論文

Orthotropic Formulation of Hygrothermal Stress in FRP Tubes

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FRP 튜브의 열 및 습도변화에 의한 내부응력

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초 록

무한대로 길며 두꺼운 섬유강화 복합재료 Tube의 각층과 모든 섬유방향에 대하여 열 혹은 습도에 의한 응력변화를 계산할 수 있는 orthotropic 공식을 유도하였다. 이 공식은 섬유강화 복합재료 tube의 환경변화, 즉 온도 혹은 습도의 변화가 있을 때 tube 자체내에 생기는 응력을 계산할 수 있따. 이 공식을 유도할 때 튜브방향으로 변화하는 정상상태 온도변화(steady-state temperature gradient)를 고려하여 튜브의 내부 온도와 외부 온도가 다를 때도 적용되도록 하였다.

ABSTRACT

An orthotropic hygrothermal stress solution has been formulated for an infinitely long fiber-reinforced tube of any number of plies of any material, with arbitrary orientation of each of the plies. The solution allows the determination of stresses when the tube is subjected to changes in temperature and moisture content. In the formulation, a teemperature gradient through the thickness has been taken into account such that the formulation can be applied when the temperature inside the tube is not the same as that outside. This set of equations, togehter with the prescribed boundary conditions, has been solved numerically. It is shown that the present formulation can calculate hygrothermal stresses for FRP tubes.

1. Introduction

When designing a fiber-reinforced tube to be used in areas where the environmental conditions change, the residual stresses induced due to changes of temperature and moisture content should

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be taken into consideration along with any of the external loads acting on the tube.

This paper presents a planar orthogonal-anisotropic(or orthotropic) formulation for stresses induced in fiber-reinforced tubes due to changes of temperature and moisture. The solution is appropriate for any number of plies of any material(isotropic or laminated material) for any orientation of the plies of an infinitely long thin tube whose radius to thickness ratio, R/t, is greater than 10. A temperature gradient through the thickness has been included. Although radial stresses are smaller than the other stress components, radial thermal expansion effects have a significant impact on the stress state. This is the primary reason for an orthotropic approach, as opposed to a laminated shell approach to the solution.

An extension of the orthotropic solution given by Hyer and Rousseau[1] is presented at the beginning of this paper. Hyer and Rousseau have discussed the elastic solution for thermal stresses in multiple-layer angle-ply tubes. Their work has been extended to include the effects of temperature variations through the thickness of the tube and the effects of absorbed moisture. The response of single and multiple-layer tubes to mechanical loads using elasticity, laminated shell, and finite element approaches have been discussed by the authors in references 2-9, respectively.

Whitney[6] has given a limited discussion of thermal stresses in angle-ply tubes. Four authors (Birger, Tauchert, et. al., Tauchert and Hyer, et. al.[10-13]) have discussed the thermal response of layered tubes from an elasticity point of view. The authors, in references[14-17], have developed orthotropic solutions for single-layer tubes and for multi-layer tubes, where the fibers in each layer are all in the circumferential direction, by increasing the thickness of the single-layer tube.

Residual stresses in composite laminates are the result of an expansional mismatch between fibers and matrix. Expansional anisotropy of plies leads to residual stresses in constituent plies as the fiber direction changes from ply to ply[18]. The presence and seasonal change of residual stresses are clearly demonstrated by the warping of unsymmetric laminates.

Hahn[19] has shown the severeness of the central deflections of $(0_4/90_4)$ T300/5280 laminates, 10×10cm square, when left in the laboratory for a year. Although the temperature was kept fairly constant at 23℃, the humidity changed from a low of 10 percent in winter to a high of 85 percent in summer. The deflection was higher in the winter and lower in the summer. Moisture swelling partially cancels thermal shrinkage after the cure cycle and produces the observed variations in warping.

Ply residual stresses can be calculated using laminated-plate theory. Under nonhostile environments the assumption of elastic behavior provides a good estimate when the cure temperature is used as the stress-free temperature[20]. With increasing temperature and moisture concentration, however, the matrix resin becomes viscoelastic and the relaxation of residual stresses can no longer be neglected[21, 22]. For example, the maximum transverse tensile stress in a T300/5208 laminate can be reduced by as much as 40 percent in just 10 minutes when the laminate contains 1.4 percent moisture at 125℃. On the other hand, the correspondins stress relaxation at room temperature is negligible[19, 21, 23]. The formulation for stresses in fiber-reinforced tubes which are used in a hostile environment should include both temperature and moisture terms as well as shear terms which exist due to the angle plies. The stresses will combine with the stresses due to external loads and the residual stresses to determine the final operating stress state.

2. The Orthotropic Solution

The x-θ-r cylindrical coordinate system of Fig. 1 is used in the analysis. In addition to describing the cylindrical coordinate system, Fig. 1 shows the commonly used 1-2-3 notation for the lamina coordinate system.

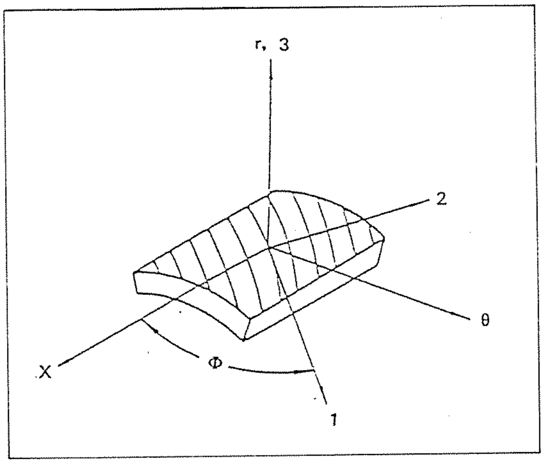

Fig. 1　Cylindrical Coordinate System Used and Definition of Off-Axis Ply Angle Φ.

Since a planar approach is being used, none of the stresses, and through the stress-strain relations, none of the strains, are functions of the axial coordinate, x. In addition, since the temperature is assumed to be spatially uniform, none of the tube responses are dependent on the circumferential coordinate, θ. As a result of these two assumptions, the radial displacement is not dependent on the axial coordinate x. The axial, circumferential and radial displacements take the form

$$u(x,\ \theta,\ r)=u(\theta,\ r)$$
$$v(x,\ \theta,\ r)=v(\theta,\ r)$$
$$w(x,\ \theta,\ r)=w(r)$$

The strain-displacement relations then simplify to

$$\varepsilon_x=\frac{\partial u(x,\ r)}{\partial_x}\ ;\ \varepsilon_\theta=\frac{w(r)}{r}\ ;$$

$$\varepsilon_r=\frac{dw(r)}{dr} \quad \cdots\cdots (1)$$

$$\tau_{\theta r}=\frac{\partial v(x,\ r)}{\partial r}-\frac{v(r)}{r}\ ;$$

$$\tau_{xr}=\frac{\partial u(r)}{\partial_r}\ ;\ \tau_{x\theta}=\frac{\partial v(r)}{\partial_x} \quad \cdots\cdots (2)$$

The most general anisotropic form of the linear elastic stress-strain relation is given by

$$\sigma_{ij}=c_{ijkl}\ \varepsilon_{kl}$$

For general orthotropic lamina, the stress-strain behavior in the x, θ, r coordinate system can be written for each layer as [24] or, reversing this relations,

$$\begin{Bmatrix}\varepsilon_x\\ \varepsilon_\theta\\ \varepsilon_r\\ \gamma_{\theta r}\\ \gamma_{xr}\\ \gamma_{x\theta}\end{Bmatrix} = \quad \cdots\cdots (3)$$

$$\begin{bmatrix} S_{11} & S_{12} & S_{13} & 0 & 0 & S_{16}\\ S_{12} & S_{22} & S_{23} & 0 & 0 & S_{26}\\ S_{13} & S_{23} & S_{33} & 0 & 0 & S_{36}\\ 0 & 0 & 0 & S_{44} & S_{45} & 0\\ 0 & 0 & 0 & S_{45} & S_{55} & 0\\ S_{16} & S_{26} & S_{36} & 0 & 0 & S_{66}\end{bmatrix}\begin{Bmatrix}\sigma_x\\ \sigma_\theta\\ \sigma_r\\ \tau_{\theta r}\\ \tau_{xr}\\ \sigma_{x\theta}\end{Bmatrix}$$

However, when the temperature and moisture effects are considered, the strain tensors in the above equation are replaced with the following relations similar to what was done by Tsai and Hahn for laminate plates[20].

$$\varepsilon_x=\varepsilon_x-\alpha_x T(r)-\beta_x\Delta M \quad \cdots\cdots (4)$$

$$\varepsilon_\theta=\varepsilon_\theta-\alpha_\theta T(r)-\beta_\theta\Delta M \quad \cdots\cdots (5)$$

$$\varepsilon_r=\varepsilon_r-\alpha_r T(r)-\beta_r\Delta M \quad \cdots\cdots (6)$$

$$\gamma_{\theta r}=\gamma_{\theta r} \quad \cdots\cdots (7)$$

$$\gamma_{xr}=\gamma_{xr} \quad \cdots\cdots (8)$$

$$\gamma_{x\theta}=\gamma_{x0}-\alpha_{x\theta}T(r)-\beta_{x\theta}\Delta M \quad \cdots\cdots (9)$$

3. Temperature Distribution, T(r)

Under the assumption of steady state heat transfer through the thickness direction, the heat flow rate per unit length, q, is[25]

$$q= 2\pi rk\frac{dT(r)}{dr} \quad \cdots\cdots (10)$$

Integrating,

$$T(r)=\frac{q\ln r}{2\pi k}+c \quad \cdots\cdots (11)$$

Eliminating the constant term and rearranging using a two layer tube system, q for the inner layer has the following form

$$q=2\pi k_i(T_b-T_a)\ln\left(\frac{a}{b}\right) \quad \cdots\cdots (12)$$

Again formulating from a two-layer-tube system, the temperature distribution equations for an N layer tube can be formulated as follow

$$q^{(N)}=2\pi k^{(N)}[T_o^{(N)}-T_i^{(N)}]\ln(r_i^{(N)}/r_o^{(N)}) \quad \cdots\cdots (13)$$

$$T^{(N)}{}_{(r)}=T_i^{(N)}-\frac{q^{(N)}}{2\pi k^{(N)}}\ln\frac{r^{(N)}}{r_i^{(N)}} \quad \cdots\cdots (14)$$

4. The Tensor Transformation Law

The tensor transformation law for equation (3) is given by

$$C'_{ijkl}=A_{im}\ A_{jn}\ A_{ko}\ A_{lp}\ C_{mmnop} \quad \cdots\cdots (15)$$

where A_{ij} is the consine of the angle between the ith direction in the 1, 2, 3 systems and the th direction in the x, θ, r systems for all transformations. Tasking the x, θ, r axes as being rotated about the 3 axis of the 1, 2, 3 systems gives[24],

$$C'_{11}=m^4C_{11}+2m^2n^2(C_{12}+2C_{66})+n^4C_{22} \quad \cdots\cdots (16)$$

where $m=\cos\theta$, $n=\sin\theta$, and θ is the angle of roatation. Rest of C'_{ij}'s can be obtained by similar manner. The C_{ij} can be calculated from the values of the Poisson's ratios and the moduli of elasticity in the 1, 2, 3 directions[26].

Because of the assumptions made at the beginning of the discussion, three of the six compatibility equations are automatically satisfied. The three remaining equations are[27]

$$\frac{d^2\varepsilon_x}{dr^2}=0\ ;\quad \frac{1}{r}\frac{d\varepsilon_x}{dr}=0\ ;$$

$$\frac{d}{dr}\left[\frac{1}{r}\frac{d}{dr}(r\gamma_{r\theta})\right]=0 \quad \cdots\cdots (17)$$

The simplified forms of the equilibrium equations are

$$\frac{d\sigma_r}{dr}+\frac{\sigma_r-\sigma_\theta}{r}=0\ ;\ \frac{d\tau_{\theta r}}{dr}+\frac{2\tau_{\theta r}}{r}=0\ ;\ \frac{d\tau_{xr}}{dr}+\frac{\tau_{xr}}{r}=0 \quad \cdots\cdots (18)$$

The first two compatibility equations indicate that within each layer ε_x is constant, i.e.,

$$\varepsilon_x(r)=\varepsilon \quad \cdots\cdots (19)$$

and the remaining compatibility equation integrates to

$$\gamma_{x\theta}=\gamma^\circ r+\frac{D}{r} \quad \cdots\cdots (20)$$

γ° and D being constant. The quantity γ° has the physical interpretation of radians of twist per unit length of tube. An interesting result is that ε° and γ° are the same in each layer for constant temperature and moisture conditions. The second and third equilibrium equations result directly in

$$\tau_{\theta r}=\frac{E}{r^2},\qquad \tau_{xr}=\frac{F}{r} \quad \cdots\cdots (21)$$

E and F being constant. By using the stress-strain relations, equation (5) and integrating the strain-displacement relations, $\gamma_{\theta r}$ and γ_{xr} it can be shown that

$$u(x,\ r)=\varepsilon^{\circ}x-\frac{S_{45}E}{r}+S_{55}F\ln r-A \quad \cdots\cdots\cdots (22)$$

$$v(x,\ r)=\gamma^{\circ}xr-\frac{S_{44}E}{2r}-S_{45}F+Br \quad \cdots\cdots\cdots\cdots (23)$$

where A and B are constants representing rigid body displacement and rotation, respectively.

The first equlibrium equation, along with the stress-strain and strain displacement equations can be used to determine the differential equation governing the radial displacement. The right hand side of the following is the typical equilibrium equation written in terms of radial displacement [14, 15, 16].

$$\frac{d^2w}{dr^2}+\frac{1dw}{rdr}-\frac{w}{r^2}C'_{22}/C'_{13}=$$

$$\frac{\varepsilon^{\circ}}{r}(C'_{12}-C'_{13})/C'_{33}-2\gamma^{\circ}C'_{36}/C'_{33}$$

$$+(\gamma^{\circ}+D/r^2)C'_{26}/C'_{33} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (24)$$

The solution to the above differential equation is

$$w(r)=A_1r^k+B_1r^{-k}-r\Omega/(C'_{33}-C'_{22})$$

$$+\gamma^{\circ}r^2(C'_{26}-2C'_{36})/(4C'_{33}-C'_{22})$$

$$+\varepsilon^{\circ}r(C'_{12}-C'_{13})/(C'_{33}-C'_{22}) \quad \cdots\cdots\cdots\cdots\cdots\cdots (25)$$

where A and B are constants and

$$\Omega=(C'_{13}-C'_{12})(\alpha_xT(r)+\beta_x\Delta M)+$$
$$(C'_{23}-C'_{22})(\alpha_\theta T(r)+\beta_\theta\Delta M)+$$
$$(C'_{33}-C'_{23})(\alpha_rT(r)+\beta_r\Delta M)$$
$$+(C'_{36}-C'_{26})(\alpha_{x\theta}T(r)+\beta_{x\beta}\Delta M)$$

and

$$K=(C'_{22}/C'_{33})^{1/2}$$

For an N-layer tube there are N A's, J B's, N A's and N B's, or 8N unknown constants of integration. These constants are determined by satisfying the traction-free conditions at the inner and outer radii, satisfying continuity of three of the six traction equations at each interface between adjacent layers, satisfying the continuity of displacements at each interface between adjacent layers, suppressing rigid body motion, and applying two integrated conditions on the cross section of the tube. The integrated conditions are a result of the analysis being a planer one. Specifically, the traction-free conditions at the inner and outer surface can be written as

$$\sigma_r^{(1)}(r_i)=\tau_{\theta r}^{(1)}(r_i)=\tau_{xr}^{(1)}(r_i)=0 \quad \cdots\cdots\cdots\cdots\cdots\cdots (26)$$

$$\sigma_r^{(N)}(r_o)=\tau_{\theta r}^{(N)}(r_o)=\tau_{xr}^{(N)}(r_o)=0 \quad \cdots\cdots\cdots\cdots\cdots (27)$$

where the superscript refers to layer number, layer 1 being the inner layer and layer N being the outer layer. Continuity of tractions leads to

$$\sigma_r^{(k)}(r_k)=\sigma_r^{(k+1)}(r_k) \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (28)$$

$$\tau_{\theta r}^{(k)}(r_k)=\tau_{\theta r}^{(k+1)}(r_k) \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (29)$$

$$\tau_{xr}^{(k)}(r_k)=\tau_{xr}^{(k+1)}(r_k) \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (30)$$

where k=1, 2, …, N-1. Here r_k is the location of the interface between layers k and k+1. Continuity of displacements results in

$$u^{(k)}(x,\ r_k)=u^{(k+1)}(x,\ r_k) \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (31)$$

$$v^{(k)}(x,\ r_k)=v^{(k+1)}(x,\ r_k) \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (32)$$

where k=1, 2, …, N-1. Rigid body motions can be suppressed by setting A and B of equations (22 and 23) in the inner layer to zero. The two integral conditions can be expressed a:

$$2\pi\sum_{k=1}^{N}\int_{r_{k-1}}^{r_k}\sigma_x^{(k)}(r)rdr=0 \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots (33)$$

$$2\pi\sum_{k=1}^{N}\int_{r_{k-1}}^{r_k}\rho_{x\theta}^{(k)}(r)r^2dr=0 \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (34)$$

The first intergral enforces the condition that the net axial force acting on the tuve cross section is zero. The second integral enforces the zero torsion condition. Both conditions must be enforced beacuse there are no loads being applied to the tube.

With the above conditions there result enough equations to solve for the 8N constants. A computer program has been written to calculate the stresses due to temperature and moisture effects for thin tubes of any number of layer(s) and with any orientations of the layers.

5. Sample Solutions

The material and geometric properties of the filamentary wound laminated composite cylinder used in the 1st example discussed here are the same as those used by Hyer and Rousseau[1]. The layup consists of 44 total layers, each with a thickness of 0.0762mm(0.003 in.), for a total shell thickness of 3.353mm(0.132 in.). The ply layup, from the inner to outer surface of the cylinder, is given as$\Phi/\Phi/0_{40}/-\Phi/\Phi$. The inner and outer radii of the cylinder ar 21.8mm(0.858 in.) and 25.15mm(0.990 in.), respectively. The cylinder is assumed to be infinitely long. The individual layers, made of P75s/934, are assumed to be orthotropic.

Since the author is unaware of any results of

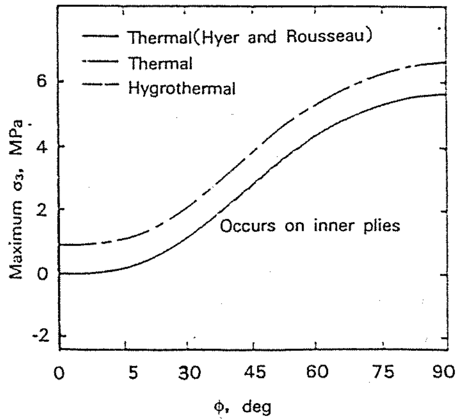

Fig. 3 Influence of the Off-Axis Ply Angle on σ_3 When Subjected to Temperature Change of -321 K with Layup of[$\Phi/-\Phi/0_{40}/\Phi/\Phi$].

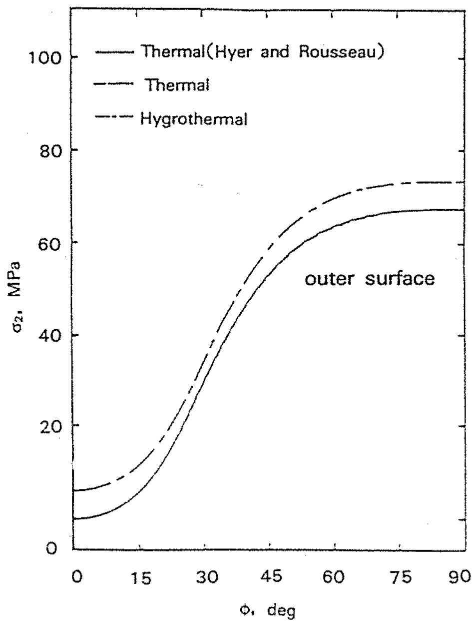

Fig. 2 Influence of the Off-Axis Ply Angle on σ_2 When Subjected to Temperature Change of -321 K with Layup of[$\Phi/-\Phi/0_{40}/\Phi/\Phi$].

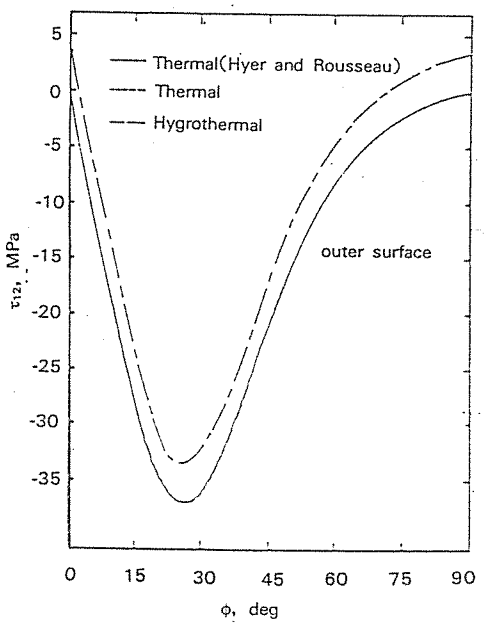

Fig. 4 Influence of the Off-Axis Ply Angle on τ_{12} Temperature Change of -321 K with Layup of[$\Phi/-\Phi/0_{40}/\Phi/\Phi$].

moisture loading on composite cylinders, they cannot be compared directly. Also, because of lack of data on through-the-thickness properties, the values for the thermal coefficient, and the moisture expansion coefficient, the values have been assumed to be equal to those in the transverse direction.

In Fig. 2-4, the present formulation is compared with that of Hyer and Rousseau[1], under the thermal loading of -321K which results when the tubes are operating at -120K in the environment of space. In the same figures, the hygrothermal loading is also shown. Hyer and Rousseau, pointed out that the three components of stress that influence matrix cracking are σ_{21}, σ_3 and τ_{12}. For this reason, the comparsion of σ_1 is omitted. For σ_2 and τ_{12} the stresses shown are the stresses at the outermost radial location in the outermost layer. For σ_3, the stresses shown are the largest stresses among all plies. In all three figures, the present formulation agrees quite well with that of Hyer and Rousseau. At 75℃, the Gr/Ep absorbs maximum of 0.9 percent moisture in a 100 percent relative humidity environment[31]. For σ_2 and σ_3, the presence of moisture raises the stresses by about 10 percent whereas for τ_{12} the stress is lowered about 11 percent. Thus, the stresses induced due to moisture increase the σ_2 and σ_3 stresses but they decrease the τ_{12} stress.

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