Static finite element analysis of three-closed box thin-wall beam based on Pseudo-elastic SMA hybrid composite material ANSYS

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Abstract. The Auricchio model based on shape memory alloy and the finite element analysis software ANSYS Workbench firstly simulated the pseudo-elastic characteristics of SMA bar during the stretching cycle loading and unloading. Secondly, based on ANSYS Material Designer module, a SMA/glass/epoxy resin composite Material model was established and its Material parameters were obtained. ANSYS ACP module was used to establish the finite element model of pseudo-elastic SMA hybrid composite box thin-walled beam. Finally, the static response of SMA composite box thin-walled beam under transverse load is studied, and the influences of SMA, layout Angle, width to height ratio and volume content of SMA layer on the static response of box girder are discussed. The results show that the transverse displacement of the free end of the thin-walled beam increases with the increase of the laying Angle whether there is SMA fiber or not. After embedding SMA, the transverse displacement of the free end of the box thin-wall beam of hybrid composite was smaller. The transverse displacement of the free end of the thin-walled beam with the change curve of the lay-up Angle under the two con Figurations is consistent and basically consistent. At the same laying Angle, the transverse displacement of the free end of SMA hybrid box thin-walled beam decreases with the increase of the width to height ratio and the volume content of SMA monolayer.

1. Introduction
Wind turbine blade is a key component of wind turbine. It is a flexible and long body, which is easy to be stimulated by external power, such as wind load and earthquake load. When these loads continuously act on the wind turbine blades, the blades will vibrate, which will have a great impact on the life of the wind turbine blades, and may even lead to complete damage of the wind turbine, thus affecting the conversion of wind energy. The large wind turbine blade has the characteristic of multi-closed composite box-type thin-walled beam. Composite thin-walled beams are widely used in engineering structures due to their characteristics of high specific strength, high specific modulus and light weight. The structures of composite thin-walled beams are widely used in helicopter rotor blades and wind turbine blades. Due to the complex stress state and deformation of composite thin-walled beams in practical engineering applications, mechanical behaviors such as load coupling, structural elastic coupling, and nonlinear large deformation and deflection [1] make the solving of dynamic problems of large wind turbine blades more complex. Intelligent structure, which integrates sensors, controllers, actuators and structures, has
received much attention. There are few reports on the application of intelligent materials in the intelligent control of wind turbine blade flutter and vibration [2]. The intelligent material is pasted on the surface of the blade or embedded in the blade to produce a small distortion or change its aerodynamic characteristics. At present, the application of smart materials in composite thin-wall structures mainly focuses on the active control of vibration by embedding piezoelectric sensors and piezoelectric actuators into composite structures to make sandwich materials [3-7]. Lin et al. [8] established a two-dimensional cross section analysis model of anisotropic thin-walled single closed-cell beam with active SMA materials, and studied the influence of excitation temperature, lamination Angle, content of SMA fibers, and initial strain of SMA on the deformation driving performance of SMA. Khalili et al. [9] analyzed the nonlinear dynamic response of a SMA hybrid cantilever beam with phase transition and material nonlinear effects. The vibration response of the composite cantilever beam is reduced when the pseudo-elastic SMA is embedded in the outer layer of the beam. Ren Y S et al. [10] embedded SMA fibers into thin-walled composite beams and proposed a constitutive model of forth-displacement relation of thin-walled laminated beams with SMA fibers. Based on this model, the action law of volume fraction and laying Angle of SMA on the static deformation characteristics of thin-walled composite beams with extensional, flexural and torsional properties was discussed. Du Xianghong [11] simplified the wind turbine blades into slender thin-walled beams and buried SMA fibers into the thin-walled beams, and studied the influence law of SMA fibers on the deformation characteristics of thin-walled beams under temperature excitation. However, there are few reports about the passive vibration control of thin-walled composite structures by using phase change pseudo-elasticity of SMA. Due to the high cost of experimental research, this paper uses commercial finite element software ANSYS Workbench to carry out static finite element analysis on shape memory alloy (SMA) hybrid composite multi-closed box thin-walled beam. It is expected to lay a foundation for the engineering application of SMA pseudo-elasticity and the prediction of mechanical properties of SMA composite with complex structure.

2. SMA material constitutive model in ANSYS software
The Auricchio model [12,13] was used to describe the stress-stress relationship of the shape memory alloy. Assuming that the volume fraction of Martensite is composed of the volume fraction of residual irreversible Martensite and the volume fraction of reversible martensite, that is,

\[ \xi_M = \xi_R + \xi \]  

Within the small deformation range, the total strain is defined as:

\[ \varepsilon = \varepsilon^e + \xi_M \beta - \xi_R (\beta - \kappa) + \alpha (T - T_0) \]  

Where, \( \varepsilon^e \) is the elastic strain; \( \xi_M / \beta \) is the inelastic strain caused by phase transition, where is the internal variable describing the direction of Markov body weight; \( \beta \) is the training parameter; \( \alpha \) is the linear expansion coefficient; \( T \) is temperature.

It is assumed that there is a linear relationship between stress and elastic strain of SMA, namely:

\[ \sigma = E \varepsilon^e = E \left( \varepsilon - \xi_M \beta + \xi_R (\beta - \kappa) - \alpha (T - T_0) \right) \]  

Where, \( E \) is the elastic modulus, which can be expressed as:

\[ E(\xi_M) = \frac{E_A E_M}{E_M + \xi_M (E_A - E_M)} \]  

Where, \( E_A, E_M \) are respectively the elastic modulus of austenite and martensite.

The stress-strain curve of SMA materials based on the Auricchio model is shown in Figure 1. The model consists of three transformation regions: elastic region, positive phase transition region and inverse phase transition region.
In Fig. 1, A→M is the region of positive martensitic phase transition, M→A is the region of inverse Martensitic phase transition, and the others are elastic regions. In the definition of SMA material attribute by ANSYS software, 6 parameters need to be specified, $C_1$ - martensitic initial stress; $C_2$ - End-stress of martensitic transformation; Initial stress of martensite inverse phase transition; $C_3$ - End stress of martensite inverse phase transition; $C_5$ - Maximum residual strain; $C_6$ - Parameters reflecting the difference in tension and compression.

3. Mechanical properties analysis of pseudo-elastic SMA bars
SMA bar is an important part of SMA damper. In this section, ANSYS software is used to simulate the stress-strain relationship of SMA bars during tensile cycle loading and unloading, and the influence of different displacement amplitude-values on the single-coil energy dissipation, equivalent stiffness and equivalent damping ratio of SMA bars are studied.

3.1. SMA material parameters and finite element model
The density of SMA bar is 6450kg/m³, poisson's ratio is 0.33, and austenite elastic modulus is 40GPa. The number of other materials [14] is shown in Table 1.

| $C_1$ / MPa | $C_2$ / MPa | $C_3$ / MPa | $C_4$ / MPa | $C_5$ | $C_6$ |
|-------------|-------------|-------------|-------------|-------|-------|
| 440         | 540         | 250         | 140         | 0.042 | 0     |

The diameter and length of the SMA rod are 25.4mm and 150mm respectively. The grid division is shown in Figure 2. One end of the SMA bar is fixed, and the other end is applied with displacement load to simulate material tensile cyclic loading. The loading process is illustrated in Figure 3.
3.2. Analysis and discussion of results

When the strain amplitude of tensile cyclic loading and unloading is 1%, 2%, 3%, 4%, 5% and 6% respectively, the stress-strain curve of SMA bar simulated by ANSYS software and the experimental results in reference[15] are shown in Fig. 4. Where, Fig. 4(a) is the test result in literature[15], and Fig. 4(b) is the result simulated by ANSYS in this paper.

As can be seen from Fig. 4, except that the strain amplitude is 6%, the variation trend and value of the stress-strain curve of SMA bars simulated by ANSYS Workbench in this paper are basically consistent with the sample results in literature[15]. When the strain amplitude is 1%, only elastic deformation occurs in SMA bar, and no martensitic transformation occurs. When the strain amplitude was 2%, 3%, 4% and 5%, the SMA bars underwent positive and inverse martensitic phase transitions in the process of tensile loading and unloading, and the stress-strain curves formed closed hysteretic rings. And with the increase of strain amplitude, the area enclosed by the stress-strain curve of SMA bar increases gradually. In addition, as can be seen from Fig. 4(b), when the strain amplitude reaches about 5.2% in the loading process, the SMA bar has completely changed from austenite to Martensite, and then only the elastic deformation of martensite occurs in the loading process, with the maximum stress of about 750MPa. The reason is related to the constitutive model. When the SMA deformation reaches a certain degree, the description effect of the model on the complete martensite elastic deformation is not ideal.
4. Finite element modeling of box thin-walled beams with SMA hybrid composites

Considering a SMA hybrid composite with one end fixed and one end free, the shape structure and finite element model of a three-closed box thin-walled beam are shown in Fig. 5 and Fig. 6. The size of the box beam is the structure size in literature [16], where \( L = 1.500m, a = 0.075m, b = 0.025m \).

![Fig. 5 Structural model of three closed box thin-walled beams](image)

![Fig. 6 Finite element model of thin-walled beam](image)

4.1. Establish the finite element model of SMA hybrid composite box thin-walled beam

We built a box thin-walled beam surface model in Pro ENGINEER, imported Geometry into ANSYS Workbench, and then carried out mesh division in ANSYS ACP module to define composite material overlay information, including: overlay order, overlay material attributes, overlay thickness and overlay direction Angle, etc.

Two common stiffness configuration methods for composite laminates are considered, namely circumferential uniform configuration (CUS) and circumferential antisymmetric stiffness configuration (CAS). The two layups are shown in Figure 7. The finite element models of the two stiffness configurations are established respectively.

![Fig. 7 Lay-up method of three-closed box thin-walled beam](image)
4.2. Material selection

For the wall surface of the 6-layer SMA/Glass/Epoxy box-type thin-wall beam, the material parameters of Glass/Epoxy resin were adopted in the material parameters of ANSYS Workbench material library, as shown in Table 2. The material parameters of SMA wire are shown in Table 3.

Table 2 Material parameters of Glass/Epoxy resin

| Material parameters | The numerical |
|---------------------|---------------|
| $\rho$ (kg/m³)      | 2000          |
| $E_x$ (GPa)         | 45.0          |
| $E_y$ (GPa)         | 10.0          |
| $E_z$ (GPa)         | 10.0          |
| $G_{xy}$ (GPa)      | 5.00          |
| $G_{xz}$ (GPa)      | 5.00          |
| $G_{yz}$ (GPa)      | 3.84          |
| $PR_{xy}$ (GPa)     | 0.3           |
| $PR_{xz}$ (GPa)     | 0.3           |
| $PR_{yz}$ (GPa)     | 0.4           |

Table 3 Parameters of SMA wire materials

| Material parameters | The numerical |
|---------------------|---------------|
| $C_1$ (MPa)         | 400           |
| $C_2$ (MPa)         | 420           |
| $C_3$ (MPa)         | 150           |
| $C_4$ (MPa)         | 110           |
| $C_5$               | 0.07          |
| $C_6$               | 0             |
| $E_x$ (GPa)         | 45            |
| $\rho$ (kg/m³)      | 6450          |

The Material Designer module in ANSYS Workbench was used to build a SMA/Glass/Epoxy monolayer board. The volume fraction of SMA/Glass/Epoxy monolayer board was 50%. The Material parameters of SMA/glass/epoxy monolayer board obtained were shown in Table 4.

Table 4 Material parameters of SMA/Glass/Epoxy monolayer board

| Material parameters | The numerical |
|---------------------|---------------|
| $E_x$ (GPa)         | 45            |
| $E_y$ (GPa)         | 19.68         |
| $E_z$ (GPa)         | 19.68         |
| $G_{xy}$ (GPa)      | 8.85          |
| $G_{xz}$ (GPa)      | 8.85          |
| $G_{yz}$ (GPa)      | 6.54          |
| $PR_{xy}$           | 0.30          |
| $PR_{xz}$           | 0.30          |
| $PR_{yz}$           | 0.32          |
4.3. Determination of lay-up plan
For the two types of stiffness configuration, 6 layers are laid on the upper, lower and left walls of the composite thin-walled beam, 12 layers are laid on the middle wall, and the single-layer thickness \( t = 0.127 \text{mm} \). SMA fiber is laid on the upper and lower walls of the thin-walled beam in an interlayer hybrid way, with the laying Angle of 45°. Taking CAS configuration as an example, the upper \([\theta / 45^\circ]_3\) and lower walls \([-\theta / -45^\circ]_3\) are respectively and. The left and right middle wall paving layers are \([\theta / -\theta]_3\), where \( \theta \) is the glass fiber laying Angle, 45° is the SMA fiber laying Angle.

5. Finite element analysis and discussion of box thin-walled beam with SMA hybrid composite material
In order to further analyze the pseudo-bomb energy dissipation characteristics of the composite cantilever beam during vibration, CAS configuration in 3.1 was taken as an example. Considering that the lateral forces of the three-closed cantilever beam with one end fixed and one end free were 400N, 600N, 800N, 1000N, 1200N and 1400N respectively, loading and unloading were carried out to study the static response of the free end of the cantilever beam. Stress-strain results of the top SMA at the free end are shown in Figure 8.

![Stress-strain curve of SMA on top of SMA hybrid composite cantilever beam](image)

As can be seen from Figure 8, the lateral force of the top SMA in the loading and unloading process formed a closed hysteresis loop, this is because in the loading and unloading process of the pseudo-elastic SMA stress induced martensite positive and negative phase transitions. Where, the area of the hysteresis loop is the dissipated energy.

Using the pseudo-elastic properties of SMA, the deformation law of box girder embedded with hybrid composite material of SMA can be further analyzed.

As can be seen from Figure 9, in the six load loading and unloading processes, the free end deflection of the SMA composite beam and the external load all form a closed curve. Moreover, with the increase of the external load, the maximum deflection of the free end of the composite beam and the area of the closed curve increase gradually. Taking \( F = 800 \text{N} \) as an example, the maximum deflection of the free end of the cantilever beam reaches 1m. The area of the closed curve formed between the deflection and the external load represents the energy dissipated during the loading and unloading of the SMA composite beam. When the force \( F \) is 400N, in the loading and unloading process, because SMA composite beam does not reach SMA phase transformation stress, there is no martensitic positive phase transformation and inverse phase transformation. When the forces were 600N, 800N, 1000N, 1200N and 1400N, the composite beam underwent martensitic transformation. The energy dissipation were 8.41 kN-mm, 44.47 kN-mm, 94.18 kN-mm, 150.88 kN-mm, 211.75 kN-mm. It can be seen that when \( F = 1200 \text{N} \), the dissipated...
energy is 3.34 times that when F=800N, and the energy dissipation capacity of the SMA composite cantilever beam increases significantly with the increase of external load.

![Graph showing relation between deflection and load](image)

**Fig. 9** Relation between free end deflection and load of SMA composite beam

5.1. The presence or absence of SMA

Figure 10 shows the variation curve of the lateral displacement of the free end of the thin-walled beam with the laying Angle under CAS configuration without and with SMA fibers. Figure 10(a) shows the volume content of SMA of single layer as 0.1, and Figure 11(b) shows the volume content of SMA of single layer as 0.5. By can be seen in Figure 14, regardless of whether there is a SMA fiber, the free cod of a thin-walled beam horizontal displacement increases with the increase of laying Angle, when ordinary fiber laying Angle is greater than 60°, the free cod of a thin-walled beam lateral displacement amplitude decreases, and thus it can be seen that SMA transformation and fiber laying Angle between mutual coupling mechanism of complex layer Angle changes lead to the change of the SMA fiber stress, makes the SMA in different laying under the Angle of energy dissipation capacity. As can be seen from Figure 10(a), when the volume content of the monolayer SMA fiber is 0.1, because the volume content of the monolayer SMA fiber is lower at this time, when the SMA phase transition occurs, the content of the martensite generated by the austenite transformation is lower, leading to the decline of SMA energy dissipation capacity. As can be seen from Figure 10(b), when the volume content of single-layer SMA increases, compared with Figure 10(a), the transverse displacement of free end of thin-wall beam containing SMA fiber decreases, indicating that the energy dissipation capacity of SMA fiber increases when the volume content of single-layer SMA fiber increases.

![Graph showing variation of horizontal displacement with Angle](image)

**Fig. 10** Variation curve of lateral displacement of free end of thin-walled beam with laying Angle under CAS configuration without and without SMA fibers
5.2. Different configuration methods
The volume content and width/height ratio of single-layer SMA fiber were taken as 0.5 and 3 respectively. Fig. 11 shows the variation curve of lateral displacement of free end of SMA hybrid composite box thin-wall beam with the change of layup angle under two configurations, in which the influence of layup angle was taken into account.

As can be seen from FIG. 11, whether CAS configuration or CUS configuration, the transverse displacement of free end of SMA hybrid thin-walled box beam increases gradually with the increase of the paving angle. The transverse displacement of the free end of the box thin-wall beam with SMA hybrid composite material in the two configurations is consistent with the change curve of the layup angle, which is basically consistent. The results show that, under the condition of a certain volume content and width to height ratio of single SMA fiber, the influence of different configuration methods on the transverse displacement of free end of SMA hybrid thin-walled box-girder is not obvious with the change of layup angle.

![Variation curve of lateral displacement of free end of SMA hybrid composite box thin-walled beam with lay-up Angle under two configuration modes](image)

6. Conclusion
The Auricchio model based on shape memory alloy and the finite element analysis software ANSYS Workbench were used to study the static response of the pseudo-elastic SMA hybrid composite box thin-walled beam, and the main conclusions were as follows:

1) The strain amplitude has a great influence on the energy dissipation capacity of the pseudo-bomb during the stretching cycle loading and unloading of SMA bars.
2) For the SMA composite cantilever beam subjected to transverse concentrated force, when the external load reaches the martensitic positive and negative phase transition stress of SMA composite beam, the pseudo-elastic effect of SMA layer also presents the pseudo-elastic energy dissipation characteristics. With the increase of external load, the pseudo-elastic energy dissipation capacity of SMA hybrid beam increases gradually.
3) Regardless of the presence of SMA fiber, the transverse displacement of the free end of thin-walled beam increases with the increase of layin Angle. Compared with box thin-walled beams without SMA hybrid composites, the transverse displacement of free end of box thin-walled beams with PSEUDO-elastic SMA hybrid composites decreases.
4) Under the condition of a certain volume content and width to height ratio of single-layer SMA fiber, the transverse displacement of free end of box thin-wall beam with SMA hybrid composite under two configurations is consistent and basically consistent with the change curve of layup angle.
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