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To cite this article: Pezhman Khoshrooz, Mohammadreza Farahani, Majid Safarabadi Farahani & Reza Khazaee (2020): Experimental and numerical investigation on the residual distortion and stress fields in un-symmetric hybrid composite laminates induced by the manufacturing process, Mechanics Based Design of Structures and Machines, DOI: 10.1080/15397734.2020.1784199

To link to this article: https://doi.org/10.1080/15397734.2020.1784199

Published online: 29 Jun 2020.
Experimental and numerical investigation on the residual distortion and stress fields in un-symmetric hybrid composite laminates induced by the manufacturing process

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ABSTRACT
Due to the high strength to weight ratio of composites, their applications are extending rapidly in many industries. Composites can be fabricated by using different constituent (including fiber and matrix) materials. Different curing cycles and thermal expansion coefficients of matrix and fibers in hybrid composites may lead to residual stresses and distortion. Residual stresses can decrease the durability of the part during commissioning, and distortion makes the assembly process more difficult or even impossible. In this study, different inter-ply hybrid laminates reinforced by carbon and glass fibers are fabricated by hand lay-up method. After curing, they are cooled by three different rates. Distortions of laminates are measured by coordinate measurement machine and their residual strains are measured by the incremental hole drilling method. Calibration factors are calculated by simulation and finally, residual stresses are determined. Also, residual stresses and distortion of laminates are predicted by classical lamination theory and finite element method. The obtained results are compared and acceptable conformity is seen. Comparison of experimental distortion results showed that cooling rates in the laminate which have more degree of un-symmetry will lead to 100 percent deviation of numbers.

1. Introduction
Nowadays, applications of composites are extending in many industries like aerospace, marine industry, petrochemical, etc. Composites have a high strength to weight ratio and due to this aspect, they are used in lightweight applications (Sam-Daliri et al., 2018). Despite of all advantages, there are manufacturing difficulties during fabrication of composite products. Delamination, formation of residual stresses and distortion, nonhomogeneous distribution of fiber in a matrix and weak joint of fiber and matrix are the main challenges (Ghabezi et al., 2016). A large group of composites are hybrid composites. Hybrid composites are fabricated by a combination of more than one matrix or a type of fiber or both of them. A popular group of inter-ply hybrid composites are Carbon/Glass-reinforced laminates (C/Gs). Carbon fiber composites have high strength, but their fracture strain is very low and have brittle behavior. Based on this aspect and considering economical benefits, glass fibers can replace some carbon layers to increase the laminate toughness (Wang et al., 2018). These two fibers have different coefficients of thermal...
expansion. There is also a difference between the fibers and matrix thermal expansion coefficients that intensify the formation of distortion (Nosouhi et al., 2018). Depending on the type of resin which is used in a polymer composite, curing at a specified temperature and with a special curing curve is needed. Due to different thermal expansion coefficients of resins and fibers, the residual stresses form and results in further distortion. These production problems shall be predicted and reduced as much as possible.

This paper focuses on the distortions of inter-ply hybrid laminates caused by different cooling rates and different stacking sequences. In these laminates, carbon and glass fibers are used with epoxy as resin. A code in MATLAB has been developed to predict the distortions of laminates and also their residual stresses. These distortions and residual stresses are compared to the result of finite element simulation using ABAQUS software. The modeled laminates are also fabricated with the hand lay-up method. Consequently, their distortions are measured by coordinate measurement machine and the remained stresses are measured by the incremental hole drilling method. Finally the numerical and analytical results are compared to the obtained experimental observations to evaluate the accuracy of the developed models.

2. Background and literature review

The first step in a multi-layered design is to select the number of layers and the direction of fibers. After selecting these two variables, the arrangement of layers is in vogue as an important parameter (Ghabezi and Farahani, 2017). As a historical sight, composite materials have been created to reduce the weight of the structures and offer the manufacturers and customers a durable material.

As mentioned in the previous section, conventional composites include a unique fiber type and a type of matrix; in other hands, hybrid composites are composed of a combination of different fiber types in a single matrix or a combination of one or more types of fibers in several different matrices. The development of hybrid composite materials is due to the increase in demand for such advanced materials in the automotive, aerospace, shipbuilding industries, and so on.

Different mechanisms cause distortion in the composite which have been investigated in numerous studies (Choi et al., 2015). Fernlund et al. (2002) described various factors, which could result in distortion of the composite material. These factors were the thickness, lay-up process and curing process. They showed that by using a process model based on COMPRO, finite element will predict flange spring-in more accurately. Shiau and Kuo (2004) investigated the thermal buckling of composite sandwich plates. Sandwich total transverse displacement consisted of bending of the plate and shear deformation of the core. Fiber orientation and aspect ratio of the plate was the effective parameters in buckling mode. Paris (2009) worked on deformation of finite two-ply laminate cord composite cylindrical shell subjected to edge loads and internal pressure. They showed that shell behavior depends on parameters such as cord-ply angle, large axial stiffness, small cord volume fraction, etc.

Tavakol et al. (2013) presented a three-dimensional thermo-mechanical finite element method to investigate the residual stresses and distortions caused by the curing process. Complex mechanical and thermal boundary conditions were applied to the layers. Ortega et al. (2017) investigated the fracture toughness of special hybrid laminates which was caused by tensile and pressure loads. Nine inter-ply hybrid laminates were fabricated by mixing two of three different plies. Zhang et al. (2013) performed a study on the effects of the hybridization on the mechanical properties of a hybrid composite laminate (glass and unidirectional flax used as reinforcements). They showed that the tensile strength of the material will improve by increasing the percentage of the glass fibers inside the composite.

Attia et al. (2017) investigated the inter-ply and intra-ply hybrid composites which where epoxy-based and reinforced by glass fibers and polypropylene. Their results were extracted in a
way to show the effects of lay-up sequences and hybridization on the strength of the material. Their experiments indicated that the strength of the epoxy-polypropylene composites will improve by adding glass fibers, efficiently. In 2015, Abouhamzeh et al. (2015) showed that curing process has an important role in the final shape of the manufactured composite laminate which consists of metal layers (Aluminum) and glass-reinforced layers. The most related research in the current paper is presented by Jung et al. (2007) that in which by manufacturing un-symmetric hybrid composite laminates and experimental study, the effects of the curing process and the cooling rate were investigated in order to obtain the final distortions. Also Jung et al. (2007) implemented an analytical method to predict the distortion of the material which was in good agreement with experiments. The error between experimental and theoretical study was from 10 to 20 percent. They predicted spring-back of hybrid composites by two numerical models: CLT method and FEM by ANSYS software.

The residual stresses have direct effects on the structure life, especially in fatigue condition. Thus, an evaluation of the residual stresses is of great importance. Abou-Msallem et al. (2010) worked on the evaluation of the residual stresses which are created by the chemical shrinkage in the curing process.

Hole drilling method proposed by Mathar (1933) for the first time. He measured deformation by extensometer around a circular hole in a plate. Schajer improved this method in his works (Schajer, 1981, 1988a, 1988b). He presented a general finite element solution and a table of calibration coefficients. His researches continued and the integral method suggested in order to calculate non-uniform stresses along with the thickness of the part by theoretical equations and experimental method. In this method, it has been proven that the released strains of each step of drilling are the accumulation of the effects of the present step and previous steps.

Shokrieh and Kamali (2005) studied the residual stress of thermoset composite materials. They proved that classical lamination theory (CLT) is powerful in predicting the residual stress of each layer neglecting temperature-dependent properties, but it is not useful in predicting the final shape of the laminate. Shokrieh and Safarabadi (2012) studied the effects of interphase on residual stresses. They introduced a three-dimensional energy-based closed-form solution. Shokrieh et al. (2012) created several structural models using finite element method and studied the influence of neighboring fibers. It was shown that neighboring fibers have minor effects on the thermal micro residual stresses and three-phase unit-cell RVE is appropriate for prediction of the residual stresses. Ghasemi et al. (2014) used the integral method to calculate the stresses of three different stacking sequence of laminates reinforced by glass fibers. Calibration coefficients were calculated by FEM. Each drilling step was equal to a layer thickness and it was shown that by increasing the drilling depth, its effect on the strain gauges will be lowered.

This research is a comprehensive study tried to find distortions and residual stresses simultaneously. Previous studies focused on one of these issues. Also, increasing the degree of asymmetries and different cooling rate effects has not been investigated at the same time. Analyzing these two parameters for hybrid composites is another innovation of this study. In addition, composite laminates with 32 layers and the same thickness have not been investigated experimentally.

3. Fabrication of laminates

As described before, laminates were fabricated from carbon and glass fibers as reinforcements and epoxy as the matrix. Unidirectional T700 12K carbon fibers supplied from Toray Co. were used. 12K means that it has 12000 bundles per tow. This type of fiber is very common for the fabrication of pressure vessels and yachts (Kaji et al., 2017). UD 200 E glass which has a little percentage of alkali was used as glass fiber. High strength along with low price are the advantages of this fiber type. Finally, a resin which is mixed from EPL1012 epoxy and EPH112 hardener with 1:0.15 ratio, supplied from Sazeh Morakab Co. was used.
The fibers were cut in $25 \times 25\, \text{cm}^2$ and after mixing with the epoxy by calculated fiber volume fraction, they were stacked based on the desired lay-up sequences $[16C_{90}/16G_0]$ and $[8C_{90}/8G_0/8C_{90}/8G_0]$. Totally 18 laminates were prepared for the curing process. All of the laminates spent similar curing process in a furnace till the cooling stage. In the following, three different cooling stages with different cooling rates was applied. Temperatures of laminates were measured by an infrared thermometer. These cycles are shown in Figure 1.

After completion of the cooling stage, 18 laminates of two stacking sequences cooled by three rates were ready for further experiments. Margins of laminates did not have acceptable qualities and had to be cut. Therefore, final models were prepared in $20 \times 20\, \text{cm}^2$ dimensions. Figure 2 shows these laminates from different viewpoints.

Mechanical properties of each layer depend on mechanical properties of fiber, matrix and fiber volume fraction. Essential parameters were calculated for carbon and glass fiber reinforced layers, separately as listed in Table 1.

![Figure 1. Cooling curves.](image)

![Figure 2. $[16C_{90}/16G_0]$ laminates. a. Glass side. b. Carbon side. c. Thickness side.](image)

<table>
<thead>
<tr>
<th>Table 1. Properties of laminates.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>$E_{CL}$ (GPa)</td>
</tr>
<tr>
<td>$E_{CT}$ (GPa)</td>
</tr>
<tr>
<td>$\sigma_{CL}$ (1/K)</td>
</tr>
<tr>
<td>$\sigma_{CT}$ (1/K)</td>
</tr>
<tr>
<td>$\mu_{12}$</td>
</tr>
<tr>
<td>$G_{CT}$ (GPa)</td>
</tr>
<tr>
<td>Thickness of layer (mm)</td>
</tr>
<tr>
<td>Planar dimensions (cm)</td>
</tr>
</tbody>
</table>
where $E_{CL}$ is the longitudinal elastic modulus, $E_{CT}$ is the transversal elastic modulus, $\alpha_{CL}$ and $\alpha_{CT}$ are the longitudinal and the transversal thermal expansion coefficients, $G_{CT}$ is shear elastic modulus and $\mu_{12}$ is Poisson’s ratio.

4. Experimental study

4.1. Flatness measurement

Coordinate measurement machine (CMM) used in this research was a fixed bridge type manufactured by DEA Italy. Totally 56 points were touched in an orderly manner. Coordinates of points were sent to software PC-DMIS which was connected to the machine and further calculations were done by software (Zargar et al., 2016). One of the capabilities of this machine is measuring how much a part is being flat. Flatness is a property of a plane that draws a surface. This definition is based on ISO1101. Tolerance of flatness is a linear parameter that specifies the tolerance zone in which flat surface should be assumed (Ghabezi and Farahani, 2018). This tolerance zone is defined by two parallel planes. These two planes shall be specified with maximum distance from each other.

4.2. Residual stress measurement

The incremental hole-drilling method was carried out to measure the induced residual stresses from the manufacturing process. The principle of this method is based on drilling of a small hole into the material. When the material containing residual stress is removed, the remaining material reaches a new equilibrium state. The new equilibrium state has associated deformations around the drilled hole. The deformations around the hole were measured during the experiment using strain gauges. The original residual stress in the material is calculated from the measured deformations according to ASTM standard. The calibration coefficients were required for converting the released strain to the residual stress values. Calculating the calibration coefficient using FEM was described in the following.

4.2.1. Calculating the calibration coefficient

In incremental hole-drilling method which is based on the step by step elimination of material, there is a relation between the released strains of each step and the captured stresses of that layer as (1) (Shokrieh and Akbari, 2012).

$$
\varepsilon(h_i) = \int_{0}^{h_i} C(x, h_i) \sigma(x) dx \quad 1 \leq i \leq n
$$

In the above equation, $h_i$ is the depth of the hole, $\varepsilon(h_i)$ is the measured strain when the depth of the hole is $h_i$, $\sigma(x)$ is the residual stress captured in $x$ depth of a hole and $C(x, h_i)$ is the kernel function which states the released strain due to unit stress in $x$ depth of the hole with $h_i$ depth.

The integral method is used for simplification of the previous equation and conversion of strains to stresses is applied (Farahani et al., 2013). Laminate is divided into segments and the thickness of each of them is the layer thickness. Stress components are assumed constant in each segment. (2) shows the conversion of the released strains to stresses of four layers.

$$
\begin{bmatrix}
C_{11} & 0 & 0 & 0 \\
C_{21} & C_{22} & 0 & 0 \\
C_{31} & C_{32} & C_{33} & 0 \\
C_{41} & C_{42} & C_{43} & C_{44}
\end{bmatrix}
\begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\sigma_3 \\
\sigma_4
\end{bmatrix}
= 
\begin{bmatrix}
\varepsilon_1 \\
\varepsilon_2 \\
\varepsilon_3 \\
\varepsilon_4
\end{bmatrix}
$$
Each $C_{ij}$ of the above matrix is a $3 \times 3$ matrix. Matrix $C_{ij}$ shows released strains from $j$ layer when $i$ layer is being drilled. So, this matrix is meaningful when $i$ is more than $j$; otherwise, the matrix will be zero. Also, each of $\sigma_i$ and $\varepsilon_i$ is a $3 \times 1$ matrix that represents their components in two major directions and shear direction as below:

$$
C_{ij} = \begin{bmatrix}
C^{11}_{ij} & C^{12}_{ij} & C^{13}_{ij} \\
C^{21}_{ij} & C^{22}_{ij} & C^{23}_{ij} \\
C^{31}_{ij} & C^{32}_{ij} & C^{33}_{ij}
\end{bmatrix}
$$

(3)

$$
\sigma_{\text{layer},i} = \begin{bmatrix}
\sigma^x_{\text{layer},i} \\
\sigma^{xy}_{\text{layer},i} \\
\sigma^y_{\text{layer},i}
\end{bmatrix}
$$

(4)

$$
\varepsilon_{\text{layer},i} = \begin{bmatrix}
\varepsilon^x_{\text{layer},i} \\
\varepsilon^{xy}_{\text{layer},i} \\
\varepsilon^y_{\text{layer},i}
\end{bmatrix}
$$

(5)

$X$ is the direction of glass fiber, $y$ is perpendicular to glass fiber direction and $xy$ is related to shear. Each C matrix needs a separate simulation to be calculated. Same as Figure 3, for obtaining $C_{ij}$ matrix, three simulations shall be done. At first, unit stress is loaded on the surface of the hole from the first layer to $i_{th}$ layer along $x$-axis. The next step is removing the hole in the $j_{th}$ layer. Then, three strains are read by strain gauges which are the components of the first column. Applying shear and transverse stresses are necessary simulations for obtaining the second and the third column of C matrix. Reference system which consists of 1, 2 and 3 directions is shown in Figure 4b and strain gauges were numbered based on this system according to Figure 5a. Based on this system it is obvious that 1 direction is the same as $x$-direction; 2 is the same as $xy$ and 3 is the same as $y$. Generally, the reference system is arbitrary in this kind of simulation and gauges shall be simulated in the same location as real gauges which were installed in experiments. So, the calibration coefficients and the strains which were read in each drilling step could be utilized to calculate the residual stresses of each layer.

Calculating the calibration coefficients of the laminate was done by FE simulation in ABAQUS. Based on ASTM E837, a 2 mm diameter was assumed on the surface (Sabokrouh and Farahani, 2019). Also, a 5.13 mm diameter rosette was simulated. Figure 4 shows the simulated laminate, surfaces that were assumed as the strain gauges and the meshing around the hole.

In this simulation, applying unit stress as residual stress was done by implementing a load module in ABAQUS and defining the predefined field. Also, removing the material of the hole was done by model change capability of the software (Akbari et al., 2012). This feature enables removing one layer in the hole region. So, layers removed and simultaneously unit residual stresses in arbitrary directions remained in the layer (Figure 3). Boundary conditions were assumed the same as the real experiments. C3D8R element type was chosen and 58080 elements in 2048 regions were created. The fine mesh size around the created hole was used. The mesh size changes between 0.2 mm to 0.4 mm altered the released strain values lower than 4%. Consequently, the mesh size about 0.3 mm was used at the strain measurement locations.

4.2.2. Experimental residual strain measurement

One of the laminates with $[8C_{90}/8G_0/8C_{90}/8G_0]$ sequence was chosen and drilled in 4 steps. Each step of drilling was 0.35 mm which was equal to the thickness of one layer. Three strain gauges were fixed. Strain gauge 1 was perpendicular to glass fibers direction, strain gauge 3 was
parallel to fibers direction and strain gauge 3 was installed in 135-degree angle with strain gauge 1 as shown in Figure 5.

After installation of gauges, drilling device was fixed on the laminate as Figure 5b. Drilling started and after each drilling increment, relaxation time was given to the drill bit in order to stabilize the thermal balance during the test. Recorded numbers of data logger were in millivolts. Therefore, conversion of Wheatstone bridge voltage change was done (Farahani and Sattari-Far, 2011). All of the geometrical parameters such as hole size, rosette diameter and gauges sizes adjusted based on ASTM E837.
5. Theoretical study

5.1. Classical lamination theory

CLT is applied in many researches to analyze different types of composite laminates (Mobarakian et al., 2020a). CLT has some simplifying assumptions that draw attentions from complicated three-dimensional elasticity to a simple two-dimensional problem (Yazdi, 2019). CLT is an extension of the classical plate theory for isotropic and homogeneous material as mentioned by Kirchhoff – Love. The plate theory needs some modifications and simplifying assumptions shall be added to take into account the in-homogeneity in the thickness direction (Mobarakian et al., 2020b). Assumptions are as below:

- Laminates consist of perfectly bonded layers and there is no slip between the adjacent layers.
- Each layer is a homogeneous layer and mechanical properties are known.
- Each layer is in a state of plane stress.
- Strains perpendicular to the middle surface are ignored. In other words, normal to the mid-plane remains normal without length change after deformation.

The mid-plane of the laminate is assumed to be a reference of Z-axis and displacement of any arbitrary point can be obtained by mathematical equations and it depends on the axial location.
of the point and the slope of the laminate mid-plane with the x and y directions. \( u, v \) and \( w \) are displacements of a point along x, y and z-axis. It should be noted that generally, x-direction is along the glass fiber direction, y is perpendicular to glass fiber direction in its plane and z is parallel to the thickness of the laminate. (6), (7) and (8) are the equations of three components of the strain matrix (Dabbagh et al., 2020).

\[
\varepsilon_x = u_{,x} = u_{0,x} - zw_{0,xx} \tag{6}
\]

\[
\varepsilon_y = v_{,y} = v_{0,y} - zw_{0,yy} \tag{7}
\]

\[
\gamma_{xy} = u_{,y} + v_{,x} = u_{0,y} + v_{0,x} - 2zw_{0,xy} \tag{8}
\]

Therefore, strain matrix can be calculated as (9).

\[
\begin{bmatrix}
\varepsilon_x \\
\varepsilon_y \\
\gamma_{xy}
\end{bmatrix} = 
\begin{bmatrix}
\varepsilon_x^0 \\
\varepsilon_y^0 \\
\gamma_{xy}^0
\end{bmatrix} + z
\begin{bmatrix}
K_x \\
K_y \\
K_{xy}
\end{bmatrix}
\tag{9}
\]

In the laminates which are not symmetric, temperature changes will be the reason for out-of-plane deformations. This deformation is called warpage. \( K \) matrix shown in (4) is representative of this kind of distortion. \( K \) matrix represents the mid-plane curvatures. The terms \( K_x \) and \( K_y \) are the bending moment curvatures and \( K_{xy} \) is the twisting moment-curvature.

In general, temperature change \( \Delta T \) during cooling down from processing temperatures causes a thermal contraction that is as (11). \( \varepsilon_T \) is the thermally-induced strain and \( \alpha \) is the coefficient of thermal expansion. Different coefficients and orientations produce residual stresses in the layers. The stresses of the \( k_{th} \) layer is calculated as (12).

\[
\varepsilon_T = \alpha \Delta T \tag{11}
\]

\[
\sigma = [Q] k \begin{bmatrix}
\varepsilon_x^0 \\
\varepsilon_y^0 \\
\gamma_{xy}^0
\end{bmatrix} + z
\begin{bmatrix}
k_x \\
k_y \\
k_{xy}
\end{bmatrix} - \Delta T
\begin{bmatrix}
\alpha_x \\
\alpha_y \\
\alpha_{xy}
\end{bmatrix} \tag{12}
\]

5.2. Finite element modeling

According to the fact that CLT ignores insignificant stresses formed along the thickness of the laminate, these should be assumed as a shell in the FE software. Therefore a three-dimensional
shell was modeled. The same as CLT, mechanical properties like elastic modulus, Poisson’s ratios, coefficient of thermal expansions, etc. shall be determined in FE simulation. All mechanical and geometrical properties were defined based on fabricated models. Due to the existence of two different materials in the laminate, these parameters were defined separately. In addition, the material of each layer, the thickness of layers and the fiber orientation of each layer were specified. After defining physical geometry and mechanical properties, initial and final state including temperature and mechanical restraints were defined. The temperature change was the same as the cooling stage of the curing process. As there were no mechanical restraints in the curing process of fabricated models, no mechanical restraint considered in finite element simulation. Mesh sensitivity analysis was carried out to define the optimum mesh size. The obtained results in this finite element model, show negligible mesh dependency. The mesh size changes between 1 mm to 4 mm altered the deformation and residual stress values lower than 3%. Consequently, the mesh size about 2 mm was used to show the remained stress and deformation smoothly.

6. Results and discussion

Applied code used defined inputs and based on CLT carried out the calculations. The main output of the mathematical equations were the residual stresses of each layer. It had been assumed that the layers which were reinforced by glass fibers were top layers and carbon-reinforced layers were bottom layers in the side view. \( \sigma_x \) was parallel to the glass fibers direction and \( \sigma_y \) was perpendicular to them. Figures 6 and 7 show the distribution of \( \sigma_y \) in \([16C_{90}/16G_0]\) and \([8C_{90}/8G_0/8C_{90}/8G_0]\) laminates, respectively. \( \sigma_x \) was nearly zero and shear stresses were absolutely zero for all the layers of two stacking sequences. Therefore, they were negligible and not shown in the graphs. In Figure 6, the negative part of the horizontal axis relates to the glass-reinforced layers and its positive part relates to the carbon-reinforced layers. In Figure 7, parts with negligible slopes of changes are the glass-reinforced layers and the rest parts of the graph are the carbon-reinforced layers.

![Figure 7. CLT calculated residual stresses of \([16C_{90}/16G_0]\) laminate(\(\sigma_y\)).](image)

| Sample \([16C_{90}/16G_0]\) | Sample \([8C_{90}/8G_0/8C_{90}/8G_0]\) |
|-----------------|-----------------|-----------------|-----------------|
| \(K_x\)         | \(K_y\)         | \(K_{xy}\)      | \(K_x\)         | \(K_y\)         | \(K_{xy}\)      |
| CLT 0.008957    | 0.082932        | 0               | -0.0025442      | 0.018558        | 0               |
| FEM -0.008726   | 0.082851        | 0               | -0.0025595      | 0.018533        | 0               |

Table 2. Computed K coefficients.
Figure 8. Deflection of the horizontal line for the sample \([8C_{90}/8G_0/8C_{90}/8G_0]\).

Figure 9. Deflection of the vertical line for the sample \([8C_{90}/8G_0/8C_{90}/8G_0]\).

Figure 10. Deflection of the horizontal line for the sample \([16C_{90}/16G_0]\).
Table 3. Measured distortion parameter by CMM.

<table>
<thead>
<tr>
<th>Distortion parameter (mm)</th>
<th>[16C90/16G0]</th>
<th></th>
<th></th>
<th>[8C90/8G0/8C90/8G0]</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hot Env.</td>
<td>Room Env.</td>
<td>Cold Env.</td>
<td>Hot Env.</td>
<td>Room Env.</td>
<td>Cold Env.</td>
</tr>
<tr>
<td>2.019</td>
<td>1.934</td>
<td>1.83</td>
<td></td>
<td>0.59</td>
<td>0.67</td>
<td>0.75</td>
</tr>
<tr>
<td>1.96</td>
<td>1.89</td>
<td>1.82</td>
<td></td>
<td>0.468</td>
<td>0.66</td>
<td>0.745</td>
</tr>
<tr>
<td>1.92</td>
<td>1.812</td>
<td>1.79</td>
<td></td>
<td>0.34</td>
<td>0.625</td>
<td>0.721</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.049</td>
<td>0.062</td>
<td>0.021</td>
<td>0.125</td>
<td>0.024</td>
<td>0.015</td>
</tr>
</tbody>
</table>

Table 4. Calculated calibration coefficients of [8C90/8G0/8C90/8G0].

<table>
<thead>
<tr>
<th>C_{11}</th>
<th>C_{21}</th>
<th>C_{31}</th>
<th>C_{41}</th>
<th>C_{51}</th>
<th>C_{61}</th>
</tr>
</thead>
<tbody>
<tr>
<td>-3.68</td>
<td>-4.53</td>
<td>0.683</td>
<td>-4.05</td>
<td>-5.26</td>
<td>0.976</td>
</tr>
<tr>
<td>-5.12</td>
<td>8.72</td>
<td>-3.78</td>
<td>-5.45</td>
<td>9.53</td>
<td>-4.63</td>
</tr>
<tr>
<td>0.992</td>
<td>-0.873</td>
<td>-12.54</td>
<td>1.24</td>
<td>-0.653</td>
<td>-13.31</td>
</tr>
<tr>
<td>C_{12}</td>
<td>C_{22}</td>
<td>C_{32}</td>
<td>C_{42}</td>
<td>C_{52}</td>
<td>C_{62}</td>
</tr>
<tr>
<td>-4.22</td>
<td>-5.41</td>
<td>1.02</td>
<td>-4.86</td>
<td>-7.23</td>
<td>1.11</td>
</tr>
<tr>
<td>-5.62</td>
<td>9.84</td>
<td>-4.98</td>
<td>-5.95</td>
<td>15.32</td>
<td>-4.06</td>
</tr>
<tr>
<td>1.33</td>
<td>-0.438</td>
<td>-13.63</td>
<td>3.88</td>
<td>-0.984</td>
<td>-19.92</td>
</tr>
<tr>
<td>C_{13}</td>
<td>C_{23}</td>
<td>C_{33}</td>
<td>C_{43}</td>
<td>C_{53}</td>
<td>C_{63}</td>
</tr>
<tr>
<td>-4.31</td>
<td>-5.68</td>
<td>0.991</td>
<td>-4.94</td>
<td>-7.41</td>
<td>1.08</td>
</tr>
<tr>
<td>-5.67</td>
<td>10.05</td>
<td>-5.09</td>
<td>-6.01</td>
<td>15.46</td>
<td>-4.15</td>
</tr>
<tr>
<td>1.44</td>
<td>-0.331</td>
<td>-13.89</td>
<td>4.01</td>
<td>-0.892</td>
<td>-20.09</td>
</tr>
<tr>
<td>C_{44}</td>
<td>C_{54}</td>
<td>C_{64}</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-4.62</td>
<td>-9.31</td>
<td>1.13</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-6.02</td>
<td>24.87</td>
<td>-0.472</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.70</td>
<td>-0.311</td>
<td>-31.94</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In both of the sequences, due to the directions of fibers, no shear stresses were created. When the fiber angles are not 0 or 90 degrees, shear stress will form.

According to Figures 6 and 7, captured residual stresses of the carbon-reinforced layers were greater than the residual stresses in the glass-reinforced layers. Whenever there was a change in the type or the direction of fibers, there would be a discontinuity in the graph of residual stresses as per Figures 6 and 7. This fact is obviously seen in both of the figures. The CLT code of this research had been applied for laminates of Schajer (1988b). Comparison of results showed that errors were less than 5 percent. Therefore the validity of the code was proved.

The same stacking sequences were modeled in the FE software and the residual stresses were calculated. These stresses were very close to the CLT calculated stresses and the differences were at most one percent.
Exact conformity of the results showed that ABAQUS utilized the CLT equations for its calculation. So, whenever predicting stresses of a composite laminate is needed, one of FEM simulation or CLT equations is enough and there is no need for the other one.

Another output of the CLT analysis was $k$ parameter. This parameter straightly affected the distortion of the laminates after curing. Table 2 shows the computed $k$ parameters in three directions by FEM and CLT. As mentioned previously, the outputs of CLT and FEM were equal as Table 2 and the differences were below three percent. The little differences might be due to numerical errors.

It has been shown that $K_{xy}$ is zero in both sequences. Source of this component was the existence of twisting moment. Due to the fiber directions, the twisting moment had not been created. The $K_y$ was more than $K_x$ and also their signs were against each other. This meant that the distortion in y-direction was more than x-direction. Positive and negative signs led to the horse saddle shape of the laminates.

According to the computed $k$ parameters for both of the sequences and their final distorted shapes, the $[16\,C_{90}/16\,G_0]$ laminate was more distorted and its $k$ parameter was more. The degree of un-symmetries was the main effective parameter in the $k$ parameters.

Another result was extracted from thermal simulation. Two perpendicular paths on the surfaces of both of the laminates were assumed. The vertical line was parallel to y-axis and the horizontal line was parallel to x-axis. The through-thickness displacements of points of these paths parallel to z-axis relative to the middle point of the surface were extracted. The same process was performed for one sample of each of the stacking sequences which were cooled in the hot environment by using the CMM. Experimental and simulation graphs are compared in Figures 8–11.

Due to the greater quantity of $K_y$ than $K_x$ and their opposite signs as shown in the above figures, deflections of vertical lines in y-direction were negative and deflections of horizontal lines along x-axis were positive. Also, the values of the deflection of the vertical lines were greater than horizontal lines. As shown in the above figures, when the distance from the middle point of the surface became more, differences in the experimental values and the simulation values became more. This meant that the simulation and CLT predicted the final shape flatter.

The flatness of each laminate was measured by the CMM. This was performed for all of the fabricated laminates. The measured quantities are listed in Table 3.

### Table 5. Measured strains of incremental hole drilling [με].

<table>
<thead>
<tr>
<th>ε₁</th>
<th>ε₂</th>
<th>ε₃</th>
<th>ε₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>-17</td>
<td>-64</td>
<td>14</td>
</tr>
<tr>
<td>9</td>
<td>-48</td>
<td>-181</td>
<td>-59</td>
</tr>
<tr>
<td>-360</td>
<td>-577</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 6. Incremental hole drilling calculated stresses [MPa].

<table>
<thead>
<tr>
<th>Layer</th>
<th>Stress Tensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>First layer</td>
<td>$\sigma_1 = [C_{11}]^{-1} [\varepsilon_1] = [0.32, 0.57]$</td>
</tr>
<tr>
<td>Second layer</td>
<td>$\sigma_2 = [C_{22}]^{-1} ( [\varepsilon_2] - [C_{21}] [\varepsilon_1] ) = [0.73, 5.90]$</td>
</tr>
<tr>
<td>Third layer</td>
<td>$\sigma_3 = [C_{33}]^{-1} ( [\varepsilon_3] - [C_{31}] [\varepsilon_1] - [C_{32}] [\varepsilon_2] ) = [0.26, 6.20]$</td>
</tr>
<tr>
<td>Fourth layer</td>
<td>$\sigma_4 = [C_{44}]^{-1} ( [\varepsilon_4] - [C_{41}] [\varepsilon_1] - [C_{42}] [\varepsilon_2] - [C_{43}] [\varepsilon_3] ) = [-0.12, -0.16, 6.68]$</td>
</tr>
</tbody>
</table>
According to Table 3, the values of \([16C_90/16G_0]\) sequence were closer to each other than the other stacking sequence. Also, increasing the cooling rate led to less distortion. However, the measured parameters for different rates of \([16C_90/16G_0]\) had an overlap and this made the prediction complex. Therefore, the conclusion for the effect of cooling rate on the distortion of this sequence was complicated and getting a comprehensive result was not possible. By comparing the results of different sequences, it was deduced that whenever the laminate is closer to symmetric laminate, the cooling rate has more effect on the distortion. As seen in the above table, the results of \([8C_90/8G_0/8C_90/8G_0]\) laminate were less than the other sequence and different rates had wide range without any overlap. This meant that increasing the cooling rate of this laminate will lead to more distortion and its effect is significant.

In addition to previous results, captured residual stresses of the first four layers of \([8C_90/8G_0/8C_90/8G_0]\) sample which were reinforced by glass fibers were measured experimentally by the incremental hole-drilling method. As described previously, calibration coefficients were calculated by FEM simulation as listed in Table 4.

All numbers of the above table shall be multiplied by \(10^{-12}\). In addition to calibration coefficients, the strains of each drilling step were recorded by the strain gauges and a data logger as listed in Table 5.

The strains of the above table are in micro strains. By having the strains and the calibration coefficients and based on the Equation (8), the stresses were calculated as listed in Table 6.

According to the stresses of four layers, \(\sigma_y\) of the first four layers were logical and close to the theoretical values. The comparison showed that error percent was less than 30 percent, which was due to a variety of differences between fabrication and ideal state which the simulation and the mathematical relations assume.

\(\sigma_y\) was the dominant component of the stress matrix and the other components were negligible. \(\sigma_x\) and shear stresses of all of the layers were zero in both of the experimental and the theoretical results.

The stress results of CLT, FEM and the experimental methods are compared in Figure 12.

7. Conclusions

In this study formation of the residual stresses and the distortions of inter-ply hybrid composite laminates with two different stacking sequences were investigated. The laminates were fabricated from epoxy as the matrix and carbon and glass fibers as the reinforcements. Totally 9 laminates of \([16C_90/16G_0]\) sequence and 9 of \([8C_90/8G_0/8C_90/8G_0]\) sequence were cooled by three different rates. Numerical, finite element and experimental methods were applied for evaluation of the distortions and the residual stresses and the related results are compared.
The residual stress graphs of two stacking sequences showed that slopes of changes in the carbon-reinforced layers in \([16C_{90}/16G_0]\) were about five times more than the other sequence and also, the maximum quantity of the residual stress in this laminate was two times more than the maximum of \([8C_{90}/8G_0/8C_{90}/8G_0]\). The glass-reinforced layers of both of the stacking sequences had approximately equal residual stresses and the differences were less than 2 MPa. In addition, comparison of K parameters of two sequences showed more distortion in both of the x and the y directions in laminates with \([16C_{90}/16G_0]\) sequence. The differences between Young’s modulus and thermal expansion coefficients of carbon and glass fibers caused different residual stresses profiles and different stacking sequences were the reason for the inequality of laminates curvatures.

Comparison of the vertical displacement of surface points parallel to z-direction in the simulation and the experimental results showed that simulation predicts the curvatures optimistically and the distortion of laminates, in reality, is more critical. In other words, the simulation assumes that laminates become flatter than experiments after curing. The experimental and the simulation results had about 30 percent difference. The simulation assumed the ideal state and did not consider the fabrication difficulties. Due to the difference between the sample fabrication process and the differences due to the experimental test and data accusation, the observed differences between the predicted distortion and the calculated ones seem to be inevitable.

The residual stresses of the four layers of a laminate of \([8C_{90}/8G_0/8C_{90}/8G_0]\) were measured by incremental hole drilling and compared to the theoretical results. Normal stresses in the x-direction and shear stresses were nearly zero. So, they could be neglected and only the transverse stresses in y-direction could be compared. Below 30 percent errors were observed; the same as distortion, variety of error sources in the fabrication and also the hole drilling method made these differences.

**Funding**

The authors are grateful for the support of the Iran National Science Foundation (INSF), Project No. 98012558.

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**References**


