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Cured shape prediction of fiber metal laminates considering interfacial interaction

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ABSTRACT

During the manufacturing process of fiber metal laminates (FMLs), incompatible residual strain leads to the problem of slippage interaction at the interface between the metal layer and the fiber layer. An analytical model and finite element (FE) model considering slippage effect are established to obtain the cured shape and deformation of cross-ply [Al/0/90/Al] FMLs. Both analytical and FE results are in good agreement with experimental results. The predicted models proposed in this paper can accurately and effectively calculate the equilibrium configurations of FMLs at room-temperature. In order to reveal the curing deformation characteristics of FMLs, the influence laws of geometry dimensions and metal ply thickness on the cured stable shapes are obtained by using the prediction models for the square and rectangular laminates.

1. Introduction

Fiber metal laminates, i.e. combinations of composites and metal alloys, have high-performance to be used in aircraft structures like fuselage panels and leading edges of tail planes [1]. The manufacturing of high-performance composite materials always involves high temperature and even high pressure. Therefore, the mismatch in coefficients of thermal expansion between constituents and plies with different fiber orientations can induce thermal residual stresses during the cool-down process [2]. The shapes of the unsymmetric laminates would change from flat planes to curved plates due to bending-stretching and bending-twisting couplings from the residual stresses. The deviations between the actual shape of the laminate and the required shape could result in difficulties in assembly and even quality issues. Therefore, the cured shape should be accurately predicted to eliminate the effect of thermal residual stress on the FMLs.

For the pure unsymmetric composite laminates, the cured shape has been intensively and deeply studied using analytical and FE techniques by many researchers [3–12]. Initially, Hyer [3–5] extended classical lamination theory by considering von-Karman geometric non-linearity in the form of strain–displacement relationships, and explained that room-temperature shapes of thin unsymmetric laminates exhibit two stable cylindrical states instead of a cured saddle shape, as depicted in Fig. 1. The Hyer's model predict the deformations of square cross-ply laminates, which are in good agreement with FE model results [6]. Following Hyer's work, the complexity of analytical methods has been increased to include in-plane shear strains [7], higher-order plate theory with the transverse shear strain [8] and complex boundary conditions [9,10]. In addition, the out-of-plane displacement function of Hyer's model has been expanded by increasing the order of the polynomials, which also introduced more unknown terms in order to improve the accuracy of the predicted room-temperature shapes and bifurcation behavior [13–16]. Several factors influencing the cured shapes of unsymmetric laminates have been discussed in the following researches, such as aspect ratio [16,17], chemical shrinkage [18,19], moisture absorption [20,21], imperfection [22,23], initial curvature [24,25] and thermal gradient [26] etc.

Being different from the pure composite laminates, the interaction between the metal layer and the fiber layer leads to the bond-slip phenomenon at the interface during the curing process of hybrid laminates [27–29]. It is obviously not appropriate to predict the cured shape of the hybrid laminates by using the above method. Therefore, the effect of this slippage interaction on the curing deformation of hybrid laminates should be taken into account. Daynes et al. [27] quantitatively described the slipping at the metal-fiber interface and optimized the thermal expansion coefficient of the component materials. Thus, the equilibrium configuration of $[0_n/M/90_n]$ unsymmetric hybrid laminates with an inner isotropic metallic layer was accurately predicted by using the optimized coefficients of thermal expansion for each component. Similarly, Dai et al. [28] studied the curing behavior of $[0/90/Metal]_T$ twisted bistable unsymmetric hybrid laminates with an external isotropic metallic layer and obtained the same sign

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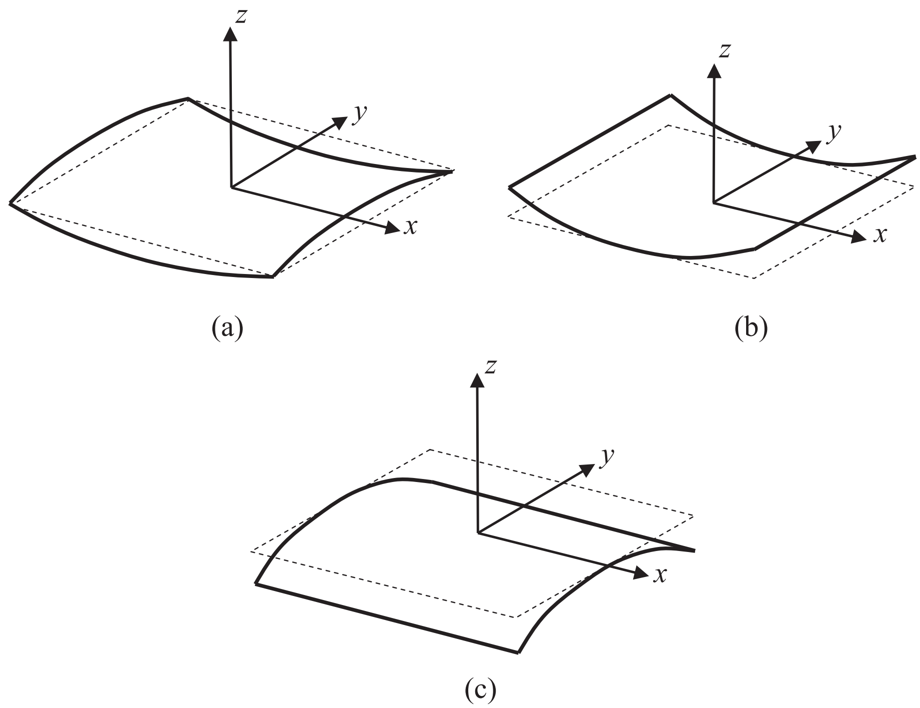

Fig. 1. Cured shapes of unsymmetric cross-ply laminates at room-temperature: (a) unstable saddle shape, (b) one stable cylindrical shape, (c) the other stable cylindrical shape.

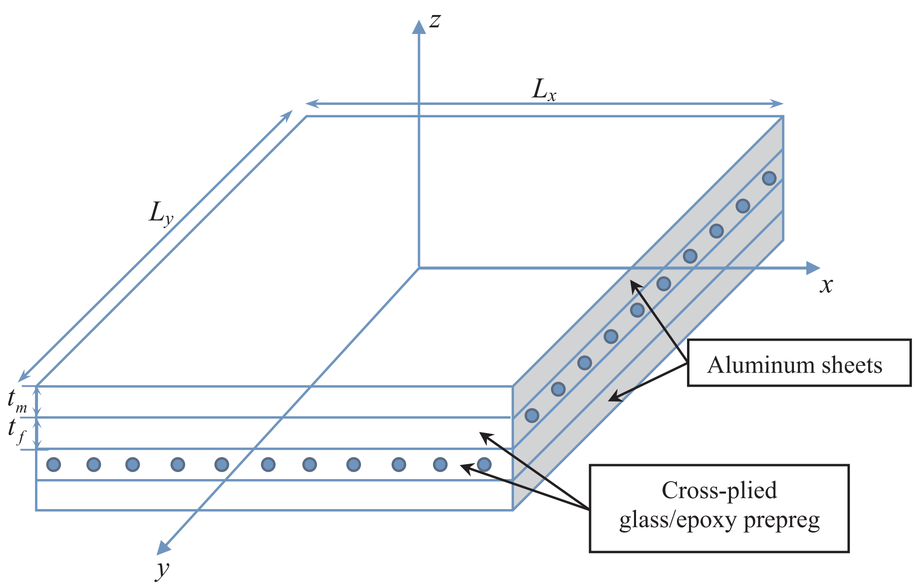

Fig. 2. Schematic figure of cross-ply FML.

curvatures in two stable states. Abouhamzeh et al. [30] showed that the thermal deformation and residual stresses of cured FMLs were predicted using a thermo-viscoelastic model.

The influence of slippage on the curing deformation of hybrid laminate is taken into account in the analytical model by the modification of the coefficients of thermal expansion [27]. However, the mathematical expressions of interfacial slippage strain cannot be given directly. From the viewpoint of energy, this paper proposes an analytical model considering slippage effect and expounds the influence mechanism of slippage interaction on the curing deformation of FMLs. Based on a sixth-order polynomial out-of-plane displacement function in combination with the Rayleigh-Ritz method, the room-temperature shape of cross-ply [Al/0/90/Al] FMLs is accurately predicted by introducing the slippage strain energy into the total potential energy function. What's more, the mathematical expressions of interfacial slippage strain in the metal layer and the fiber layer in the fiber direction are given. Subsequently, a FE model is established to simulate the interfacial slippage effect by applying spring elements. Both the analytical and FE results are well coincident with experimental results, which indicates that the models proposed in this paper are reasonable and applicable. Finally, the influence of the laminate dimensions, metal ply thickness and aspect ratio on the cured stable configurations is studied by using the established analytical and FE analysis models.