Analysis of Shape-memory alloy wire embedded laminated composite to imitate turtle's lag

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Abstract

In this study, to imitate turtle's lag, SMA(Shape memory alloy) embedded composite that has various stacking sequence is used. Bending and twisting deformation is induced by large phase transformation strain and recovering stress of SMA. In order to predict the deformation of composite, finite element method and analytical method based on the classical laminated plate theory are used. To represent the behavior of SMA, Lagoudas model is used. From this study, the bending curvature and twisting angle is estimated with respect to various stacking sequences and angles. The result obtained by analytical method shows a good agreement with the result obtained by FEM.

Keywords: Shape-Memory-Alloy, Finite Element Method, Classical Laminated Plate Theory, Biomimetics.

Introduction

Biomimetics, which imitate optimized motion of animal, is widely used to generate robot's efficient motion [Triantafyllou, 1995]. For example, human's bipedal mechanism, one of the land creasture's characteristic, is utilized to enhance bipedalism for bipedal robot[Tobias Luksch 2010]. Moreover, recently, not only the mechanism of land creature, the movement mechanism of underwater creatures is also attracting the interest of researcher. The underwater creature usually has optimized swimming skill and shape for reducing energy consumption or for enhancing speed. Actually, among underwater creatures, ocean turtle has optimized swimming skill to travel 50 km per day and accelerate up to 9 km per hour [Eckert, 2002]. If this swimming mechanism is applied to underwater robot, the swimming performance of the robot will be improved. For this reason, ultimately, objective of this study is to imitate ocean turtle's swimming skill. In order to imitate the swimming motion which have a bending-twisting coupling, SMA wire embedded composite is considered. SMA wire is a role of a driving part of composite due to its large recovery force (~1000Mpa), large transformation strain (4~5%) and fast repeated motion in water. Composite is a role of inducing a bending-twisting coupling motion. The motion of SMA wired embedded composites are predicted and analyzed by finite element method and classical laminated theory.

Modeling of SMA wire embedded composite

Composite used in analysis consist of five layers. Top and bottom layer are pure PDMS, and SMA wire is embedded in middle of each this layer. Middle three layers are composite which consist of PDMS and scaffold. PDMS is matrix part and scaffold is fiber part of composite. To generate bending with twisting motion like figure 1 (a) [$\theta/\theta+15/\theta$] stacking sequence is used and pure twisting motion like figure 1 (b) [$\theta/90/-\theta$] is used.

To describe shape memory effect, Lagoudas model is used. Lagoudas model define transformation function like equation (1), and according to transformation direction transformation tensor Λ_{ij} is defined differently.[Lagoudas, 1996]

$$\pi = \sigma_{ij}\Lambda_{ij} - \rho\frac{\partial G}{\partial \xi}, \qquad \Lambda_{ij} = \begin{cases} \frac{3}{2}H\left(\overline{\sigma}\right)^{-1}\sigma_{ij}\ , & forward \\ H\left(\overline{\varepsilon^{t}}\right)^{-1}\varepsilon^{t}{}_{ij}\ , & reverse \end{cases} \tag{1}$$

,where H is maximum transformation strain, ξ is martensite volume fraction. Forward transformation means transformation from austenite to martensite.

Fiber direction modulus(123.7MPa) of composite is gained by tensile test. Through this test, volume fractions of PDMS and scaffold, transverse direction modulus (1.948MPa) and shear modulus (6.958MPa) are gained.

Finite element method and classical laminated theory

To analysis SMA wire embedded composite 20 node hexahedron element is used for composite and PDMS layer and 1D truss element for SMA wire. Total Lagrangian description is used to describe nonlinear effect of finite element. Figure 1 shows FEM result.

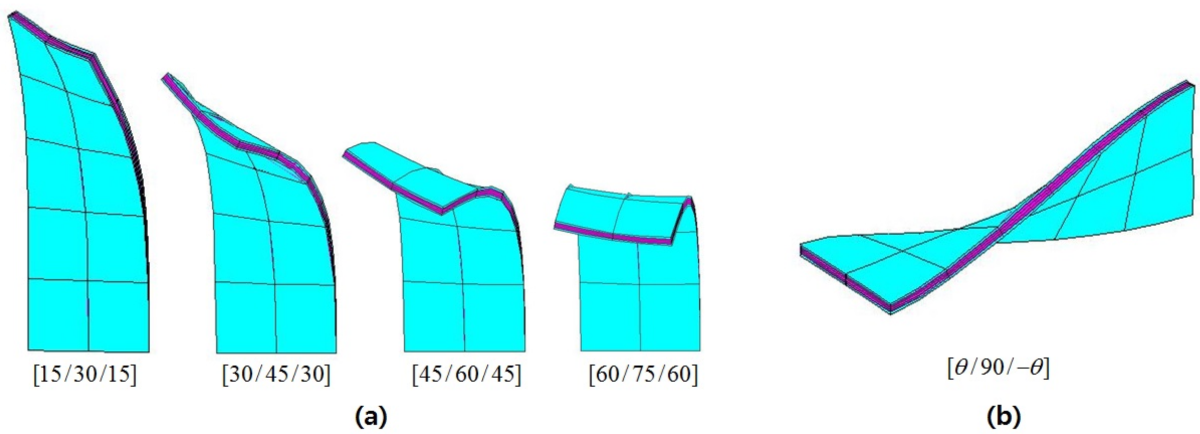

Figure 1. (a) FEM deformation result of bending with twisting motion (b) pure twisting motion

FEM analysis takes a lot of time to get solution about 1 hr. Because this model is simple shape of long hexahedron, classical laminated theory can be applied to analysis. CLT model including shape memory effect is considered to compare the FE model. By utilizing the CLT model, mid-plane strain and curvature are calculated, however, it need post-processing to get final shape of composite. To get final shape of composite, Hessian matrix of curvature from CLT is constructed. After that, principle direction and principle curvature are calculated by eigenvalue analysis. Deformed shape is described by assuming cylindrical displacement field.

Result and discussion

Length direction bending curvature and twisting angle of free end are used to compare FEM result and CLT result. Curvature of FEM result is calculated by equation (2).

$$\kappa = \frac{1}{R} = \frac{8d}{C^2 + 4d^2} \quad (2)$$

,where distance between both end of SMA wire(C) end distance from middle point of SMA to this line(d).

Twisting angle is calculated by dot product of width direction vector of free end and base vector. Figure 2 shows curvature and twisting angle result of both FEM and CLT.

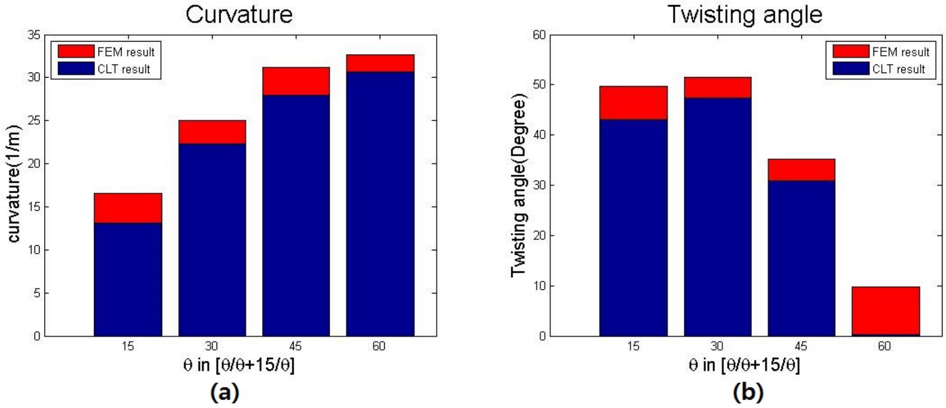

Figure 2. (a) Curvature and (b) twisting angle of FEM and CLT result

Although value of CLT and FEM results are somewhat different, both results shows a good agreement when considering tendency of CLT and FEM result. When stacking angle θ is 15° or 30°, value of curvature is small compare to stacking angle 45° or 60°. Stress generated in SMA wire is increased because length direction modulus is strong compare to stacking angle 45° or 60°. This increasing stress suppresses the transformation of SMA from martensite to austenite.

Conclusion

In this study, the motion of SMA wire embedded composite was predicted and analyzed to imitate the bending-twisting coupling motion of ocean turtle's lag by using FE model. From this study, we showed that this structure generate not only bending motion but also twisting motion by temperature control of SMA wire. Moreover, from different stacking sequence, various curvatures and twisting angle was induced.

In order to reduce the computation time of FEM, CLT model including SMA effect was developed. The both result of FEM and CLT model are well matched each other, so it means that this simple CLT model can help choose suitable stacking sequence of composite showing suitable bending-twisting coupling motion of robot to imitate the turtle lag's swimming motion.

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