ACTIVE SHAPE CONTROL OF COMPOSITE STRUCTURES UNDER THERMAL LOADING

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Keywords: *thermal distortion, active shape control, piezocomposite, finite-element, experiment*

Abstract

Maintaining the shape of high-precision structures such as space antennas is a challenging issue for designers. Varying temperature conditions will induce thermal distortions in these structures. Development of smart materials offers great potential to correct the shape. In this study, shape control of a composite structure under thermal loading using piezocomposites is investigated. Macro-Fibre Composite (MFC™) patches are bonded to the structure. The structure is subjected to a through-the-thickness temperature gradient which induces thermal distortion. The objective is to apply electric potential to the MFC actuators such that the out-of-plane deflection can be minimized. Finite-element analyses are conducted using the commercial software ABAQUS. Experiments are performed to study piezoelectric actuation, thermally-induced distortion, and compensation of thermal distortion using the MFC actuators. A control loop based on strain measurements is used to actively control the structure. Results show that MFC actuators can compensate thermal distortion and that is an efficient methodology.

1 Introduction

Maintaining the shape of high-precision structures such as space antennas and optical mirrors is still a challenging issue for designers. These structures are subjected to varying temperature conditions which often induce thermal distortions.

The development of smart materials and structures offer great potential to correct the shape and to minimize surface error. As a result, research in this area has been very active over the past decade.

So far, piezoceramic materials have been the most widely used smart material to control the shape of a structure. Koconis, Kollar, and Springer [1, 2] were among the first ones to investigate the change in shape of composite beams, plates and shells by embedded piezoelectric actuators. Studies on determining the optimal length, actuator locations and applied voltage have been reported by Agrawal and Treanor [3], Bruch et al. [4], Sun and Tong [5] and different optimization techniques have been proposed. Thermal deformation compensation has also received considerable attention in recent years. Several coupled thermal-piezoelectric-mechanical models have been developed. For example, Ashida and Tauchert [6] proposed a general solution procedure for the analysis of composite circular plates subjected to thermal loading and piezoelectric actuation. Tan [7] developed a simulation procedure using a co-located sensing and actuating scheme based on strain measurements and applied it to compensate thermal deformation of a paraboloid shell of revolution. Song, Zhou and Binienda [8] performed finite-element analyses and experiments to investigate the compensation of thermal distortion in a composite beam. Unfortunately, the experimental results on shape control are not compared with finite-element results. It turns out that the great majority of the studies published so far on shape control are theoretical and numerical. Experimental testing to validate model predictions is very scarce.

Although piezoceramic actuators have been the most widely considered for shape control, they present certain disadvantages that make them difficult to use in realistic industrial applications. For example, they exhibit a very brittle behaviour and are therefore vulnerable to damage. Moreover, it is difficult to make them conform to curved surfaces. To overcome the difficulties associated with using piezoceramic materials, piezoceramic composite actuators have been developed. Presently, there are three types of piezoceramic composite available commercially: 1-3 composites manufactured by Smart Materials Corporation, Active Fibre

Composite actuators developed by MIT [9], and Macro-Fibre Composite (MFC) actuators recently developed by NASA Langley Research Center [10]. An overview of the different piezoceramic composite actuators can be found in Williams et al. [11].

The MFC shown in Figure 1 is an innovative actuator that offers high performance and flexibility. It consists of thin rectangular piezoceramic (PZT) fibres embedded in an epoxy matrix and sandwiched between Kapton films layered with copper interdigitated electrodes, as shown in Figure 2. With the interdigitated electrodes, the electrical field is applied along the fibres (1-direction) which produces much higher in-plane actuation strain than traditional monolithic piezoceramic actuator poled through-the-thickness.

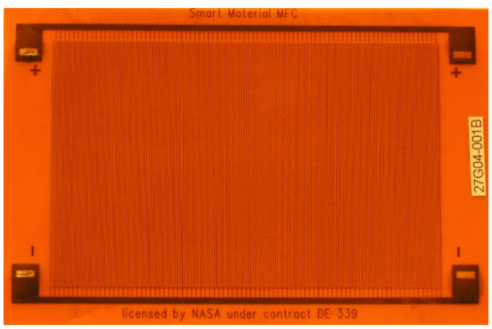

Fig. 1. The MFC actuator

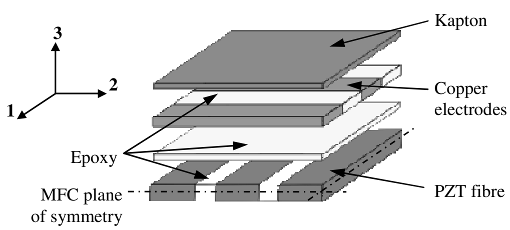

Fig. 2. Lay-up of the MFC actuator (symmetric about the middle of the PZT/epoxy layer)

Williams [12] investigated the mechanical and piezoelectric behaviour of the Macro-Fibre Composite. So far MFC actuators have been used in a few applications. Moses et al. [13] investigated the use of MFC actuators to reduce buffeting loads on twin-tail fighter aircraft flying at high angles of attack. Schultz and Hyer [14] studied the use of MFC actuators to induce snap-through of bi-stable unsymmetric composite laminates. Sodano, Park and Inman [15] used MFCs as means to control vibrations of an inflatable and as impedance sensors for structural health monitoring. MFC actuators also offer great potential for static shape control of structures but, to the authors' knowledge, it has not yet been explored.

This paper presents a study conducted to investigate the use of MFC actuators to compensate thermal deformation in composite structures. The specific objective of the study is to determine if MFC actuators bonded to the surface of a composite sandwich plate have the ability, when actuated, to counteract thermal deformations generated by a through-the-thickness thermal gradient. Both finite-element analyses and experiments are performed. First, the constitutive equations governing the MFC behaviour are presented. Then, the finite-element model developed using the commercial software ABAQUS is presented and a series of analyses are carried out comparing numerical and experimental results. Finally, a feedback control loop based on strain measurements is implemented in the data acquisition system to actively control the response of the structure.

2 Macro-Fibre Composite Constitutive Equations

With the coordinate system presented in Figure 3, where the fibres are aligned in the 1-direction and the electric field is applied in the fibre direction, the coupled constitutive equations for a MFC actuator can be written in matrix form

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_6 \end{Bmatrix} = \begin{bmatrix} d_{11} & \alpha_1 & s_{11} & s_{12} & 0 \\ d_{12} & \alpha_2 & s_{12} & s_{22} & 0 \\ d_{13} & \alpha_3 & s_{13} & s_{23} & 0 \\ 0 & 0 & 0 & 0 & s_{66} \end{bmatrix} \begin{Bmatrix} E_1 \\ \Delta T \\ \sigma_1 \\ \sigma_2 \\ \sigma_6 \end{Bmatrix}. \qquad (1)$$

This equation represents inverse piezoelectric effect. In this form, σ, ε and s are the stress, the strain and the compliance, respectively. E_1 and d are the applied electric field and piezoelectric strain coefficients. Finally, α and ΔT are the thermal expansion coefficient and the temperature variation. The electric field E_1 which is developed in the MFC actuator under the application of voltage (V) can be estimated by [12],

$$E_1 = \frac{V}{w_{pitch}}, \qquad (2)$$

where w_{pitch} is the center-to-center interdigitated electrode spacing.

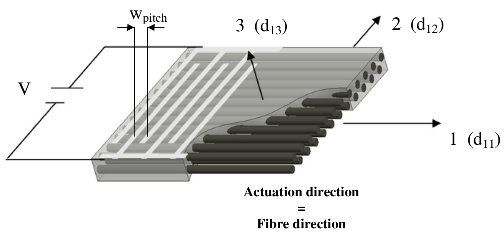

Fig. 3. Coordinate system and actuation direction of the MFC

3 Problem Description

In this study, a through-the-thickness thermal gradient is applied on a composite sandwich plate to induce thermal deformation. The plate is clamped along one side and free along its three other sides. The thermal gradient is induced by a heating lamp placed on one side of the plate. MFC patches are activated to counteract the thermal deformation as shown in Figure 4. Midplane deformation induced by the through-the-thickness temperature gradient is characterized by the transverse displacement component w. The composite structure is a 280 mm-long and 70 mm-wide composite sandwich plate. It is made of a foam core and two carbon epoxy face sheets. The foam core is 6 mm-thick and each face sheets are 0.35 mm-thick. The material properties of each component are listed in Table 1.

Table 1. Material properties

Material properties	Panex 33/RS-1	Foam	MFC
E_1 (GPa)	95.6	0.0094	30.3
E_2 (GPa)	6.8	0.0094	15.9
E_3 (GPa)	6.8	0.0094	11.47
G_{12} (GPa)	3.01	0.0036	5.515
G_{13} (GPa)	3.01	0.0036	2.60
G_{23} (GPa)	2.71	0.0036	2.14
ν_{12}	0.318	0.3	0.31
ν_{13}	0.318	0.3	0.289
ν_{23}	0.458	0.3	0.327
α_{11} (μ/°C)	-0.06	61	5.9
α_{22} (μ/°C)	41.7	61	29.6
α_{33} (μ/°C)	41.7	61	21.0
k_{11} (W/m*K)	11.1	0.028	11.1
k_{22} (W/m*K)	0.87	0.028	0.87
k_{33} (W/m*K)	0.87	0.028	0.87
emissivity	0.95	-	0.95
d_{11} (pm/V)	-	-	360
d_{12} (pm/V)	-	-	-190
d_{13} (pm/V)	-	-	-190
w_{pitch} (mm)	-	-	0.5

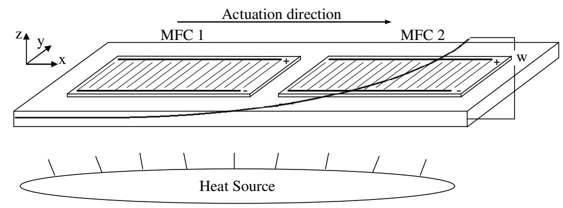

Fig. 4. Description of the composite sandwich plate-MFC actuators combination

4 Cantilever Composite Sandwich Plate Subjected to MFC Actuators

4.1 Finite-Element Analysis

The finite-element software ABAQUS CAE is used to develop a 3D model predicting the response of a cantilever plate with two bonded MFC actuators, as the one represented in Figure 4. The composite sandwich plate was modeled using 20 node quadratic continuum elements with reduced integration (C3D20R). Similar elements with an extra degree of freedom for the electrical potential (C3D20RE) were used to model the active part of the MFC. Figure 5 shows the geometry and dimensions of the modeled structure.

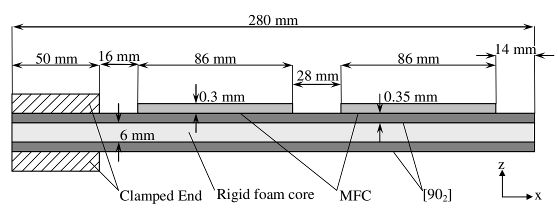

Fig. 5. Geometry of the composite sandwich plate with two MFC actuators

Figure 6 presents the mesh used for the analysis. The active part of the MFC is modelled with 2 elements through the thickness, 6 elements along the width and 17 elements along the length. The composite sandwich plate is meshed with 8 elements through the thickness, 2 for each face sheets and 4 for the foam core. There are 14 elements along the width and 56 elements along the length. The displacements of the nodes corresponding to the clamped end are set to zero in the x-, y-, and z-directions. The electric field was applied to the actuator through the boundary condition corresponding to the extra degree of freedom of the piezoelectric elements.

The voltage was set to a positive value at the end of each MFC near the clamped end and was set to zero at the other end.

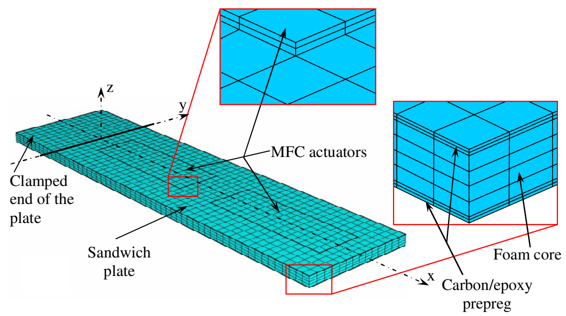

Fig. 6. Mesh of the sandwich structure

4.2 Numerical Results

First, finite-element analyses were performed to study the response of the composite sandwich plate as the MFC patches are actuated. Figure 7 presents the out-of-plane displacement of the plate along its length. Results are shown for 100, 300, 500 and 1000 V actuations. As shown in Figure 7, the displacement reaches a maximum of 1.1 mm under a 1000 V actuation.

4.3 Experimental Set-up

The composite sandwich structure was built using a foam core and face sheets made of two prepreg plies with fibres oriented at 90º with respect to the longitudinal direction of the plate. The assembly was cured at 65 ºC for half an hour and at 94 ºC for 12 hours.

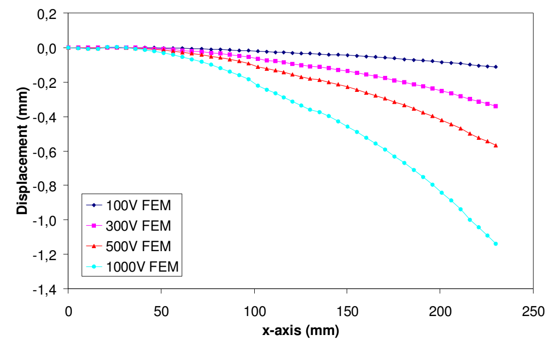

Fig. 7. Predicted out-of-plane displacement of the composite sandwich plate subjected to MFC actuation

The face sheets were bonded to the foam core by the prepreg resin during the cure process. Two Macro-Fibre Composite patches were bonded to the face sheet with Loctite (HP-E120) epoxy adhesive. Vacuum was applied and the assembly was let to room temperature for 3 hours.

Next, the composite sandwich plate with the two MFC patches bonded was oriented vertically and clamped at one end on a 50 mm-length. The room temperature was 23 ºC and the structure was initially flat. Voltage level varying from 0 to 1000 V was applied to the MFC actuators. The induced out-of-plane displacement is measured by a 3D image correlation system. Figure 8 shows the experimental set-up.

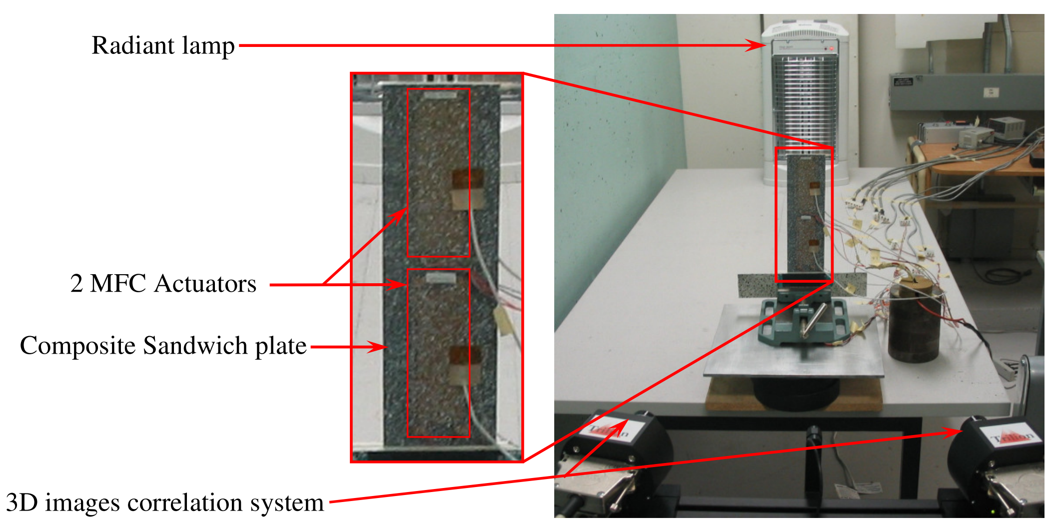

Fig. 8. Experimental set-up

4.4 Experimental Results

The 3D image correlation system is based on images taken by two cameras. The system combines the two images to determine the coordinates of each point on the plate. From the coordinates, displacements are computed. To do this, a pattern is applied to the plate surface. Figure 9 presents the out-of-plane displacement of the composite sandwich plate when 100, 300, 500 and 1000 V are applied. For comparison, finite-element predictions obtained with the model are also presented. As can be seen, the experimental results are slightly larger than the finite-element results. In the finite-element model, the maximum displacement is about 4% smaller than the experimental one when low voltage is applied. With higher voltage, the difference increases to 9%.

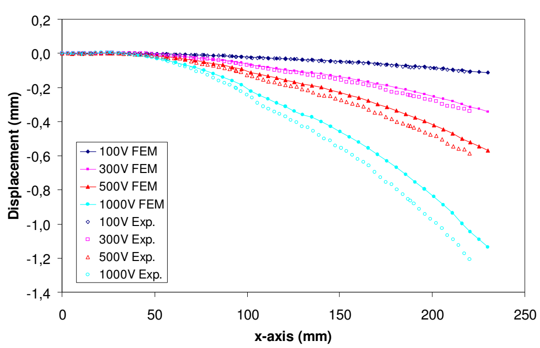

Fig. 9. Out-of-plane displacement of the composite sandwich plate subjected to MFC actuation

5 Composite Sandwich Plate Subjected to Thermal Loading and MFC Actuation

5.1 Finite-Element Analysis

Two analyses were performed. The objective of the first analysis is to compute the temperature distribution on the plate. The elements used to model the entire structure are coupled-temperature displacement elements (C3D20RT). The room temperature is set equal to 22.9 ºC (experimental value). The plate is subjected to radiation and convection on its surface. The surface heat flux of the lamp is assumed to be equal to 92 W/m^2. This value was adjusted by trial and error using experimental results. Natural convection with room temperature at 22.9 ºC is assumed. The convection coefficient is calculated to be 3 and 4 W/m^2K^{-1} for the cold and hot side, respectively [16]. Radiation with surroundings at room temperature is taken into account. The emissivity of the surface is set to 0.95. In the second analysis, temperature distribution is applied. 3D and piezoelectric elements (C3D20R and C3D20RE) are used to model the structure. Different voltages are applied to the MFC actuators as boundary conditions.

5.2 Numerical Results

Figure 10 presents the out-of-plane displacement of the plate along its length. Results are shown for 0, 400, 700 and 800 V actuations. The mean temperatures on each side of the composite sandwich plate are 30.0 ºC and 25.3 ºC which induce a 4.7 ºC thermal gradient. As shown in Figure 10, the thermal deflection can be compensated by applying a voltage of about 800 V.

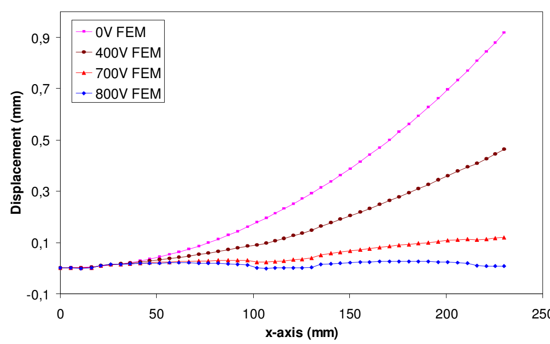

Fig. 10. Predicted out-of-plane displacement of the composite sandwich plate subjected to thermal gradient and MFC actuation

5.3 Experimental Set-up Modifications

In this experiment, the same composite sandwich plate with two MFC actuators was used and placed in the same conditions as in the first experiment. A radiant heating lamp Holmes was added and positioned at 130 cm away from the plate. The composite sandwich plate was vertically centered with the lamp to produce the most uniform heat flux on the surface of the plate. Four RTD surface temperature sensors were used to measure the temperature on both surfaces. They were placed on each side of the structure at 6 and 17 cm away from the free end of the plate. At time t=0, the plate was at room temperature and flat. The heating process started at time t=2 min. From time t=15 min, voltage was applied incrementally until 1100 volts was reached.

5.4 Experimental results

Figure 11 shows the temperature measured by the 4 temperature sensors. The temperature is 30.5 ºC on the exposed side of the plate and 26.4 ºC on the other side. The induced thermal gradient is 4.1ºC which is slightly different from the 4.7 ºC used for the numerical prediction. The shape of the plate at different times t_1, t_2, t_3 and t_4 is shown in Figure 12. The applied voltages at these times were respectively 0, 400, 700 and 800 volts. For comparison, finite-element predictions are also presented. The difference in temperature gradient might explain the differences between the measured and predicted shapes plotted in Figure 12.

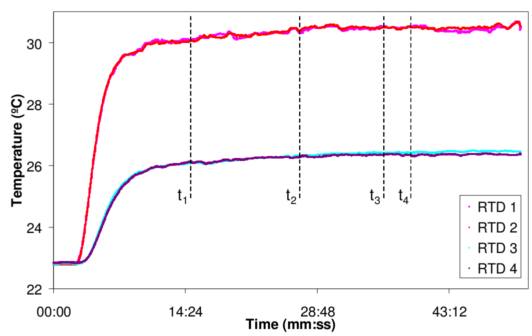

Fig. 11. Temperature increase during experimentation

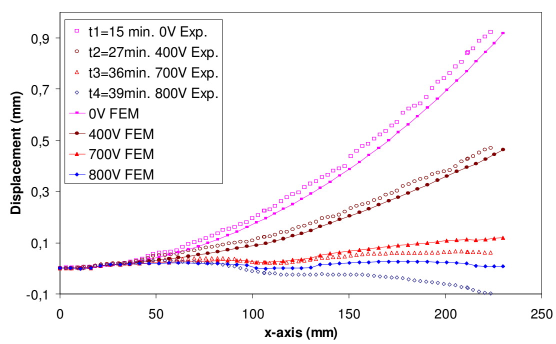

Fig. 12 Out-of-plane displacement of the composite sandwich plate subjected to thermal gradient and MFC actuation

6 Composite Sandwich Plate Subjected to Thermal Loading and Active Control

6.1 Active Control Scheme

The objective of this experiment is to study the feasibility of using MFC actuators to actively compensate the thermal deformation induced by a through-the-thickness temperature gradient in a composite sandwich plate. The control loop was created within the commercial data acquisition software Dasylab. It is based on the strain difference between each side of the plate. It is assumed that the plate is flat if the difference between the strains on each side of the plate is zero. On the side of each actuator, a 104 mm-long strain gage was bonded with M-Bond AE-10 glue. A second set of strain gages were bonded on the other side of the plate as depicted in Figure 13. The average of the difference between back-to-back strain gages was used to determine the voltage applied to both MFC actuators. This can be written as

$$\Delta\varepsilon = \frac{(\varepsilon_1 - \varepsilon_4) + (\varepsilon_2 - \varepsilon_3)}{2}, \qquad (3)$$

where ε_1, ε_2, ε_3, and ε_4 are the signals of the strain gages presented in Figure 13.

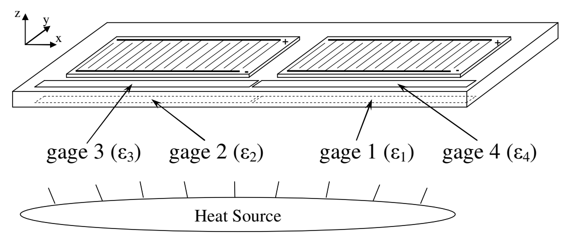

Fig. 13. Strain measurements

The feedback controller diagram is shown in Figure 14.

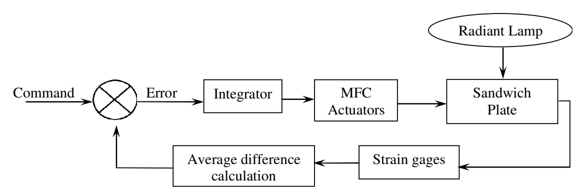

Fig. 14. Active control scheme diagram

An integral feedback controller was used. The controller received the average of the difference of the back-to-back strain gages. As soon as the average was not zero, the controller activated the MFCs to correct the shape of the composite sandwich plate. The integral value used is I=0.03.

6.2 Active Control Results

The composite sandwich plate with two MFC actuators bonded on one side was initially at room temperature. The strain gages were set to zero. The control of the plate started at time t=1 min. At time t=2 min, the lamp was turned on to generate the temperature gradient. The temperature stabilized after about 10 minutes and the control continued for another 10 minutes. The temperature on each side of the plate is shown in Figure 15. The temperature was 30.0 ºC on the exposed side of the plate and 25.9 ºC on the other side. Therefore, the thermal gradient was 4.1 ºC. Voltage applied to both MFC actuators is presented in Figure 16. The shape of the plate at time t=2, t=4, t=8 and t=14 min is shown in Figure 17. Previous results obtained without control are also presented. Figure 17 shows that active control allows to maintain the shape of the plate within 0.06 mm from its initial flat position at all time.

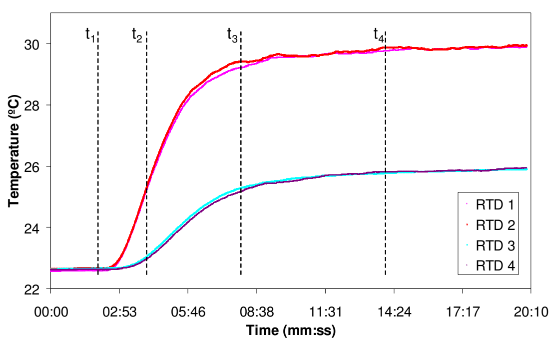

Fig. 15. Temperature increase during experimentation

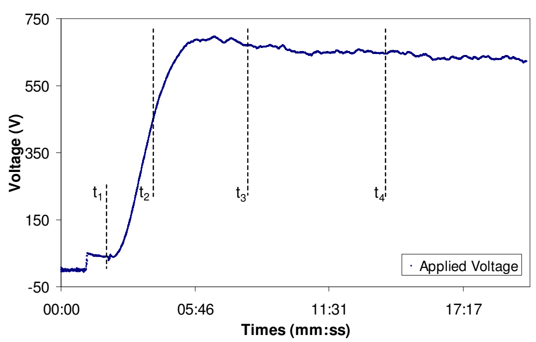

Fig. 16. Voltage during experimentation

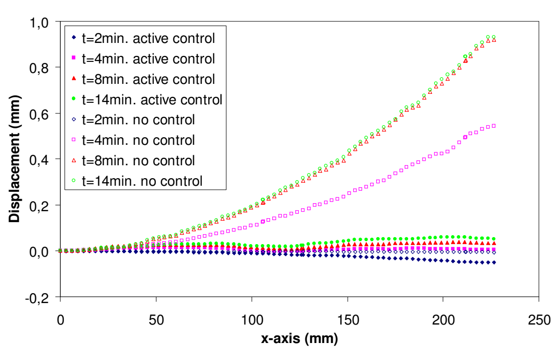

Fig. 17. Out-of-plane displacement, with and without active control

7 Conclusion

The study presented in this paper investigated the use of Macro-Fibre Composite actuators to compensate thermally-induced deformations in composite structures. Finite-element analyses were performed and a few experiments conducted to check the validity of the predictions. First, the response of a composite sandwich plate with two MFC actuators bonded to the surface was studied. Next, a through-the-thickness temperature gradient was applied which induces bending of the composite sandwich plate. The MFC actuators were then actuated to compensate the thermally-induced deflection.

The main results of the experimental and theoretical work are that:

- The response of simple cantilever composite sandwich plates subjected to MFC actuators can be predicted with a good accuracy at low voltage.
- The finite-element model can predict the compensation of deformations induced thermally in a composite sandwich plate using MFC actuators.
- MFC actuators are efficient to compensate thermally-induced distortions in composite sandwich structures.
- The experiments performed validate the MFC efficiency to actively control the deformation of a composite sandwich plate subjected to a through-the-thickness thermal gradient using strain gages.

As future work, numerical developments will be conducted to simulate the active control of through-the-thickness thermal deformation in a composite sandwich plate using MFC actuators and strain measurements. Work on a curved structure will be investigated.

References

[1] Koconis D., Kollar L. and Springer G. “Shape Control of Composite Plates and Shells with Embedded Actuators I. Voltages Specified”. *Journal of Composite Materials*, 28: pp 415-458, 1994.

[2] Koconis D., Kollar L. and Springer G. “Shape Control of Composite Plates and Shells with Embedded Actuators II. Desired Shape Specified”. *Journal of Composite Materials*, 28: pp 459-482, 1994.

[3] Agrawal B. N. and Treanor K. E. “Shape control of a beam using piezoelectric actuators”. *Smart Materials and Structures*, 8 pp729-740, 1999.

[4] Bruch J. C., Sloss J. M., Adali S., Sadek I. S. "Optimal Piezo-Actuator Locations/lengths and Applied Voltage for Shape Control of Beams". *Smart Materials and Structures*, 9 pp 205-211, 2000.

[5] Sun D. and Tong L. "Design Optimization of Piezoelectric Actuator Patterns for Static Shape Control of Smart Plates". *Materials and Structures*, 14 pp1353-1362, 2005.

[6] Ashida F. and Tauchert T. R. "A General Plane-stress Solution in Cylindrical Coordinates for a Piezothermoelastic Plate". *International Journal of Solids and Structures*, 38: pp 4969-4985, 2001.

[7] Tan D. "Compensation for Thermal Deformation of a Paraboloid Shell Using Distributed Structural Actuation". *International Journal of Solids and Structures*, 38: pp 2893-2919 2001.

[8] Song G., Zhou X., and Binienda W. "Thermal Deformation Compensation of a Composite Beam Using Piezoelectric Actuators". *Smart Materials and Structures*, 13: pp 30-37. 2004.

[9] Bent A. A. "Active Fiber Composite for Structural Actuation". Ph.D. thesis, Massachusetts Institute of Technology 1997.

[10] Wilkie W. K., Bryant G. R., High J. W., Fox R. F. Hellbaum R. F., Jalink A., Little B. D. and Mirick P. H. "Low-Cost Piezocomposite Actuator for Structural Control Applications". Proceedings of the SPIE 7th annual international Symposium on Smart Structures and Materials, Newport Beach, CA 2000.

[11] Williams R. B. "Nonlinear Mechanical and Actuation Characterization of Piezoceramic Fibre Composites". Ph.D. thesis, Virginia Polytechnic Institute and State University 2004.

[12] Williams R. B. "*Nonlinear Mechanical and Actuation Characterization of Piezoceramic Fibre Composites*". Ph.D. thesis, Virginia Polytechnic Institute and State University, 2004.

[13] Moses R. W., Weiseman C. D., Bent A. A. and Pizzochero A E. "Evaluation of New Actuators in a Buffet Loads Environment". *Proceedings of the SPIE 8th Annual International Symposium on Smart Structures and Materials*, Newport Beach, CA 2001.

[14] Shultz M. R. and Hyer M. W. "Snap-through of Unsymmetric Cross-ply Laminates using Piezoceramic Actuator". *Journal of Intelligent Material Systems and Structures*, 14: pp 795-814 2003.

[15] Sodano, H. A., Park G. and Inman D. J. "An Investigation into the Performance of Macro-Fiber Composites for Sensing and Structural Vibration Applications," *Mechanical Systems and Signal Processing*, 18(3): pp 683-697, 2004.

[16] Incropera I. I. and DeWitt D. P. "*Fundamentals of heat and mass transfer*". 5th edition, John Wiley & Sons, 2002.