Finite Element Simulation for In-plane Tensile Behavior of Shape Memory Alloy Honeycombs

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1 Introduction

Shape memory alloy (SMA) is considered as a promising function material. By proper external stimulus, SMA could recover its original shape after large inelastic deformation.

Honeycomb structure as one type of cellular structures, has a high stiffness-to-weight ratio on certain direction. Common type honeycomb structures in the form of honeycomb Sandwich Panel (HSP) could be found as structural components in many fields. Another type of honeycomb, the low shear stiffness type honeycomb structure (Fig. 1) is considered as a good candidate for smart structures. Early researches include SMA honeycomb core actuator [1], in-plane tensile testing [2] and in-plane compressive simulation [3].

To fully discover its potential, this research focuses on low shear stiffness honeycomb's tensile behaviour. Simulations in this research adopt an improved version of SMA computational model. This model considers different material properties of twinned martensite phase and crystallographic re-orientation process between variants of martensite phases. The research can be considered as essential part of fundamental research about low shear stiffness honeycomb.

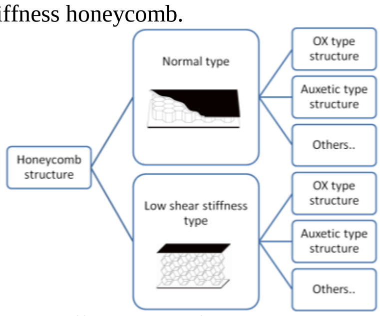

Fig. 1. Different kinds of honeycomb structures

2 SMA numerical model

This research adopts an improved version of SMA based on phenomenon model proposed by Brinson [4] and Toi [5]. The incremental form of stress strain relation is as follows:

$$\{\sigma\} = D\{\varepsilon\} + \xi_S\{\Omega\} + T\{\theta\} \tag{1}$$

where $\{\Omega\}$ is the transformation coefficient vector; D is stiffness; $\{\theta\}$ is the thermal elastic coefficient vector; $\{\sigma\}$ is the stress vector; $\{\varepsilon\}$ is the strain vector; T is the temperature; ξ_S is the stress-induced martensite volume fraction.

As improvements to conventional model, new elements were embedded into model, which are:

1. Consider tensile and compressive asymmetry by using Drucker-Prager equivalent stress
2. Distinguish twinned martensite phase and detwinned martensite phase
3. FEM techniques such as Euler-Bernoulli element and layered beam element

Extensive discussions related to improvement No.1 could be found in Toi [5], which are supported by experiment results in Aurrichio [6]. Improvement No.2 considers different material properties between twinned martensite and detwinned martensite, as well as the irreversible phase transformation kinetics (or crystallographic re-orientation) from twinned martensite phase to detwinned martensite phase. FEM techniques are specialized for in-plane frame which could provide both axial and radical distribution of internal variables.

3 Numerical studies

3.1 Material level validation

Since conventional models do not differentiate stiffness of twinned martensite and detwinned martensite, a much better stress strain fitting could be obtained by using the new model. In Fig. 2, new model reproduced the different stiffness of two variants. This fitting could be considered as material level validation of the new model.

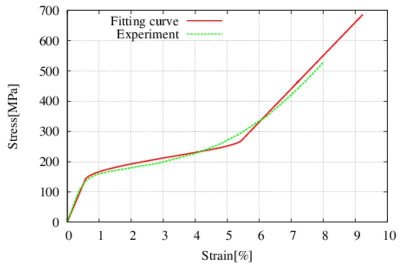

Fig. 2.Experiment [2] and fitting result of stress strain relation

Numerical studies include two kind of honeycomb structure: OX type honeycomb structure with positive Poisson's ratio, and auxetic type honeycomb structure with negative Poisson's ratio. Their original shapes and boundary conditions are in Fig. 3.

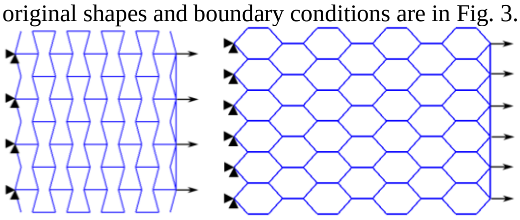

Fig. 3. Original shape and boundary conditions of auxetic type (left) and OX type (right) honeycomb structure

3.2 Auxetic type honeycomb structure

Auxetic type honeycomb structure simulation consists of two full cycle simulations.

One is in relatively low temperature when only variants of martensite phase exist. In this situation, temperature is lower than reverse phase transformation start temperature. Irreversible phase transformation from relatively symmetry twinned to single oriented detwinned martensite phase occurs in this situation.

Average stress and strain relation is plotted in Fig. 4. Loading part starts when honeycomb structure in elastic status, the average stress and strain relation is approximately a straight line. Then crystallographic re-orientation starts along with stiffness weakening. This behaviour is identical to experimental result in Hassan's research [2]. New model is validated in structural level in this case. During unloading, honeycomb structure is in elastic status. Therefore stress strain curve is a straight line in Fig. 4.

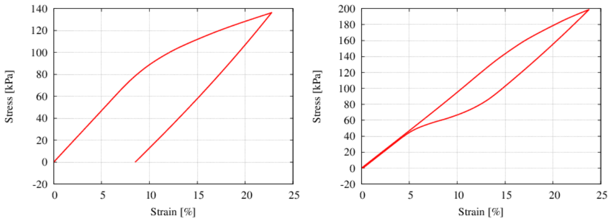

Fig. 4. Full cycle tensile loading of auxetic type honeycomb structure in low temperature (left) and high temperature (right)

Another is simulation in temperature higher than reverse phase transformation finish temperature. Average stress strain curve could be found in Fig. 4. In this case, martensite phase transformation and reverse phase transformation could occur. As a result, two stiffness weakening region in stress strain curve and full recovery could be observed. Deformation shape and martensite phase fraction under maximum loading could be found in Fig. 5. Martensite phase was induced in elements near each joint. Maximum fraction is around 50%. In this state, expansion in both vertical and horizontal directions could be observed, which means auxetic honeycomb structure has a negative Poisson's ratio.

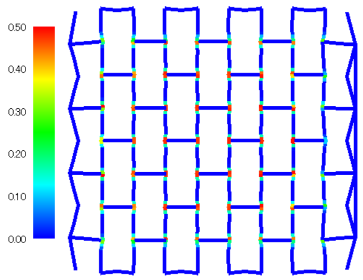

Fig. 5. Deformation and martensite phase fraction distribution under maximum loading. Honeycomb is in high temperature

3.3 OX type honeycomb structure

For OX type honeycomb structure, both high temperature and low temperature simulations are conducted. The average stress strain curves of whole structure in two situations are very similar. Fig. 6 is the loading histories in both temperatures. Its loading part could be validated with experiment result in Hassan's [2]. Similar behaviour in two results proved another qualitative validation in structural level for improved model.

Different from auxetic type honeycomb structure, bifurcation behaviour was observed in deformation plots of Fig. 7 and 8. Stress concentration in "X" shape region in OX type honeycomb induced phase transformation. Phase transformations in these regions weaken stiffness, which becomes the main cause of localized deformation. No matter in high temperature or in low temperature, or in other words, no matter the phase transformation is reversible or irreversible, similar bifurcation behaviour could be observed. Convex cells in "X" regions become concave during unloading process.

Further studies supported discussion above. When loading force is small, or the material is elastic, no bifurcation happens.

4 Conclusion

An improved computational model for SMA is developed, validated and finally applied in SMA honeycomb structure simulation. The model takes account of twinned martensite phase's different material property and its phase transformation process to detwinned martensite phase. The improvement could provide better accuracy in low temperature condition.

Simulations were conducted by fitting SMA experimental stress strain curve for material level validation, and honeycomb structure simple tensile loading for structure level validation. OX type's positive Poisson's ratio and auxetic type's negative Poisson's ratio were reproduced.

Finally full cycle tensile simulations were conducted for OX and auxetic type honeycomb structure. Bifurcation behaviour was discovered in OX type simulation. This behaviour is due to stress concentration and the resulting SMA phase transformation. This discovery demonstrated better structural stability of auxetic type honeycomb structure.

References

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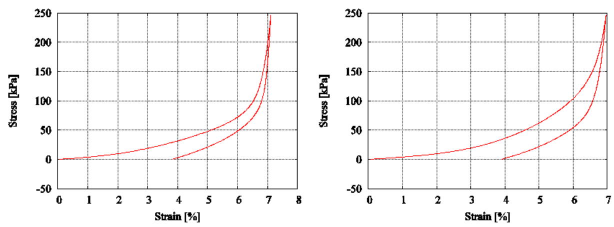

Fig. 6. Full cycle tensile loading of OX type honeycomb structure in low temperature (left) and high temperature (right)

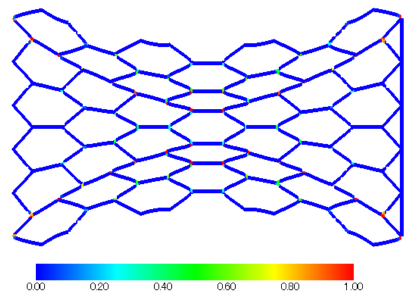

Fig. 7. Deformation and martensite phase fraction distribution under maximum loading. Honeycomb is in high temperature

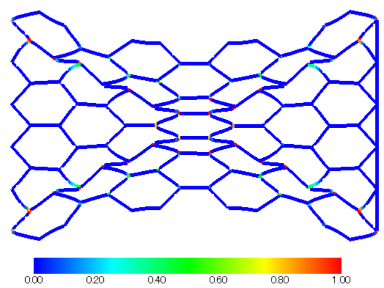

Fig. 8. Deformation and martensite phase fraction distribution after unloading. Honeycomb is in high temperature