論文の内容の要旨
Abstract of Dissertation

論文題目　Computational Modeling of Plane Frames Using Shape Memory Alloy and Its Applications to Honeycomb Analysis

（形状記憶合金を用いた平面骨組構造の計算モデリングとハニカム解析への応用）

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Among many kinds of function materials, shape memory alloy is considered as one of the most attractive members. Its existing and potential applications can be widely found in industries such as aerospace, medical, sports and many others. However, high cost is one main limitation of their applications. Even though shape memory alloys have attractive features like shape recovery and hysteresis, they are still not economically efficient enough as structural material, when comparing with conventional materials such as iron, steel and aluminum. As the result, applications of SMAs are mostly in the form of actuators and sensors, and in the fields of aerospace industry and medical industry. Due to the scale and functionality requirements, these fields of application demand deeper understanding of material properties of SMAs. Simulation tools with better accuracy and functionality are required in designing process and production.

Since the establishment of first SMA model in 1980s, computational models about this magic alloy are getting more and more advanced in past years. However, so far SMA computational models are still relatively simple. Essential simulation functions are still not supported in conventional models. Often used functions such as cyclic effect, plasticity and fatigue are still not included. New experimental results have shown more detailed information of shape memory alloys. But those behaviors are rarely considered into conventional models. Considering relatively simple models of SMAs and limited support from commercial FEM software, consistent improvements of SMA numerical model are essentially required.

To meet those needs, this thesis proposes several improvements on legacy SMA models. As most applications of SMA are in the shape of wire or film, numerical studies using improved models are focused on SMA plane frames applications. Those studies cover applications in simple beams, braced frames, as well as complex honeycomb structures, which are low weight, functional structures that have a great potential in smart structure, actuators and sensors. Material level and structural level validation, as well as new discoveries from numerical studies will be discussed in detail.

In this thesis, chapter one is the overall introduction. Brief review about shape memory alloys contributes the first part of this chapter. Martensite phase and austenite phase of SMA, and two variants of martensite phase, the detwinned martensite phase and twinned martensite phase were introduced in this part. Its special features such as shape memory effect, superelasticity, as well as high actuation frequency and energy density were discussed with internal phase transformations. Following its major application examples in aerospace and medical industry, SMA computational models were reviewed. Advantages and disadvantages of each model were discussed. Functionality of each major SMA model was listed and compared with improved model in this thesis. Besides SMA model, SMA honeycomb structure was briefly discussed. Its potential application as smart structure is the major reason of its extensive studies in the following chapters. Finally, purpose of research was discussed. Consistent improvement of SMA model in both accuracy and functionality is always the mission of researcher in this field.

Computational modeling is the topic of chapter two. After a brief review of conventional SMA model by Brinson (1993) and Toi et al. (2004), which is basis of this research, detailed explanation of each improvement could be found in this chapter. Based on the stress strain relationship, kinetics of phase transformation and compressive-tensile asymmetry in conventional SMA model, a new kinetics of phase transformation using logistic sigmoid model was introduced at first. The physical basis, as well as its short demonstration was included. Cyclic effect model dependent on accumulated strain was introduced. Comparison with other two cyclic effect models, its physical meaning and influence factor picking differentiate this model from others. Based on experimental results, model considering twinned martensite phase was introduced. Kinetic of phase transformation from twinned martensite to detwinned martensite as well as its logistic sigmoid function improvement were presented. Embedded plasticity model into superelasticity and quasiplasticity is another major contribution to SMA model improvement. Based on experimental data, different yielding condition for martensite phase and austenite phase was considered. A linear mix rule of yielding was established for martensite-austenite-mixed phase. For shape memory effect, a more stable phase transformation condition was introduced. Finally, FEM models used in this thesis were introduced. Major models are Euler-Bernoulli cubic beam element, finite deformation model and beam layered approach.

Chapter three is about validations of logistic sigmoid function model for phase transformation. Logistic sigmoid function model is a major improvement after introduction of phenomenological models. It combines the widely used framework of Brinson's model and the flexibility of logistic sigmoid type of phase transformation mechanism. Instead of cosine function phase transformation mechanism in the existing model, the new model presented a much better fitting of stress strain relationship about shape memory alloys. The usability of new model was proved in one dimensional testing as material level validation. Structural level validation of this model was performed in an SMA beam four-point bending simulation. Better fittings with experimental data were obtained compared with results from other models.

Chapter four includes material level validation and application of newly developed cyclic effect model. Qualitative validation was performed by comparing with one dimensional cyclic loading experiment. Three major cyclic effects were well reproduced: (1) residual strain increases as cyclic loading continues; (2) critical phase transformation starting and finishing stresses decrease as cyclic loading continues; (3) material parameters' changes convergence as cyclic loading continues. The model was later applied in simulation related to energy absorbing of an SMA-braced frame. Weaker damping capacity of SMA brace was found when considering cyclic effect.

The significantly different properties between normal type honeycomb structure and low shear stiffness honeycomb structure have determined their potential applications. Low shear stiffness honeycomb structure using shape memory alloy shows its potential in applications such as actuator, sensor and adaptive structure. Under proper control, functions including actuating, shape controlling could be achieved. External stimulus includes temperature change could induce phase transformation inside honeycomb structure. Macroscopic deformation due to phase transformation is the reason for its actuating and shape controlling. Besides, deformation induced phase transformation inside SMA honeycomb structure could lead to latent heat or electrical resistance change. By taking advantage of this feature, sensoring function of SMA honeycomb structure could also be achieved.

Considering attractive potentials of SMA honeycomb structures in functional structures, their thermomechanical behaviors were extensively studied in following three chapters. Chapter five implemented accuracy improved model into in-plane tensile behavior of SMA honeycomb structures. This model takes consideration of different material properties between twinned martensite phase and detwinned martensite phase. Two kinds of honeycomb structures were examined in simulations: OX type honeycomb structure, which has a positive Poisson's ratio and auxetic type honeycomb structure, which has a negative Poisson's ratio. Simple tension behaviors of these two types of honeycomb structures were compared with experimental result by Hassan et al. (2009). Qualitative agreement was proved. Full cycle tension loading simulation was performed afterward. Localized deformation due to bifurcation of OX type honeycomb structure was discovered, which demonstrates less stability of OX type honeycomb structure than auxetic type. This phenomenon was due to stress concentration in particular regions. High stress level induced phase transformation, which largely weakened stiffness.

Similar localized deformation was not observed for the same structure under smaller tensile loading, or the same structure made of elastic material. Critical stress to induce bifurcation for this specific OX type honeycomb structure was also calculated.

Further studies related to in-plane behavior of SMA honeycombs could be found in chapter six. Newly developed plasticity model was applied in simulations of this chapter. This new model embedded plasticity model into superelasticity and shape memory effect. Different yielding conditions for austenite phase and martensite phase, as well as mixed phase were taken into consideration. Qualitative agreement was proved by comparing with simulation data from Michailidis et al. (2009). Then this model was applied in full cycle loading, coupling of plasticity and superelasticity induced permanent deformation in simulation. On the other hand, imperfection of honeycomb structures was another topic in this chapter. Simulations show no obvious instability of imperfect honeycomb structures than perfect ones. However, lower stiffness was observed.

Low shear stiffness type SMA honeycombs is considered as ideal candidate for smart structures. After extensive fundamental studies of this type in chapter five and chapter six, application about this type of structures as actuator is simulated in chapter seven. As one of the latest proposed smart structure, honeycomb core actuator by Okabe [Sugiyama (2009), Okabe et al. (2011)] was extensively studied. It is a temperature induced actuator. Its actuation process includes a forced shear deformation process and a heating process. Reasonable fitting with experimental results could be found in two aspects. Similar cell shape deformation between simulation and experiment could be proved as a qualitative validation. The quantitative validation could be found in comparison of actuating range, as well as its dependence to temperature. Besides, more detailed information was provided by simulation program such as stress, martensite phase distribution inside actuator. This could be considered as pioneering computational tool for advanced design of SMA honeycomb core actuators.

As more and more applications related to shape memory alloys come out every day, lacking of widely accepted numerical model becomes an urgent topic for researchers in this field. This thesis provided several major improvements on the conventional phenomenological model, aiming for a highly reliable model for shape memory alloy simulation. Models in this thesis are more accurate, more flexible and more adaptive for industrial needs. Experiments have validated its reliability in several aspects. With the validations and application examples, we have enough confidence to apply this model in broader fields. More applications using this model are expected in the future.