Composite structures with shape memory property

G. L’Hostis*, A. Basit*, b. Durand*

a. Laboratoire de Physiques et Mécanique textile, 11 rue Alfred Werner 68093 Mulhouse Cedex.

Résumé :
Les polymères a mémoire de forme ou shape memory polymer (SMP) ont connus de nombreux développements en tant qu’actionneur, et ceci dans des domaines technologiques variés tel que la micro robotique, le spatial ou la biomécanique. Pour des raisons de gain de poids, ils peuvent être des substituts aux alliages métalliques à mémoire de forme (AMF). Cependant pour un même niveau de déformation restituée, les efforts restitués par les SMP restent faibles ce qui limitent leur capacités d’actionnement. Certaine pistes de solutions ont été explorées, par exemple l’introduction de micro ou nano charges élastiques ou l’utilisation d’un couplage SMP/AMF conduisant à des structures plus performantes et possédant des propriétés d’activations particulières. Dans ce travail après avoir définis les notions de one way shape memory effect ou de two way shape memory effect ainsi que les notions de dual shape, de triple shape ou de multi shape, notions qui conditionnent les propriétés de changement de forme des SMP, nous présenterons un matériau composite de grande rigidité, à mémoire de forme et à forte capacité d’actionnement. Ce composite a été obtenus en couplant grâce à une activation thermique, des propriétés de mémoire d’une matrice époxy avec des propriétés de modification de forme du composite. L’étape d’éducation du composite sera détaillée. Les étapes de recouvrance en déformation et en force permettront de caractériser le travail mécanique de recouvrance du composite afin d’obtenir ces propriétés d’actionnement. Enfin des aspects structuraux seront abordés, au travers de l’influence de l’organisation de la constitution du composite, sur les différentes grandeurs mécaniques intervenant dans l’étape d’éducation et de recouvrance.

Abstract:
For actuation and in various technological fields such as micro robot, space or biomechanics, the shape memory polymers and shape memory polymer (SMP) have known many developments. For a weight gain point of view, they may be substitutes for metal alloys with shape memory (SMA). However for a same level of recovery deformation, the corresponding recovery force given by SMP remains low compare to SMA, and limits the SMP actuation property. Different solutions have been explored, for example the introduction of micro or nano fillers or a elastic coupling using SMP / AMF structures leading to more efficient and having specific activation properties. In this paper, after a definition of one way or two way shape memory effect and the notions of dual, triple or multi shape, properties which characterized the nature of the SMP, we present a high rigidity shape memory composite material which have high-capacity of actuation. This composite is obtained by coupling with a thermal activation, the shape memory properties of an epoxy matrix with the morphing property of an active composite. The step of programming will be detailed. To obtain the actuation properties and from the two steps of unconstrained and constrained recovery the recovery mechanical work will be defined. Finally the structural aspects will be studied, through the influence of the organization of the constitution of the composite.

Mots clefs: Shape memory composites, thermal active composite

1 Functionalities of Shape memory polymers and composites

For many industrial applications, the active structures can be a substitute for standard technology. In the field of active structure, composite materials have a main advantage compared to the metallic materials, because of their ability to integrate multiple functions for example the morphing and the shape memory functions. In the shape memory field, the shape memory polymers (SMP) are capable of recovering large deformations by applying specific stimulus. Out of all the stimuli (light, humidity, electric field, etc), temperature is mostly studied. For this stimulus, one of the main parameters is the glass transition temperature (Tg), because it
plays a key role in fixing and recovery properties [1-3]. The different functionalities based on the direction of activation and deactivation of a SMP (Fig.1) can be one-way SME or 2-way SME. Similarly, based on the different shapes, dual shape or triple shape or even multi-shapes have been defined. In dual shape, the sample can have two shapes. In triple shape, it can have three shapes and similarly, in multi-shapes, it can have many shapes.

For dual shape and one-way SME, the samples become active on providing stimulus and get the other shape, however, when stimulus is removed, the sample maintains this position and cannot return to the initial position. For dual shape and 2-way SME, the samples become active on providing stimulus and get the other shape, however, when stimulus is removed, the sample returns to the initial position. Hence, the sample can repeat this phenomenon on giving and removing the stimulus.

For triple shape and one-way SME, the samples become active on providing stimulus and get the 1st shape. On further providing the stimulus, it gets the 2nd shape. However, when stimulus is removed, the sample maintains this position and cannot return to the 1st shape or initial position. In 2-way SME, the samples become active on providing stimulus and get the 1st shape. On further providing stimulus, it gets the 2nd shape. However, when stimulus is removed, the sample returns to the 1st shape and then to the initial position. Hence, the sample can repeat this phenomena on providing and removing the stimuli.

For triple shape and one-way SME, the samples become active on providing stimulus and get the 1st shape. On further providing the stimulus, it gets the 2nd shape. However, when stimulus is removed, the sample maintains this position and cannot return to the 1st shape or initial position. In 2-way SME, the samples become active on providing stimulus and get the 1st shape. On further providing stimulus, it gets the 2nd shape. However, when stimulus is removed, the sample returns to the 1st shape and then to the initial position. Hence, the sample can repeat this phenomena on providing and removing the stimuli.

In this work, we have developed a conventional shape memory composite with 2W-SME by coupling an active composite with an epoxy resin having shape memory property. The Controlled Behavior Composite Material (CBCM) is a morphing thermal active composite, based on the bimetallic strip effect, and generally asymmetric [4-5]. The internal heat source producing the thermal activation of the composite is generated by carbon yarns inserted in the composite, the thermal active layer $A_\text{t}$ (Joule effect). Like any morphing composite, the CBCM has the 2W effects corresponding to the active and non-active positions. For the CBCM, the active position is variable and controllable by the temperature field through the composite thickness and consequently by the level of current intensity. By the thermal field the coupling between the CBCM effect and the SMP property of epoxy resins is easily obtained and controlled.

In a first time, the programming cycle is performed on plates with different layer organisation and the influence of the composite asymmetry is studied.

In a second time, based on the two classical test of recovery, the total recovery work is characterized. A way to separate the mechanical work given by the CBCM effect and the mechanical work due to the shape memory property is proposed, and then the influence of the asymmetry of the plate is highlighted.

![Functionalities of SMPs and their composites](image)

**FIG. 1 – Functionalities of SMPs and their composites**

2 Methods, material and programming cycle

Different asymmetrical composite plates (395×12.5×2 mm$^3$) made of six layers: two layers ($2\text{D}^G$)$_2$ of plain weave Glass fabric (196 g/m$^2$), two layers ($90^G$)$_2$ of Glass unidirectional (588 g/m$^2$), the thermal
active layer ($A_1$) and two layers ($2D^A$)$_2$ of plain weave Aramid fabric (173 g/m$^2$) have been manufactured (Table 1). $0^\circ$ is along the longitudinal direction of the plate.

<table>
<thead>
<tr>
<th>Composite plate type</th>
<th>organization</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBCM</td>
<td>(2D$^G$)$_2$/((90$^0$)$_i$/A$_1$)/(2D$^A$)$_2$</td>
</tr>
<tr>
<td>CBCM$^{1/2}$</td>
<td>(2D$^G$)$_2$/((90$^0$)$_i$/((0$^0$)$_i$/A$_1$)/(2D$^A$)$_2$</td>
</tr>
<tr>
<td>CBCM$_{1/2}$</td>
<td>(2D$^G$)$_2$/((0$^0$)$_i$/((90$^0$)$_i$/A$_1$)/(2D$^A$)$_2$</td>
</tr>
<tr>
<td>CBCM-L</td>
<td>(2D$^G$)$_2$/((0$^0$)$_i$/A$_1$)/(2D$^A$)$_2$</td>
</tr>
<tr>
<td>SYM</td>
<td>(2D$^G$)$_2$/((90$^0$)$_i$/((2D$^A$)$_i$/((90$^0$)$_i$/((2D$^G$)$_i$</td>
</tr>
</tbody>
</table>

TAB 1- Organizations of different composite plates

A three-point bending test has been chosen to characterize the behavior of the composite structure. The plates are supported by two rigid cylinders placed (L = 300 mm) apart. The thermo-mechanical cycle (Figure 2) starts with the pretension of 0.3 N. During 800 s of heating, the deforming temperature ($T_D$) is stabilized ($T_g + 20^\circ$C). Then the plate is heated for 800 seconds, the initial or free displacement due to CBCM effect is given by AB ($d_A = 13.47$ mm). Then a load is applied to get the specific bending deformation $\varepsilon_S = \frac{d_S}{L}$ where $d_S = 25$ mm, the total prescribed displacement (BC). This displacement is the maximum displacement that can be obtained without any damage (e.g. delamination) to the plates. This deformation is maintained and cooled for 1000 s to get the ambient temperature (CD). When the plate becomes cooled, load is reduced to the pretension of 0.3 N (DE). Here, at point E, initial fixity is obtained. The fixing or programming cycle is completed. The programming cycle can also be explained in terms of different forces acting during the cycle. The total force $F_I$ (A-A$_2$) which is the sum of two forces: the blocking force $F_B$ (A-A$_1$), corresponding to the active part. The force $F_1$ (A$_1$-A$_2$), which is imposed to reach the prescribed displacement $d_S = 25$ mm. Similarly, during cooling, the total force $F_T$ (C-C$_1$), is the combination of three forces: the blocking force $F_B$ (C-C$_1$), the stabilization force $F_S$ (C1-C2), and the elastic force $F_E$ (C2-C$_2$). The blocking force $F_B$ disappears simply due to the cooling of the composite and $F_E$ is restituted force during the elastic recovery (DE) to the preloaded position. $F_E$ is the result of the equilibrium of the whole structure during the unloading step. The fixity $d_F^i$ is linked to the value of $F_S$. Fixity will be more if $F_S$ is more and vice versa. So, values of $F_S$ and $d_F^i$ characterize the internal mechanical work stored in the composite structure after the programming cycle.

All the characteristic values of the programming cycle are given in Table 2. The use of the rigidities which appear during the programming cycle is a convenient characterization of the structure behavior. The structural characteristics have an influence on several phenomenon like: the loss of matrix stiffness versus temperature, the new organization of the polymer after the programming or the geometrical rigidity induced by the structure curvature that may change during the activation. $K_A$ and $K_1$ are characteristic of the non-programming plate behavior at $T_D$. The rigidity $K_2$ (path DE) during unloading is the characteristic of the programming plate at ambient temperature ($T_A$). It can be compared to the non-active rigidity $K_{NA}$ that is the characteristic of the non-programming plate at $T_A$. The level of internal stress in the composite plate induced by its new shape ($d_F^i$) leads to the value of $K_2$ higher than $K_{NA}$.

For a given temperature, the asymmetry of the composite may be defined by the plate curvature and the value of the corresponding displacement $d_A$. Thus, CBCM and CBCM-L appear to be the most and the least asymmetrical composites respectively. For the different composites, the evolution of $F_S$ is in accordance with the evolution of $d_A$. This result confirms that $F_S$ is induced by the composite asymmetry and can be used to characterize the level of the asymmetry. Due to the lower value of $F_E$ (elastic force responsible for the spring-back of the composite) and despite the lower value of the total force $F_I$, the maximum value of $F_I$ minus $F_E$ is obtained for the CBCM. The direct consequence of this result is given by the value of $d_F^i$, CBCM has the maximum value of the initial fixity displacement $d_F^i$. 

3
FIG. 2 – Thermo-mechanical programming cycle, force versus displacement at the center of the plate

<table>
<thead>
<tr>
<th>Characteristic values</th>
<th>CBCM</th>
<th>CBCM\textsuperscript{1/2}</th>
<th>CBCM\textsuperscript{1/2}</th>
<th>CBCM-L</th>
<th>SYM</th>
</tr>
</thead>
<tbody>
<tr>
<td>(d_A) (mm)</td>
<td>-13.47±0.75</td>
<td>-11.64±0.27</td>
<td>-9.57±0.57</td>
<td>-6.81±0.35</td>
<td>-0.93±0.3</td>
</tr>
<tr>
<td>(F_B) (N)</td>
<td>31.48±1</td>
<td>34.90±0.14</td>
<td>27.57±0.6</td>
<td>23.5±0.61</td>
<td>1.1±0.12</td>
</tr>
<tr>
<td>(K_A) (N/mm)</td>
<td>2.33±0.1</td>
<td>2.99±0.06</td>
<td>2.88±0.15</td>
<td>3.4±0.12</td>
<td>1.18±0.2</td>
</tr>
<tr>
<td>(F_T) (N)</td>
<td>57.70±1.94</td>
<td>66.61±1.06</td>
<td>69.37±0.81</td>
<td>74.80±0.86</td>
<td>33.44±0.9</td>
</tr>
<tr>
<td>(K_1) (N/mm)</td>
<td>2.2±0.24</td>
<td>2.25±0.08</td>
<td>2.45±0.1</td>
<td>2.67±0.05</td>
<td>1.37±0.1</td>
</tr>
<tr>
<td>(F_S) (N)</td>
<td>14.31±2.06</td>
<td>9.86±0.49</td>
<td>6.87±0.8</td>
<td>5.92±0.5</td>
<td>2.88±1.1</td>
</tr>
<tr>
<td>(F_E) (N)</td>
<td>11.91±1.62</td>
<td>21.85±0.81</td>
<td>34.93±0.67</td>
<td>45.38±0.75</td>
<td>29.46±1.3</td>
</tr>
<tr>
<td>(d_F) (mm)</td>
<td>9.18±0.63</td>
<td>8.25±0.42</td>
<td>7.08±0.48</td>
<td>6.42±0.54</td>
<td>8.64±0.2</td>
</tr>
<tr>
<td>(K_2) (N/mm)</td>
<td>4.24±0.39</td>
<td>3.79±0.13</td>
<td>3.7±0.1</td>
<td>3.6±0.18</td>
<td>1.98±0.32</td>
</tr>
<tr>
<td>(K_{NA}) (N/mm)</td>
<td>3.34±0.36</td>
<td>3.6±0.37</td>
<td>3.76±0.1</td>
<td>4.1±0.13</td>
<td>1.8±0.14</td>
</tr>
</tbody>
</table>

TAB 2 - Characteristic values of the programming cycle

The maximum value of \(F_B\) obtained for CBCM\textsuperscript{1/2} may be explained by two effects: the thermal activation and the loss of mechanical properties of the matrix because of the heat and more particularly for \(T_D=150^{\circ}C\). These effects can be different depending on the reinforcement organization in the structure and particularly the orientation of the glass unidirectional layer. For the Glass unidirectional layer along the transversal
direction, the greater properties of dilation are along the longitudinal direction, but in this direction, the loss of rigidity of the matrix is also high. The competition between these two effects explains the greater value of $F_B$ for CBCM$^{1/2}$, as for the combination of these two unidirectional layers, the bottom layer at 0° decreases the loss of rigidity while maintaining good properties of dilatations for the two layers. For the two other composites (CBCM$^{1/2}$ and CBCM-L), the two unidirectional layers give lesser values of $d_A$ and $F_B$ due to a greater rigidity $K_1$ at $T_D$ and $K_NA$ at $T_a$.

The variation of the rigidity $K_2$ defined by $d_F$ and $F_E$ versus the asymmetry is in accordance with $d_F$ and $F_S$. $K_2$ is more for more asymmetry. $K_2$ reflects the level of internal stress in the composite after the programming cycle.

3 Unconstrained and constrained recovery tests and mechanical work

The recovery properties are investigated by two classical tests, unconstrained and constrained recovery test performed for a recovery temperature $T_R$ equal to the deformed temperature $T_D$. The unconstrained recovery test consists of measuring the free displacement $d_{RT}$ of the free loading structure. The constrained recovery test consists of measuring the total recovery force $F_{RT}$. The unconstrained and constrained recovery tests are used to calculated, the recovered mechanical work due to the shape memory property $W_R$ (Eq. 1) where $W_T$ is the total recovered work [6] and $W_{CBCM}$ is the work performed by CBCM during activation without programming.

$$W_R = W_T - W_{CBCM} \quad \text{with} \quad W_T = \frac{1}{2} F_{RT} \cdot d_{RT} \quad \text{and} \quad W_{CBCM} = \frac{1}{2} F_B \cdot d_A$$

(1)

Based on the recovery properties (force and displacement), the different characteristic straight lines (Fig. 3 and 4) summarize the overall results for the different composites. These curves highlight the high actuation performances of CBCM and especially the greatest properties of recovery properties due to SME of the matrix.

![Graph](image)

**FIG. 3 – Characteristic straight lines of $d_A$ and $F_B$, CBCM actuation properties**

In Figure 4, the rigidity $K_R$ of SYM uniquely for SME is least as SYM has least $F_R$. So, comparing to SYM, the different asymmetric composites give high actuation properties. Hence, it can be concluded that the asymmetry of the composite has an influence on the actuation property induced by the SME.
For the SME, the maximum work calculated by $F_R$ and $d_R$ for CBCM, CBCM$^{1/2}$, CBCM$_{1/2}$, CBCM-L and SYM are 0.035 J, 0.0248 J, 0.02, 0.016 J and 0.02 J respectively. It can be observed, the work induced by SME is the least for CBCM-L, and however, for SYM and CBCM$_{1/2}$, it is equal. This shows that for the SME, the rigidity $K_{NA}$ can limit these effects.

IV.1.6) Conclusion

During the study of the effect of change in position and orientation of unidirectional Glass layers in the composite, it is observed that the asymmetry of the composite changes which affect all the characteristic parameters. It changes not only the free displacement and blocking force but also changes the shape memory properties of the composite. The initial fixity is degraded as the rigidity increases with the change of position and orientation of unidirectional glass layers in the composite. As a result, the recovered work is also affected. It is found that the composite having more asymmetry gives higher actuation properties than the other composites.

References