Effect of ply orientation angle on residual stress in carbon fibre laminates

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Abstract. The mechanical performance of a composite structure is influenced by residual stresses induced during curing and post-processing. Therefore, residual stress evaluation is important especially as layers increase in laminated composites. The general aim of this study is to present a fundamental relation between residual stresses (due to manufacturing process) and the relative angle between plies (±θ) in a two-layered, carbon-fibre reinforced epoxy-resin laminate. The residual stresses along the loading direction were determined using the X-Ray Diffraction technique at different locations in a specimen. The maximum numeric value obtained was compared with the residual stress obtained from the Abaqus software using Universal Tensile Test data for failure.

Keywords: Composite, residual stress, laminate, ply-orientation, X-Ray Diffraction

1. Introduction
The most common type of composite used is a Polymer Matrix Composite (PMC) with fibre-shaped reinforcements. It is nearly 5 times stronger than steel on a weight-to-weight basis. Epoxy resins are the most commonly used matrix material for making PMCs. [1] There are several composites which cover a wide variety of applications in different domains. The method of fabrication depends primarily on factors such as type of matrix and reinforcement; shape and size; the properties and use of the final product. [2] A common way of manufacturing composites is performing a wet layup process in an Autoclave or through Vacuum Bagging Process. These methods have the advantages of providing a near void-free composite with greater control over the thickness and fibre-fraction of the moulded part. Like metals and alloys, composites develop internal resistance to deformations in the form of stresses. These stresses are developed only when composite material is loaded in any form. Just like metals and alloys, composite materials are also prone to the development of residual stresses which are present when there is no loading. The determination of residual stresses can be done based on response to released residual stresses, changes in failure patterns, changes in material structure and response to change in temperature. [3] Among the Non-destructive methods, X-Ray Diffraction (XRD) technique was used in this study and the Failure Strength for all the multi-axial laminates was experimentally found out using Universal Testing Machine (UTM). The Abaqus FEA simulation software was used to generate the standard data (without residual stresses) for the specimens. The use of XRD to determine the residual stresses in polymeric materials was done by introducing metallic filler particles as ‘stress markers’. As the cross-linking occurred during manufacturing, the
developed residual stresses were shared by these particles as well. [4] The choice of the filler metal depends highly upon the temperatures involved and penetration power of XRD equipment. It was found that 4-5\% (by mass) of the epoxy is about the right amount of filler particle powder to be added between the layers in a PMC. [5] Different metals have different Stress Sensitivity which is a measure of how small value of residual stress can be detected by the combination of given X-ray wavelength and filler metal. [6] The residual stress in the matrix can be calculated using Hahn’s relation as [6]

$$\bar{\sigma}_{im} = \eta \bar{\sigma}_{if}$$

where  
\( \eta \) – Hahn’s factor  
\( i \) – the direction along which stress is applied  
\( \bar{\sigma}_{f} \) – stress in the filler particles obtained by XRD  
\( \bar{\sigma}_{m} \) – stress present in the matrix

The residual stresses are categorised into two broad categories, namely, micro-stresses and macro-stresses. The former is due to the difference in phases in a single lamina while the latter is due to the constraints offered by the neighbouring plies. [7] Laminated composites have three distinct modes of failure depending upon their ply-angle, which are: [8]  
a) Fibre separation – only in \( \pm 90^\circ \)  
b) Fibre breakage – only in \( \pm 0^\circ \)  
c) Ply delamination

Some common reasons for the presence of residual stresses in composite materials are: [9]  
a) the anisotropic properties of each unidirectional layer.  
b) the moisture absorption by the epoxy matrix during and after curing.  
c) the Poisson’s ratio mismatch of layers in the vicinity of the free edges.

The origin of the residual stresses can also be accounted to chemical shrinkage (and also thermal contraction which was not considered in this study). The FEA simulations can be used to model ideal composite materials with no residual stresses present. [10]  
Like superalloys, principal residual stresses in composites may or may not be along the longitudinal directions. [11] The relation:

$$\sigma_{total} = \sigma_{applied} + \sigma_{principal\ residual} \cdot \cos\beta$$

where  
\( \beta \) – the angle between maximum principal residual stress and applied stress

can be used to determine one when the other quantities are known.  
It has been developed over the years that a clear pattern of residual stresses exists between the fibre and matrix of a unidirectional fibre-reinforced composite due to mismatch of intensive properties of the fibre and the matrix material. In addition, residual stresses also exist between plies of a laminated composite since the in-plane thermal and mechanical properties of one ply may not necessarily match with the other ply stacked over it even if they both have the same angle of alignment of fibres. The previous work done in this area suggests that there should also be a pattern of residual stresses between plies depending upon the orientation of fibres. This study has been conducted in the context of this belief and is a development over the previous finding.

2. Experimental  
Vacuum Bag Moulding process was used to manufacture the carbon-fibre-epoxy-resin laminates used. This process is highly suitable for the fabrication of planar laminates due to its relative ease of manufacturing and low cost. A 200gsm unidirectional carbon-fibre cloth was used along with Araldite® LY 1564 epoxy and Aradur® 22962 hardener. The volume fraction of fibre was approximately 65\%. The measured amount of aluminium powder (5\% of epoxy) was spread evenly between the plies. The
residual stresses developed during the manufacturing of the laminates were measured using two methods to verify the results.

2.1 Finite Element Method

The 2-D model of the specimen was created in Abaqus as per the standard sheet-type specimen dimensions of ASTM E8. [12] The elastic material behaviour was selected for the lamina that included the contribution of a matrix (epoxy) and reinforcement (carbon fibre). Using the micromechanics approach, the values of longitudinal modulus ($E_1$), transverse modulus ($E_2$), Major poison ratio ($\theta_{12}$), in-plane shear modulus ($G_{12}$ and $G_{23}$) and axial shear modulus ($G_{13}$) were calculated which were later plugged into the software. These values were calculated through the relations shown below:

Note that y-axis was along the length of the specimen (see Fig. 2) in the software and thus, direction y was longitudinal while x was transverse.

Longitudinal modulus,

$$E_y = V_f (E_f) + V_m (E_m)$$

Transverse modulus,

$$\frac{1}{E_x} = \left(\frac{V_f}{E_f}\right) + \left(\frac{V_m}{E_m}\right)$$

Major Poisson’s ratio,

$$\gamma_{yx} = \gamma_f (V_f) + \gamma_m (V_m)$$

In-plane Shear Modulus,

$$\frac{G_{yx}}{G_m} = \frac{1+\xi\eta V_f}{1-\eta V_f}$$

where $\xi$ is called the reinforcing factor and is dependent upon the geometry & loading conditions

$$\xi = 1 + 40 (V_f)^{10}; \quad \eta = \frac{G_f}{G_m} - 1 \quad \frac{1}{\xi}$$

**Table 1.** Elastic properties of specimen.

| S. No. | Parameter | Value       |
|--------|-----------|-------------|
| 1      | $E_y$     | 150.5675 GPa|
| 2      | $E_x$     | 8.50484 GPa |
| 3      | $\gamma_{yx}$ | 0.3175     |
| 4      | $G_{yx}$  | 6.006 GPa   |
| 5      | $G_{xy}$  | 6.006 GPa   |

*Figure 1:* Setting up the orientation angle of plies in Abaqus

The plies were arranged over each other in $+\theta/-\theta$ rotation angle orientation for seven values of $\theta$ ranging from $0^\circ$ to $90^\circ$. 
After the composite layup, meshing of the specimen was performed using element size approximately equal to 0.25 mm. One grip section of the specimen was fixed using ENCASTRE boundary condition BC-1 where linear and rotational displacements were set equal to zero. The other grip section was constrained to displace in Y direction only using BC-2. The value of the displacement in Y direction was given using BC-3 as per the UTM data for different ply orientation angles.

2.2 XRD Method

In X-Ray Diffraction method, the strain present in the crystal lattice is measured and the associated residual stress is determined from the elastic constants by assuming a linear elastic distortion of the appropriate crystal plane. Usually, this method is best suited for measuring surface residual stresses but with some angle of incidence, X-rays can penetrate to a certain depth. The penetration depth depends on the anode, material and angle of incidence.

A Pulstec μ-X360 X-Ray Diffraction machine was used to analyse the specimens for longitudinal residual stress using the cosα method as shown in the Fig. 3.

2.3 UTM Testing

The specimens were tested in Universal Testing Machine as shown in Fig. 4, that provided with the Stress vs Strain & Force vs Displacement curves for ±0°, ±15°, ±30°, ±45°, ±60° and ±75° orientation angles.
3. Results and Discussion

XRD residual stress analyser was used to detect the residual stresses generated in all the specimens with orientations ±0°, ±15°, ±30°, ±45°, ±60°, ±75° and ±90°. The magnitude of residual stress was found to be maximum for ±30° fibre orientation.

The residual stresses obtained from XRD for each orientation are shown in Table 2.

Table 2. The maximum numeric value of Residual stress obtained for all specimens

| Orientation | XRD Residual Stress (MPa) |
|-------------|---------------------------|
| ±0°         | 23                        |
| ±15°        | -71                       |
| ±30°        | 76                        |
| ±45°        | 27                        |
| ±60°        | 14                        |
| ±75°        | 50                        |
| ±90°        | 5                         |

The Fracture Strength obtained from the tensile testing of the specimens is plotted in the Fig. 6. The graph shows that the ±0° specimen had the maximum strength to bear the tensile load and this strength fell as the orientation angle increased. The maximum strength for ±0° can be understood from the fact that fibres were aligned along the direction of loading.
Stress vs Strain curves were also obtained from the UTM for each specimen. The curve for the fibre orientation $\pm 30^\circ$ is shown in Fig. 7. The specimen with orientation $\pm 90^\circ$ did not have enough strength to be mounted on the UTM because all the fibres were aligned in the transverse direction. The specimen had almost no strength in the longitudinal direction and got damaged while trying to load into the UTM. Thus, UTM Testing could not be performed for this specimen.

Abaqus FEA Software was used to simulate the loading conditions in a Tensile Test to obtain a Stress vs Strain curve for each specimen free of any residual stress.

The Stress vs Strain curve for $\pm 30^\circ$ orientation obtained from Abaqus is shown in the Fig. 9.
A ‘residual stress-free’ Fracture Strength was obtained by calculating the Stress from the slope of the Abaqus curve at the Fracture Strain obtained from the Tensile Test on the UTM. The difference between this value and the value of the Fracture Strength obtained from the UTM data was used to calculate the residual stresses in different ply orientation specimens except for ±90°.

\[ \text{Analytical Stress} = \text{Slope} \cdot \epsilon \]  
\[ \text{Residual Stress} = \text{Analytical Stress} - \text{Actual Stress} \]

where \( \epsilon \) is the value of Fracture Strain in tensile loading of the specimen.

Eq. (9) is an extension of eq. (2) where \( \beta = 0° \) since only the residual stresses along the loading direction were considered. The analytical residual stresses obtained using tensile loading and FEA analysis in Abaqus for each mentioned orientation is listed in Table 3.

Table 3. Residual stress obtained by combining UTM data with Abaqus results

| Orientation | Analytical Residual Stress (MPa) |
|-------------|----------------------------------|
| ±0°         | 20.39                            |
| ±15°        | -60.32                           |
| ±30°        | 63.26                            |
| ±45°        | 28.88                            |
| ±60°        | 11.923                           |
| ±75°        | 44.57                            |
| ±90°        | -                                |

The data obtained from both the methods mentioned in the above sections provided the values of residual stress in each specimen. These results were compared to check the validity of the results obtained which was found to be satisfactory.

The residual stresses are self-equilibrating, thus, the net force acting on any specimen due to residual stress distribution was zero. This means that the positive or negative values of residual stress were just indicative of its nature in a particular direction at some specific location. Assuming a uniform variation of residual stress in the specimen, equal and opposite values of residual stress may exist along two different directions at the same location in a specimen. A negative value of residual stress for ±15° specimen could be due to this fact. In other words, this negative value of residual stress was a counter value for a possible positive value along some other direction balancing this stress. Therefore, going forward only the magnitude of the residual stress obtained held significance.
As can be seen from the Fig. 10, the results for each specimen vary significantly. To make the problem one-dimensional, Residual Stress as a fraction of Fracture Strength was calculated for each specimen separately. These values were plotted and then a curve was fitted linearly, ignoring the outlier which was the value obtained for ±15°. A linear fit was used for curve fitting.

Figure 10: Graph comparing the results obtained from the XRD method and Analytical method

![Graph comparing the results obtained from the XRD method and Analytical method](image)

Figure 11: Linearly fitted curve showing a trend in the fraction of residual stresses

![Linearly fitted curve showing a trend in the fraction of residual stresses](image)

4. Conclusions
The experimental and analytical study conducted on the two-layered, carbon-fibre reinforced epoxy-matrix laminate showed the following results:

1. It was found that the Fracture Strength of the specimen depends upon the ply orientation angle, with ±0° orientation laminate having the highest strength.
2. The residual stress generated in most of the specimens was tensile in nature except ±15° orientation which showed compressive residual stress. This could be a counter value for positive residual stress along some other direction in the specimen.
3. To visualise the effect of residual stresses on the strength of the laminate, they were divided by their respective fracture strength. This ratio was a measure of the extent to which the residual stresses affected the strength at that particular orientation.
4. The above-mentioned ratio showed a linearly increasing trend with an increase in the orientation angle.

![Linearly fitted curve showing a trend in the fraction of residual stresses](image)
5. References

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