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Determination and Reducing of Curvature from Residual Stresses in Cured Shapes by Using Carbon Nanotubes in Unsymmetric Carbon/Epoxy Laminates

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ABSTRACT: In this research, the curvature of cured three-phase un-symmetric cross-ply composite laminates and the effect of carbon nanotubes on it have been studied. The un-symmetric cross-ply composite laminates are including three different phases: carbon fiber, polymer epoxy, and carbon nanotube particles. The different volume fraction of carbon nanotubes as %0, %1, %2 and %3 have been considered in the three-phase un-symmetric cross-ply composite laminate. Different micromechanics models such as Halpin-Tsai, bridging and Schapery models have been used to determine the mechanical and thermal properties. Adding %1 volume fraction of carbon nanotubes leads to decreasing the longitudinal and transverse coefficient thermal expansions and increasing the longitudinal, transverse and shear modulus ones in the composite laminate. Hyer model has been employed to investigate different parameters such as curvature, critical length, and deformed shape in different lengths of square un-symmetric cross-ply laminates. Results show that the addition of 1% volume fraction of carbon nanotubes decreased the critical length and curvature about 9% and 14%, respectively. In addition to Hyer model, the finite element analysis has been used to determine the curvature of the cured un-symmetric cross-ply laminate. The results of finite element analysis and Hyer model have been compared together that showed appropriate conformity and less than 10% error.

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1- Introduction

Composite materials are used widely in the industry according to special properties as mechanical strength to weight ratio and Resistance to environmental factors. The existence of more than one material in composite materials with different mechanical and thermal properties caused residual stresses in these materials. Residual stresses caused deformed shape (curvature and warpage) in un-symmetric laminates. In 1981, Hyer [1, 2] investigated the cured shape of un-symmetric laminates as experimental and using Classical Laminate Theory (CLT). Hyer observed inconsistency of experimental with CLT results. The CLT predicted saddle shape for the cured shape of un-symmetric cross-ply laminates but experimental results showed a cylindrical shape. He introduced a model to prediction of curvature in un-symmetric composite laminates after the curing process that confirm with experimental [3]. Ren et al. [4] established a model based on energy method to the investigation of effects of different parameters as layer thickness, mold radius and laminate lay-up on curvature in the cured un-symmetric laminate.

After the discovery of nanomaterials, these materials used in different industries for special mechanical properties, such as high elastic modulus and mechanical strength, and thermal properties such as low thermal expansion coefficient. Ghasemi and Mohammadi [5] studied the distribution of residual stresses in three-phase composite materials. They used Carbon Nanotubes (CNTs) to reinforce carbon fiber by electrophoresis method in three-phase composite materials. They studied the effects of different CNTs volume fraction on the distribution of residual stresses as two and three dimensional. Hassanzadeh-Aghdam et al. [6] used a combination of two micromechanics to determine mechanical properties of the nanocomposite. They employed Eshelby method for modeling the random orientation state of carbon nanotubes within the matrix. Two fundamental aspects affecting the mechanical behavior including the carbon nanotube waviness and the interphase considered in the unit cell method.

In this research, determination of curvature and the effects of different volume fractions of CNTs are investigated on the cured shape of three-phase un-symmetric cross-ply composite laminates $[0_2/90_2]_T$. Mechanical and thermal properties of three-phase composite laminate are determined using micromechanics models. Hyer model and finite element analysis are employed to determine curvature according to different parameters as volume fractions of CNTs and side length in un-symmetric cross-ply composite laminates $[0_2/90_2]_T$. Thermal loading is considered fix and uniform in the curing process.

2- Hyer model

Hyer [4] considered displacement of the composite laminate in different direction x_1, x_2, x_3 as:

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$$u_1^0 = cx_1 - \frac{1}{6}a^2 x_1^3 - \frac{1}{4}abx_1x_2^2 \quad (1)$$

$$u_2^0 = dx_2 - \frac{1}{6}b^2 x_2^3 - \frac{1}{4}abx_2x_1^2 \quad (2)$$

$$u_3^0 = \frac{1}{2}\left(ax_1^2 + bx_2^2\right) \quad (3)$$

a and b parameters are mid-plane curvature of laminate and c, d parameters are mid-plane strain of laminate. The total potential energy of laminates after curing that can be obtained as:

$$W = \int_{-\frac{L_1}{2}}^{\frac{L_1}{2}} \int_{-\frac{L_2}{2}}^{\frac{L_2}{2}} \int_{-\frac{h}{2}}^{\frac{h}{2}} \varphi \, dx_1 \, dx_2 \, dx_3 \quad (4)$$

ϕ is energy density that depends on different parameters as:

$$\phi = \frac{1}{2}\bar{C}_{ij}\left(e_i e_j - \alpha_i e_j \Delta T\right), \qquad i,j = 1,2,6 \quad (5)$$

ei is a component of strain tensor, αi is thermal expansion coefficient, $\bar{C}_{ij}$ is the elasticity constants and ΔT is the difference between curing and room temperature. By considering the minimal potential energy based on Rayleigh-Ritz method, unknown parameters as a, b, c, and d are obtained. To determine mechanical and thermal properties of the three-phase composite laminate, Halpin-Tsai, bridging and Schapery models are used for the different volume fraction of CNTs.

3- Results and Discussion

According to micromechanics model, mechanical and thermal properties of the three-phase composite laminate including carbon fiber (%60 volume fraction), polymer matrix and CNTs are obtained for different CNTs volume fraction that shown in Table 1. Increasing CNTs volume fraction caused improvement of mechanical property and decreasing transverse thermal expansion coefficient.

Table 1: Mechanical and thermal properties of three-phase composite laminate with different CNTs volume fraction

% CNT	%0	%1	%2	%3
E_L (GPa)	139.2	139.47	139.69	139.9
E_T (GPa)	7.72	8.51	9.21	9.84
G_{LT} (GPa)	4.46	5.12	5.78	6.43
α_T(°C)$^{-1}\times10^{-6}$	44.06	35.74	34.58	34.05
α_L(°C)$^{-1}\times10^{-6}$	0.165	0.09	0.13	0.18

According to Hyer model, The results of curvature of three-phase un-symmetric cross-ply laminate $[0_2/90_2]_T$ after the curing process ($\Delta T = 100°C$) are shown in Table 2. Adding %1 CNTs caused decreasing curvature from 6.379 (m^{-1}) to 5.442 (m^{-1}) for side length 0.3 (m). For %2 and %3 CNTs cases, changes in curvature are not significant. In addition Hyer model, results of finite element analysis is shown in Fig. 1 and compared to Hyer model that shown good agreement.

Table 2: Effect of CNTs volume fraction on curvature in cured un-symmetric cross-ply laminate $[0_2/90_2]_T$

CNT	curvature (m^{-1}) (side length 0 (m))	curvature (m^{-1}) (side length 0.3 (m))
%0	6.53	6.379
%1	5.61	5.442
%2	5.546	5.46
%3	5.73	5.53

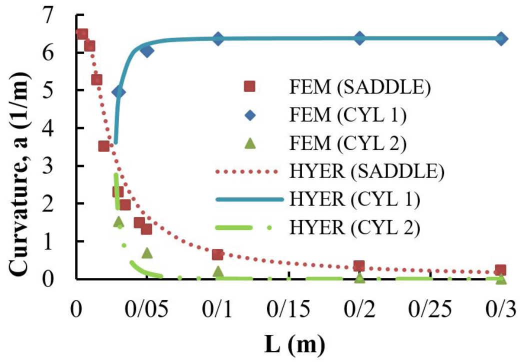

Fig. 1. Comparison of results of curvature in Hyer model and finite element analysis for 0% CNTs

4- Conclusion

In this research, the effects of different CNTs volume fraction as %0, %1, %2 and %3 were investigated on the cured shape of un-symmetric cross-ply composite laminate. Micromechanics models as Halpin-Tsai, bridging and schapery employed to determine mechanical and thermal properties of the three-phase composite laminate including carbon fiber, polymer matrix, and CNTs. Adding %1 CNTs volume fraction increased elastic modulus equal %10, shear modulus equal %14, transverse CTE equals %19 and longitudinal CTE equals %45 in comparison with two-phase composite laminate. Hyer model was used to determine the curvature of un-symmetric cross-ply laminate $[0_2/90_2]_T$ after the curing process. Adding %1 CNTs volume fraction was decreased curvature of un-symmetric cross-ply laminate equal %15 in comparison with two phase composite laminate. Changes of curvature were not significant for %2 and %3 CNTs volume fraction. Results of finite element analysis were confirmed Hyer model results for the curvature of the cured un-symmetric cross-ply composite laminate

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