LIFE ENHANCEMENT AND REPAIR OF STRUCTURES USING SHAPE MEMORY ALLOY COMPOSITE PATCHES

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SUMMARY: This paper focuses on the force produced by a shape memory alloy (SMA) fibre/epoxy matrix patch when the SMA fibres are activated. Experimental and finite element results of the resultant forces are compared. It is found that heated SMA wires are able to generate a significant contracting force within the SMA composite patch. When the patch is used to repair cracked metallic structures then the force produced by activating the SMA wire can provide significant crack closure forces across the crack. Therefore, these types of repairs offer a potential alternative repair technique for cracked metallic structures.

KEYWORDS: shape memory alloys, bonded composite patches, fatigue life enhancement, life extension.

INTRODUCTION

Cracks developed in metallic structures can lead to disastrous consequences. For example, during the 1950's, a series of fatal Comet aircraft accidents, caused by fatigue cracks developed in the corners of square windows, led to a better understanding of fatigue and its aftermath.

To complement existing methods of fatigue life enhancement of metallic components, such as existing mechanical metallic and bonded composite repairs [1, 2], a repair technique using shape memory alloys (SMA's) is being investigated. SMA's are a group of alloys that exhibit an interesting phenomenon known as the shape memory effect. The alloys have the ability to "recover" their original shape when heated above a certain transition temperature, after being pseudo-elastically deformed. There is also a large recovery strain, of up to 8%, associated with the transition. Because of this unique property, a large research effort is currently being undertaken, directed towards the use of SMA's in the actuation of smart structures for shape and vibration control, and for damage mitigation, [3], [4] and [5].

To-date, researchers have studied the use of SMA's embedded in carbon fibre/epoxy matrix composites and neat epoxy resins, [3] and [4] respectively, in order to prevent damage or induce damage mitigation within those material systems. This paper investigates the possibility of embedding the SMA wires in an epoxy matrix for the repair of cracked metallic specimens. Experimental studies on the measured actuation forces produced by these SMA wire/epoxy matrix composite patches are described here. A finite element model (FEM) of an epoxy patch with embedded SMA wires, attached to a metallic substrate, was performed to determine the actuation force once the SMA wires are activated.

EXPERIMENTAL SETUP AND PROCEDURE

The main impetus behind this experiment is to manufacture a SMA wire/epoxy matrix patch and then to experimentally determine the force produced by the SMA composite patch.

The SMA wires used were 0.15 mm in diameter and supplied by Shape Memory Applications Inc. USA. Using a differential scanning calorimeter (DSC), the transformation temperatures for these wires were found to correspond to A_s=50°C, A_f=79°C, M_s=58.4°C and M_f=32.4°C. Here A_s and A_f corresponds to the austenitic start and finish temperatures, and M_s and M_f correspond to the martensitic start and finish temperatures, respectively.

A mould, as shown in Figure 1, was designed whereby the wires could be prestrained and embedded *in situ*. To prevent debonding of the SMA wires and ensure a greater bond adherence with the epoxy matrix, the surface of the SMA wires were firstly roughened using sand paper, then wiped using acetone and ethanol, and subjected to an ultrasonic rinse and then dried [6]. The wires were then placed in the mould, a distance of 1 mm apart, and prestrained to 4%.

Araldite F (CIBA-GEIGY) was mixed with a hardener, piperidine, in a weight ratio of 100:5 after all air bubbles were removed. It was then mixed and added to the mould. Any excess epoxy was removed in order to obtain a specimen thickness of 1 mm. Finally, the epoxy patch was cured at 120°C for 16 hours.

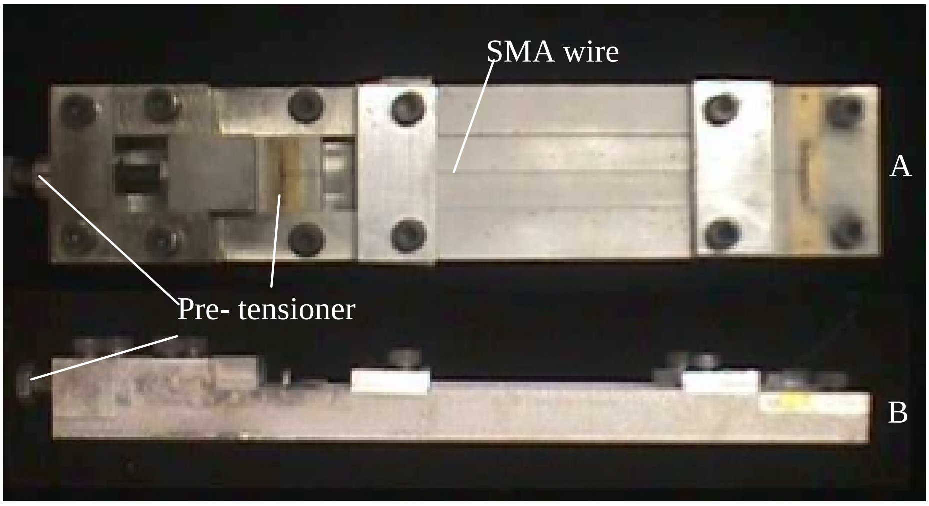

Figure 1. Mould used for SMA wire/epoxy matrix patches; A. top view, B. side view.

Aluminium end tabs were placed on the ends of the patches, as shown in Figure 2, using high strength araldite. The patches were positioned in a uni-axial hydraulic Instron testing machine and the test specimen was enclosed in an oven to allow testing at elevated temperature. The specimen was held at a constant displacement and the force was monitored with increasing temperature. In this case a 1.5 kN capacity load cell was used. The oven was ramped to a temperature of 150°C, since this is well above the transformation temperature of the SMA wires and the wires would be completely transformed from their martensitic to austenitic phase. As the wires are heated above the transformation temperature they contract and therefore exert a contracting force on the testing machine. The testing machine then records a positive force, since the clamps are held at a constant displacement.

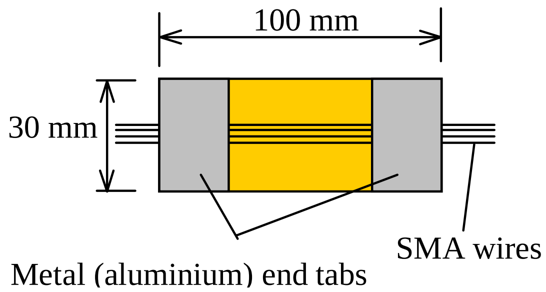

Figure 2. SMA wire/epoxy matrix patch with metal end tabs.

FINITE ELEMENT MODELLING

A two-dimensional finite element model, consisting of three layers was used to estimate the stresses produced by the activated SMA wires, embedded in an epoxy patch, as shown in Figure 3. The top and bottom layers are epoxy and the middle layer is a combination of epoxy and SMA wire, herein known as the SMA layer. The thickness of the SMA layer was equal to the diameter, d, of the wire used.

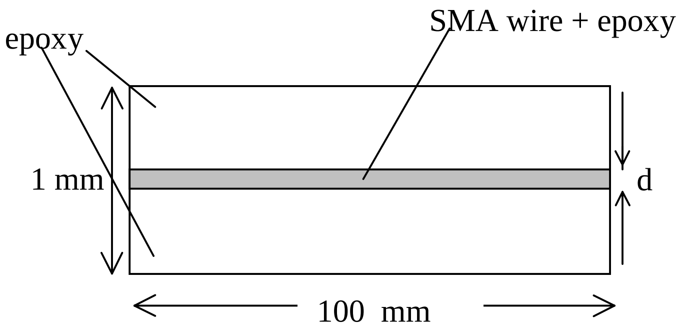

Figure 3. Schematic of the SMA patch used in finite element analysis.

An experiment was undertaken to determine the variation of Young's modulus with temperature of the SMA wire. A piece of wire, approximately 10 mm long, was placed in a dynamic mechanical analyser (DMA) and the temperature was held constant while the tensile force on the wire was slowly ramped to 15 N. Figure 4 shows the variation of Young's modulus with temperature. It is seen that the A_s temperature occurs at about 50°C which corresponds to A_s measured by the DSC.

The epoxy has a Young's modulus of 2.8×10^{9} Pa, a Poisson ratio of 0.33 and a coefficient of thermal expansion of 54×10^{-6} /°C. An effective Young's modulus and an effective coefficient of thermal expansion were used for the modelling of the SMA layer since the fibre volume fraction of the SMA to the epoxy needs to be considered.

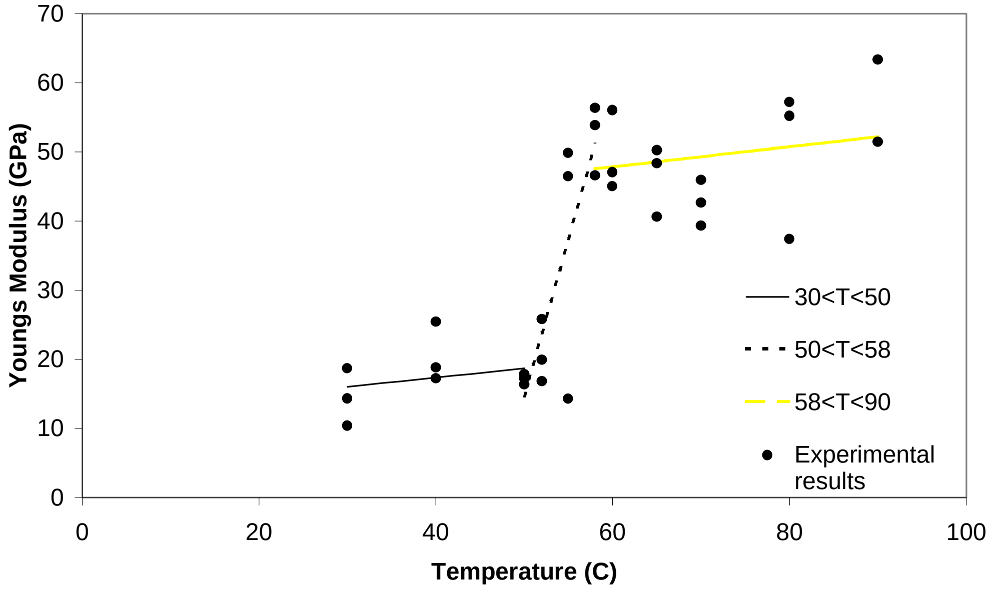

Figure 4 . Variation of Young's modulus with temperature of a one-way SMA wire. Straight lines are least squares fit of the experimental data.

The effective Young's modulus for the SMA layer is given by

$$E_{eff} = \frac{A_{SMA}}{A_T} E_{SMA} + \frac{A_M}{A_T} E_M \qquad (1)$$

where A_{SMA} and A_M are the cross sectional areas of the SMA wire and the epoxy matrix, respectively, A_T is the total cross sectional area of the system, E_{SMA} is Young's modulus of the SMA wire, determined from the experiment described previously, and E_M is Young's modulus of the epoxy. The effective coefficient of thermal expansion for the SMA layer in the FEM is derived as

$$\alpha_{eff} = -\left(\frac{\alpha_{SMA} A_{SMA} E_{SMA} + \alpha_M A_M E_M}{E_{eff} A_T} \right) \qquad (2)$$

where α_{SMA} and α_M are the coefficients of thermal expansion of the SMA and epoxy matrix, respectively. For the FEM, α_{SMA} is determined by

$$\alpha_{SMA} = \frac{\varepsilon}{\Delta T}, \qquad (3)$$

where ε is the pre-strain, of which 4% was used at a temperature, ΔT, of 70°C. At this temperature, the SMA has undergone an austenitic transformation. The SMA wire will have 4% pre-strain partially recovered, due to the constraint effects of the substrate. The negative value of α_{eff} is used to account for the fact that the SMA wires contract when heated. The SMA wire was given a Poisson ratio of 0.33.

The areas, A_T, A_M and A_{SMA} involved in the calculations for α_{eff} and E_{eff} were determined by considering the spacing between two wires embedded in an epoxy patch, 1 mm apart, as shown in Figure 5. This enables the determination of the forces produced using different fibre volume fractions, within the SMA layer.

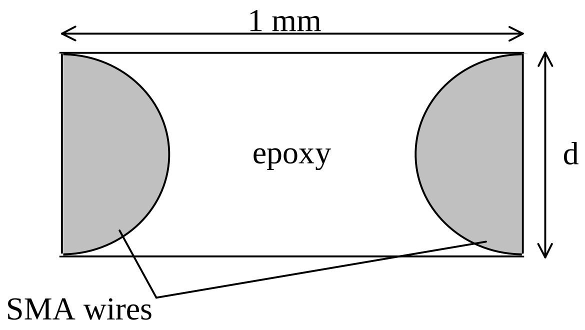

Figure 5. Diagram of the epoxy + SMA wire layer used in the FEM.

RESULTS

Preliminary results showed that when the wires were activated, the patch itself expanded slightly at the beginning of the heating cycle, corresponding to thermal expansion of the epoxy. However, once the transformation temperature of approximately 60°C was reached the patch started to contract. The forces then increased positively, reaching a maximum before levelling off. This means that the patch is contracting when the wires are heated. Figure 6 shows a typical heating cycle for a patch with 2 SMA wires.

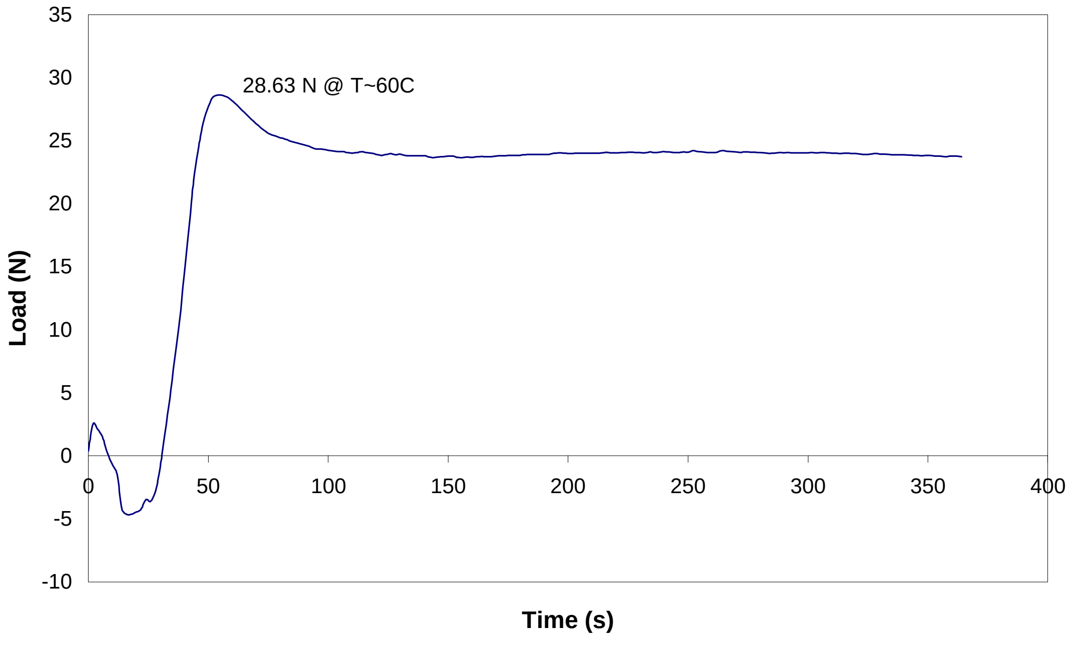

Figure 6. Load vs. time graph for SMA patch incorporating 2 SMA wires, during the heating cycle.

It was also noted that during the cooling cycle, the forces obtained increased significantly**.** This could be caused by the removal of the thermal expansion of the epoxy so that the patch experiences the full effect resulting from the activated SMA wires.

The experimental results for SMA patches incorporating 2, 4, 6 and 24 wires are shown in Table 1. Table 2 compares the measured and predicted in-plane forces for 6 and 24 wires embedded in the SMA patch.

Table 1: Experimental results of forces obtained after heating the SMA patches with different numbers of SMA wires embedded.

Number of SMA wires	Dimensions (mm) of patch Width × length × thickness	Maximum force (N) during heating
2	30.3 × 30.6 × 1.0	28
4	30.2 × 64.9 × 1.1	28
6	8.3 × 74.7 × 1.3	36
24	30.3 × 65.0 × 1.6	170

Table 2. Comparison of measured and predicted in-plane forces of the activated SMA composite patch.

	In-plane Force (N)	
	6 wires	24 wires
Experiment	36	170
FE Analysis	53.5	193.6

From the experimental results it was observed that the forces produced by a patch, embedded with 24 SMA wires, and then heated to a point above the SMA transformation temperature, is capable of producing forces of around 170 N. Using FE modelling it was shown that the forces obtained are 193.6 N. The differences in the forces can be attributed to several factors. Firstly, the FE model has not considered the effects due to the epoxy ends which exist in the experimental case, i.e. the FEM assumes fully clamped edges whereas the specimen has flexible ends and therefore the predicted force should be greater then the measured value. Secondly, the FE model has also not taken into account the effect of the edges of the patch. That is, an effective Young's modulus and thermal coefficient of expansion were calculated for a fibre volume fraction of 1 wire per mm in the SMA layer. Therefore, for 24 wire case, the 30 mm wide patch has several wires missing at the patch edges whereas in the theoretical model the effective modulus and coefficient of thermal expansion don't take this into consideration. A similar situation occurs for the 8 mm wide, 6 wire patch. Thirdly, the Young's modulus used in the calculation of the effective modulus and expansion coefficient may not be exactly correct, since, as can be seen from Figure 4, the Young's modulus is not constant and changes with temperature. There might also be an effect, caused by the thermal expansion of the epoxy patch, during the experiment, where the full shape memory effect is reduced due to thermal expansion.

CONCLUSION

Experimental results showed that a contracting force, ranging from 28 N to 169 N, was produced by patches incorporating 2 to 24 SMA 0.15 mm diameter wires, respectively, when they were heated to above the SMA transformation temperature. The forces obtained using FE analyses compare favorably to those of the experimental results. Interestingly, it was observed that during the cooling cycle of the SMA patches the forces obtained continued to increase to fairly large values. This could be due to thermal expansion effects being removed and, thus, the full shape memory effect is observed. Further investigation into these differences is being carried out. Overall, these results are encouraging and illustrate the potential of the technique as an alternate repair technique in the area of life enhancement and damage control.

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