperature as shown in Figure 2. As long as the adhesive is sufficiently rigid or the length of the patch sufficiently long, the transfer length is shorter than the half-length of the patch and the strain obtained at the center of the patch reaches its maximum value, given by

\[
e^p_{ss,\text{max}} = \lim_{l_x \to \infty} e^p_{ss}(x = \frac{l_x}{2}) = \frac{(\alpha_p - \alpha_s) \Delta T}{e_a e_p E_p} \left( 1 + \frac{e_p E_p}{e_s E_s} \right)
\]

The evolution of this strain versus temperature in this case is linear and does not depend on the value of \(G_a\). This corresponds to the linear part of the curves in Figure 6, where both experimental and theoretical results are in good agreement up to 80°C.

The second part of the curves, beyond 80°C, includes a peak corresponding to a critical temperature at which even if the temperature variation \(\Delta T\) increases, the adhesive becomes too flexible to completely transfer the loading and thus the maximum value given by Equation 3 is not reached.

This phenomenon may only appear in the case of an increasing temperature, since the evolution of parameters \(\Delta T\) and \(G_a\) have opposite effects. This would not happen for a decreasing temperature, where both abs(\(\Delta T\)) and \(G_a\) would increase and thus lead to an increasing strain. The theoretical strain peak is in good correlation with the experimental results, even if there is a shift in terms of temperature between the two curves. This shift may be explained by the non-homogeneity of the temperature field or by the uncertainties on the different parameters of the model.

4. Conclusion

An experimental study has been performed in order to highlight the influence of a thermal loading on the strain fields which take place in a bonded joint. Full-field measurement techniques have been used for this purpose. The temperature field is captured by an infrared camera. The displacement field is
obtained with the grid method. Results obtained are in good agreement with theoretical expectations, even though some difference can be observed.

Further work is underway to take into account thermo-viscoelasticity properties of the adhesive and temperature gradient in the patch.

![Graph showing measured strain in the middle of the patch compared with its theoretical counterpart based on the average temperature measured.](image)

**Figure 6** – Measured strain in the middle of the patch compared with its theoretical counterpart based on the average temperature measured.

**Acknowledgements**
The DGA/French Ministry of Defense is gratefully acknowledged for its support during this study.

**References**

[1] C. Badulescu, J.D. Mathias, M. Grédiac, and D. Roux. A procedure for accurate one-dimensional strain measurement with the grid method. *Experimental Mechanics*, 2008. Accepted for publication.

[2] Y. Surrel. Moiré and grid methods in optics: a signal-processing approach. In *Interferometry '94: Photomechanics*, volume 2342, 1994. The International Society for Optical Engineering, SPIE.

[3] A. Deheeger, J.D. Mathias, and M. Grédiac. A closed-form solution for the thermal stress distribution in rectangular metal/composite bonded joints. *International Journal of Adhesion and Adhesives*, 2008. Accepted for publication.

[4] O. Volkersen. Die niekraft in zugbeanspruchten mit konstanten laschenquerschritten. *Luftfahrtforschung*, 15:41-47, 1938.

[5] J.L. Piro and M. Grédiac. Producing and transferring low-spatial-frequency grids for measuring displacement fields with moiré and grid methods. *Experimental technics*, 28(4), 2004.

[6] L.J. Hart-Smith. Adhesive-bonded double-lap joints. Technical Report, CR-112235, NASA, 1973.