Spring-back of Thick Uni-Directional Carbon Fibre Reinforced Composite Laminate for Aircraft Structure Application

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Abstract. The springback phenomena of CFRP after curing process through autoclave manufacturing method results on the out of tolerance for its utilisation in aerospace industry. This paper relates to the measurements of springback for Uni-directional flat laminate as a first steps to the springback study for the real aircraft composite laminate structures. A flat laminate with dimension of 300 mm x 300 mm, 400 mm x 400 mm and 500 mm x 500 mm with different number of ply; 20, 24 and 28 are manufactured. The choice of dimension and number of lay-up corresponds to the dimension and lay-up of rib structure. After process, the springbacks are measured using 3D scanner (optical-based three-dimensional) with an accuracy of 42 micrometers to obtain an accurate measurement. The analysis of the effect of dimension and number of ply to the magnitude of springback are presented within the range of specimen studied in this work.

1. Introduction

The increasing use of fiber-reinforced polymers in aerostructures as well as other industrial applications necessitates that their manufacturing quality and performance be continuously improved to allow rapid product development. In applications such as aerospace where precision is paramount, warpage of composite parts should be minimized to meet tight tolerance specification. Parts that warped beyond tolerance would demand excessive pre-stressing during assemblies to allow mating parts to get fastened. This pre-stressing would reduce the strength margin of the composite structures, risking premature failure.

Structures that undergo elevated temperature curing would always present post-cure warpage due to thermal expansion or contraction. This warpage is also known as springback. The thermal expansion mismatch between tools and laminates causes residual stresses to build up within the laminates [1-11]. Nonetheless, a practical solution such as predictive numerical model is crucial in quantifying the springback deformation [12-14].

A previous study [13-14] has been carried out which managed to develop a predictive numerical model to predict the warpage or springback deformation of flat thin laminates. Prediction accuracy was excellent for some configurations but mediocre for some others. However, the validation of the model was only limited to thin specimens (four plies) since no empirical data was available for thicker ones. The actual composite parts are five to six times thicker, which may exhibit a totally different behavior...
that the existing model may not be able to predict. This work is aimed at extending the applicability of that model by providing validation baseline of thick laminates through empirical database.

2. Specimen fabrication process

The material used in this work is a typical one for aircraft structure application which a uni-directional (UD) carbon fibre pre-impregnated in epoxy resin (AIMS05-27-002). This material underwent the following manufacturing processes; cold storage, kitting, layup, curing, demould, trimming, non-destructive test (NDT), painting, assembly, and packaging.

Springback can be observed after demould process and therefore for this study the specimens underwent processes only until demould. In terms of inspection, only visual inspection was carried out, observing attributes such as surface appearance and colour. NDT, which can detect internal defects was not performed due to cost constraint. Furthermore, these specimens were cured together with production parts in the same autoclave using the same curing recipe so that any non-conformance would be reported through the production parts.

The composite specimens were made up of multiple plies laid up in a specific sequence and orientation [15]. These plies were cut to their shapes from the raw material roll using automated ply cutters. As such, the machines required input data in the form of nesting programs. Using a CAD software together with a nesting software, the nesting programs were created in such a way that will maximize the use of the materials. After being cut, the plies were sorted and kitted according to each specimen to be made.

The mould tools would determine the final shape and surface finish of the specimens. One flat mould tool with a dimension of 1.2 m x 1.2 m was used for this work as shown in Figure 1. The mould has a surface roughness, $R_a$ of 1.0 to 1.6 $\mu$m as required for industrial application.

![Figure 1. Mould tool used for the layup of the specimens](image)

After all plies had been laid up, final bagging was performed using standard bagging procedure. The curing recipe followed the production standard, with double dwell. Due to confidentiality issue, the exact recipe is not shared in this text.

Using this manufacturing methods, a certain number of square flat UD laminates were fabricated (as shown in Table 1) for the springback study.

| No. of Ply | 20 | 24 | 28 |
|-----------|----|----|----|
| Length    | 300| 400| 500|
| Number of Panel | 3 | 2 | 3 |
| Length    | 300| 400| 500|
| Number of Panel | 3 | 4 | 3 |
| Length    | 300| 400| 500|
| Number of Panel | 3 | 3 | 3 |
| Length    | 300| 400| 500|
| Number of Panel | 3 | 3 | 27 |

3. Springback measurement method

The springback deformation or warpage of the specimens was quantified through the measurement of surface deviation on the tool side the mould tool from its nominal contours. To get the most accurate reading as possible, a non-contact optical-based three-dimensional measurement was employed. A non-contact measurement was chosen to avoid any possible flexing of the specimens due to contact force from any contact-based measurement device. Thus, the most accurate reading is guaranteed. Plus, the
speed at which a typical laser scanning device acquires measurement data is many times that of conventional contact-based probing [16].

This study requires a measurement accuracy of at least 150 micrometers (equivalent to one-third of the tolerance of a typical aerospace composite parts). The type of measurement device used in this case was the latter, a triangular-based 3D laser line scanner mounted on a six degrees of freedom portable measuring arm, as shown on the left side of Figure 2.

![Figure 2](image)

Figure 2. A two-dimensional representation of the measuring arm with the laser scanner (left) and the measurement principle of triangulation method (right)

There are two measurement principles used in this setup, one for the measuring arm and the other for the laser scanner. The measuring arm uses rotation-to-translation coordinate transformation based on input from rotary encoders built in each of its joint. For example, to get the coordinate of a two-dimensional measurement \((x,y)\), the following transformation equation is employed:

\[
\begin{align*}
x &= L_1 \cos \theta_1 + L_2 \sin \theta_2 + L_3 \cos \theta_3, \\
y &= L_1 \sin \theta_1 + L_2 \sin \theta_2 + L_3 \sin \theta_3
\end{align*}
\]

L1 and L2 are known from the physical dimension of the arm while L3 is acquired from the distance measurement of the laser scanner based on triangulation method as shown on the right side of Figure 2 [17]. The term triangulation stemmed from the fact that the three components (laser source, specimen, and sensor) form a triangular. When the laser beam strikes the surface of the specimen at a distance, some components of the reflected light ray would fall onto a spot along the optical sensor. A calibration is thus required to accurately map the laser spot position along the sensor with its physical position counterpart. Furthermore, when the distance of the specimen relative to the scanner is changed \((\delta Z)\), a corresponding change in the position of the reflected spot along the sensor \((\delta Z')\) can be measured. This change also needs to be calibrated accordingly to reflect the actual physical change of the distance, taking into account non-linearity effect of the triangulation. There will therefore be a range limit at which the scanner will be able to register its distance from the specimen, depending on the length of the sensor.

Table 2. Basic specification of the measuring arm (left) and the 3D laser scanner (right)

| Parameter              | Specification |
|------------------------|---------------|
| Measuring Range (m)    | 2.0           |
| Point Repeatability (mm)| 0.030        |
| Volumetric Accuracy (mm)| 0.042        |
| Arm Weight (kg)        | 7.4           |

| Parameter              | Specification |
|------------------------|---------------|
| Accuracy (mm)          | 0.040         |
| Sampling Rate (Hz)     | 45,000        |
| Line Width at mid-field (mm) | 80         |
| Stand-off Distance (mm) | 135 ± 45     |
| Minimum Point Spacing (mm) | 0.08     |
The result of the measurement from the laser scanner are clouds of point scattered throughout the three-dimensional space. An average number of measurement points for a specimen is 1.5 million. Considering that the actual number of measurement points to be included in the database is less than 20, the scanning capability in terms of resolution is somewhat an overkill. Nevertheless, more is always better when it comes to data especially when resources are abundant. More data means that more information could be extracted from the measurement results alone without the need to refer back to the physical specimens, which is a real time saver.

**Figure 3. General workflow of the measurement process**

The general workflow of measurement is shown in Figure 3. Scanning involved sweeping the scanner normal to the surface of specimens at a stand-off distance of about 150mm at a rate of about 50mm per second. Both tool and bag sides of each specimen were scanned in order to obtain as much information as possible, especially in regards to its thickness. Inspecting their thickness acts as a validation tool to ensure that all specimens were fabricated according to their respective specification.

After a complete points cloud was acquired, some trimming was done to remove unwanted noise from the model. Then the points cloud was converted to polygonal mesh. Polygonal mesh was used in this study since it can inherently define the normal direction of any point on a surface to be used in analyses such as thickness and surface deviation colour plots. Later, the CAD model of the mould tool would be imported into the project file to be used for data alignment, which is explained in the following paragraphs.

From the polygonal mesh of the specimens, nine extraction points were defined. The standard extraction pattern is depicted in Figure 4.

**Figure 4. Extraction pattern (left) and thickness colour plot (right)**

Each extraction point, known as comparison point, as its name implies, compares the three-dimensional location of the measurement point against the nominal surface of the CAD model of the mould tool. However, a valid comparison can only be done after a proper alignment be made between the data object (polygonal mesh) and the reference object (CAD model). Alignment for the specimen was accomplished through a best-fitting of the data object with the layup surface of the mould tool.

The in-plane position of each polygonal mesh with respect to the CAD model was approximated to be at its centre. This assumption was made since there is no record of the exact in-plane position of each specimen during the layup process. Furthermore, a thorough inspection of the mould tool itself revealed...
that the tool has satisfied the fabrication tolerance of 0.15mm throughout its layup surface. So any in-plane alignment position of the specimen should give similar output.

The extracted points were exported as spreadsheet workbook to be compiled into a database as shown in Table 3.

| No. of Ply | 20 | 24 | 28 |
|-----------|----|----|----|
| Length    | 300, 400, 500 | 300, 400, 500 | 300, 400, 500 |
| Average of Warpage (mm) | 0.033, 0.379, 0.955 | 0.135, 0.296, 0.361 | 0.106, 0.187, 0.284 |

4. Springback data analysis

In the dataset of this study, two parameters, size and thickness, are considered as the factors for the warpage or springback effects. The warpage was derived by calculating the difference between the highest and lowest measurement point along fibre direction. Graphs of the out-of-plane warpage versus the specimen size and thickness are depicted in Figure 5.

Each data point in both graphs above has been averaged among three measurement data points. The error bars indicate the range between maximum and minimum values for respective data points. From the graphs, all data series are showing similar trends which increasing with size and decreasing with thickness, except for specimen thickness of 20 plies at sizes 300 mm. This can also be seen from their rather large error bars. The reason behind this outlying data is still under investigation. Nevertheless, these outliers have been excluded from the regression analysis. The mathematical models with respect to both parameters were derived through the best-fitting of normalized measurement data. Plots of the normalized warpage as a function of both parameters are illustrated in Figure 6.
The result of the regression analysis yielded two mathematical equations, one for each factor, as follows;

\[ W(L, t) = \left( \frac{L}{500} \right)^{2.5} \times \left( \frac{20}{t} \right)^{2.7} \times 0.955 \]

Where \( W \), \( L \), and \( t \) are warpage, specimen length, and thickness respectively. Using these equations, the warpage of a specimen of different size and thickness can be predicted.

5. Conclusion and future works

The springback measurement and analysis for thick flat UD laminates have been carried-out. The normalized warpage trend takes the form of power function which conforms with thin laminates one with a difference on its magnitude. The warpage measurements in this work completes the range of number of UD layers for ribs aircraft structure application. A follow-up from this finding is the development of predictive numerical models in order to postulate mechanisms that govern the spring-back behavior. Ultimately, this numerical model will be utilized in the design of mold tools in order to compensate for the effect of spring-back and reduce manufacturing cost.

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