Finite element simulation of a self-healing shape memory alloy composite

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Abstract

A self-healing, metal matrix composite reinforced by shape memory alloy wires is simulated using finite element analysis. A one-dimensional constitutive model for SMA behavior is implemented as a user-defined truss element in ABAQUS. The matrix is brittle and a mode I crack is allowed to propagate through the specimen upon loading. During the loading process the wires undergo a martensitic phase transformation, bridging the crack. To heal the composite, simple heating is required which reverse transforms the wires and brings the crack faces back into contact. When using pre-strained SMA wires for reinforcement, the reverse transformation of the wires during heating causes a closure force across the crack. The method to simulate cracking and “healing” behaviors of the composite allow assessment of the effects of component properties and composite geometry. The results shed light on design of self-healing composites using shape memory alloys.

Keywords: Shape memory alloy; SMA; Composite; Finite element; Self-healing

1. Introduction

Shape memory alloys (SMAs) have material properties which vary with applied stress, temperature, and load history. As such, they are uniquely suited for use in composites. For instance, pseudoelasticity allows SMAs to have extremely large, apparently elastic, strains, thus enabling SMA reinforcements to prevent fracture of a composite. Other applications exploit the shape memory effect in which SMA components return to a “remembered” size or shape when heated, leading to options for shape control of the composite.

The shape memory behavior is caused by a thermoelastic crystalline phase transformation between a high symmetry parent phase (austenite) and a low symmetry product phase (martensite)
This transformation is reversible and is a function of both stress and temperature as indicated in Fig. 1. For a typical NiTi shape memory alloy, the parent phase austenite exists as a cubic crystal lattice structure (Fig. 1a), and upon cooling with no applied load, it transforms to martensite. This phase has a lower symmetry and forms in a self-accommodated structure in which different variants of martensite form together in order to form zero distortion interfaces (habit planes) with the parent phase. The martensitic variants are crystallographically twin-related structures, i.e. of identical crystallographic structure, but with differing spatial orientation. When formed by cooling, all habit plane variants (typically 24 for a given system) appear equally and there is no macroscopic strain (Fig. 1b). Upon heating, the martensite undergoes a reverse transformation to austenite (Fig. 1a).

If the martensitic structure is mechanically loaded at constant temperature, the crystallographic twins will reorient to the particular variant favored by the orientation of the load: this process is called reorientation and results in a macroscopic strain (Fig. 1c). Further loading in different directions results in additional reorientation and changing macroscopic strain (Fig. 1d). Upon unloading, if the temperature is still low, the macroscopic strain remains. However the strain can be recovered upon heating back to the austenite phase, and this load–unload-heat-recovery cycle (path given by Fig. 1a–b–c–a) is often called “pseudoelasticity” or “superelasticity”.

These complex material behaviors necessitate complex macroscopic constitutive laws to capture material response to thermomechanical loading. Most of the early models were one-dimensional, including models by Tanaka et al. (1986), Pence (1994), Boyd and Lagoudas (1994), Brinson (1993) and Patoor et al. (1988, 1994). In one-dimensional models it is not necessary to consider all possible martensite variants explicitly and consequently these models have simpler analytic forms than three-dimensional models.

Actual physical systems are naturally three-dimensional although certain structures like wires or plates can be idealized as one- or two-dimensional structures. However current three-dimensional models are either not robust enough to adequately model all aspects of complicated shape memory behavior present in true three-dimensional situations (Auricchio et al., 1997; Qidwai and Lagoudas, 2000; Juhasz et al., 2002) or are too computationally intensive to be used for modeling entire structures (Gao et al., 2000; Patoor et al., 2000). The modeling approach used in this paper combines a one-dimensional SMA model with a more general model for the rest of the structure to enable the simulation of a composite which is not one-dimensional and which displays full thermo-mechanical SMA behavior.

One-dimensional constitutive models for SMAs are particularly relevant because there are many applications using SMA wires or ribbons in which the SMA material behavior is primarily one-dimensional. In many of these applications, the SMA components act mainly by a change in their length with no significant non-uniaxial forces, so a one-dimensional model captures their essential actions. A number of different types of SMA composites use SMA wires or ribbons embedded in a matrix. Matrix materials that have been used include polymers (Sittner et al., 2002; Sun et al., 2002b), metals (Armstrong, 1996; Song et al., 1999; Yue and Wan, 2002).
present a modeling strategy that can fully describe this type of self-healing composite and thus provides a tool to optimize material parameters and composite design.

In contrast to the special composite user elements, which would have to be reformulated for different composite characteristics, in this paper the SMA wires and elastic–plastic matrix material are modeled separately. Thus the method can be easily adapted for different composites: the material properties of the matrix and the wires and the locations and positions of wires can all be changed independently without reformulation of the constitutive model for the whole composite. Other studies, which used separate elements for the SMA wires, implemented a simpler form of the SMA constitutive law which does not permit SMA in the twinned martensite state (Lee et al., 1999; Lee and Lee, 2000). The work here implements a SMA constitutive law with robust kinetics to allow full implementation of the range of SMA behaviors shown in Fig. 1.

Some experimental studies have examined the phenomenon of matrix crack formation and closure by SMA wires (Shimamoto et al., 2001; Hamada et al., 2003), but few studies have attempted to simulate the behavior using numerical methods (Araki et al., 2002). The work by Araki et al. is performed using a homogenization micromechanical approach using eigenstrains for the transformation strains in the SMA inclusions. The work considers crack bridging, but not healing, and thus differs significantly from the work here. To the authors’ knowledge, this work represents the first study of self-healing SMA composites. In addition, the numerical implementation of the SMA constitutive law exceeds previous work in ability to address the full space of SMA transformation/reorientation behavior and has general application to adaptive stiffening, shape control and other SMA composite behavior.

In the following sections of the paper, we present first the constitutive model used for the SMA elements, then the finite element modeling strategy and results, including specific examples of crack propagation, and healing.

2. SMA constitutive model

The SMA constitutive model used is based on a model originally formulated by Tanaka et al. (1986), and modified by Liang and Rogers (1990)
and subsequently by Brinson (1993), Brinson and Huang (1996), Bekker and Brinson (1998). The one-dimensional model is based on phenomenological macro-scale constitutive behavior and can be written as

$$\sigma = E(e - e_L \xi_S) + \Theta \Delta T$$  \hspace{1cm} (1)

where $\sigma$ is stress and $e$ is strain; $\xi_S$ is the stress-induced martensite fraction, $E$ is the elastic modulus, $e_L$ is the maximum transformation strain, and $\Theta$ is related to the thermal coefficient of expansion for the material.

Coupled to the constitutive law, a kinetic law must be used to determine the martensite volume fraction based on the stress and temperature loading history. The transformation criteria can be represented on an experimentally determined phase diagram shown in Fig. 2. The kinetic law used in the simulations for this paper includes both twinned and detwinned martensite variants (Brinson, 1993), as is essential to properly handle the issue of martensitic variant reorientation. The kinetics are further enhanced to consider the full thermomechanical history implemented through “switching points” for changes in load path direction (Bekker and Brinson, 1998). This allows the model to appropriately model hysteresis effects in the phase transformation and to capture cyclic or repetitive loading conditions, under which many kinetic laws fail. The reader is referred to the previous work for a full explanation and examples of the algorithms. Only a brief synopsis is presented here for transformation between the [M] and [A] regions.

Whenever the thermomechanical state of the SMA material enters the shaded areas on the diagram of Fig. 2, $\xi_S$ must be updated. The thermomechanical path can be complex and the kinetic algorithm described here to update $\xi_S$ is able to consistently reproduce the path dependence of martensitic transformation. Note in Fig. 2 that the normal vectors $n_A$ and $n_M$ represent the directions of transformation change in the [A] and [M] strips respectively. At any point on the path, $\tau$ is the vector tangent to $\Gamma$. A transformation occurs whenever one of the following conditions is satisfied:

(a) $\tau \cdot n_A > 0$ in [A]
(b) $\tau \cdot n_M > 0$ in [M]

A given loading path $\Gamma$ can be subdivided into several segments ($\Gamma_n$, $n = 1, 2, \ldots$) by introducing the switching points, defined as the points where the direction or sense of the transformation changes. The switching points are points where $\Gamma$ enters or leaves the transformation strip in the direction of transformation (point A) or points inside the strip where the dot product between $\tau$ and $n_A$ or $n_M$ changes sign (points B, C, D). Along the portions of $\Gamma$ between two switching points, $\xi_S$ is either monotonically increasing or decreasing (when in a transformation strip and moving in a transformation direction, e.g. between A and B or C and D) or constant (when outside a transformation strip or when moving opposite to the transformation direction, e.g. between B and C, or along any portions of $\Gamma$ outside of the segment A–D).

Bekker and Brinson (1998) present three ways to formulate the local kinetic law, one of which is utilized here. We first define $Y^i = Y(T, \sigma)$, $(i = A, M)$ as the normalized distance between a given point on $\Gamma$ inside a transformation strip and the start boundary. $Y^i$ is given by the following expression

$$Y^i = \frac{\rho^i}{\rho_0}$$  \hspace{1cm} (3)

where $\rho^i$ is the distance of point $(T, \sigma)$ from the start boundary, and $\rho_0$ is the width of the strip. Fig. 2 illustrates these quantities for the case of the [M] strip.
On a given portion \( \Gamma_n \) between two switching points, \( \xi_S \) can then be updated using the appropriate one of the following expressions:

\[
\xi_S = \xi_{S,j} f^A(Y^A - Y^j_A) \quad (4)
\]

when the point is inside the [A] strip, and

\[
\xi_S = \xi_{S,j} + (1 - \xi_{S,j}) f^M(Y^M - Y^j_M) \quad (5)
\]

when the point is inside the [M] strip.

In the forgoing expressions, quantities marked with subscript \( j \) are the values of the martensite fraction and the normalized distance at the previous switching point relevant to the current transformation, \( \xi_S \) is the stress-induced martensite fraction, and \( f^j \) are interpolation functions. Here cosine interpolation functions are used, equivalent to those originally developed by Liang and Rogers (1990):

\[
f^A(Y^A - Y^j_A) = 1 - \frac{1}{2} \{1 - \cos[\pi(Y^A - Y^j_A)]\} \quad (6)
\]

\[
f^M(Y^M - Y^j_M) = \frac{1}{2} \{1 - \cos[\pi(Y^M - Y^j_M)]\} \quad (7)
\]

The kinetic law and the constitutive law presented here have been developed and implemented successfully for one-dimensional SMA response. The Brinson model has been tested and found to be an excellent SMA model for modeling SMA wire reinforced composite structures (Zak et al., 2003b).

### 3. SMA composite: finite element model

The composite that is modeled consists of a brittle metal matrix reinforced by parallel SMA wires. This composite formulation is motivated by a self-healing composite demonstrated by the Olson group (Files, 1997; Forbell et al., 1997). In this prototype composite, bonding between SMA wires and matrix was quite poor such that the wires had to be knotted/constrained at the outside edges to keep them from slipping out (Files, 1997). Other composites lack bonding between the wires and matrix due to the nature of the wire embedding. For example, researchers have fabricated a composite in which the wires run in sleeves embedded in the matrix (Sun et al., 2002b). It is noted that bonding between SMA wires and composite matrix material has been problematic in many cases (Lau et al., 2002). A paper by Jonnalagadda et al. (1997), examined different wire surface treatment strategies to attempt to achieve better bonding in a composite, noting that debonding of the SMA wire and matrix is common. With this motivation, in the composite model considered in this paper the wires are not bonded to the matrix along their length, and are fixed only at the outside edges of the matrix. The composite model is rectangular and clamped on the ends as shown in Fig. 3. It is loaded in the direction of the wires and allowed to crack in a line perpendicular to the wires.

The matrix material properties are similar to those of the material used in a prototype composite. The material is elastic–plastic with hardening and temperature-dependent softening. It is brittle at room temperature, but ductile at high temperature, as indicated in Fig. 4. At low temperature, the matrix fractures at 60 MPa, shown by an "x" on the plot. The matrix softening at high temperature enables the crack to fully close when the wires pull the crack back together. In the prototype composite realized by the Olson group, the matrix softened sufficiently upon heating to allow rewelding of crack faces in contact. The rewelding is not modeled in the current paper. The Poisson ratio for the matrix is taken as 0.3. The thermal expansion effects are small in comparison to the shape memory effect and thus are removed from the simulation by setting \( \alpha \) for both the matrix and the wires to 0.

The wires have standard NiTi properties taken from the literature (Dye, 1990; Liang, 1990; Brinson and Lammering, 1993) as shown in Table 1. The overall model has a cross-section of 30 mm² and a width of 6 mm. The model has five evenly spaced reinforcement wires, so that the wires are spaced

![Fig. 3. Schematic of self-healing composite showing SMA reinforcing wires, propagating crack and healed composite after heating.](image-url)
In preliminary studies, it was found that increasing the density of the wires had the expected effect of proportionally increasing the closure force upon heating. The wires have cross-sections of 0.05 mm², representative of wires with a 0.252 mm diameter. The initial temperature for the simulations is midway between the martensite start and austenite start temperatures, and the wires are initially 100% austenite for the simulations shown.

ABAQUS, a commercial general-purpose finite element analysis code, is used to run the simulations. The matrix is modeled with linear plane strain elements and the SMA wires are modeled with user-defined 2-node truss elements. The analyses are all quasi-static. For models in which matrix cracking is allowed to occur, there is a small notch in the middle of one edge to initiate the crack. At this notch, the contact surfaces are initially unbonded for the length of one element edge (0.1 mm for a 60 × 60 mesh). In ABAQUS, crack propagation is implemented as a contact option where surfaces that are initially bonded are allowed to debond when a specified fracture criterion is satisfied. In the models analyzed here, a line of potential debonding is defined to run perpendicular to the wires down the middle of the specimen due to the symmetry of the problem. The crack-tip node is allowed to debond when the local stress at the crack tip reaches the critical value of 60 MPa. This type of critical stress criterion is typically used for crack propagation in brittle materials (ABAQUS/Standard User’s Manual, Version 6.3, 2002).

Since the prototype composites were uniformly heated in an oven for healing, the simulations use a uniform temperature field during the healing process. Heat transfer in the matrix is not considered. The loading of the composite and the subsequent heating are performed quasi-statically. Thus, latent heat of transformation of the SMA wires is also not considered. Given the quasi-static loading conditions, the uniform oven heating and the thermally conductive matrix material, latent heat effects would be very small. It should be noted that if the composite were to be actuated by resistive heating of the SMA wires, heat transfer effects would be critical and would be essential in simulations. Such an actuation process would thus place significant constraints on geometric spacing of the SMA wires to ensure complete crack closure due to the non-uniform temperature field.

A user element (UEL) was written to calculate the behavior of SMA wires. Details of the UEL formulation can be found elsewhere (Gao et al., in preparation). The constitutive law described in the previous section is used and implemented in this UEL to provide accurate SMA response for conditions of martensite reorientation, inverse transformation, and including proper response under small compressive loads that might be realized in an application. The SMA elements are 2-node truss elements which can be positioned in three-dimensional space and here simply run in straight lines down the composite as shown in Fig. 3.

### 4. Results

In this section, we demonstrate the response of the self-healing SMA composite in two primary

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**Table 1**

Material properties for the Nitinol alloy used in the simulations (Dye, 1990; Liang, 1990; Liang and Rogers, 1990)

<table>
<thead>
<tr>
<th>Moduli, density</th>
<th>Transformation temperatures</th>
<th>Phase diagram parameters</th>
<th>Max residual strain, Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_A = 67 \times 10^3$ MPa</td>
<td>$M_f = 9 , ^\circ C$</td>
<td>$C_M = 8$ MPa °C⁻¹</td>
<td>$\varepsilon_L = 0.067$</td>
</tr>
<tr>
<td>$E_M = 26.3 \times 10^5$ MPa</td>
<td>$M_t = 18.4 , ^\circ C$</td>
<td>$C_A = 13.8$ MPa °C⁻¹</td>
<td>$v = 0.3$</td>
</tr>
<tr>
<td>$\Theta = 0$ MPa °C⁻¹</td>
<td>$A_s = 34.5 , ^\circ C$</td>
<td>$\sigma^{\text{f}}_S = 100$ MPa</td>
<td></td>
</tr>
<tr>
<td>$\rho = 6448.1$ kg m⁻³</td>
<td>$A_t = 49.0 , ^\circ C$</td>
<td>$\sigma^{\text{f}}_f = 170$ MPa</td>
<td></td>
</tr>
</tbody>
</table>

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Fig. 4. Yield stress–strain relation for the matrix material at room temperature and elevated temperature. The critical fracture stress is indicated by an “x” on the low temperature plot. The inset shows the variation of the Young’s modulus changing linearly between 30 °C and 80 °C. The yield stress also varies linearly with temperature in the same range. See text for remaining matrix properties.
transform back to austenite. The plastic deformation of the matrix is greater than the increase in length of the wires due to detwinning, so after the load is released, the wires are in tension and the matrix is in compression. The model is then uniformly heated, and when the temperature is increased into the austenite transformation zone, the reverse transformation of the wires causes the wires to shrink and apply a compressive force to the matrix (Fig. 5c). The force of the wires causes a slight shortening of the specimen compared to its length after the initial load was removed.

Although the matrix softens during the heating, the matrix nevertheless resists the compression resulting in tensile stresses in the wires. Considering the path of wires in the phase diagram as shown in Fig. 6a, these tensile stresses result in a higher temperature being required for reverse transformation. Given the large plastic strain achieved by the matrix material and the number of SMA wires employed, the SMA wires are unable to fully transform back to austenite and cannot reverse the achieved matrix deformation within their operating range.

**4.1. Behavior with no cracking**

A preliminary case of a specimen without cracking was analyzed. In this basic case the model does not have any debonding capabilities, so that high loading levels cause transformation from the initial austenite to stress-induced (detwinned) martensite in the SMA wires and permanent plastic deformation of the matrix. Starting from a stress-free state of the matrix and the wires, a fixed displacement is applied to one end of the model to load the model to a strain level of 4.1%.

The loading case is shown schematically in Fig. 5, with (a) being the unloaded configuration and (b) the model at full displacement. Upon loading, the stress in the wires causes transformation of the SMA to detwinned martensite and the stress in the matrix causes plastic deformation of that component. When the fixed displacement is released, there is elastic recovery of both the matrix and the wires, but the plastic deformation of the matrix remains, and since the initial temperature is below the austenite start temperature, the detwinned martensite of the wires is stable and does not reverse

![Fig. 5. (a) Initial configuration, (b) after loading causes plasticity in matrix and transformation in wires and (c) after heating causes wires to shrink.](image)

![Fig. 6. (a) Loading path for uncracked composite overlaid on the phase diagram for the SMA wires. Composite is first loaded and unloaded at low temperature to achieve detwinned martensite in the wires and plastic deformation of the matrix. Heating then induces reverse transformation to austenite and increasing stress as the matrix resists the associated deformation. Cooling back to room temperature results in reformation of martensite. See text for details. (b) Change in stress-induced martensite volume fraction in response to stress and temperature loading.](image)
Consequently, the wires remain partially elongated with some detwinned martensite. When the composite is allowed to cool back to room temperature, the wires pass back through the martensitic transformation strip and thus reform detwinned martensite due to the tensile stress state as illustrated in Fig. 6b. As the wires elongate with this transformation, the stress drops as the temperature decreases, ultimately losing the recovered strain from heating, but retaining a small compressive clamping force on the matrix material. The loading path in Fig. 6a shows these transformation and stress effects.

These results are further illustrated in Fig. 7 where the response of the wires, matrix and the temperature are plotted versus time step. The changes in the wire stresses here can be clearly correlated with the associated temperature and martensite volume fraction. Notice that the martensite volume fraction decreases during heating, but increases again during the cooling step and is associated with the drop in clamping stress. This complex material response underscores the difficulty of designing with shape memory alloys and the need for effective modeling strategies to predict and understand material behavior.

4.2. Crack propagation simulation

To realize a self-healing composite, it is essential to achieve a clamping force from the SMA upon heating. Considering the example above, it is clear that with the matrix undergoing significant plastic deformation in the vicinity of the propagating crack, heating of the composite will not necessarily provide sufficient contraction force from the SMA wires upon reverse transformation to achieve clamping forces across the full width of the crack. Thus, in order to guarantee full crack closure, the embedded wires in the composite thus need to be pre-strained to contain some detwinned martensite when embedded in the composite.

In the example demonstrated here, the wires are pre-strained to an initial detwinned martensite fraction of 0.30 when unloaded to zero stress. The composite model containing pre-strained wires is then loaded by a fixed displacement of one end as shown in Fig. 3. As described above, a small notch defect is placed in this composite and material allowed to debond to simulate crack propagation when the stress at the crack tip reaches the prescribed failure stress. The critical stress to debond is taken as 60 MPa. The SMA wires accommodate the elongation by forming detwinned martensite and bridge the crack as it propagates. In the simulation presented here, the wires transform to a final fraction of 0.84 detwinned martensite. As the crack propagates, the area ahead of the crack tip is highly stressed and undergoes plastic deformation. The stress contours (Fig. 8) show that the highest stress occurs in two lobes on either side of the crack tip as expected.

Contour plots are shown in Fig. 9 for the area around the crack for selected snapshots of load history. After the crack propagates across the full width of the composite, the loading boundary condition of the end is released to allow the wires to recover elastically. Some residual stress due to the plastic deformation can be seen in Fig. 9b, which shows the von Mises stress contours.

When the entire model is heated, the wires reverse transform to austenite causing them to shorten and pull the fractured matrix halves back together. The crack faces that were the last to fracture are the first to come back into contact because that is where the most plastic deformation took place (Fig. 9c). With continued heating, the crack becomes fully closed and the matrix is compressed. At the end of heating, the residual stresses due to

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**Fig. 7.** Thermomechanical loading time history for uncracked composite. Wires embedded in matrix material start as austenite and develop martensite as the composite is loaded. After unloading, the composite is heated and then cooled back to room temperature to illustrate shape recovery features of SMA composite. See text for detail.
plastic deformation are almost completely reversed (Fig. 9d).

Similar to the uncracked model, the temperature must be raised to well above the austenite finish temperature to significantly transform the SMA wires to austenite. Fig. 10b illustrates that the martensite volume fraction decreases rapidly prior to the crack faces coming back in contact. Subsequently, the rate of inverse transformation decreases substantially due to the resistance of the matrix material. Considering the loading path on the phase diagram, Fig. 10a, the temperature-stress path moves diagonally upward through the austenite transformation zone after the crack faces contact. Thus, additional austenite formation occurs at a very slow rate (Fig. 10b).
Fig. 10. (a) Loading path for cracked composite overlaid on the phase diagram for the SMA wires. SMA wires are pre-strained to 30% detwinned martensite before history shown here. Composite is then loaded/unloaded at low temperature and a crack is allowed to fully propagate across the composite. The entire composite is uniformly heated to initiate self-healing and then cooled back to room temperature. See text for details. (b) Reverse transformation from detwinned martensite to austenite with increasing temperature. Decrease in rate of martensite volume fraction changes after crack faces touch and further recovery of austenite requires compression of the matrix.

Fig. 11 shows that for the SMA material properties used, the A and M zones intersect at high stress and temperature values. This intersection is physically reasonable and can be seen even at zero stress for some SMA materials in which $M_S < A_S$. A plasticity zone would occur at still higher stresses and temperatures, but this is not shown in the figure. In the simulation, the unloading occurs before the system reaches the region of the phase diagram with overlapping zones.

Fig. 11 shows the change in temperature, matrix yield strength, stress in the wires and martensite volume fractions on the same graph. The plots show nearly identical results for simulations starting from twinned martensite compared to starting from austenite, except of course for the temperature-induced martensite volume fraction. The slight differences in the stress in the wires and stress-induced martensite volume fraction are due to the different Young’s modulus values of martensite and austenite.

The matrix properties allow the material to soften at higher temperatures as motivated by the composites created by the Olson group (Files, 1997; Forbell et al., 1997; Bernikowicz, 1998; Kang et al., 2002). This softening enables the wires to fully close the crack upon heating and reverse much of the localized plasticity formed in the matrix during the fracture process. Without sufficient softening, the strong resistance by the matrix prevents the wires from closing the crack fully as shown in Fig. 12a. The figure also shows that when the crack does not fully close, more of the residual stress remains since the plasticity is not reversed. Fig. 12b explicitly demonstrates the impact of matrix softening on the crack opening at the healing temperature: matrix softening as shown in Fig. 4 results in complete crack closure, while less softening results in a partially open crack and the crack remains open across nearly the entire specimen in the case without matrix softening.

The high clamping forces attained by the wires in this heating stage are also critical in order to help heal the composite as the matrix partially flows and rewelds. As is seen in Fig. 10a, during cooling back to room temperature there is an initial increase in stress due to increasing matrix properties, followed by a decrease in stress as the austenite transforms to martensite. As shown in Fig. 11, during this cooling process the martensite fraction increases.
slightly, but the wires remain mostly austenitic and are able to exert a clamping force on the matrix material. The clamping force shown in Fig. 13 decreases significantly but is maintained.

With stiffer matrix materials, the loading path in Fig. 10a becomes nearly parallel to the zone boundaries, corresponding to an iso-martensite fraction path. In this case, little or no additional austenite is formed after the crack faces first touch at the bottom of the crack during heating. The resistance to closing is due to insufficient plastic deformation of the matrix during the heating stage to bring the upper faces of the crack back in contact, as seen in Fig. 12. In addition, although the stress still rises during heating, the residual clamping force after cooling is somewhat smaller than for a soft matrix. With use of the simulation tool presented here, we were able to determine appropriate matrix properties to allow self-healing of a cracked composite as shown in Fig. 9.

5. Conclusions

In this paper, a self-healing SMA composite is simulated via a finite element approach that allows crack propagation in a brittle matrix material. The
SMA wires are carefully modeled using a one-dimensional SMA constitutive model and implemented into user-defined truss elements. Loading of the composite allows a crack to propagate from an initiation site and the wires bridge the crack as detwinned martensite forms with the applied loading. Self-healing is initiated upon heating which causes reverse transformation of the wires, resulting in strain recovery. Results show that the wires are able to pull the crack faces back together to demonstrate healing under certain conditions. Use of prestrained SMA wires in the composite is critical for a closure force to develop and adequate matrix material softening is required during heating in order for the crack faces to heal across the full width of the crack.

An advantage of the simulation method developed here in which separate elements for the wires and matrix are used is that material properties or composite geometry can be changed easily. Other approaches in which special composite elements are developed which combine both SMA and matrix properties are more application specific. The flexibility of the current approach allows the technique to be used to explore design issues for a composite. This capability was illustrated here by selecting the appropriate matrix softening characteristics to allow self-healing to occur. This design tool can also be applied to general active SMA composite structures to investigate the effects of adaptive stiffening, vibration control and shape control.

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References


