Shape memory-based multifunctional structural actuator panels

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ABSTRACT
A multifunctional panel concept is presented in which a lightweight, structural sandwich panel is able to undergo a reversible change in shape upon application of a localized thermal stimulus. The shape change is effected by metallic (or polymeric) shape memory (SM) face sheet elements, which exploit a “one-way” SM effect only. Unlike other designs, no external or bias forces are required to complete the full cycle of shape change. This is accomplished by a core design which, when one of the two face sheets is activated and thus undergoes a length change, forces the opposite (inactive) face sheet to martensitically deform in tension. By alternately heating one face sheet and then the other, to transform the martensitic structure to austenite, the sandwich beam or panel is able to perform fully reversible cyclic shape changes. Heating can be accomplished electrically or by other means. The performance of the sandwich panel, in terms of required thermal power, actuation frequency, peak load bearing capacity, stiffness, and weight, can be optimized by proper selection of face sheet material and its thickness, the overall core thickness, core member thickness and length, and the design of the joint connecting core members and face sheet.

Keywords: shape memory alloy, actuator, multifunctional, Ni-Ti, sandwich panel, cellular metals, phase transformation

1. INTRODUCTION

New multifunctional materials concepts for lightweight, load-bearing materials and structures capable of controlled, reversible shape changes are needed for a wide range of space, communications, transport, civil and power generation applications. Such shape-morphing structural elements offer potential as replacement for existing systems relying on separate structural and actuation components, such as for example, a hydraulically actuated wing flap, or undersea vehicle rudder. This paper discusses the development, testing and analysis of a reversible, shape-morphing structural element which relies on a shape memory alloy for actuation. Shape memory alloys (SMA) have been extensively applied in micro-electro-mechanical systems (MEMS)1, surgical devices2 and prostheses, and smart materials concepts3. SMA, such as those based on Ni-Ti and Cu-Zn-Al, rely on a martensitic phase transformation to absorb inelastic strains (as high as 5-8%) and heating above the austenite start transformation temperature to recover their original shape. The spontaneous return of the deformed SMA to its original shape (or dimensions) upon heating is referred to as the one-way shape memory effect. A two-way effect is also possible, in which the SMA cycles between two fixed shapes during cycling between an upper and lower transformation temperature. More detailed information on the structure, composition and constitutive behavior of SMA can be obtained in the literature.4-6

Most SMA-based actuators are needed to operate cyclically between two states and so, if based on the one-way effect, require a biasing force (such as a spring) to return the SMA to its low-temperature (martensitic) state. Lu et al have recently analyzed a lightweight, shape-morphing sandwich panel incorporating a single SMA face sheet bonded to a truss-core7. The design is based on shape reversal achieved using a two-way shape memory effect, in which one shape is acquired at the upper transformation (Austenite finish, \(A_f\)) temperature and another, distinct shape at the lower transformation (Martensite finish, \(M_f\)) temperature. Using a statically determinate core design, they are able to minimize storage of elastic strain energy in the core and therefore propose a highly efficient design. While possible, this concept may be impractical for many applications due to the very low (sub-freezing) temperatures needed to reach the \(M_f\) temperature of many SMA, and the relatively small (< 2%) length change available via the two-way effect5. In a second approach, Lu et al have proposed the use of a single face sheet, one-way SMA actuator that uses a bias force to restore the structure to its

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original configuration.\textsuperscript{8} This is less efficient because of the need to store energy in the mechanical structure used to cause the shape reversal.

Here, we describe the design of a lightweight, shape-reversing structural panel (or beam element) which requires no bias force and relies on the one-way shape memory effect only. The concept is a face sheet-stiffened sandwich panel, in which both face sheets are one-way SMA, bonded to a truss core exhibiting a very low resistance to out-of-plane bending, combined with a relatively high resistance to in-plane deformation. The design is such that, when one of the two face sheets is heated to the $A_f$ temperature, the other (low-temperature) face is subjected to deformation by the formation of stress-induced martensite. Our prototype is constructed using Ni-Ti SMA face sheets bonded to a stainless steel truss core. While the face sheets deform inelastically via the formation of stress-induced martensite, the core experiences elastic deformations only. The shape is reversed by heating the opposite face sheet to $A_f$, and cycled at a frequency determined by the rate at which the face sheets cool after heating. We expect this approach to result in reversible actuator panels with performance comparable to designs using an external bias mechanism, but at lower system weight.

We first discuss the concept in greater depth and introduce the detailed design. Next, we present an analysis of the concept and use this to predict expected performance and to develop guidelines for the identification of optimal designs. Finally, model predictions for actuator force and displacement are compared with the limited experimental results currently available.

2. DESIGN CONCEPT

Figure 1 shows a schematic illustration of the actuator panel concept, consisting of SMA face sheets bonded to a stainless steel truss core. Heating of the SMA face sheets can be achieved by Joule (direct electrical resistance) heating, by radiative mechanisms, or by flow of a heated gas or liquid over the sheets. The central core sheet separates these flows from the opposite face sheet. The core is constructed by forming corrugated sheets which are then brazed to both sides of the flat (stainless steel) core sheet. Geometric design variables include the face sheet thickness, $t_f$, truss member thickness, $t_t$, core sheet thickness, $t_c$, truss angle, $\theta$, overall core thickness, $h$, and length, $l$.

The as-received SMA face sheets, prior to attachment to the core, are first heated above the $A_f$ temperature to ensure the material is in its austenitic form. This is followed by uniaxial elongation to roughly half the alloy’s expected shape memory strain. The direction of elongation will be referred to as the longitudinal direction of the face sheet. The face sheets are then oriented so the longitudinal direction is perpendicular to the core’s corrugations, and attached to the core, which is held in its flat, neutral configuration (i.e. the panel has no overall curvature).

Figure 1. Design concept for a two-way, shape-reversing, structural element based on shape memory materials exhibiting a oneway shape memory effect only.
If the upper face sheet is then heated to its austenite start temperature \(A_s\), it begins to contract, recovering the previously imposed tensile elongation as the temperature approaches \(A_f\). The heated face sheet is referred to as the active face sheet, the unheated face as the inactive face sheet. The core is designed such that, as the active face sheet contracts in the longitudinal direction, an equal, but opposite (tensile) stress is imposed upon the inactive face sheet. Since the yield strength of the austenitic phase is much greater (roughly a factor of five in the case of Ni-Ti) than the stress required to induce the martensitic transformation in the inactive face sheet, the inactive face further elongates to nearly its expected shape memory strain. Since the core is designed to resist compression in the longitudinal direction (i.e. to withstand the force required to deform the inactive face sheet), contraction of the active face causes the panel to become curved, with the active face sheet towards the center of curvature. Once the active face sheet has cooled to below the austenite start temperature, the opposite face sheet is heated to \(A_f\), causing the panel to reverse its curvature. Alternate heating and cooling of the face sheets thus allows the panel to be cycled between the two shapes as shown in Fig. 2. The frequency of cycling is limited by the rate of cooling of the active face sheet in the case of natural cooling, but could be accelerated by forced cooling, and as pointed out by Bart-Smith et al\(^9\), by arranging for the face sheet’s quiescent temperature to be close to \(A_s\).

![Figure 2. Alternate heating (and cooling) of the SMA face sheets enables the structural actuator to cyclically reverse shape between two limiting configurations.](image)

Optimal performance is obtained by maximizing the shape change or actuation force, and/or cycling frequency of the panel, while minimizing total weight. Constraints on the design are that it must not fail due to buckling or plastic yielding (of face sheet, core sheet or truss member). An analysis of these performance attributes is developed in the following section and applied to identify some design guidelines. The results are compared with preliminary experimental results in Section 4.

### 3. ANALYSIS

The proposed shape-morphing structural panel must be able to perform useful work against specified actuation loads, displacements (or curvature) and displacement rates. The optimal design will satisfy these performance requirements at the lowest weight and power consumption. It may also be required that the structure be able to cycle its shape at a specified minimum frequency. An analysis of the structure illustrated in Fig. 1 is developed to address such design issues. The analysis considers a cantilever beam of length, \(L\), overall height, \(h\), and width, \(B\).

#### 3.1 Actuator Displacement

When the top face of the cantilever beam shown in Fig. 1 is heated to \(A_f\) the face will contract by an amount given by \(\Delta L = -\varepsilon_{\alpha\beta}L/2\), where \(\varepsilon_{\alpha\beta}\) is the shape memory strain. As the top face contracts, the bottom face sheet is deformed in tension by the same amount (provided core failure does not occur). The stress needed to deform the bottom (inactive) face sheet is given by \(\sigma_{\alpha\beta}\), the austenite to martensite (\(\alpha \rightarrow \beta\)) transformation stress (Fig. 3). The core, including the central
core sheet, remains undeformed (except for elastic strains, which are much smaller than $\varepsilon_{\alpha\beta}$), and so, with no externally applied forces, the beam’s curvature is $\kappa = 2\varepsilon_{\alpha\beta}/h$. From the geometry, it follows that the tip displacement

$$\delta_0 = \frac{h}{2\varepsilon_{\alpha\beta}} \left( 1 - \cos \left( \frac{2\varepsilon_{\alpha\beta} L}{h} \right) \right)$$

Eqn. (1) approximates reasonably well to $\delta_0 = \varepsilon_{\alpha\beta} L^2/h$, for $h/L > 0.1$, from which it is seen that actuator displacement is increased by designing thinner, longer beams using SMA face sheets having a high transformation strain.

If an external load, $N$, is applied to the end of the beam (as shown in Fig. 1), the tip displacement is $\delta = \delta_0 - \delta_F$, where the forced displacement, $\delta_F$, is

$$\delta_F = \delta_{\text{bend}} + \delta_{\text{shear}} = \frac{NL^3}{3(EI)_{eq}} + \frac{NL}{(AG)_{eq}}$$

Here, $(EI)_{eq}$ and $(AG)_{eq}$ are the equivalent flexural and equivalent shear rigidity, respectively. Assuming $t_f/h \ll 1$ and that the bending stiffness of the core alone is negligible, then the flexural rigidity is dominated by the bending moment of the faces about the centroid of the sandwich beam, so that $(EI)_{eq}$ becomes $(EI)_{eq} = Bt_f E_f h^2/2$ 10, where $E_f$ is the elastic stiffness of the face sheet. The shear rigidity is given by $(AG)_{eq} = BhG_c(\theta)$ 11, again assuming thin face sheets, and where $G_c$ is the transverse shear stiffness. The transverse shear stiffness for the truss-core sandwich of Fig. 1 is given by

$$G_c = 2E_c \left( \frac{t_f}{h} \right) \sin^2 \theta \cos \theta$$

where $E_c$ is the elastic stiffness of the truss members, and achieves a maximum at a corrugation angle of $\theta = 54.7^\circ$. 

Substituting expressions for $(EI)_{eq}$ and $(AG)_{eq}$ into Eqn (2), combining with the net displacement relation, and normalizing by the length, $L$, leads to

![Stress-strain-temperature plot illustrating the one-way shape memory effect in the Ni-Ti SMA. At room temperature, stressing to $\sigma_{\alpha\beta}$ results in perfectly plastic behavior while the austenite phase ($\beta$) transforms to martensite ($\alpha$). A plastic “shape memory” strain ($\varepsilon_{\alpha\beta}$) remains after unloading. Heating to the austenite start temperature ($A_s$) and to $A_f$, the austenite finish temperature results in reversion of martensite to austenite and a consequent recovery of the shape memory strain.](image)
Eqn. (4) can be used to find the aspect ratio \( h/L \) providing the maximum displacement possible for a given applied load. (The core sheet and truss are taken to be the same material, so \( E_c \) is also the stiffness of the core sheet.) Figure 4 illustrates the dimensionless tip displacement predicted by (4) as a function of the beam’s aspect ratio \( h/L \) and the applied load \( N \). Failure (by face sheet yielding) occurs at higher beam aspect ratio with increasing applied load.

\[
\frac{\delta}{L} = \varepsilon_a \left( \frac{h}{L} \right)^{-1} - \left( \frac{2N}{3Bt_fE_c} \frac{h}{L} \right)^2 + \frac{N}{2Bt_fE_c \sin^2 \theta \cos \theta}
\]

Figure 4. Predicted displacement capacity as a function of beam geometry (aspect ratio, \( h/L \)) and applied force (units of \( N \)). Increasing applied force at decreasing aspect ratio leads to failure of the element by face sheet yielding.

### 3.2 Input Power Requirement and Peak Cycling Frequency

The frequency with which the structural SMA panel can alternate between its two limiting shapes is dependent on the rate of heat transfer into and out of the SMA faces. We consider the case in which the SMA face sheets are heated resistively by directing current \( I \) through the sheets. The power \( P \) supplied is then \( P = I^2 R \), where \( R \) is the resistance in ohms. Also, it is assumed that the core is isolated from the face sheets, so that the core is not resistively heated and to minimize heat loss by conduction to the core. Following Lu et al\(^7\), the governing heat transfer equation for the heating portion is

\[
\rho_f c'_f \frac{\partial T}{\partial t} = k_f \frac{\partial}{\partial x} \left( \frac{2h}{L} \right) (T - T_0) + \sigma_p \left( \frac{I}{Bt_f} \right)^2 + \frac{\rho_f B L t_f \Theta}{\Delta t}
\]

where \( \rho_f \) is the face sheet density, \( c'_f \) is the specific heat capacity, \( k_f \) is thermal conductivity, \( h \) is the surface heat transfer coefficient, \( \sigma_p \) is the resistivity, and \( \Theta \) is the latent heat associated with the martensitic phase transformation. The terms on the RHS of Eqn. (5) represent, from left to right, the energy absorbed in raising the face sheet temperature, losses to due convective heat transfer (radiative losses are neglected), energy supplied by Joule heating, and the latent heat of phase
change. Eqn (5) can be simplified by observing that the latent heat term is negligible compared to the Joule heating term. Also, since we can neglect any convective heat loss through the face sheet’s edges (given their relatively small surface area), we obtain

\[ \rho_f c_p \frac{\partial T}{\partial t} = -\frac{2\hat{h}}{t_f} (T - T_0) + \sigma \left( \frac{I}{(Bt_f)} \right)^2 \]  

(6)

With the initial condition that \( T = T_0 \) for \( t = 0 \), for the first cycle, and \( T = T_1 \) at \( t = 0 \), for subsequent cycles, Eqn. (6) can be solved analytically for the face sheet temperature as a function of time during heating.

The cooling cycle is determined from Eqn. (6), less the Joule heating term:

\[ \rho_f c_p \frac{\partial T}{\partial t} = -\frac{2\hat{h}}{t_f} (T - T_0) \]  

(7)

with the initial condition: \( T = T_2 \) at \( t = 0 \). In solving Eqns. (6) and (7), it is assumed that convective heat transfer occurs equally from both sides of the faces sheets. The solution to (6) for the heating cycle is given by

\[ T(t) = T_0 + \frac{\sigma t_f}{2\hat{h} (Bt_f)} \left( \frac{I}{t_f} \right)^2 \left( 1 - e^{-\frac{t}{\tau}} \right) \]  

(8)

where the time constant, \( \tau \), is defined as \( \tau = \rho_f c_p t_f / (2\hat{h}) \). During subsequent heating cycles, the temperature is given by

\[ T(t) = T_0 + (T_1 - T_0) e^{-t/\tau} + \frac{\sigma t_f}{2\hat{h} (Bt_f)} \left( \frac{I}{t_f} \right)^2 \left( 1 - e^{-\frac{t}{\tau}} \right) \]  

(9)

The temperature during cooling is given by

\[ T(t) = T_0 + (T_2 - T_0) e^{-t/\tau} \]  

(10)

The frequency with which the temperature can be cycled between a lower limit, \( T_1 \), and an upper limit, \( T_2 \), is then

\[ \nu = \frac{1}{2} \left( \frac{\ln \frac{T_2 - T_0}{T_1 - T_0}}{\ln \frac{T_1 - T_0}{T_2 - T_0}} \right)^{-1} \]  

(11)
The effect of increasing input current on the cycling frequency can be seen from Fig. 5; at high current input, the cycling frequency saturates due to the dominance of the cooling rate. Thinner face sheets allow the frequency of cycling to be increased.

Figure 5. Predicted panel shape cycling frequency as a function of input current. Thinner face sheets lead to increased operation frequency through increased heating and (natural) cooling rates.

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<th>Value</th>
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<td>Resistivity ($\sigma_f$)</td>
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<td>Austenite finish temperature ($A_f$)</td>
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<td>Heat capacity ($c_p$)</td>
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<td>Heat transfer coefficient ($\tilde{h}$)</td>
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<td>Elastic modulus ($\alpha$-SMA)</td>
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4. EXPERIMENTAL

Several prototypes of the reversing actuator panel concept were built and tested. All of these have incorporated the core design illustrated in Fig. 1, and constructed using 304 stainless steel. Strips of 0.5” (12.5 mm) width were cut from 0.016” (0.4 mm) sheet, then either corrugated using a small brake or left flat. Corrugated stainless strips were then joined to both sides of a flat strip using a brazing process (brazing alloy Ni-25Cr-10P). The earliest prototypes relied on a high strength epoxy adhesive to join the SMA face sheets to the truss core. While the polymer adhesive acted to insulate the core both electrically and thermally from the face sheets during actuation, it was found that the shear strength of the adhesive joint was insufficient, leading to premature failure.

The current generation prototype, which has successfully demonstrated reversible shape-change, reinforces the adhesive with a threaded fastener. The core is held in place by the adhesive while holes are marked and drilled (using a CNC milling machine) for the fasteners (two per 12.5 mm wide core-face joint). The Ni-Ti face sheets were prepared by cutting 0.5”
(12.5 mm) x 4” (10 cm) strips from 0.0045” (0.11 mm) thick SMA sheet, and heating these to slightly above the \( A_f \) temperature (90°C). This ensures the elimination of any residual, stress-induced martensite. The next step is to attach the face sheets to the core. Two different approaches have been tried, both of which appear successful. The first method involves holding the core in a curved position (with a curvature approximating that which would be obtained during actuation of the completed panel), while the first face sheet is attached to the concave side. The core plus one face sheet is then bent (using a 3-point bend fixture designed for the purpose) until the fully reversed curvature is achieved. This elongates the attached face sheet, which deforms by the formation of stress-induced martensite, preparing it for contraction upon heating. Once the curvature has been reversed, the remaining face sheet (austenitic) is attached to the opposite side, which is now concave. Heating the first (stretched) face sheet will now reverse the beam’s curvature, elongating the second face sheet, forming martensite, enabling it to contract upon heating, thus reversing the panel’s curvature, and so on.

A second method offers the advantage of allowing the face sheets to be attached to the core in a flat position. The heat treated strips are first mounted in a tensile test machine and elongated at room temperature to a 2% tensile strain (or approximately one-half the SMA’s shape memory strain, \( \varepsilon_{\text{vB}} \)). Extra material may be included for gripping, which can be afterwards trimmed prior to attachment with the core. Both face sheets are then attached to the core, which is held in a flat position. The panel can be actuated by heating either face sheet. Regardless of the attachment method, care must be taken not to heat both face sheets at once. Even if failure of the panel is avoided, the panel’s actuation ability will be permanently impaired.

Prototypes prepared using both of the assembly processes described above have successfully demonstrated the two-way shape-reversing concept. Some preliminary experimental data for tip displacement (in one direction) as a function of applied load are presented in Fig. 6. The load was applied by attaching a free weight to the end of the cantilever, and lifted upwards by activating (heating) the upper face sheet. The length of the cantilever was 6.15” (156 mm), height 0.48” (12 mm) and width 0.48” (12 mm). The predicted tip displacement given by Eqn. (4) is also shown, with the shape memory strain (\( \varepsilon_{\text{vB}} \)) adjusted to provide approximate agreement with the observed zero-load displacement. While the predicted tip displacement (using Eqn. (4)) reflects a linear dependence of displacement on applied load, the data exhibit a more parabolic relationship. Several factors may have contributed to this discrepancy, including an apparent localized buckling failure of the central core sheet at the two highest applied loads.

Further experimental study is needed to fully assess performance and to suggest improvements for the next generation device. Current design issues include stress concentrations at face sheet-core joints (and in particular at the holes drilled through the face sheets), loss of heat by conduction into the core, and high currents needed to heat the faces by direct resistance.

Figure 6. Initial experimental results for tip displacement as a function of applied load; the non-linear behavior at the higher loads is the result of localized buckling failure of the central core sheet, and is not predicted by the model (Eqn. (4)).

* Stainless steel, slotted bolt (size #120, 0.034” dia.) with hex nut.
5. SUMMARY

A concept for a two-way, shape-reversing structural element (panel, beam) has been described, which relies on SMA components exhibiting the one-way shape memory effect only and uses no external bias mechanisms for shape reversal. The concept is based on incorporation of a lightweight core design exhibiting a combination of very low flexural rigidity and relatively high in-plane stiffness. A prototype structural element (cantilever beam) has been constructed using Ni-Ti SMA face sheets joined with a stainless steel truss core, and tested for shape-reversal and load actuation capacity. Tests of the prototype were able to successfully demonstrate the shape-reversing capability of the design, and to obtain a preliminary indication of its performance. An analysis of the structural actuator’s displacement and load capacity, power consumption and cycling frequency are developed to provide further design guidance.

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