A STUDY OF INTERLAMINAR RESIDUAL STRESSES IN FIBRE–ALUMINUM ADHESIVE –BONDED LAMINATES*

Li Hongyun, Hu Hongjun, Zheng Ruiqi
(Beijing institute of Aeronautical Materials,Beijing China)

Abstract

In this paper, the residual stresses of the ordinarily cured unidirectional laminate and prestressed laminate are analyzed quantitively.In order to examine the analyzing formulations,strain gages were embeded in the unidirectional aramid–aluminum laminates (ordinarily cured and prestressed) to determine the residual stresses in the aluminum layers .The calculated residual stresses are in good agreement with the experimental values in longitudinal direction. Therefore, the works in this paper can be used to calculate ,determine and design the longitudinal residual stresses according to the manufacture and application demands.

I. Introduction

Fibre–aluminum adhesive–bonded laminate is a new kind of hybrid composite.It has low density,high yield and ultimate tensile strength ,low fatigue crack propagation rate and excellent damage tolerance .Nevertheless, due to the large difference in thermal expansion coefficient of both the fibre and metal,large residual stresses are built up during the curing cycle. The unsuitable residual stress system may seriously constrain its outstanding properties ,so it is very important to understand the formation mechanism of the residual stresses and seek the way to adjust them.

Oken and June(1)analyzed the longitudinal residual stress caused by the difference in coefficient of thermal expansion of the constituents in the laminate.But the analyzing equation neglected the anisotropic effect of the fibre layers.

It was reported that two kinds of method can adjust the residual stresses(1)(2).One is called prestrain method which is to stretch the as cured laminates to yield a suitable permanent elongation. Another is called prestress method which is to apply a load to the fibre layers during curing and unload after the laminate is cured. Prestrain method has been widely used for the laminates to adjust the residual stresses,but little study about the prestress method was reported.

In this paper,the residual stresses in ordinarily cured laminate and prestressed laminate were analyzed quantitively.In order to examine the analyzing formulation ,embeded strain gages were used to determine the residual stress.

II. Analysis of Residual Stresses

2.1 Formation of residual stresses

The residual stresses are formed during the entire curing cycle. But each period of the cycle gives different percentage of the total residual stress.During the heating period before the resin gels,the viscosity of the resin is low .It almost makes the fibre and aluminum sheets expand freely and there is no residual stress built up in the laminate. But if there is a large compression applied on the laminate at that time , the friction between fibres and aluminum sheets may restrain the expansion and a little residual stress may be built up. As the resin gels, the viscosity of the resin becomes higher.The expansion of the constituents may be restrained and residual stresses are accumulated.

After the resin completely cures,the fibres and the aluminum sheets become an integrated laminate.When it cools,the expansion or shrinkage of the constituents would restrain each other and residual stresses are formed.Generally,this part of residual stresses is much larger than that formed in the heating period.therefore,only residual stresses formed in the cooling period is discussed as below

2.2 Residual stresses in ordinarily cured lamimate

It is assumed that

1.the residual stresses are in the plane of the laminate;

2.the configuration of the laminate is symmetrical.that means there is no residual mement in the laminate;

3.when the cured laminate cools, the deformation of each layer is consistent;

4.there is no release of residual stresses during the cooling period.

According to the assumptions, the real laminate can be considered as the model shown in figure 1.

When the cured laminate cools from curing temperature T_0 to a certain temperature T,each layer must yield a strain.Either strain of the fibre layers or that of the aluminum is equal to the sum of its thermal strain and residual strain.Due to the consistent total strain of the fibres and aluminum layers,there is

---

* This research was supported by the national foundation of natural science

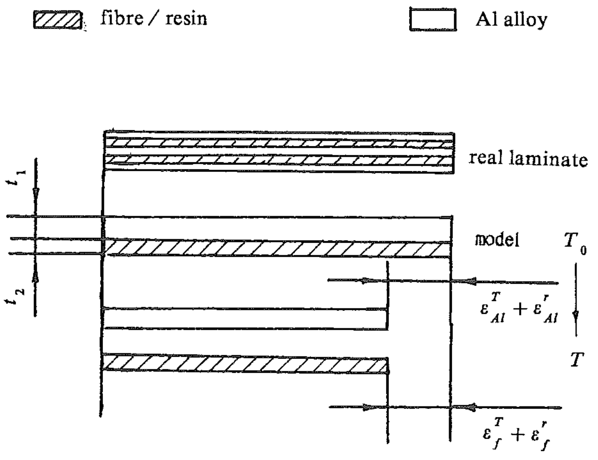


Fig.1 Model of laminate for Analysis of Residual stresses

$$\begin{bmatrix} \frac{1}{E_1} & -\frac{v}{E_1} \\ -\frac{v}{E_1} & -\frac{1}{E_1} \end{bmatrix} \cdot \begin{bmatrix} \sigma_{x1} \\ \sigma_{y1} \end{bmatrix} + \begin{bmatrix} \alpha_1 \\ \alpha_1 \end{bmatrix} \Delta T$$

$$= \begin{bmatrix} \frac{1}{E_{x2}} & -\frac{v_{xy}}{E_{y2}} \\ -\frac{v_{yx}}{E_{x2}} & \frac{1}{E_{y2}} \end{bmatrix} \cdot \begin{bmatrix} \sigma_{x2} \\ \sigma_{y2} \end{bmatrix} + \begin{bmatrix} \alpha_{x2} \\ \alpha_{y2} \end{bmatrix} \Delta T \quad (1)$$

where σ,E,α,v are residual stress,Young's modulus, thermal expansion coefficient and Poisson ratio respectively.The subscripts x,y represent the longitudinal and transvers direction of the laminate.The subscripts 1,2 represent the aluminum and fibre layers.

$\Delta T = T - T_0$

Since the resultant of forces in the laminate is zero,there is

$$\begin{bmatrix} \sigma_{x1} \\ \sigma_{y1} \end{bmatrix} t_1 + \begin{bmatrix} \sigma_{x2} \\ \sigma_{y2} \end{bmatrix} t_2 = 0 \quad (2)$$

where t_1,t_2 are the total thickness of the aluminum and fibre layers respectively.

From the equation (1) and (2) ,the residual stresses in the aluminum layers can be inferred as equation (3)

$$\sigma = A^{-1} C \Delta T \quad (3)$$

where

$$\sigma = \begin{bmatrix} \sigma_{x1} \\ \sigma_{y1} \end{bmatrix}$$

$$\mathbf{A} = \begin{bmatrix} \frac{1}{E_1} + \frac{t_1}{t_2 E_{x2}} & -\frac{v_1}{E_1} - \frac{t_1 v_{xy}}{t_2 E_{y2}} \\ -\frac{v_1}{E_1} - \frac{t_1 v_{yx}}{t_2 E_{x1}} & \frac{1}{E_1} + \frac{t_1}{t_2 E_{y2}} \end{bmatrix}$$

$$\mathbf{C} = \begin{bmatrix} \alpha_{x2} - \alpha_1 \\ \alpha_{y2} - \alpha_1 \end{bmatrix}$$

$\Delta T = T - T_0$

If the transvers residual stress is neglected, equation (3) can be simplified as below

$$\sigma_{x1} = E_1 \left(1 + \frac{t_1 E_1}{t_2 E_2}\right)^{-1} (\alpha_{x2} - \alpha_1) \Delta T \quad (4)$$

Equation(4) is just the Oken and June's formulation.

2.3 Residual stresses in prestressed laminate

The schematic diagram of prestress arrangment is shown in figure 2.

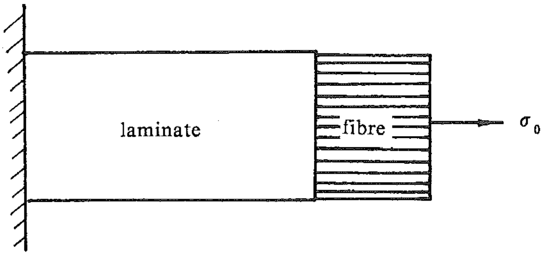


Fig.2 Schematic Diagram of the prestress arrangment

A tensile stress is applied to the fibre layers of the laminate before the laminate cures. This stress doesn't unload untill the laminate completely cures and cools to room temperature. According to abve assumptions ,the residual stresses of the aluminum layers in the laminate can be inferred as equation (5).

$$\sigma = \mathbf{A}^{-1} \mathbf{C} \Delta T + \mathbf{A}^{-1} \mathbf{D} \sigma_0 \quad (5)$$

where σ, A, C are the same as in equation (3)

$$\mathbf{D} = \begin{bmatrix} -\frac{1}{E_f} \\ \frac{v_{yx}}{E_f} \end{bmatrix}$$

where σ_0 is the prestress applied on the fibre layers.E_f is the modulus of the fibre.

If the transvers residual stress is neglected, equation (5) can be simplified as

$$\sigma_{x1} = E_1 \left(1 + \frac{t_1 E_1}{t_2 E_2}\right)^{-1} \left[(\alpha_{x2} - \alpha_1) \Delta T - \frac{\sigma_0}{E_f} \right] (6)$$

Ⅲ. Experiment

3.1 Materials

In the experiment,residual stresses in 3/2 unidirectional aramid–aluminum laminate residual stresses were measured. The configuration of the laminate is given in Table 1.The properties of the constituent materials are shown in Table 2.

3.2 Embeded strain gage method

Residual stress can't be measured directely.It is usualy calculated from the residual strain using the material constitutive relations. Embeded strain gage method was used to measure the residual strains only.

It is known that residual strain of the materials is the difference between the restrained strain and the free strain,so the residual strain of the aluminum layers in laminate can be expressed by equation (7)

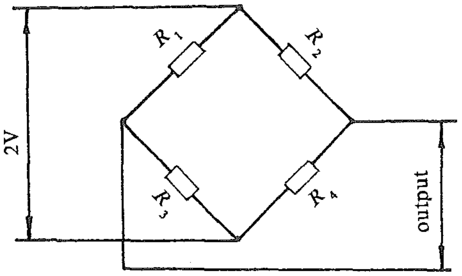
$$\varepsilon^{r}_{Al} = \varepsilon^{T}_{La} - \varepsilon^{T}_{Al} \qquad (7)$$

where ε^{T}_{La} is the strain of the aluminum layers in laminate; ε^{T}_{Al} is the thermal strain of a free aluminum sheet under the same condition of the laminate.

In the experiment ,two strain gages were attached to two sheets of aluminum respectively.One sheet was layed up together with fibre / resin prepregs in the laminate;Another was put aside to the laminate and kept under the same conditions as the laminate during curing for compensation.

All the leading wires of the strain gages must be insulated from the aluminum sheets and connected to the electric bridge shown in figure 3.If $R_3 = R_4$,$R_1$and $R_2$are the same type of strain gages(the sensitivity and the thermal output of the two gages are equal) and under same condition ,the output of the bridge is just the residual strain as expressed in equation (7).

Connect the output wires of the bridge to a dynamic strain meter . link the meter to a record.install a thermocouple on the laminate and wire to the record. When the experiment begins, the residual strain versus temperature will be recorded.



R_1strain gage embeded in laminate;R_2strain gage attached to the Al sheet

Fig.3 Schemetic diagram of the electric bridge

Ⅳ. Results and Discussion

Figure 4 shows the residual stresses in the aluminum layers in ordinarily cured 3/2 aramid-aluminum laminate.The solid lines represent the results calculated according to equation (3).The points are the experimental values measured by the embeded strain gages.Every point is the average of residual stresses of three specimens.

As showm in figure 4,the longitudinal residual stress in the aluminum layers is tensile and becomes larger with decrease of temperature.On the other hand, the residual stress in fibre / resin layers must be compressive.It is known that the resistance capability of fibre / resin to compressive stress is poor,so the residual stress system in ordinarily cured laminate is unfavourable to its properties and must be adjusted.

It can be seen from figure 4 that the experimental values are very close to the calculated line in longitudinal direction.

Figure 4 also show that the transvers residual stress in the aluminum layers is compressive and that in fibre / resin layers must be tensile.But the calculated line does not fit the experimental points.The reason may be that the resin behaves viscoelastically while equation (3) neglects it.The behavior of residual stress in transvers direction needs further work.

Table 1 Configuration of the laminate

constituent	type	thickness (mm)	number of layers	remarks
Al alloy	LY12CZ	0.3	3	
aramid / epoxy	unidirection	0.2	2	$V_f = 50\%$

Table 2 Properties of the constituent materials

constituent	direction	modulus (GPa)	Poisson ratio	thermal expantion coefficient $\times 10^{-6}$
Al alloy		63	0.33	23
aramid / epoxy	x	62	0.35	−2
	y	4	0.029	72.3

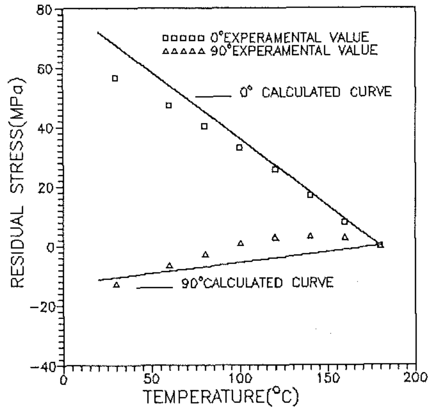


Fig.4 Residual stresses of Al layers in ordinarily cured 3 / 2 laminate

The relationship between residual stresses in longitudinal direction and prestress is shown in figure 5.The solid lines represent the calculated results using equation (5) and the points are the experimental values.

When the prestress increases,the residual stress in the aluminum layers decreases from positive to negetive.On the other hand, the residual stress in the fibre / resin layers must be inverted.It can also be seen that the experimental values are close to the calculated lines.Therefore,we can use equation (5) and the pretress method to design and adjust the residual stresses of the laminate according to the manufacture and application demands.

The calculated results indicate that the transverse residual stresses of the laminate is hardly affected by the longitudinal prestress.

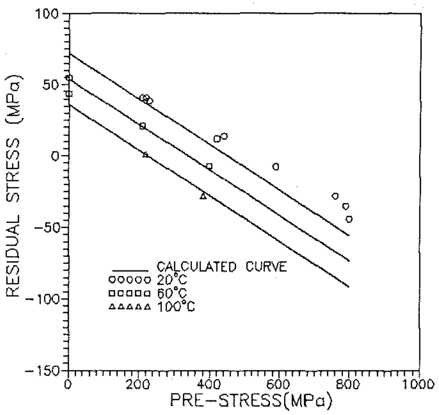


Fig.5 Logitudinal residual stresses in Al layers versus prestress on fibre layers

V. Conclussions

1. The longitudinal residual stresses of ordinarily cuered laminate can be precisely calculated by equation (3).

2. The longitudinal residual stresses of the laminate can be designed by equation (5) and adjusted by prestress method.

3. The embeded strain gage method can precisely measure the residual stresses of the laminate during the curing cycle.

VI. Reference

[1] L.B.Vogelesang,Development of a New Hybrid Material(ARALL) for Aricraft,Ind.Eng.Chem.Prod.Res.Dev. 1983,22,492–496

[2] L.B. Vogelesang, J. W. Gunnink et al, New Developments in ARALL Laminates ,ICAS,1988.