Original Article

A novel failure analysis of SMA reinforced composite plate based on a strain-rate-dependent model: low-high velocity impact

Mengzhou Chang, Zhenqing Wang*, Wenyan Liang, Min Sun

College of Aerospace and Civil Engineering, Harbin Engineering University, Harbin 150001, China

1. Introduction

Fiber reinforced composites have been widely used in aerospace industry due to their unique properties: high stiffness, high strength and low density [1]. However, the low impact resistance in unidirectional cross-ply fiber/matrix laminates is the main limitation in applications. Obviously, the reason for this disadvantage can be traced to the low strength, stiffness between the adjacent layers during manufacturing process which will result in delamination and fiber breakage [2]. The overall property can be improved by adding new materials in matrix, such as short glass fiber and shape memory alloy (SMA).

As for short fibers, the mechanical properties of the composites are strongly influenced by the manufacturing process, such as injection position, sample geometry, pressure and temperature during molding [3,4]. Other factors that affect the mechanical properties, such as fiber location, length, diameter and orientation have been studied by Thomason [5–7]. Also, tensile strength (or elastic modulus) of samples machined perpendicular to mold flow direction are nearly 40% lower than that of samples machined parallel to mold flow direction [8,9].

* Corresponding author.
E-mail: wangzhenqing@hrbeu.edu.cn (Z. Wang).

https://doi.org/10.1016/j.jmrt.2018.06.012

2238-7854/© 2018 Published by Elsevier Editora Ltda. on behalf of Brazilian Metallurgical, Materials and Mining Association. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
As for SMA, it has been embedded in the adjacent layer for the reinforcement purpose considering their unique properties: changing shape (elastic modulus) in accordance with temperature and stress [10–12]. SMA has the ability to change shape, to repair damage and to improve impact property according to Sun’s experiment and Shariyat’s analysis [13,14]. However, the interfacial debonding between SMA and matrix has been found exists extensively in composite. It is still a key problem in the development of SMA reinforced composites [15].

The new structure bonding of the conventional fiber reinforced polymer with metal layer is also found has advantage of subjecting to impact loading [16]. Other structures, such as adding particle [17,18], sandwich plate [19–22] and 3D fabric [23,24], have been developed in recent year.

SMA reinforced composites has been studied in this paper. Several works relevant to low velocity impact of SMA reinforced composites taking the assumption of uniform distribution of martensite phase in SMA has been founded [25,26]. Along with modified linearized Hertz contact law and Brinson’s model of SMA, Shariyat and his co-authors have proposed several theory to analysis preload effect, impact response and forced vibration of SMA reinforced composites, such as mixed order hyperbolic global-local plate theory [14,18–21]. Strain rate shows significant effect on SMA which may change phase transform process [27]. As for Glass/Epoxy composite, both strengths and modulus at tensile, compressive and in plane shear case are increased generally under higher strain rate [28–30]. However, theoretical models relating low-high velocity have rarely discussed due to the difficulties associated with the face-face contact in simulation (between SMA and matrix; fiber and matrix).

The highlight of our work is to introduce an interphase part with reasonable volume fraction rather than two surfaces. Embedding visco-hyperelastic theory in this part to characterizing the effect of strain rate, the rest of the elements can be regarded as single material. Numerical simulations of tensile tests and pull-out tests of SMA reinforced composite has been conducted to verify the accuracy of the model by comparing with experimental data. Furthermore, Finite element analysis has been presented to evaluate the effect of velocity on the impact resistance of SMA reinforced composites.

## 2. Mechanics of material models

The whole system is consisted by three phases: matrix, reinforce and interphase.

### 2.1. Mechanical property of the three phases of composites

#### 2.1.1. Mechanical property of matrix

For most matrix, taking epoxy resin as an example, a nearly linear elastic behavior can be founded:

\[
\epsilon_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \tag{1}
\]

\[
\sigma_{m,ij} = 2G_m\epsilon_{ij} + \lambda_m\epsilon_{kk}\delta_{ij} \tag{2}
\]

where \(u, \varepsilon\) and \(\sigma\) are displacement, strain and stress (\(\{i, j = x, y, z\}\) are the reference coordinates \(X_i\), respectively. \(\lambda_m = E_m\mu_m / (1 + \mu_m)(1 - 2\mu_m)\) is the Lame’s constant, and \(G_m = E_m / (2 + \mu_m)\) is the shear modulus, \(E_m\) and \(\mu_m\) are the elastic modulus and Poisson’s ratio, \(\delta_{ij}\) is the Kronecker delta (\(\delta_{ij} = 1\) if \(i = j\), and \(\delta_{ij} = 0\) otherwise).

#### 2.1.2. Mechanical property of reinforce

Differently, mechanical property of reinforce is complicated due to the difference between the materials used. A similar stress–strain relationship as Eq. (2) can be observed if the reinforce is isotropic elastic, taking glass fiber as an example. However, the constitutive model of SMA is sensitive to temperature. Brinson’s model [11,12] has been referred to most often in subsequent studies reported in the literature. Here, the constitutive law of SMA based on energy balance equations is derived considering the effects of temperature \(T\) and phase conversion between martensite and austenite can be denoted as:

\[
d\sigma_m = E_m (\varepsilon_m, T) d\varepsilon + \Omega (\varepsilon_m, T) d\varepsilon + \Theta (\varepsilon_m, T) dT \tag{3}
\]

where \(\sigma_m\) and \(\varepsilon_m\) are the Piola–Kirchhoff stress and Green strain of SMA; \(\xi\) is the martensite fraction charactering the phase conversion; also, \(E_m, T, \Omega, \Theta\) are the elastic modulus, transformation coefficient and thermal coefficient.

To simplify the application, some assumptions are taken as follows: the elastic modulus is a function of martensite fraction \(\xi\); the transformation function is also connected with elastic modulus:

\[
E_m (\xi, T) = E_a + \xi (E_m - E_a) \tag{4a}
\]

\[
\Omega (\xi) = -\xi E_a (\xi) \tag{4b}
\]

where \(E_a\) and \(E_m\) are elastic modulus for pure martensite and austenite state, \(\xi_1\) is the maximum residual strain. The temperature and stress determined equations of phase conversion between martensite and austenite can be expressed as:

(a) Phase conversion to martensite

\[
T > M_s \text{ and } \sigma_{mT} > C_m (T - M_s) < \sigma < \sigma_{mT} + C_m (T - M_s)
\]

\[
\xi_m = \frac{1 - \xi_0}{2} \cos \left( \frac{\pi}{\sigma_{mT} - \sigma_m} (\sigma - \sigma_m - C_m (T - M_s)) \right) + \frac{1 + \xi_0}{2} \tag{5a}
\]

\[
\xi_T = \xi_m - \frac{\xi_m}{1 - \xi_m} (\xi_s - \xi_0) \tag{5b}
\]

(b) Phase conversion to austenite

\[
T < M_s \text{ and } \sigma_T < \sigma < \sigma_{mT}
\]

\[
\xi_m = \frac{1 - \xi_0}{2} \cos \left( \frac{\pi}{\sigma_{mT} - \sigma_{mT}} (\sigma - \sigma_{mT}) \right) + \frac{1 + \xi_0}{2} \tag{5c}
\]

\[
\xi_T = \xi_m - \frac{\xi_m}{1 - \xi_m} (\xi_s - \xi_0) + \Delta T \tag{5d}
\]

\[
\Delta T = \begin{cases} 
\frac{1 - \xi_0}{2} \cos \left( \frac{\pi}{a_m (T - M_s)} \right) + 1 : M_f < T < M_s \text{ and } T < T_0 \\
0 : \text{else}
\end{cases} \tag{5e}
\]
(b) Phase conversion to austenite

If \( T > A_s \) and \( C_a \left( T - A_f \right) < \sigma < C_a \left( T - A_s \right) \)

\[
\xi = \frac{\xi_0}{2} \left\{ \cos \left[ a_2 \left( T - A_s - \frac{\sigma}{C_a} \right) \right] + 1 \right\}
\]

\[\xi = \xi_0 - \frac{\xi_0}{2} \left( \xi_0 - \xi \right)\]

\[\xi_0 = \xi_0 - \frac{\xi_0}{2} \left( \xi_0 - \xi \right)\]

In Eqs. (5) and (6), parameters \( a_m = \pi / \left( M_s - M_f \right) \) and \( a_s = \pi / \left( A_f - A_s \right) \). Four important parameters are introduced to characterize the phase conversion temperature: \( M_s \) – start temperature of martensite phase; \( M_f \) – finish temperature of martensite phase; \( A_s \) – start temperature of austenite phase; \( A_f \) – finish temperature of austenite phase. The stress-strain relationship at any temperature \( T \) can be obtained according to Eqs. (3)-(6).

2.1.3. Mechanical property of interphase

A clear visco-hyperelastic behavior has been observed in composite materials according to our previous work [31]. In a completely analogous manner, we can derive an expression relating stress \( \sigma_{m,j} \) to strain in a sample that has experienced some continuous strain history given by the function \( \varepsilon_{m,j} \):

\[
\sigma_m (t) = \int_0^t g (t - t') \varepsilon_{m,j} (t') \, dt'
\]

or \( \sigma_m (t) = \int_0^t M (t - t') \varepsilon_{m,j} (t') \, dt' \)

where \( g \) (or \( M \)) is relaxation modulus, \( t' \) is new time variable, \( \varepsilon_{m,j} (t) = d\varepsilon_{m,j} (t') / dt' \) is strain rate. Using the Boltzmann superposition principle, the stain history \( \varepsilon_{in} \) can be calculated. Also, the relaxation modulus \( g \) can be expressed using discrete relaxation spectrum as follows:

\[
g (t) = g_0 + \sum_{i=1}^n g_i \varepsilon^i
\]

where \( g_0, g_i \), and \( t_i \) are the related parameters which can be obtained from relaxation tests.

2.2. The modified Hashin’s failure criterion

Hashin’s failure criterion accounts for fiber failure and matrix failure is embedded in ABAQUS using subroutine. Two failure models are considered for fiber: tensile failure and compressive failure, the damage variables can be expressed as [32]:

Tensile failure of fiber,

\[
d_{f} = 1 : \begin{cases} \left( \frac{\sigma_{11}}{X_T} \right)^2 + \left( \frac{\sigma_{12}}{X_{12}} \right)^2 & \geq 1 \\ \sigma_{11} > 0 \end{cases}
\]

Compressive failure of fiber,

\[
d_{c} = 1 : \begin{cases} \frac{\sigma_{11}}{X_C} \geq 1 \\ \sigma_{11} < 0 \end{cases}
\]

Similarly, tensile failure and compressive failure of matrix can also be obtained [33,34].

Tensile failure of matrix,

\[
d_{mt} = 1 : \begin{cases} \left( \frac{\sigma_{11}}{Y_T} \right)^2 + \left( \frac{\sigma_{12}}{Y_{12}} \right)^2 + \left( \frac{\sigma_{22}}{Y_T} \right)^2 + \frac{\sigma_{22}^2 + \sigma_{22}^2}{Y_C} \geq 1 \\ \sigma_{22} + \sigma_{23} > 0 \end{cases}
\]

Compressive failure of matrix,

\[
d_{mc} = 1 : \begin{cases} \left( \frac{\sigma_{11}}{Y_T} \right)^2 + \left( \frac{\sigma_{12}}{Y_{12}} \right)^2 \geq 1 \\ \sigma_{22} + \sigma_{33} < 0 \end{cases}
\]

Using the damage variables and the related parameters, stress is decreased linearly to zero once the failure criterion is reached. The stiffness coefficients should be re-calculated at damage state, as:

\[
c_{11} = E_1 \left(1 - \psi_{23} \psi_{32} \right) \Gamma \left(1 - d_f \right)
\]

\[
c_{22} = E_2 \left(1 - \psi_{13} \psi_{31} \right) \Gamma \left(1 - d_f \right) \left(1 - d_m \right)
\]

\[
c_{33} = E_3 \left(1 - \psi_{12} \psi_{21} \right) \Gamma \left(1 - d_f \right) \left(1 - d_m \right)
\]

\[
c_{12} = E_2 \left(\psi_{21} + \psi_{31} \psi_{23} \right) \Gamma \left(1 - d_f \right) \left(1 - d_m \right)
\]

\[
c_{13} = E_1 \left(\psi_{31} + \psi_{21} \psi_{32} \right) \Gamma \left(1 - d_f \right) \left(1 - d_m \right)
\]

\[
c_{24} = G_{12} \left(1 - d_f \right) \left(1 - s_{mt} \psi_{mt} \right) \left(1 - s_{mc} \psi_{mc} \right)
\]

\[
c_{55} = G_{23} \left(1 - d_f \right) \left(1 - s_{mt} \psi_{mt} \right) \left(1 - s_{mc} \psi_{mc} \right)
\]

\[
c_{66} = G_{13} \left(1 - d_f \right) \left(1 - s_{mt} \psi_{mt} \right) \left(1 - s_{mc} \psi_{mc} \right)
\]

\[
\Gamma = 1 / (1 - \psi_{12} \psi_{21} - \psi_{23} \psi_{32} - \psi_{13} \psi_{31} - 2 \psi_{21} \psi_{32} \psi_{13})
\]

where \( s_{mt} \) and \( s_{mc} \) are the factors that control reduction in shear stiffness according to tensile and compressive failure, respectively. Parameters \( d_f = 1 - (1 - d_f) (1 - d_c) \) and \( d_m = 1 - (1 - d_m) (1 - d_mc) \) are the global damage variables characterizing fiber and matrix, respectively.

In fact, the relationship between stress and strain during entire damage process can be expressed as:

\[
\sigma_{ij} (t) = H \left( \varepsilon_{ij}, t \right)
\]

where \( H \) is equivalent function of Hashin’s failure criterion, obviously, affected by parameters X, Y and S. As for interphase, the values of X, Y and Z are also influenced by time, this behavior is further studied in Section 3.2.
where \( S \) and \( n \) are the area of cross section and the number of fibers, respectively. The comparison is carried out to decide the two phase system is appropriate. If a large error is found between the simulation results and experimental results, then a three-phase system is needed in finite element analysis (adding interphase). Volume fractions of the three phase system, \([\nu]\), are as follows:

\[
[\nu_1]_3 = \frac{\pi nr^2}{S} = [\nu_1]_2 \times k^2_m
\]

(16a)

Fig. 1 – (a) Two phase system of the composite. (b) Three phase system of the composite.

Fig. 2 – An algorithm for estimation of interphase parameters.

2.3. Homogenization method for the multi-phase system

Considering the two phase system generally used in simulation: reinforce and matrix, cohesive zone model is embedded in the elements between reinforce and matrix [35], as shown in Fig. 1a. A bilinear cohesive law is employed to simulate the interfacial behavior in Section 3. The new material property ‘interphase’ is introduced in the investigation, as shown in Fig. 1b.

A clear distinguish are needed to characterizing the real size of reinforce in two phase system, taking fiber as an example, \( R_f \) is radius of pure material. The process extending two phase system to three phase system is shown in the flow chart (Fig. 2).

Two important assumptions are adopted in long fiber reinforced composite: (a) fibers are distributed uniformly in the matrix; (b) mechanical property of fiber and matrix are both homogeneous isotropic. The reinforce volume fraction in two phase system [12] can be expressed as:

\[
[\nu_1]_2 = \frac{\pi nr^2}{S} < \frac{\pi}{4}; \quad [\nu_m]_2 = 1 - [\nu_1]_2
\]

(15)

where \( r \) and \( n \) are the area of cross section and the number of fibers, respectively. The comparison is carried out to decide whether the two phase system is appropriate. If a large error is found between the simulation results and experimental results, then a three-phase system are need in finite element analysis (adding interphase). Volume fractions of the three phase system, \([\nu]\), are as follows:

\[
[\nu_1]_3 = \frac{\pi nr^2}{S} - [\nu_1]_2 \times k^2_m = [\nu_1]_2 \times k^2_m
\]

(16b)

\[
[\nu_1]_3 = 1 - [\nu_1]_2 - [\nu_m]_3
\]

(16c)

where \( k_m = r_f/R_f, \ k_{out} = r_m/R_m \) is the geometry parameters charactering the relationship between the radius of reinforce and interphase in three phase system, respectively; \( \theta_1 = \pi - 4 \arccos \left( \sqrt{\frac{\pi R_m^2}{[\nu_1]_2 R_f^2}} \right) \) and \( \theta_2 = \arccos \left( \sqrt{\frac{\pi R_f^2}{[\nu_1]_2 R_m^2}} \right) \) charactering the overlap region of the interphase between two neighboring representative volume elements (RVE).

Considering that the composite is stacked by several layers with different angles along thickness direction. For a single layer, the effective material properties may be related to those of fiber and matrix through using Voigt and Reuss micromechanical rules for the longitudinal direction-1, transverse in-plane direction-2 and out of plane transverse direction-3, respectively [36].

\[
\hat{E}_1 = E_f[\nu_1]_3 + E_m[\nu_m]_3 + E_m[\nu_m]_3; \quad \hat{E}_2 = \hat{E}_3 = \hat{E}_2
\]

\[
\hat{G}_{12} = \hat{G}_{13} = \frac{G_f[\nu_1]_3 G_m[\nu_m]_3 G_m + [\nu_m]_3 G_f G_m + [\nu_m]_3 G_f G_m}{[\nu_1]_3 G_m[\nu_m]_3 G_m + [\nu_m]_3 G_f G_m + [\nu_m]_3 G_f G_m};
\]

\[
\hat{G}_{23} = G_f[\nu_1]_3 + G_m[\nu_m]_3 + G_m[\nu_m]_3
\]

(17b)

\[
\hat{\nu}_{12} = \hat{\nu}_{13} = \frac{\nu_f}{[\nu_1]_3 \nu_m[\nu_m]_3 + [\nu_m]_3 \nu_f \nu_m + [\nu_m]_3 \nu_f \nu_m};
\]

\[
\hat{\nu}_{23} = \nu_f = [\nu_1]_3 + \nu_m[\nu_m]_3 + \nu_m[\nu_m]_3
\]

(17c)

where \( \hat{E}, \hat{G} \) and \( \hat{\nu} \) are the equivalent elastic modulus, shear modulus and Poisson’s ratio of one layer, respectively.

3. Numerical simulation

3.1. Determination of material parameters

For the sake of simply process extending the two phase system to three phase, the mechanical properties of interphase (taking elastic modulus \( E_m(t) \) as an example) are considered changing between \( E_f \) and \( E_m \). The elastic modulus of glass fiber and epoxy resin are in the range of 3–4 GPa and 70–80 GPa, and value chosen for the study are 3.6 GPa and 72.0 GPa according to summary in [1,2], respectively. The equivalent elastic modulus of RVE with different configurations is investigated in this section. This can be practically implemented and is used as a basic of determination of material parameters.
The maximum and minimum value of instantaneous elastic modulus \( E_{\text{rev}} = \frac{dE_{\text{rev}}}{dt} = \frac{d\varepsilon_{\text{rev}}}{d\varepsilon_{\text{rev}}} \) can be obtained according to Eqs. (7) and (8), as follows:

\[
\text{Min} \left( \dot{E}_{\text{rev}} \right) = g_0; \quad \text{Max} \left( \dot{E}_{\text{rev}} \right) = g_0 + \sum_{i=1}^{n} g_i \tag{18}
\]

A practical expression can be derived using the simpler form of Eq. (8), \( g(t) = g_0 + g_1 e^{-t/t_1} \), as follows:

\[
\text{Min} \left( \dot{E}_{\text{rev}} \right) = g_0; \quad \text{Max} \left( \dot{E}_{\text{rev}} \right) = g_0 + g_1 \tag{19}
\]

Parameters \( g_0, g_1, \) and \( t_1 \) can be determined according to one tensile test curve, weather other parameters are need is depends on comparison of tensile tests under different strain rates [36]. Relationship between elastic modulus and parameter \([\nu_I]_2\), \( k_{\text{out}} \) and \( k_{\text{in}} \) are shown in Fig. 3.

From Fig. 3, it is obviously that the instantaneous elastic modulus of an RVE \( E_{\text{rev}} \) is affected by fractions of the three phases \([\nu_I]_3, [\nu_{\text{in}}]_3, [\nu_{\text{out}}]_3\) from the original two phase system with fraction \([\nu_I]_2\). Considering a given fraction \([\nu_I]_2\), \( E_{\text{rev}} \) is increased with effective elastic modulus of the interphase generally. \( E_{\text{rev}} \) is mainly influenced by outside ratio \( k_{\text{out}} \) when effective modulus of the interphase is small \( E_{\text{in}} = 3.6 \text{ GPa} \). Differently, the instantaneous elastic modulus is mainly influenced by inside ratio \( k_{\text{in}} \) when effective modulus of the interphase is large \( E_{\text{in}} = 72 \text{ GPa} \). If \( 3.6 \text{ GPa} < E_{\text{in}} < 72 \text{ GPa} \), \( E_{\text{rev}} \) is increased with increasing of \( k_{\text{in}} \) or \( k_{\text{out}} \). Beyond that, \( E_{\text{rev}} \) is also be founded increased with \([\nu_I]_2\) once parameters \( k_{\text{in}}, k_{\text{out}} \) and \( E_{\text{in}} \) are kept as constants. Under different loading speed, the simulation results using three phase model compared against experimental data of tensile tests of glass/epoxy composite (Fig. 4).

### 3.2 Simulation of tensile test

As mentioned before, the tensile strength can be modified by phenomenological theory, taking tensile strength of interphase as an example:

\[
X_t = [X_t]_S \times \left( 1 + \alpha \times e^{\beta} \right) \tag{20}
\]

where \([X_t]_S\) is the tensile strength under quasi-static loading, \( \dot{\varepsilon} \approx 0 \).

The tensile properties of glass fiber reinforced composites have been studied extensively [1,36]. On the basis of it, effect of loading speed on tensile properties of composites has been experimentally investigated by researchers [28]. The results indicate that the elastic modulus, tensile strength and failure strain are increased with strain rate, and an exponential law can be used to model the effect, as shown in Eq. (20).

Simulation results of the three phase model extending fiber fraction \([\nu_I]_2 = 0.5\) with parameters \( k_{\text{in}}, k_{\text{out}} \) (parameters are shown in Table 1). For different strain rates, from 0.017/s to 85/s, there is a good agreement between simulation results and experimental data. Similarly, simulation results of tensile strength are also acceptable comparing with experimental results.
Fig. 4 – Tensile tests of glass/epoxy composites under various strain rates and simulation results. (a) stress vs strain; (b) tensile strength vs strain rate [28].

Table 1 – Material parameters of the three phase system.

<table>
<thead>
<tr>
<th>Material</th>
<th>$k_a$ [−]</th>
<th>$k_b$ [−]</th>
<th>$g_0$ [GPa]</th>
<th>$g_1$ [GPa]</th>
<th>$t_1$ [s]</th>
<th>$a$</th>
<th>$b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass-epoxy</td>
<td>0.90</td>
<td>1.15</td>
<td>3.6</td>
<td>68.4</td>
<td>0.995</td>
<td>0.24</td>
<td>0.78</td>
</tr>
<tr>
<td>SMA-epoxy</td>
<td>0.96</td>
<td>1.20</td>
<td>3.6</td>
<td>47.4</td>
<td>10.376</td>
<td>0.30</td>
<td>0.92</td>
</tr>
</tbody>
</table>

3.3. Simulation of pull-out test

Pull-out tests of SMA (Nitinol) reinforced matrix(epoxy resin) have been implemented in our lab. The surface of SMA wire was washed with acetone to remove dust particles on surface before embedded them in epoxy. Epoxy resin used was epoxy vinyl resin with an accelerator and hardener in a mass ratio of 1:2%, 2%, the matrix was uniformly stirred, and then the matrix was removed into a vacuum oven for drying at room temperature for 20 min to ensure that the resin bubbles are excluded. The matrix was poured into the mold and cured for 24 h in the vacuum oven at room temperature.

Two series of pull-out test were performed to evaluate the interphase property, and the radius of SMA are $d_{SMA} = 0.5\,\text{mm}$ and $1.0\,\text{mm}$, respectively. As shown in Fig. 5, the length and radius of the three phase model in simulation with cylindrical shape before pull out is 20 mm and 10 mm, respectively.

From Fig. 6a, one can conduct that simulation results match well with the experimental results both for $d_{SMA} = 0.5\,\text{mm}$ and $d_{SMA} = 1.0\,\text{mm}$. With embedding SMA, $d_{SMA} = 0.5\,\text{mm}$, tensile force is increased quickly with pull displacement (when it is small than 1 mm) then kept in steady state with small vibration. The force–displacement relationship indicates typical phase transformation from austenite to martensite with weak interphase effect. Differently, as for embedded SMA with $d_{SMA} = 1.0\,\text{mm}$ a typical force–displacement relationship can be observed: force increased quickly to peak value then decreased to a low level suddenly due to the general debonding. Mises stresses of the three phase model shown in Fig. 6b and c, and the comparison reveal that mechanical property of interphase is affected by geometry.

4. Impact resistance of SMA reinforced composite

4.1. Numerical model for the simulation

A layer including glass fiber and epoxy resin is regarded as anisotropic material. The stacking sequence of the glass fiber is [0°, 90°]$_6$, and the total thickness of the sample is about 2.4 mm (0.2 mm for each layer). For each layer without SMA the volume fraction of fiber glass is about 34%, and this is the basic for determining material properties of each layer according to Eq. (17). Between layer 3–4 and layer 9–10, SMA wires are embedded after washing on surface. The distance of two adjacent SMAs is 5 mm, the number of SMA at each layer is 15 (total $15 \times 2 = 30$), as shown in Fig. 7a.

In the impact experiment, a sample with dimension $L_x \times L_y \times L_z = 100\,\text{mm} \times 100\,\text{mm} \times 2.4\,\text{mm}$ is impacted by a rigid half ball-cylinder on the center of the top surface. Marginal areas on the up and down surfaces of sample are clamped to ensure the fixed boundary condition, as shown in Fig. 7b. The diameter of the half ball of the impactor is 10 mm, and the
mass of the impactor is 4.2 kg (Steel). In the simulation, only the impacted region are considered to simply the finite element model, also, a ball (diameter 10 mm) is used to simulate the impactor based on two principles: same mass and same geometry of impact surface, as shown in Fig. 7b.

Three impact energies are considered in the low velocity impact tests 10, 15 and 20 J, and the corresponding impact velocities are 2.18 m/s, 2.67 m/s and 3.09 m/s. As for high velocity, three energies have been considered: 100, 1000 and 10,000 J, and the corresponding impact velocities are 6.89 m/s, 21.78 m/s and 68.9 m/s.

The two phase model and three phase model are used in the simulation to fully understand the mechanism of the impact process. However, it is quite unrealistic modeling each glass fiber in ABAQUS considering the complexity both for the two models. Homogenization method is used in each layer both for the two models.

Two phase model: the interface between layer-layer and matrix-SMA are characterized using cohesive zone model (bilinear cohesive law) in ABAQUS.

Three phase model: the interface between layer-layer of three phase model is characterized using subroutine of ABAQUS.
(VUMAT). As for the interphase between matrix and SMA, a novel part is added to simulate the interphase.

4.2. Numerical investigation of SMA reinforced composites under impact.

4.2.1. Low velocity impact
The simulation results of three aspects (velocity, displacement and energy) of impactor using two models (three phase and two phase) are plotted and compared with the experimental data, as shown in Fig. 8. In Table 2, the relative errors of the two models are shown, from which we can also concludes that the three phase models shows a better result.

Under lower impact energy, 10J, a generally elastic behavior of the composite laminate can be draw as: deformation is increased with time t at initial state (t<5.6 ms) until the maximum deformation is reached, then deformation is decreased (t>5.6 ms). This behavior can be found in the composite with SMA or without SMA, as shown in Figs. 9a, d and 10a, b, e and f. The simulation results of the two models for this case are both acceptable. Whole dynamic impact process of composite without SMA (10J) can be found in videos: Two-phase-noSMA-10J and Three-phase-noSMA-10J; as for SMA reinforced composite, the simulation results using the two models can be found in videos: Two-phase-SMA-10J and Three-phase-SMA-10J.

Differently, the composite is destroyed completely under higher energy, 20J, as shown in Figs. 9c, f and 10d, h. During this simulation, the impactor is founded moving along top layer to the bottom layer of the composite without bounced back. However, the velocity of impactor is reduced due to the friction of the hole of the composite during the breakdown process. This behavior can also be founded in the composite with SMA or without SMA using the same parameters from tensile tests, the simulation process of the two phase model cannot demonstrate this behavior.

As for impact energy 15J and composites without SMA, no clear bounded back behavior has been clearly founded in the test. However, the impactor shows bounded back during this impact process due to the embedding of SMA. This indicates that the resistance property of composite is increased by using SMA, increasing the superelasticity of the composites. Furthermore, the absorbed energy has increased from 14.6J to15J.

4.2.2. High velocity impact
In this section, three impact energies have been considered: 100J, 1000J and 10,000J, the related velocities are 6.89 m/s, 21.79 m/s and 68.9 m/s. The simulation times are chosen properly to balance the computational cost and computational accuracy. \( T_{\text{sim}} = 5 \text{ ms}, 16 \text{ ms} \) and 0.5 ms for 100J, 1000J and 10,000J, respectively. As shown in Fig. 11a–c, the ratio of
velocity to the original velocity is decreased with the increasing of the velocity, both for two phase model and three phase model and both for composite with SMA or without SMA. When comparing the last three figures in Fig. 11, it can be concluded that the absorbed energy is increased with velocity under the range 2.18 m/s to 68.9 m/s, gradually. As shown in Fig. 12, the absorbed energy of SMA reinforced composite is increased from 10J to 54.56J using the three phase model (19.38J for two phase model); the absorbed energy is smaller for composites without SMA, 22.28J and 30.92J, respectively. Generally, the energy absorbed by SMA reinforced composites is larger than that without SMA, increasing 35–80%.

More details about the simulation process can be found in Fig. 13. The comparison between the two models indicate that with increasing impact velocity the damage state of composite is more obviously using the three phase model. As shown in Fig. 13h, the damage state is clearly demonstrated in the regions lack of SMA and boundary. Without SMA, the dynamic damage process of composites (100J) and 10,000J) using the two models can be found in videos: Two-phase-noSMA-100J, Three-phase-noSMA-100J, Two-phase-noSMA-10,000J and Three-phase-noSMA-10,000J; also, the dynamic damage process of SMA reinforced composites using the two models can be found in videos: Two-phase-SMA-100J,

Table 2 – Comparison between the two models (10J/15J/20J).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum error</td>
<td>0.67/0.57/0.96</td>
<td>0.97/0.86/1.49</td>
<td>2.76/1.90/4.21</td>
<td>4.16/2.97/6.69</td>
<td>3.32/4.46/4.14</td>
<td>4.65/6.23/6.19</td>
</tr>
<tr>
<td>Maximum error</td>
<td>0.35/0.15/0.23</td>
<td>0.40/0.16/0.54</td>
<td>1.47/1.51/2.19</td>
<td>1.46/1.37/1.13</td>
<td>2.59/1.16/1.88</td>
<td>2.19/0.86/2.13</td>
</tr>
</tbody>
</table>
Fig. 11 – Simulation results of composites under high velocity impact: (a) velocity-100 J; (b) velocity-1000 J; (c) velocity-10,000 J; (d) energy-100 J; (e) energy-1000 J; (f) energy-10,000 J.

Fig. 12 – The absorbed energies of composites under different impact energies.

Three-phase-SMA-100 J, Two-phase-SMA-10,000 J and Three-phase-SMA-10,000 J.

4.3. Analysis of damage state

4.3.1. Damage state of different layers after impact

Comparing with the two models, a less integrity can be kept using the three phase model due to the effect of strain rate on the modified Hashin’s failure criterion. Without SMA, a hole shape damage can be found on several layers for both models, also, an arbitrarily damage on the layer 1 can also be found. With SMA, the layers between the SMA layers (3–4 and 9–10) are damaged more extensive considering the deboning of SMA wires, as shown in Fig. 14.

The damage area can be separated to two parts: hole area and arbitrarily damage area. The two areas of different layers are shown in Fig. 15. As for composites without SMA, the hole area is generally larger than the arbitrarily damage area for energy level 10 J, 15 J, 20 J, 100 J and 1000 J; as for highest impact energy 10,000 J, the arbitrarily damage area is larger than the hole area, especially for surface layer 1 and 12. When embedding SMAs, the arbitrarily damage area is much larger than the previous case.

4.3.2. Damage state during impact process

In Fig. 16, the impact processes of composites using different models are demonstrated. A distinct bending behavior along the impact direction during the impact process, when t < 2 ms, can be observed. After deviating from composites, the velocity of impactor is kept constant. As the same time, the composite is vibrating along the opposite impact direction.

As mentioned before, the displacements of points along Z direction show a parabola shape when the impact energy is 10 J. As for higher impact energy 100 J and 10,000 J, the simulation results indicate a vibrating from negative direction to positive direction with amplitude −9 to 9 mm, as shown in Fig. 17. Comparing with composites without SMA, SMA
Fig. 13 – Stress state of simulation results of SMA reinforced composites laminates under high velocity impact using different models.

Fig. 14 – Fracture morphology of the different layers of composite laminate with impact energy 100 J: (a) layer 1 (bottom); (b) layer 3; (c) layer 7; (d) layer 10; (e) layer 12 (upper).
4.4. Working mechanism and failure mechanism of SMA

As mentioned before, SMA sustain load extensively at early time during impact, as shown in Fig. 10a. The working mechanism is mainly focused on the larger elastic modulus and larger strain of SMA. However, the working mechanism is strongly restricted by the interface behavior between SMA and matrix both for two phase model and three phase model.

The characters ‘B’ and ‘U’ denote the SMA in bottom layer (3–4) and upper layer (9–10), respectively. Effective SMA ratio means subtracting the deleted parts of SMA in two phase model. Differently, in three phase model, this denotes the percentage of interphase without deleting. The existence of interphase is the only reason that the SMA working
effectively. The effective ratio is decreased with the increasing of impact energy, as shown in Fig. 18. The effective of upper layer is generally lower than that of bottom layer both for the two models. Effective ratio in three phase model is larger comparing with two phase model, that is, the reason why this model demonstrates more absorbed energy in Section 4.2.

5. Conclusions

The effect of velocity (from low to high) on impact resistance of SMA reinforced composite laminate has been investigated based on a novel strain-rate-dependent model. Three main parts are used to charactering the whole system: matrix, reinforce and interphase. A modified 3D finite element model based on Hashin’s failure criterion was employed in ABAQUS to study the destruction process. Some of the simulation results can be concluded as follows:

- Comparison between the simulation results and our previous work with fixed boundary shows that the parameters and the simulation process of the three phase model are acceptable, meanwhile, a larger error existed in the two phase model. The relative error between the simulation results (energy or force) and the experimental data is controlled smaller than 10% for the three phase model.
- The absorbed energy is increased with increasing the impact energy (from 10 J to 10,000 J), and kept at 25–60 J for different models.
• Embedding SMA wires can enhance the resistance property of composites, especially for low velocity.
• As for SMA reinforced composites under high impact velocity, extensive damage morphology of the composite can be observed both in the center hole areas and the arbitrarily damage areas. This can be explained by the effect of strain rate on failure mechanism of interphase.
• The damage state of composite after high velocity impact is increasing due to the vibrating behavior.

Conflicts of interest
The authors declare no conflicts of interest.

Acknowledgements
The authors gratefully acknowledge the financial support of the National Natural Science Foundation of China within the project with Grant Nos. 11472086 and 11532013.

Appendix A. Supplementary data
Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jmrt.2018.06.012.

REFERENCES


