

Effect of Post-Cure Time on Residual Stress Distribution in Carbon/Epoxy Laminated Composites

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Abstract: This research investigates the effect of post-cure time on residual stresses in laminated composites. Laminated composites were made of T300 carbon fibers and epoxy resin. The post-cure process was carried out at the constant temperature of 120 °C for 6 and 12 hours for two specimens. The slitting method was employed to determine through-thickness residual stress distribution of the composite laminates. The results of experiment indicates that increasing the post-cure time leads to the reduction of maximum residual stress, as well as the uniformity of the residual stress distribution in laminated composites. Therefore, increasing the post-cure time is an effective way of reducing the destructive effects of residual stresses in laminated composites.

Keywords: Carbon/Epoxy Composites, Post-Cure Time, Residual Stress, Slitting Method

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1 INTRODUCTION

Residual stresses are defined as locked-in stresses that exist in the stressed specimen without application of any exterior forces. In the case of multidirectional laminated composites, residual stresses are introduced during the fabrication process. During this process, many chemical and thermal reactions occur within the laminate and residual stresses appear which come from various sources. After curing and cooling the composite, the matrix is subject to a tri-axial stress state. Shrinkage during curing process and the mismatch of coefficients of thermal expansion between matrix and fiber are the most important reasons for the introduction of residual stresses. Since the coefficient of thermal expansion of fiber is lower compared to the coefficient of thermal expansion of matrix, the resulting thermal residual stresses are of compressive nature in the fiber and tensile nature in the matrix. A qualitative description for the development of residual stresses during curing process is given in Fig. 1. Thermal residual stresses have a significant role in the failure of composite components. The most common results of these stresses are the matrix cracking, yield strength, and dimensional stability [1-3]. When disregarded during design, residual stresses may lead to the failure of a component below the design load or, under fatigue loading, prior to the useful design life of the part.

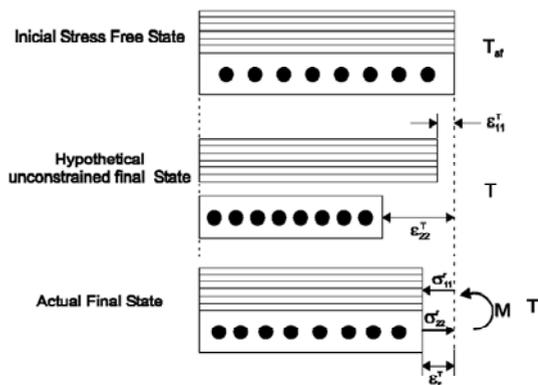


Fig. 1 Residual stress formation after curing [4]

It is therefore important to develop techniques for the reduction of residual stresses in composite components. In this research, the effect of post-cure on the residual stress distribution in carbon/epoxy composites is investigated. Residual stress distribution in each laminate was determined experimentally using slitting method. The results of experiment indicates that increasing the post-cure time can be employed as an effective method for reduction of maximum residual

stress as well as the uniformity of the residual stress distribution in laminated composites.

2 PRINCIPLES OF SLITTING METHOD

Over the past twenty five years, the slitting method has been used for residual stress determination in a vast variety of materials, such as stainless steel, functionally graded materials, metal matrix composites, aluminum alloys, friction stir welds, etc [5]. In this method, a narrow slit is progressively cut through the thickness of a stressed component. The released strains around the slit are measured using strain gauges bonded either on the top or back surfaces of the specimen. Residual stress distribution is then calculated using recorded strains and the compliance coefficients.

Fig. 2 shows the typical geometry of the slitting method with a back surface strain gauge. This geometry includes the specimen thickness ' t ', the specimen length ' L ', the specimen width ' B ', the slit depth ' a ', the slit width ' w ' and the strain gauge length ' l '. The strain gauges bonded on the back surface of the stressed part directly opposite the slit are sensitive to all residual stresses within the specimen thickness and thus generally used for through-thickness measurements. However, the strain gauges bonded on the top surface near the slit are only sensitive to near surface residual stresses (usually up to 20-25% of the thickness) and therefore are appropriate for near surface measurements.

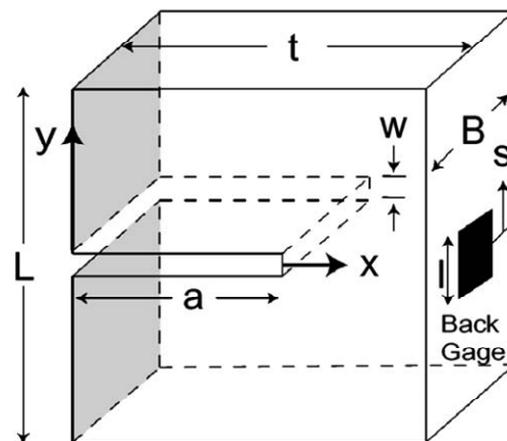


Fig. 2 Slitting method schematic

The slit starts from the top surface of the specimen and is extended in successive increments towards the back surface. For the configuration shown in Fig. 2, slitting method will determine unknown normal residual stress component perpendicular to the slit plane, $\sigma_{yy}(x)$, using

y-strain measured by back surface or top surface strain gauges. After recording released strains, the next step is to approximate the residual stress distribution from the measured strains data using an appropriate method. For this purpose, an initial distribution for residual stress must be considered. It is important to note that the form of initial stress distribution not only dictates how the compliance coefficients will be defined but also has a significant effect on the estimated residual stress. In the relaxation methods of residual stress measurement, the relationship between the residual stresses and the measured strains or deformations does not have a simple one-to-one form. This is because the measured strains depend on all released stresses within the specimen thickness, and not just those at a specific depth. Obviously, for the top surface strain gauges, residual stresses near the surface have more effect on the measured strains. Therefore, for the methods based on incremental material removal the relationship between the residual stresses and the measured strain data has the form of an integral equation [9]. For the slitting method, this relationship is in the following form:

$$\varepsilon_{yy}(a_i) = \frac{1}{E'} \int_0^{a_i} G(x, a_i) \sigma_{yy}(x) dx \tag{1}$$

where $\varepsilon_{yy}(a_i)$ is the measured y-strain when the slit depth is ' a_i '. The kernel function $G(x, a_i)$ is equal to the measured strain due to a unit stress at depth ' x ' within a slit of depth ' a_i '. In the slitting method, this function is usually obtained using a finite element method.

For a plate or beam specimen, ' E' ' is defined as [10]:

$$\begin{cases} E' = E & \text{for } \frac{B}{t} \leq 0.5 & \text{plane stress} \\ E' = \frac{E}{1-\nu^2} & \text{for } \frac{B}{t} \geq 2 & \text{plane strain} \end{cases} \tag{2}$$

In order to solve Eq. 1, an initial distribution for residual stress must be considered. The most important methods to estimate residual stress includes "Series Expansion Method" and "Pulse Method" [5]. In the "Series Expansion Method", residual stress is approximated by a continuous polynomial with unknown coefficients. Because of discrepancy of material properties of different layers, the residual stress in laminated composites is discontinuous across layers boundaries. Therefore, "Series Expansion Method" is not applicable to composite laminates. For this reason, "Pulse Method" has been used in this

research. In this research, "Pulse Method" was used for the approximation of residual stress. The main feature of the pulse method approximation is that it requires no explicit assumption for the residual stress distribution. Consider a residual stress profile acting on the faces of a slit of increasing depths a_1, \dots, a_i , as shown in Fig. 3 (a). From linear superposition the stress distribution can be estimated by a series of strip or pulse loads over each increment of the slit, denoted by σ_i and $a_{i-1} \leq x_i \leq a_i$ ($i = 1, \dots, n$), as shown in Fig. 3 (b). In other words, a uniform stress for each increment of slit depth is considered.

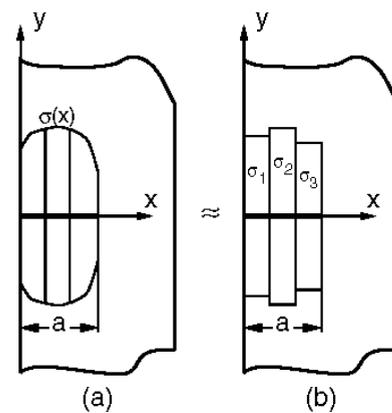


Fig. 3 (a) An unknown residual stress distribution on slit faces is approximated by (b) a series of uniform strip loads

Therefore, in the "Pulse Method" residual stress is estimated by the following equation:

$$\sigma(x_j) = \sum_{j=1}^n \sigma_j U_j(x) \tag{3}$$

where ' σ_j ' corresponds to the stress value in the ' j ' th increment. The pulse functions are defined as follows:

$$U_j(x) = \begin{cases} 1 & a_{j-1} \leq x \leq a_j \\ 0 & x \leq a_{j-1}, x \geq a_j \end{cases} \tag{4}$$

Substituting Eq. (3) in Eq. (1) results in:

$$\begin{aligned} \varepsilon(a_i) &= \frac{1}{E'} \int_0^{a_i} G(x, a_i) \sum_{j=1}^n \sigma_j U_j(x) dx = \\ &= \frac{1}{E'} \sum_{j=1}^n \sigma_j \int_{a_{j-1}}^{a_j} G(x, a_i) U_j(x) dx = \sum_{j=1}^n \sigma_j C_{ij} \end{aligned} \tag{5}$$

Therefore, ' C_{ij} ' or the elements of compliance matrix are expressed by the following equation:

$$C_{ij} = \frac{1}{E'} \int_{a_{j-1}}^{a_j} G(x, a_i) U_j(x) \quad (6)$$

Comparing to Eq. (1) indicates that a specific element of the compliance matrix, ' C_{ij} ', is the measured strain at the strain gauge location for a slit of depth when residual normal stress distribution at the domain $a_{j-1} \leq x \leq a_j$ is equal to the unit load:

$$C_{ij} = \varepsilon(a = a_i, \sigma(x) = U_j(x)) \quad (7)$$

Fig. 4 shows the physical interpretation of the compliance coefficients. There are analytical methods that can be used for calculating compliance coefficients in isotropic parts with simple geometries, such as plates, beams, cylinders, and disks, but a closed form solution is not yet available for orthotropic materials. In this work, these coefficients are calculated using finite element method.

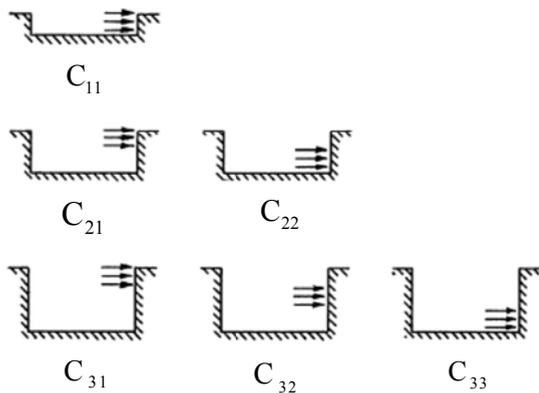


Fig. 4 Physical interpretation of compliance coefficients C_{ij}

The approximation using strip loads has its root from the hole drilling method, which assumes that the stress in each depth increment is uniform. In fact, the analysis employed in this section for slitting method applies equally to the hole-drilling method when the compliances are replaced by that for a hole of increasing depth. A disadvantage of the pulse method approximation, however, is that it is very sensitive to error in recorded strains. Tikhonov regularization is

shown to be an effective way to reduce the effect of strain measurement noise [6], [7].

3 EXPERIMENTAL METHOD

In this research, $[0_4/90_4]_s$ carbon/epoxy laminate was fabricated using hand lay-up method. The material used was T300 unidirectional carbon fibers with epoxy resin ML-506 and hardener Aradure-830. This is a high performance composite used mostly in the aeronautical and aerospace industries. In order to study the effect of post-cure time on residual stresses, two composite specimens were considered. Dimensions of the composite specimens are given in Table 1.

The curing process for each specimen involved temperature stages of 100°C during 6 hour, followed by 120°C for 6 and 12 hours respectively. The heating and cooling rates were $4^\circ\text{C}/\text{min}$. The Longitudinal tensile test, transverse tensile test and shear test was carried out to determine elastic constants. The results of the characterization tests are shown in Table 2. As mentioned in the previous section, the strain gauge can be bonded on the back surface of the specimen (back surface strain gauge) or on the top surface near the slit (top surface strain gauge). In such cases, the top surface gauge results are in error.

This strain gauge should be as close as possible to the slit edge in order to record significant amounts of strain, but its results can be affected by yielding as the stresses relax during slitting. On the other hand, slitting process can introduce additional residual stress and affect the gauge results. Also, two component of residual shear stresses released in the slit face can influence the recorded strains. Contrary to top surface strain gauge, back surface gauge is not subjected to these errors and its results are more reliable.

For this reason, back surface gauge is used in this research. However, the disadvantage of back gauge is that it is less sensitive to near surface residual stresses. Strain gauge, type UBFLA-03 with a gauge length of 0.3 mm, supplied from TML Company, was bonded to the back surface of specimen. In order to minimize the effect of averaging of the strain over the gauge length and to increase the precision of strain readings at the desired location, the gauge with smallest gauge length available among different types of gauges from different companies was selected. Before bonding strain gauges, the surface of the specimens is not abraded; it is only degreased with acetone. This is because manual abrasion can change the residual stress state of the specimen. Fig. 5 shows the prepared specimens for the slitting experiment.

Table 1 Dimensions of the composite specimens (mm)

Width (B)	Length(L)	Thickness (t)	Slit width (w)
16	62	4.82	0.252

Table 2 Elastic constants of uni-direction carbon/epoxy ply

E_x (GPa)	G_{xy} (GPa)	E_y (GPa)	ν_{xy}
104.6	3.8	7.5	0.31



Fig. 5 Prepared composite specimens

The part was clamped from one side away from slit and gauge, so the other side could deform freely and recorded strains are correct. Slitting process was carried out in a CNC milling machine with a circular saw blade. A circular cutter with 0.2 mm thickness and 23 mm in diameter is used. The rotational speed of the saw blade was 5,000 rpm. Model MS-21XUSB of DSM digital data logger was used to record strains in depth increments of 0.3 mm, which is equal to the thickness of each layer. Fig. 6 shows the relative position of strain gauge and cutter in the slitting experiment.

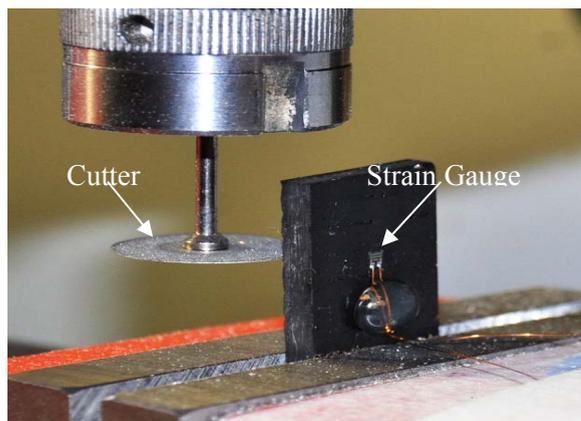


Fig. 6 Relative position of strain gauge and cutter in the slitting experiment

4 RESULTS

The measured strains of the two specimens are shown in Fig. 7, and the calculated residual stress distributions in Fig. 8. The "Pulse Method" is applied to the calculated residual stress from the measured strains.

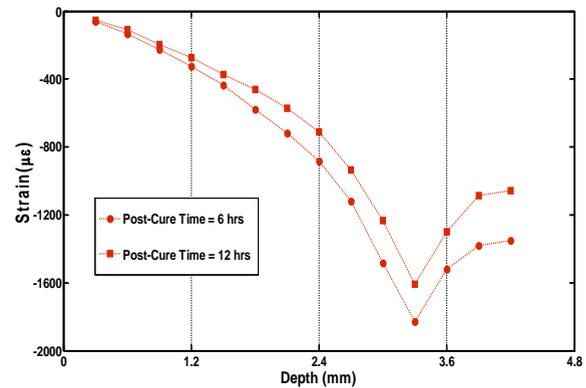


Fig. 7 Measured strains in slitting experiment

As shown in Fig. 8, the stresses are tensile through the 0° layers and compressive through the 90° layers. In the case of post-cure time of 12 hours, residual stress distribution has more uniformity. In some layers, the amount of residual stress increases and in the other ones this amount decreases. The uniformity of residual stress distribution can reduce stress concentration across layers boundaries and delay matrix cracking. Also, maximum residual stress decreases by increasing the post-cure time. In the case of this research, the magnitude of maximum stress is approximately 25% less than the other one.

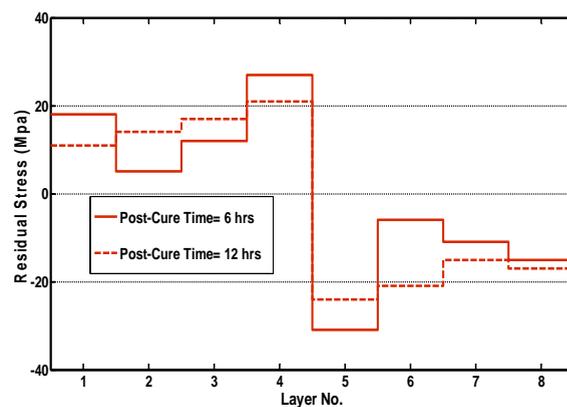


Fig. 8 Calculated stresses from the measured strains

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