INFLUENCE OF RESIDUAL STRESSES ON THE FAILURE OF THE FIRST PLIES IN COMPOSITES LAMINATES $[0_2/\theta_2]_S$

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Abstract

The present work aims to study the residual stresses in composite laminates $[0_2/\theta_2]_S$. The first part consists in determining the residual stresses by using the incremental hole-drilling method. From the results, it can be concluded that the residual stresses increase almost linearly with increasing angle θ for laminates $[0_2/\theta_2]_S$. The second part of the work concentrates on the residual stresses effects on the first ply failure in composite laminates. Through experimental study of composite laminates damage under the tensile loading, it is showed that the residual stresses make plies failures appear much earlier than expected. Acoustic emission technique is used to detect the ply failure in laminates.

1. Introduction

The combination of specific advantages such as light weight, high stiffness, high strength and corrosion resistance of carbon fiber reinforced polymer composites makes them widely used in aerospace and other industries [1]. However, process-induce residual stresses because of polymer shrinkages and mismatches of thermal coefficients between fiber and matrix have a significant impact on the performance of composite structures, potentially affecting ultimate strength, damage, failure and service life [2] and as a result is one of the limiting design criteria in composite laminates. Thus, it is of particular importance to find out a reliable method to determine the residual stresses and to evaluate their influences on the damage process of composite laminates. Recent studies pay more attention to unidirectional and cross-ply laminates. While, only a few works focus on the residual stresses determination for complex lay-ups laminates. Furthermore, the quantitative analysis is rarely touched in studying the effects of residual stresses on the damage of composite laminates.

In the present paper, the incremental hole drilling method is used to determine the residual stresses in composite laminates $[0_2/\theta_2]_S$ and the relation between residual stresses and plies orientations is analyzed. The efforts are made to investigate the residual stresses effects on the laminates damage, especially for the failure of θ° plies in laminates $[0_2/\theta_2]_S$. Through comparing the experimental results and theoretical values for the failure of the first plies in laminates $[0_2/\theta_2]_S$, the role of residual stresses is presented. Acoustic emission technique is used to detect the ply failure during experimental studies.

2. Residual stresses determination

The incremental hole-drilling method was used to determine the residual stresses in laminates $[0_2/\theta_2]_S$ (θ = 0°, 30°, 45°, 60°, 90°) considering that the residual stresses in plies with different orientations and in different through-depth were non-uniform. The determination consisted of two main steps: residual strains measurement and residual stresses determination from measured strains.

2.1. Residual strain measurement

Carbon fiber reinforced polymer (CFRP) laminates were made of prepreg unidirectional ply (HexPly® M10) of which the mechanical properties is shown in Table 1. Laminates $[0_2/\theta_2]$s were manufactured by hand lay-up and the cure process followed the cure cycle (120 °C for 1 h) proposed by the supplier with air cooling condition.

E_1 (GPa)	E_2, E_3 (GPa)	G_{12}, G_{13} (GPa)	G_{23} (GPa)	Tensile strength (MPa)	Transverse strength (MPa)	T_{ply} (mm)
135	9.5	5.27	3.39	1905	81	0.2

Table 1. Mechanical properties of materials (carbon/epoxy M10)

A strain gauge rosette with 3 measuring grids was pasted on the specimens to analyze biaxial stress states with unknown principal strain directions. Drilling was conducted with 2 flute square end mill. It should be guaranteed that drilling procedure do not introduce significant damage around the hole, such as, surface scaling and delamination crack along the ply interface. According to the previous contributions [3,4], drilling parameters were selected as follows: drill bit diameter 2 mm; translational speed 10 μm/s and spindle speed 5000 r/min. The experiments with two increments per ply (100 μm/ increment) were conducted; for laminates $[0_2/\theta_2]_s$, the hole was drilled with 8 increments up to the depth of 800 μm, which corresponds to the symmetric plane of the specimens.

2.2. Stress-strain relation

Based on the previous work [5], a formula to describe the stress-strain relation for composite laminate is deduced.

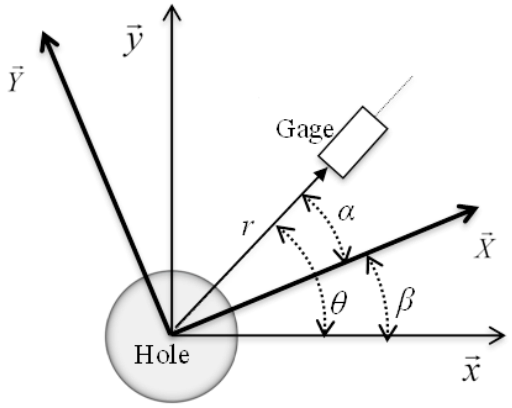

Figure 1. Coordinate system for stress-strain relation

$$\varepsilon_r = AX + BY\cos[2(\theta-\beta)] + CY\sin[2(\beta-\theta)] \tag{1}$$

In the formula, three calibration coefficients A, B and C are introduced to cover the effects of stress concentration because of hole-drilling; $X = \sigma_X + \sigma_Y$, $Y = \sigma_X - \sigma_Y$; σ_X , σ_Y and β represent two principle stresses and principle direction, respectively; θ corresponds the stain gage position and ε_r is the measured strain, as presented in Figure 1.

In the case of incremental hole-drilling method, the formula (1) should be adapted with the incremental characteristic, given as:

$$\varepsilon_{in} = A_{in}(\sigma_{Xhi} + \sigma_{Yhi}) + B_{in}(\sigma_{Xhi} - \sigma_{Yhi})\cos[2(\theta-\beta_i)] + C_{in}(\sigma_{Xhi} - \sigma_{Yhi})\sin[2(\beta_i-\theta)] \tag{2}$$

where ε_{in} represents the effect of released residual stresses within ith when the hole is drilled into the nth increment with a total depth of h_n; σ_{Xhi}, σ_{Yhi} are the principal stresses within ith increment and β_i reveals the principal direction.

These calibrations coefficients A_{in}, B_{in} and C_{in} were obtained by using the finite element method. The main principle of calibration is to apply a stress state equivalent to the released stress within an increment during the drilling process, and then the stress state for composite laminates would stay in its equilibrium [6]. All the required coefficients during the residual stresses determination were carried out by performing a three-dimensional finite element model (Figure 2) with ABAQUS/Standard.

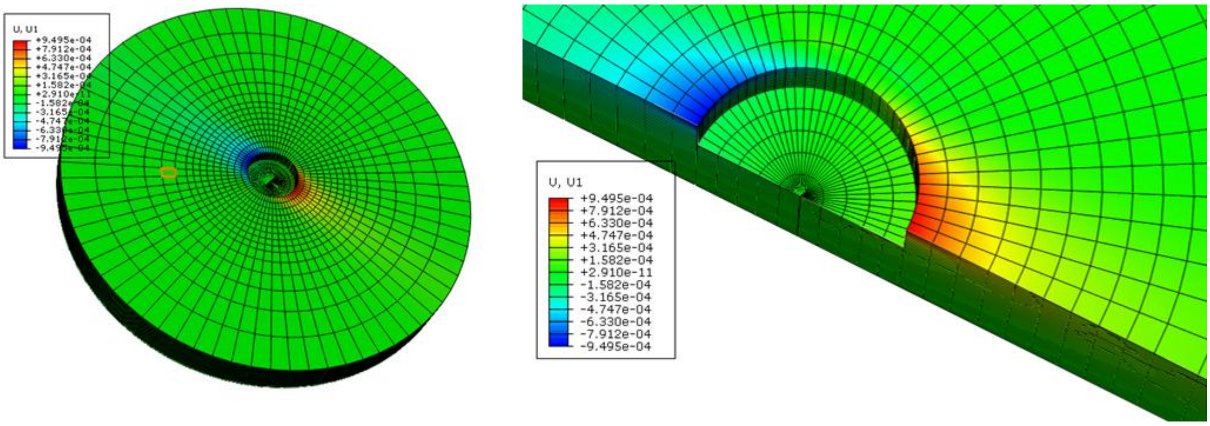

Figure 2. Numerical modeling for calibration coefficient determinations

2.3. Residual stresses in laminates $[0_2/\theta_2]_S$

From the measured residual strains using incremental hole-drilling method, the residual stresses in laminates $[0_2/\theta_2]_s$ (θ = 0°, 30°, 45°, 60°, 90°) were delivered through the stress-strain relation. According to the calculated results, the residual stresses in plies with the same orientation for each laminate are almost uniform. Figure 3 illustrate the relationship between the residual stresses and the angle θ for laminate $[0_2/\theta_2]_s$. It is observed that with the angle θ increasing, the residual stresses also increased. In the case of laminate $[0_2/90_2]_s$, the residual stresses are the most important, while for unidirectional laminate $[0]_8$, these values are so small (< 5 MPa) no matter in which ply that the results variation is equal to the final average value. As an example, for laminate $[0_2/60_2]_s$, within 0° plies, the two residual stresses are equal to -32 MPa and 44 MPa, while within 60° plies, these values correspond to be 33 MPa and -44 MPa respectively. It can be noted that for all these laminate $[0_2/\theta_2]_s$, in the fiber direction, the plies subject tensile stress and subject compression stress along the vertical direction of fiber orientation.

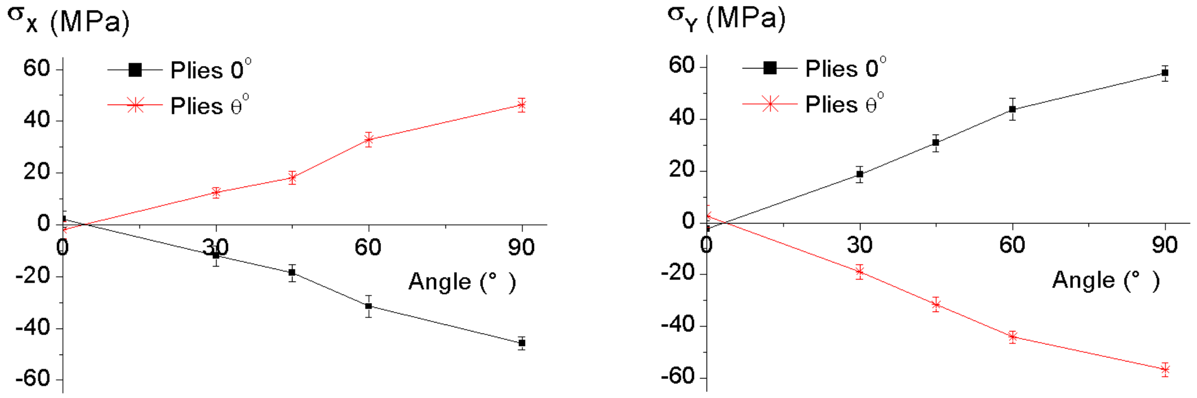

Figure 3. Residual stresses σ_X and σ_Y versus angle θ in laminates $[0_2/\ \theta_2]_s$

3. Residual stresses effects on failure of the first plies in laminates

In this part, the efforts are made to interpret the residual stresses effects on composite damage, in particular the failure of the first plies in laminates $[0_2/\theta_2]_S$ under tensile loading.

For the purpose of investigating the residual stresses effects on composite laminates damage, one approach is to study the laminates under tensile loading with different residual stresses. Post-curing cycle is generally used to vary in composite laminates [7,8]. While, it is noted that the maximum residual stresses variation after post-curing process is about 40%, which is around 20 MPa in case of laminates $[0_2/90_2]_S$, and this difference is still relative small to study the residual stresses effects on the damage of composite laminates.

Another method is to prepare composite laminates without residual stresses. Looking back to the results in section 2, the unidirectional laminates in which the residual stresses values are small enough (< 5 MPa) that can be regarded as no residual stresses sample compared with the other laminates $[0_2/\theta_2]_S$. For this reason, a conception for determining the residual stresses effects on the laminates damage process is made as follows. For each laminate $[0_2/\theta_2]_S$ (θ = 30°, 45°, 60°, 90°), another corresponding laminate $[\theta]_4$ is also prepared. For the former, the residual stress results have been obtained in the previous section 2; while the latter can be regarded as free-internal stress samples as comparison. The acoustic emission (AE) is employed to identify the damages in composite laminates during tensile loading and scanning electron microscope (SEM) is performed to observe the fracture section. Through analyzing the damage process for the unidirectional laminate and the θ° plies of laminate $[0_2/\theta_2]_S$, the residual stresses effects on the ply failure in laminate $[0_2/\theta_2]_S$ can be clarified.

3.1. Failure detection of the first plies

In order to detect the laminate damage, acoustic emission (AE) technique is used during the tensile loading. This technique consists in detecting acoustic wave emitted by the physical failure through the released energy in a structure under mechanical loading. Based on AE signal features (Amplitude, Duration, Signal energy, Counts, etc.), the damage such as, matrix cracking, fiber fracture and debonding in composite laminates can be identified [9]. The main purpose with AE technique for our work is to determine the failure of θ° plies for unidirectional laminates $[\theta]_4$ and laminates $[0_2/\theta_2]_S$. The specimens and experimental installation with AE sensor are demonstrated in Figure 4.

Figure 4. Specimens for laminates $[0_2/30_2]_S$ and the experimental installation with AE sensor

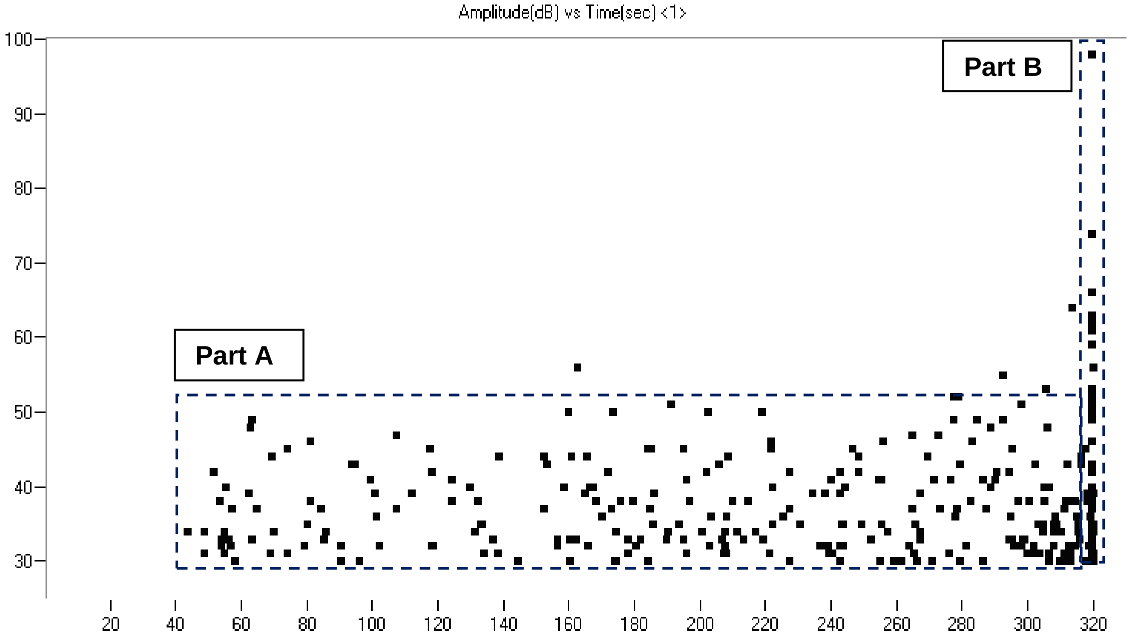

Figure 5. Acoustic emission signals (amplitude & time) for the tensile loading in case of $[30]_4$

At the first time, the testing were conducted with unidirectional laminates $[\theta]_4$ to obtain the signal reference features so as to distinguish the various signals in the case of laminates $[0_2/\theta_2]_S$. As an example, Figure 5 illustrates the emission signal (amplitude& time) in the case of laminate $[30]_4$ under tensile loading. According to the signal amplitude distribution, the whole signals area was divided into two parts: part A and part B. In part A, most of the signals were located in the area (30 dB $\leq$ Amplitude $\leq$ 50 dB), which indicates that the micro cracks appeared in composite laminates in this period almost belonged to matrix cracking, without fiber fracture or fiber pull-out according to the model proposed in the work [10]. The part B corresponded to the moment of laminate failure, it could be found that the signal amplitude was up to 98 dB at this moment and the released energy was the results of fiber fracture. It can be concluded that the most part of damage appeared in laminate $[\theta]_4$ is attributed to matrix cracking and fiber/matrix debonding; there are only fewer fiber fracture at the end of the tensile test. The SEM images (Figure 6) furthermore confirmed this conclusion. In Figures 6 (a) and (b), it's observed that fiber fracture composed only a small part of fracture section as indicated by the arrows. Figures 6 (c) and (d) demonstrated that fiber/matrix debonding and matrix cracking was the majority in the section as indicated by rectangular box.

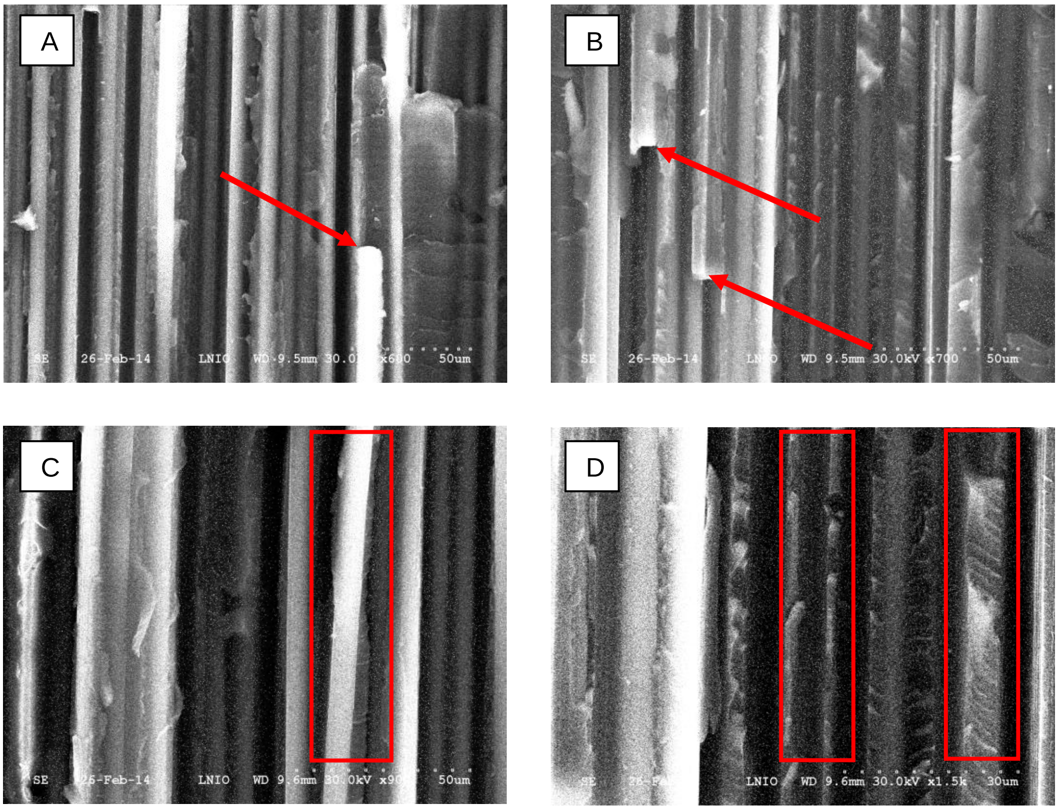

Figure 6. SEM observation of fraction section for laminate $[30]_4$

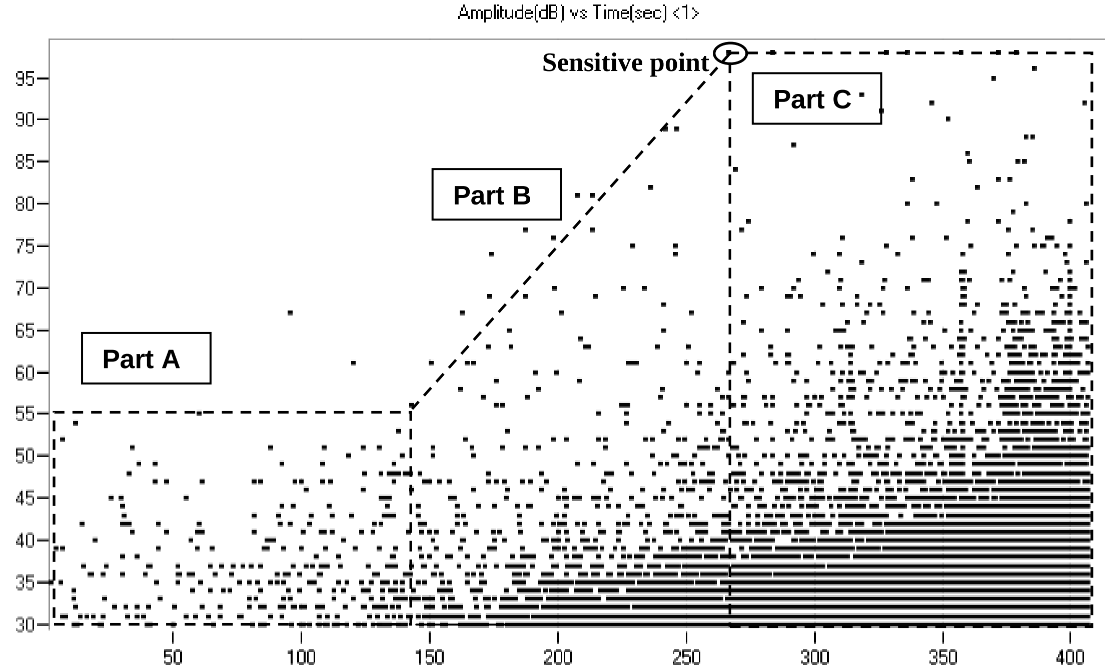

Figure 7. Acoustic emission signals (amplitude & time) for the tensile loading in case of $[0_2/30_2]_S$

For laminates $[0_2/\ \theta_2]_S$, the acoustic signals under the tensile loading was presented in Figure 7. Taking account of the fiber and matrix properties and the composite laminate fracture modes [11], the damage of laminates $[0_2/\theta_2]_S$ should be occurred within the θ° plies firstly in form of matrix micro cracking, then the failure of these plies, following with the delamination between plies in different directions and at last the failure of 0 ° plies. For this reason, the θ° plies of laminates $[0_2/\theta_2]_S$ fractured in the first time during the tensile testing. For the signal distribution in the case of $[0_2/30_2]_S$, the whole process could be divided into three parts as presented. In the first part, the signals were emitted because of the matrix cracking within 30 ° plies, which corresponded to the part A of unidirectional laminate $[30]_4$. The second part can be regarded as the damage accumulation process in the laminate, such as matrix cracking propagation and fiber/matrix debonding. On the boundary between Part B and Part C, the sensitive signal point which was linked to the first ply failure within θ ° plies for laminates $[0_2/\theta_2]_S$ was appeared; After that, the failure process continued with the loading increase until the fracture of the whole structure.

3.2. Results and discussion

With the help of AE Technique, the failure appearance can be detected and at the same time, the tensile loading under which appears the first failure of θ °plies in laminates $[0_2/\theta_2]_S$ is also available and then the tensile stress within θ° plies can be calculated by classical laminate theory. Through comparing the failure stress of θ °plies in laminate $[0_2/\theta_2]_S$ and unidirectional laminate $[\theta]_4$ and also the theoretical values, the residual stresses effects on the laminates damage can be clarified.

Theoretical value (MPa)	**Experimental Average (MPa)**	**Difference (MPa)**	**Residual stresses σ_x (MPa)**
81	36.7 ±2.2	44.3	49.3

Table 2. Failure stresses for 90 °plies in laminates $[0_2/90_2]_S$

The results for laminates $[0_2/90_2]_S$ is presented in Table 2. Using classical laminate theory, the corresponding failure stress for 90 ° plies can be calculated and it is noted that the average value equals to 36.7 MPa. While the transverse strength of material is 81 MPa (see Table 1), the difference between this theoretical value and experimental value is 44.3 MPa, which is almost the same as residual stresses (49.3 MPa, see Figure 3), determined in previous part (section 2). Thus, the residual stresses in 90 °plies for laminate $[0_2/90_2]_S$ seem to make up the difference of tensile strength with a simple superposition relation. Although this correspondence cannot give the direct evidence, it is also believe that the residual stresses in 90 ° plies make failure of these plies appear much earlier than expected and this actuality shows that the residual stresses play an important role in the damage of composite laminates.

For other types of laminates $[0_2/\theta_2]_S$, the experimental results were also reached in the same way. However, with the shearing stress appearance ($\sigma_6 \neq 0$), it is necessary to consider the laminates fracture mode and adapt these experimental values into the appropriate failure criterion to analyze the residual stresses effects on the laminates failure process. This part of work will be given as the failure criterion in consideration of residual stresses.

4. Conclusion

In this work, we pay our attention to the residual stresses in composite laminates $[0_2/\theta_2]_s$. At the first time, the residual stresses profiles for laminates $[0_2/\theta_2]_s$ are determined with the help of the numerical and experimental studies. As presented, the tendency of residual stresses in terms of angle θ for laminates $[0_2/\theta_2]_s$ is almost linear. In the second part, acoustic emission technique is used to study the influence of the residual stresses on the first ply failure of laminates $[0_2/\theta_2]_s$. Through the difference between experimental results and the theoretical values from classical laminate theory, it can be proved that the residual stresses really affect the first ply failure appearance in laminates $[0_2/90_2]_S$. These initial results give us the reference for the future work.

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