A unified comparative study on the classical lamination theory, hole drilling, slitting, and curvature measurement methods for assessment of residual stress in laminated polymeric composites

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Abstract

Residual stresses are balanced, non-uniform, undesirable, and often harmful in laminated polymer composite materials. Different methods are developed to measure these stresses in composites. In this manuscript, three experimental measurement methods, namely `hole drilling`, `slitting`, and `curvature` methods, are considered, and the results are compared with those of classical lamination theory (CLT). It is demonstrated that the hole drilling technique can be used to measure residual stress in the near-surface areas of the structures, while the slitting method is often employed to assess residual stresses through the depth of specimens. Moreover, the curvature method shows great potential for estimating the overall residual stress quality in laminated composites with un-symmetrical configurations.

Keywords: Residual stress, Hole drilling, Slitting, Curvature, Polymer composites.

1. Introduction

Residual stresses are balanced, non-uniform, undesirable, and harmful stresses locked in isotropic and composite materials during manufacturing, assembling, and loading conditions. These stresses could be trapped in the specimens, especially over the curing/cooling procedure, and often decrease the loading capacity of structures [1]. The creation of residual thermal stress in polymer composite laminates is because of different lamina directions in the structure (off-axis directions), resulting in variation of off-axis coefficient of thermal expansion (CTE) in different layers (macro-scale stresses), and also different CTEs in fiber and matrix phases (micro-scale stresses) [2-3]. Different residual stress measurement methods have been developed over the last few decades. These methods, as presented in an extensive review by Tabatabaeian et al. [1], fall into three main groups based on their level of destruction: 'non-destructive', 'semi-destructive' and 'destructive'. The destructuion level in the second group (semi-destructive), is not as much as the third group; however, the samples being tested semi-destructivley might not be used again after a test.

The hole drilling method (HDM) is a semi-destructive technique and the only method with available ASTM standards to determine residual stresses [4]. This technique could be applied to measure residual stress of isotropic materials [1, 5], metal [6], ceramic [7], and polymeric composite materials [8-10], and hybrid sandwich laminates [11-12]. The method can also be simulated in finite element (FE) commercial software to determine the calibration factors [13-14]. Change et al. [15] combined digital discrete image processing and HDM to measure residual stress of concrete samples. The eccentricity between the hole center and the rosette center of the HDM was investigated by Barsanescu and Carlescu [16] under the bi-axial loading.

Another practical method for assessing residual stresses is the slitting method [17]. Using this method, Tabatabaeian et al. [18-20] studied the effects of thermal cycling, ply composition and adding multi-walled carbon nanotubes (MWCNTs) on the residual thermal stresses of laminated composite materials. Also, Ghasemi et al. [21] characterized the different parameters' influence on the residual stresses. Using a two-step cutting procedure, Jones and Bush [22] studied the residual stress relaxation during cyclic loading. They studied the residual stresses by Legendre polynomials series and FE analysis around a hole. Kotobi and Honarpisheh [23] used this method to quantify residual stress along the thickness of rolled aluminum strips. Olson et al. [24] described a method to quantify the regularization uncertainty and compared the first-order uncertainty estimation to the new proposed uncertainty estimator.

The curvature measurement method is a non-destructive strategy for predicting residual stresses, which has been developed by linear and non-linear equations. Roux et al. [25] studied the effect of selective laser melting process parameters on the curvature measurement method's residual stresses. Hajnys et al. [26] determined the residual stresses in the selective laser melting process of the samples being printed by a 3D metal printer. The outcomes of [27-29] suggested that proper MWCNT addition would influence the cured shapes and curvature of the laminated polymer composites, decreasing the overall residual stresses. Tabatabaeian et al. [30]

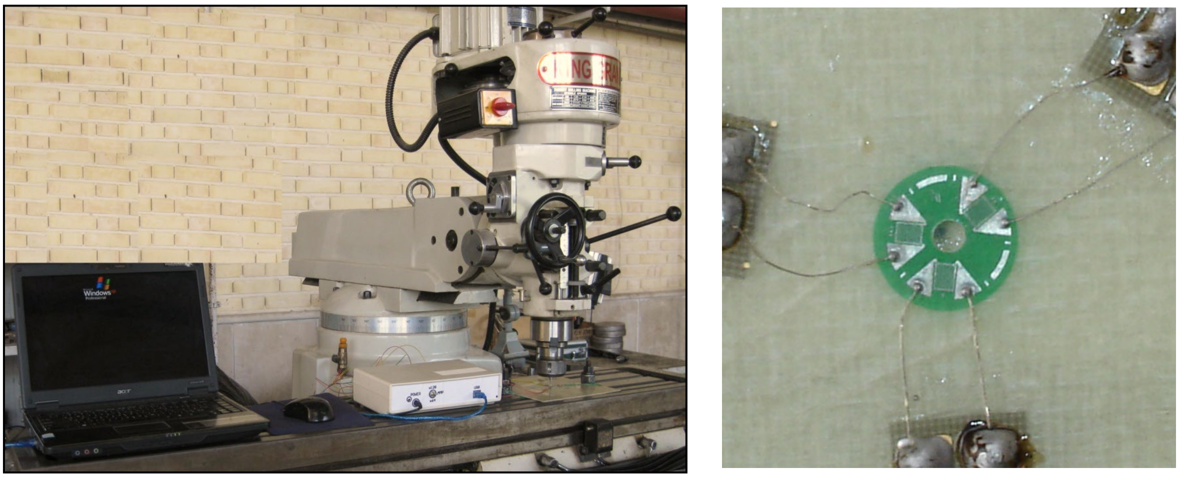
developed this method for arbitrary ply configurations and used the higher-order equations to investigate the MWCNT effect on the curvature and residual stress analytically.

The above three techniques to assess composites' residual stress are investigated and compared with classical lamination theory in the present study. Also, the underlying theories and processing of these methods and some experimental measurement results are presented and discussed. Finally, the benefits and drawbacks of each method are reported and analyzed.

2. Basic Theoretical Principles

2.1. Hole Drilling Method

The HDM is the only method for measuring residual stresses with a verified documented ASTM standard [4], widely used for determining residual stress over the thickness of composite and isotropic materials [5]. In this method, drilling is conducted on the center of a rosette. Accordingly, the strains are released and quantified using three strain gauges, as shown in Fig. 1. Next, the strains are correlated to the residual stresses of the structure, considering the calibration factors.



(a) (b)

Fig. 1. The hole drilling method for determining residual stresses a) Experimental set up; b) The strain gage rosette

It is worth noticing that residual stresses have a non-uniform nature; accordingly, the drilling is accomplished incrementally. The residual stress distribution in the thickness of specimens can be expressed by the following equation [10]:

$$\varepsilon(h) = \int_0^h C(H,h)\sigma(H)dH\,, \quad 0 \le H \le h \tag{1}$$

where the H, $\varepsilon(h)$ and $\sigma(H)$ refer to the local depth, measured released strains, and local residual stresses in each increment, respectively, and h is the depth of the removed material. This equation can be shortened to Eq. 2 in which $\boldsymbol{G}_{ij}$ represents the calibration factors.

$$\varepsilon(h_i) = \sum_{j=1}^{n} \boldsymbol{G}_{ij}\,\boldsymbol{\sigma}_j \qquad 1 \le j \le i \le n, \tag{2}$$

where n shows the total number of hole depth increments and i,j are the increment numbers in the hole drilling method. The calibration coefficient matrix should be determined using FE simulations [8-9], and non-uniform residual stresses are then determined using an inverse method referred to as an integral method. A more detailed explanation of the incremental hole drilling (IHD) method can be found in [9, 11, 20].

2.2. Slitting Method

The slitting method is a useful technique to measure in-depth residual stresses. A narrow slit is caused incrementally in the sample's thickness, and released strains are recorded in each step, correlated to the residual stresses considering calibration coefficients. The slitting method configuration and geometry dimensions are shown in Fig. 2, where 'a' and 'w' represent the slit depth and slit width, respectively. Also, the 't', 'L' and 'B' are thickness, length, and width dimensions of the sample, respectively.

The residual stresses and measured strains in the slitting method could be correlated as [21]:

$$\varepsilon_x(a_i) = \int_0^{a_i} G(y,a_i)\sigma_x\,(y)dy \tag{3}$$

where $\varepsilon_x(a_i)$ and $\sigma_x\,(y)$ are measured released strains and residual stresses, respectively; while a_i and $G(y,a_i)$ are the slit depth and function of calibration factors, respectively.

Eq. 3 can be simplified as follows, which is quite similar to the HDM formulations:

$$\{\varepsilon\} = [C]\{\sigma\} \tag{4}$$

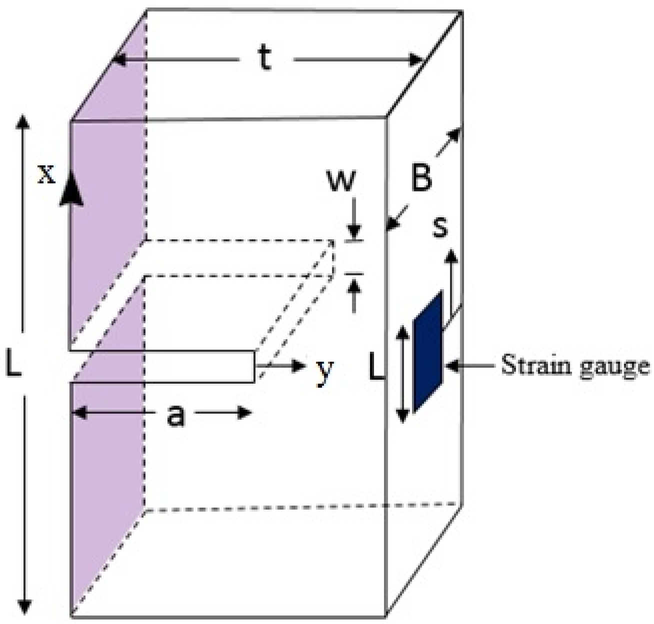


Fig. 2. The slitting method configuration and geometry dimensions [19]

In Eq.4, the released strains $\{\varepsilon\}$ can be recorded by strain gage in each step and calibration factors $[C]$ are determined using FE simulations. Accordingly, the unknown residual stresses can be determined in each increment of the slitting procedure. Considering a three-step slitting procedure, one can write the above equation as:

$$\begin{Bmatrix}\varepsilon_1\\ \varepsilon_2\\ \varepsilon_3\end{Bmatrix} = \begin{bmatrix}C_{11} & & \\ C_{21} & C_{22} & \\ C_{31} & C_{32} & C_{33}\end{bmatrix}\begin{Bmatrix}\sigma_1\\ \sigma_2\\ \sigma_3\end{Bmatrix} \tag{5}$$

The strains are only correlated to the associated residual stress at the first step, where C_{11} denotes the calibration factors used for this aim. In the second increment, the released strains can be broken down to the residual stresses in the first step by the coefficient C_{21} and residual stress in the second step by the coefficient C_{22}. By increasing the slit depth in the third step, the released strains could be attributed to: a) the influence of the first and second layer stresses by the calibration coefficients C_{31} and C_{32} , respectively; b) the influence of the residual stresses generated in the third layer, which are associated with C_{33} calibration coefficient [18-20]. In the above equation, subscripts 1,2, and 3 denote the drilling steps, not the on-axis directions. In addition, the slitting or hole drilling areas are not close to the edge of the plates.

Therefore, the boundary conditions might have a slight and negligible effect on the released residual stresses.

2.3. Curvature Method

The curvature measurement is a non-destructive method to assess the overall residual stresses and can only be implemented in laminated composites with un-symmetric ply configurations. These laminates will have a curved shape after the curing process, while the symmetrical ones will be flat. The curvature depends on the lay-up arrangement, thickness, curing temperature, geometrical and mechanical properties of the structure [27-29]. For cross-ply un-symmetric laminates, the maximum height (Y) is determined by accurate measurements as shown in Fig. 3, and the radius of curvature ($\rho_c = \frac{1}{k}$) can be derived as follows [31]:

$$Y^2 - 2Y\rho_c + \rho_c^2 \sin^2\left(\frac{L}{\rho_c}\right) = 0 \quad (6)$$

The roots of the above equation can be extracted as:

$$Y = \rho_c(1 \pm \cos\left(\frac{L}{\rho_c}\right)) \quad (7)$$

where Y, ρ_c and 2L are the maximum height, radius of curvature, and total length of the specimen, respectively. Also, the chord lengths (C) for the square panel can be obtained as [32]:

$$C = 2\,\rho_c \sin\left(\frac{L}{\rho_c}\right) \quad (8)$$

Residual stresses could then be calculated based on the classical laminate plate theory (CLPT) as follows[31]:

$$\sigma_x = \frac{E_1 E_2 S}{\rho_c(E_1+E_2)}\left[\frac{1}{2} + \frac{1}{24}\left(2 + \frac{E_1}{E_2} + \frac{E_2}{E_1}\right)\right] \quad (9)$$

In the above equation, E_x and E_y are longitudinal and transverse modulus, $\boldsymbol{S}$ is the thickness of un-symmetric laminates and ρ_c denotes the radius of curvature. This equation is sometimes written in another form as well [33]:

$$\sigma_x = \frac{E_1 E_2 h}{\rho_c(E_1 h + E_2 k)}[\frac{b+d}{2} + \frac{E_1 b^3 + E_2 d^3}{6(b+d)}\left(\frac{1}{E_1 b} + \frac{1}{E_2 d}\right)] \quad (10)$$

In an unsymmetrical laminate, the longitudinal and transverse plies thickness are shown by b and d, respectively; h and k are the corresponding longitudinal and transverse ply thicknesses in the symmetrical configuration.

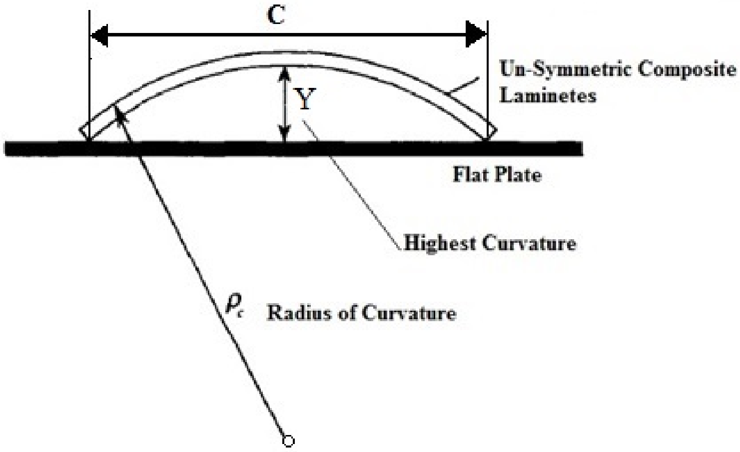


Fig. 3. The curvature method for determining the overall residual stresses of un-symmetric laminations **(Dr. Ghasemi:** please revise 'highest curvature' to 'maximum height'**)**

2.4. Analytical Method: Classical Laminate Plate Theory

Using the CLPT, one can calculate the macro-scale residual stress in the composite laminates assuming linear elastic behavior and plane stress conditions [11, 13-14, 34-36]. Due to the different off-axis CTE values in different plies, residual thermal stresses are generated inside the laminate during the cooling process (from curing temperature to room temperature). As a result of this, residual stresses are created. The thermal expansion coefficient in an orthotropic ply, in the off-axis direction, could be obtained as follows:

$$\alpha^{(k)} = \begin{Bmatrix} \alpha_x \\ \alpha_y \\ \alpha_{xy} \end{Bmatrix}^{(k)} = \begin{bmatrix} m^2 & n^2 & -mn \\ n^2 & m^2 & mn \\ 2mn & -2mn & m^2 - n^2 \end{bmatrix} \begin{Bmatrix} \alpha_1 \\ \alpha_2 \\ 0 \end{Bmatrix} \quad (11)$$

where α_x, α_y, and α_{xy} are off-axis thermal expansion coefficients, and, α_1 and α_2 are off-axis thermal expansion coefficients directions, and k shows the layer number. Thus, thermal loads in the off-axis plane are presented as follows:

$$\left(N_x^T, M_x^T\right) = \sum_{k=1}^{N} (\overline{Q}_{xx}{}^{(k)} \alpha_x^{(k)} + \overline{Q}_{xy}^{(k)} \alpha_y^{(k)} + \overline{Q}_{xs}^{(k)} \alpha_s^{(k)}) \Delta T^{(k)} (t_k, t_k \overline{z}_k) \tag{12-a}$$

$$\left(N_y^T, M_y^T\right) = \sum_{k=1}^{N} (\overline{Q}_{yx}^{(k)} \alpha_x^{(k)} + \overline{Q}_{yy}{}^{(k)} \alpha_y^{(k)} + \overline{Q}_{ys}^{(k)} \alpha_s^{(k)}) \Delta T^{(K)} .(t_k, t_k \overline{z}_k) \tag{12-b}$$

$$\left(N_s^T, M_s^T\right) = \sum_{k=1}^{N} (\overline{Q}_{sx}^{(k)} \alpha_x^{(k)} + \overline{Q}_{xy}^{(k)} \alpha_y^{(k)} + \overline{Q}_{ss}^{(k)} \alpha_s^{(k)}) \Delta T^{(k)} .(t_k, t_k \overline{z}_k) \tag{12-c}$$

Where $\alpha_i{}^{(k)}$ and $\overline{Q}_{ij}{}^{(k)}$ are the coefficients of thermal expansion and the stiffness matrix indexes, respectively. $\Delta T^{(K)}$, t_k and $\bar{z}_k$ are the temperature difference between the ambient and the stress-free temperatures, ply thickness, and lamina mid-plane height, respectively. The resultant thermal forces and the moments $N^T = (N_x^T, N_y^T, N_s^T)$ and $M^T = (M_x^T, M_y^T, M_s^T)$, could then give the strain and curvature of the mid-plane:

$$\begin{bmatrix} \varepsilon^{\circ} \\ k^{\circ} \end{bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix}^{-1} \begin{bmatrix} N \\ M \end{bmatrix} \tag{13}$$

in which A, B, and D are extensional coupling and bending stiffness matrices, respectively. The residual strains and stresses of each layer in the off-axis coordinate system can be obtained concerning the mid-plane strain and curvature:

$$\varepsilon_r^{(k)} = \left(\varepsilon^{\circ} + \overline{z}_k k^{\circ} - \alpha^{(k)} \Delta T\right) \tag{14}$$

$$\sigma_r^{(k)} = \overline{Q}^{(k)} \, \varepsilon_r^{(k)} \tag{15}$$

3. Experimental Measurement Results

3.1. Materials and Specimens Manufacturing

In this research, polymer composite samples are fabricated using unidirectional glass fiber and resin epoxy, and thermo-mechanical properties are presented in Table 1. In this Table E_1, E_2, G_{12} and ν_{12} are longitudinal modulus, transverse modulus, shear modulus, and Poisson's ratio, respectively (mechanical properties), while α_1 and α_2 are the on-axis CTE in longitudinal and transverse directions, respectively (thermal properties). The thickness of unidirectional ply is 0.2 mm, and the volume fraction of fiber was selected as 60% and controlled in the manufacturing process. The on-axis directions based on 1-2 coordinates and off-axis directions as x-y coordinates for a ply and unsymmetric laminates are shown in Fig. 4, in which θ is fiber orientation.

Table 1. Mechanical and thermal properties of unidirectional glass/epoxy ply

E_1(GPa)	E_2(GPa)	G_{12}(GPa)	ν_{12}	α_1*10^{-6}(1/°C)	α_2*10^{-6}(1/°C)
35	10	4.5	0.28	0.02	22.5

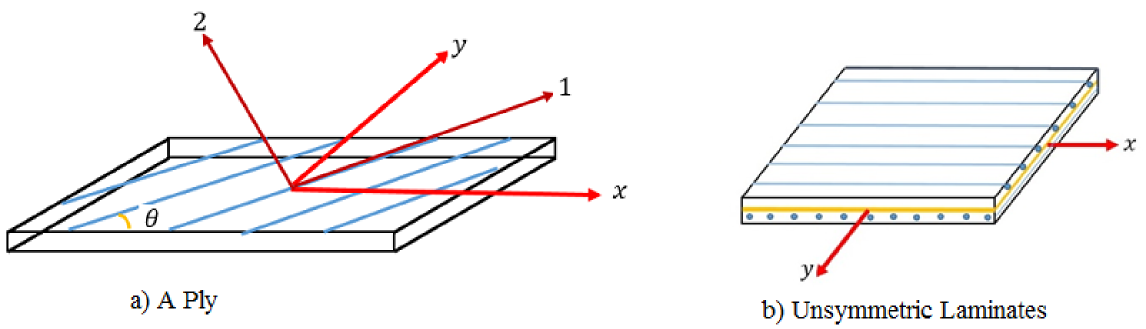


Fig. 4. The on-axis (12 coordinate) and off-axis (x-y coordinate) directions for a) A single ply and b) Un-symmetric laminates

In order to compare the results of the three methods, all samples are fabricated with [0_2/90_2] un-symmetric cross-ply sequences. The specimens are in the shape of a plate with dimensions of 15 cm by 15 cm, and the thickness is 0.8 ± 0.05 mm. All samples are manufactured using the hand lay-up technique and a vacuum bag for uniformly resin distribution. The specimens are cured according to the producer's instructions and then cooled at room temperature.

3.2. Hole Drilling Method

In the HDM, strain gauges are mounted on the surface, and the center of rosettes is carefully determined. This is performed based on the ASTM E-837 [4]. Next, the drilling is done incrementally, and released strains are recorded in each step by using the eight-channel data logger and a computer system, as shown in Fig. 5(a). The calibration factors are then calculated by the simulation hole drilling method (SHDM) as shown in Fig. 5(b). The arrays of the calibration coefficient matrix are calculated by applying the axial, transverse, and shear stress loading conditions. Next, using Eq.2, the non-uniform residual stresses through the four steps are determined and presented in Table. 2. It should be noted that each drilling step is 0.05 mm and, with the increase of depth, the strain gauge sensitivity decreases, leading to less accurate results in deeper areas. **(Dr. Ghasemi)**

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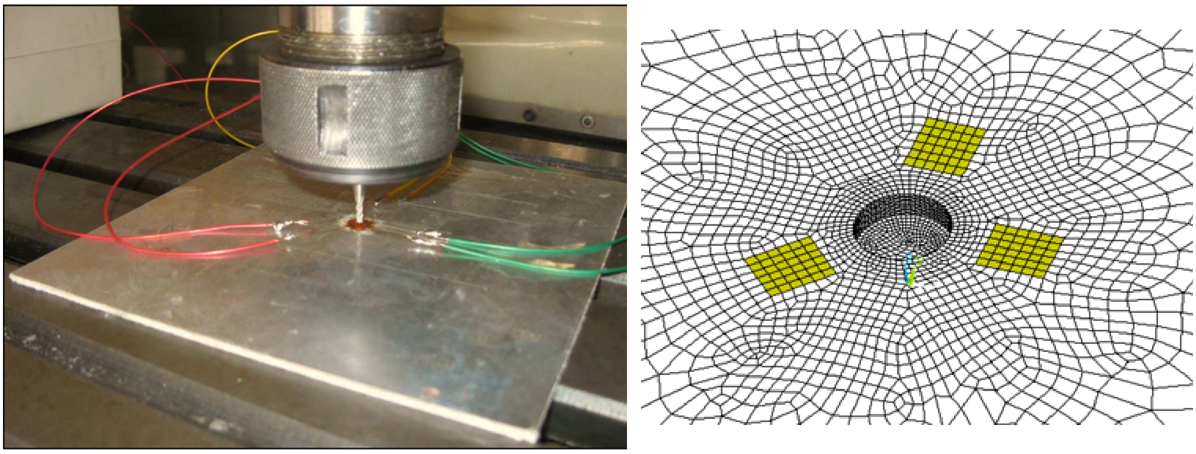


(a) (b)

Fig. 5. Determination of residual stresses: a) Set- up experiment and hole drilling machine; b) Simulation hole drilling method (SHDM) for calculation of calibration factors

Table .2. The non-uniform residual stresses in the un-symmetric cross-ply $[0_2/90_2]$ laminates by applying the hole drilling method **(Dr. Ghasemi)** **(**Please add the depth of each increment in the table)

Stresses (MPa)	First step **(... mm)**	Second step **(... mm)**	Third step **(... mm)**	Fourth step **(... mm)**
σ_x	16.8	17.5	-10.2	-7
σ_y	-15	-18.5	9	8
σ_s	+1.2	+0.8	-0.3	+0.4

3.3. Slitting Method

This section determines the residual stresses in un-symmetric cross-ply laminates with [02/902] arrangements by applying the slitting method. As shown in Fig. 2, the strain gauge is installed on the specimen's back surface. Using a circular saw blade with 40 mm diameter and 0.2 mm thickness, a thin slit is cut. The slit depth increases incrementally, and residual strains are quantified by a mounted strain gauge, as shown in Fig. 6. This process is carried out until slit depth reaches 0.6mm, 75% of the thickness. It is worth noticing that further cutting (more than 75% of the thickness) would lead to undesirable results associated with drilling noises near the strain gauge.

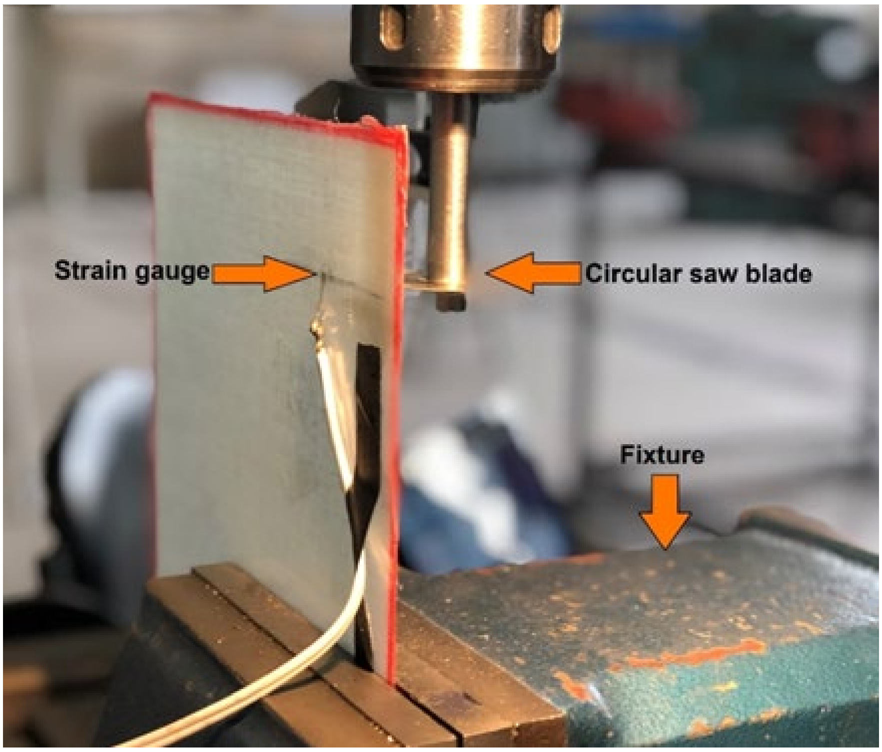
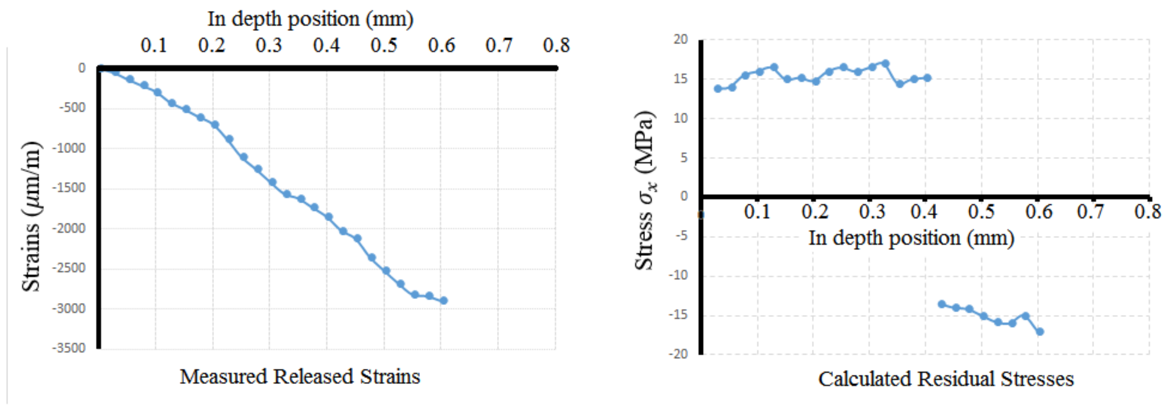


Fig. 6. Experimental set up for the determination of residual stresses using the slitting method

The released strains are recorded using strain gauges, a set-up wire, data logger, and computer system and shown in Fig. 7(a). Then, using the simulation slitting method, the calibration coefficients are obtained, and by applying Eq. 5, residual stresses are determined and demonstrated in Fig. 7(b). In this figure, a noticeable change in residual stresses from positive to negative values can be seen in the 0.4mm thickness, which is attributed to the change of the on-axis direction of ply in the laminated composite sample.



(a) (b)

Fig. 7. Residual stress measurement using the slitting method: a) Recorded released strains; b) Determined residual stresses applying slitting method

3.4. Curvature Method

The curvature of un-symmetric laminates is determined via a two-step method, 3D scanning of the whole sample using a Rexcan 3D scanner (Solutionix, Korea) (Fig. 8(a)), and measuring the position of the points on the upper curved surface of the sample using a coordinate measuring machine (CMM) (Fig. 8(b)). The curvature of un-symmetric cross-ply [$0_2/90_2$] laminates is then obtained as $k = \frac{1}{\rho_c} = 2.68\ (^1/_m)$ and seen to agree with other researches on the curvature measurements [27-29].

Moreover, using Eq. 9, the residual stress value is found to be:

$$\sigma_x = 12.4\ MPa$$

It should be noted that in the curvature method, the overall residual stress in the x-direction is obtained. The authors assumed that this stress is in the outer surface and maximum tensile stress. Therefore, the minimum stress is in the inner surface and equal to -12.4 MPa, and we can write extremum stresses as $\sigma_x = \pm 12.4$ MPa.

(a) (b)

Fig. 8. Determination of the curvature; a) Three-dimensional scanning of samples using a Rexcan 3D scanner (Solutionix, Korea), b) Measuring the position of points on the upper surface using a coordinate measuring machine (CMM)

3.4. Analytical CLPT Method

Using CLPT, the non-uniform thermal residual stresses for un-symmetric cross-ply laminates are calculated and presented in Table.3. It should be noted that the analytical method depends on the curing temperature, the stress-free temperature, and material property, which are time-dependent and change during curing.

Table .3. The non-uniform residual stresses in the un-symmetric cross-ply $[0_2/90_2]$ laminates calculated by the analytical CLPT method

Stresses (MPa)	First step	Second step	Third step	Fourth step
σ_x	6.8	14.5	-7.5	-6
σ_y	-9	-12.5	14	8
σ_s	-0.11	-0.33	0.25	+0.45

3.5. Comparison and Discussion

The results of residual stress measurement via three different experimental techniques and CLPT method in un-symmetric $[0_2/90_2]$ laminated polymer composites fabricated from glass fiber and epoxy resin are presented in this section. The HDM results include the characterization of non-uniform residual stresses in three distinct groups: fiber direction, transverse to fiber direction, and in-plane shear stresses. The residual stress values obtained in the first and second steps are about +17MPa and -17MPa in the fiber direction and transverse to the fiber direction, respectively. In the third and fourth stages, the non-uniform residual stresses are about -9MPa and +9MPa in the fiber direction and transverse to the fiber direction, respectively. Moreover, the in-plane shear residual stresses are negligible.

The slitting measurement outcomes show that the non-uniform residual stresses in the transverse-to-the-slit direction are about +15MPa and -15MPa in the depth of 0-0.4 mm and 0.4-0.6 mm, respectively. This sudden change at a depth of 0.4 mm is related to the change in the fiber direction. The overall residual stress value determined by the curvature method in specimens with the same conditions is 12.4MPa. This method is non-destructive and cannot provide the exact value of non-uniform residual stresses in each layer. However, the estimation given by this method is in agreement with other experimental results, and the difference is less than 18 %.

Furthermore, the calculated residual stresses in the x-direction are compared in Fig. 9. It is observed that hole drilling and slitting methods are in good agreement. However, the integral hole drilling method is preferred because it could provide all components of in-plane residual stresses. The difference between the results of the hole drilling and slitting methods with the curvature method is about 27% and 18%, respectively. Moreover, the results suggest that the CLPT and curvature measurement outcomes are virtually close, and the difference between the four methods is less considerable through the second and third steps. It appears from this comparison that CLPT and curvature methods can be applied as quick and easy-implementing methods when an overall residual stress value is of interest.

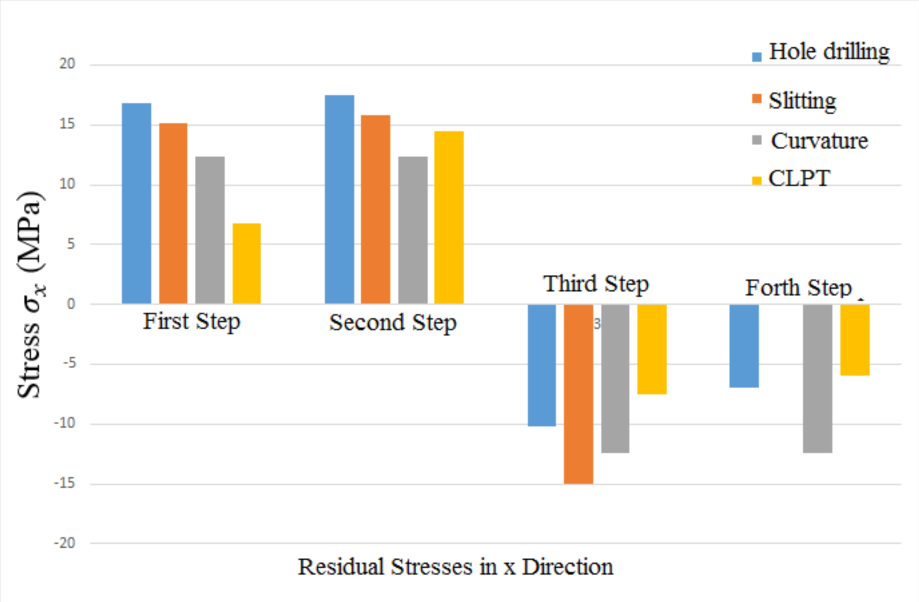


Fig. 9. Comparison of residual stresses in x-direction using hole drilling, slitting, curvature, and analytical CLPT methods.

4. Conclusions

Four different methods were used to determine non-uniform residual stresses in un-symmetric cross-ply polymer laminated composites. The hole drilling method is a standard method that is specifically useful for determining residual stresses near the sample's surface. It was indicated that by increasing the drilling depth, the accuracy of the method decreases dramatically. Moreover, the simulation process of this method involves more time and knowledge than other techniques. However, as opposed to other techniques, it can provide the non-uniform residual stresses in three directions which is a significant advantage, mainly when the determination of in-plane residual stresses is of interest. This method is semi-destructive, and the tested parts cannot be used again without some repairs.

The slitting method determines the residual stress value through the depth of specimens in only one direction. It has good accuracy in deeper through-thickness areas, while the simulation process and required equipment are simpler than the HDM. Nevertheless, this method can only measure one out of three residual stress components: perpendicular to the slit direction, and the destruction level is higher than HDM.

The curvature measurement method has received less attention but is a semi-analytical, non-destructive, and valuable method for determining residual stresses in un-symmetric laminated composite materials. This method provides an overview of the overall residual stress value and does not require a simulation process, strain gauges, etc. On the other hand, it lacks when the lay-up configuration is symmetrical. The difference between the results of the hole drilling and slitting methods with the curvature method is about 27% and 18%, respectively. It appears from this comparison that CLPT and curvature methods can be applied as quick and easy-implementing methods when an overall residual stress value is of interest.

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