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Spring-back of thick curved uni-directional carbon fibre reinforced composite laminate for aircraft structure application

M Zakaria, M S I Shaik Dawood, Y Aminanda, S A Rashidi, M A Mat Sah

Abstract--- ***Spring-back phenomena of a CFRP part takes place after it has gone through a high temperature cure cycle inside an autoclave. These phenomena have caused quality concerns for aerospace part manufacturers due to the part being out-of-tolerance for surface profile. This paper presents the results of the measurement and analysis of thick curved laminates, which are representative of the actual aircraft parts such as the main ribs of an outboard flap. It is a continuation from the previous work with results for flat uni-directional laminates. Curved laminates with sizes of 300mm, 400mm, and 500mm, corner angles of 30°, 45°, and 90°, and thicknesses of 20, 24, and 28 layers were manufactured. The spring-back effect was measured using a 3D scanner to obtain accurate measurements. Within the range of specimen studied in this work, the spring-back value increases with an increment in size. However, for the remaining two factors (thickness and corner angle), the value decreases.***

Keywords: 3D scanning; aircraft structure; spring-back; thick laminates; uni-directional carbon fibre.

INTRODUCTION

Manufacturing precision in aerospace industry has always posed challenges to aircraft structures manufacturers. The same is true for parts made out of fibre-reinforced polymer. One of the types of tolerance that is critical for aircraft composite parts is surface profile. Parts with surface profile out of tolerance will cause fitting mismatch issue during higher level assembly. Although parts can be press-fit to match mating parts, doing so will inflict residual stresses to the parts even in the absence of design loads. As such, this misfit should always be kept within its limit. The type of defect that causes this tolerance issue is known as spring-back.

Most composite parts used in aerospace application undergo elevated temperature cycle in order to mold them into their design shapes. In this case study, the material in question is a thermosetting epoxy matrix polymer reinforced with uni-directional carbon fiber. This composite material is used to produce the main rib structure of inboard and outboard flaps of Airbus A350 XWB. The material specification requires it to go through a high temperature curing cycle of 180°C and pressurized to 3 bar [1]. It is after this high temperature and pressure cycle that the material will exhibit spring-back effect. It has been made known from previous studies [2] that the spring-back effect is caused by residual stresses build-up within the composite laminates due to thermal expansion mismatch between tools and the laminates.

The design, material and process parameters affecting the spring-back are categorized into intrinsic and extrinsic [3]. This paper presents the parameter study of the effect of spring-back against the intrinsic parameters in the manufacturing of thick curved or angled composite laminates. A previous paper [4] has presented results of the same study but for flat uni-directional specimens. The term thick in this literature denotes laminates of twenty layers and above, in which highly stressed structures such as the ribs of the flaps are made of.

SPECIMEN MANUFACTURING

This study employed a full-factorial design of experiment with several intrinsic parameters namely size or dimension, thickness, and corner angle. The full-factorial design dictates that the total number of specimen to be fabricated to be equal to *m* times *n*, where *m* is the number of level (three in this study, for all factors or parameters) and *n* is the number factor or parameter (three in this case). This gives a total of 27 different configurations of the laminate specimen, as shown in Table 1.

To ensure repeatability, each laminate configuration is fabricated in duplicates of three, giving a total number of specimen for this case to be 81. Higher number of duplicates is favorable for higher repeatability but due to high manufacturing cost of composites, the number thus needed to be kept at minimum.

This material, which is of Airbus specification AIMS05-27-002 [1], undergoes typical manufacturing processes of pre-impregnated composite fabrics, as shown in Fig. 1. The specimens used in this study only underwent up to the curing process (as indicated by the dark-colored text boxes) since the scope of the parameter study covers only up the above extent. The spring-back phenomena could be observed after the specimens were extracted from their mold tools. The quality of the specimens was assured only through visual inspection on their surface appearance. Non-destructive inspection (NDI) was not carried out due to resource constraint but curing compliance was performed

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M Zakaria, Mechanical Department, Faculty of Engineering, International Islamic University Malaysia, CTRM Aero Composites, Melaka, Malaysia

M S I Shaik Dawood, Mechanical Department, Faculty of Engineering, International Islamic University Malaysia (sultan@iium.edu.my)

Y Aminanda, Universiti Teknologi Brunei, UTB, Brunei Darussalam

S A Rashidi, Aerospace Malaysia Innovation Centre, AMIC, Kuala Lumpur, Malaysia

M A Mat Sah, CTRM Test Laboratory, Melaka, Malaysia

through quality report from production parts, which were cured together with these specimens.

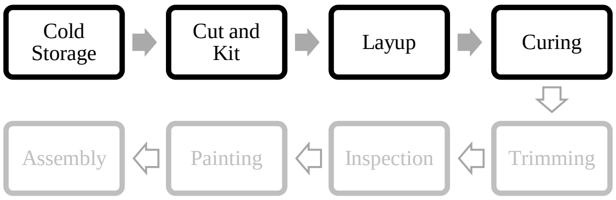

Fig. 1: Typical manufacturing processes of pre-impregnated composites.

The layup sequence of the specimens is important, as it does in actual aircraft parts since different layup will yield different laminate behavior and therefore different spring-back effect. In this study, all plies for all specimens were laid up in one direction along curvatures, as indicated in Fig. 2.

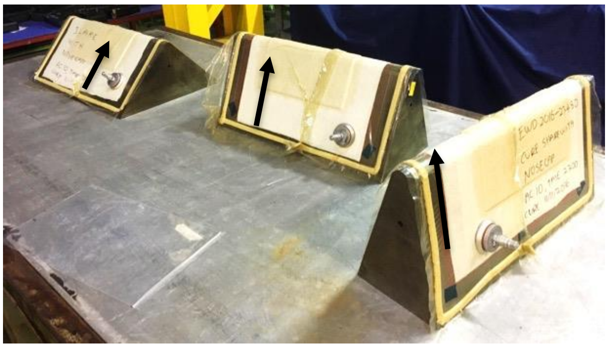

Fig. 2: Curved laminate specimens of 90° (left), 45° (centre), and 30° after cured, awaiting extraction from their mold tools. The arrows indicate direction of fibre.

The curing cycle is of double dwell as per composite manufacturer CTRM standard manufacturing process, with the first dwell at 120°C and the second dwell at 180°C. A double dwell cycle produces more spring-back compared to single dwell cycle [3]. It is important for the specimens to be cured as close as possible to the actual production parts in order to represent the same spring-back behavior. The extracted specimens are shown in Fig. 3.

Fig. 3: Curved specimens after being extracted from their mold tools.

MEASUREMENT OF SPRING-BACK

The spring-back of a curved specimen is defined as the difference between the corner angle of a specimen (under stress-free condition, after being extracted from its tool, post cure at room temperature) and that of its tool (which represents the initial condition of the specimen before being extracted from its tool), as shown Fig. 4.

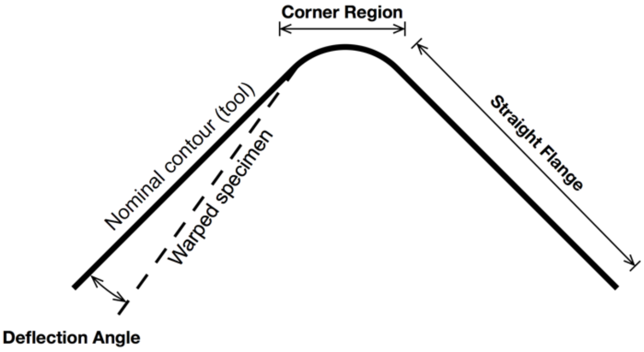

Fig. 4: Definition of spring-back, which is the difference between corner angle of warped specimen and its tool.

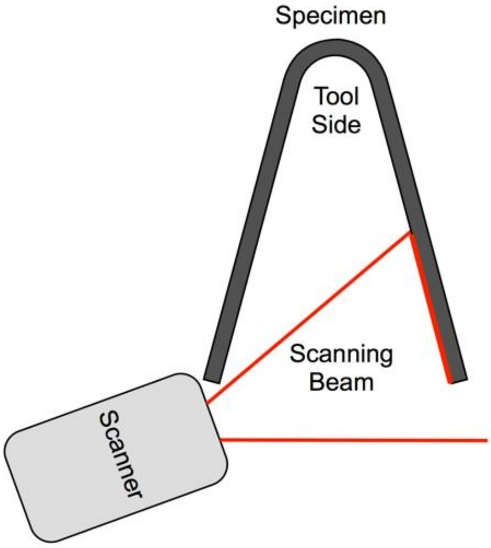

Fig. 5: 3D laser scanning of the specimen.

Another literature defined the spring-back as the deflection (in mm) of the outer end of the flange [5]. This paper will use the deflection angle. The measurement of the above spring-back was accomplished through the use of high precision non-contact three-dimensional laser scanner capable of acquiring 45,000 measurement points per second with a volumetric accuracy of 0.042mm. A laser scanner was used in order to avoid any flexing or bending of the specimen due to contact force from any contact-based measurement device. Since the surface profile tolerance of the actual aircraft part is 0.4mm [6], the industrial best practice for the required measurement accuracy should be about one-tenth of the tolerance value, which is equal to 0.04mm (hence the use of the above laser scanner).

The output from the scanner were many thousands of measurement cloud points which together formed polygonal meshes. The polygonal mesh of the specimen was superimposed onto the polygonal mesh of the respective tool. By extracting the angle deviation between surface features of the tool and the specimen in the CAM software, the amount of spring-back can be measured. The measurement result is tabulated in Table 1.

Table 1. Result of spring-back measurement for the full-factorial experiment with values predicted by regression model.

Dimension (mm)	Number of Layer	Corner Angle (°)	Average Spring-back (°)	Predicted by Regression	% Error
300 × 300	20	30	2.19	2.30	4.6%
		45	1.99	2.09	4.5%
		90	1.37	1.47	6.9%
	24	30	2.21	2.17	1.9%
		45	1.94	1.96	1.3%
		90	1.38	1.34	2.9%
	28	30	2.10	2.04	2.8%
		45	1.87	1.83	1.9%
		90	1.28	1.21	5.5%
400 × 400	20	30	2.54	2.46	3.0%
		45	2.35	2.26	4.1%
		90	1.69	1.64	3.0%
	24	30	2.28	2.34	2.4%
		45	2.13	2.13	0.1%
		90	1.40	1.51	7.2%
	28	30	2.21	2.21	0.3%
		45	2.00	2.00	0.2%
		90	1.50	1.38	8.3%
500 × 500	20	30	2.73	2.63	3.6%
		45	2.51	2.43	3.5%
		90	1.81	1.81	0.4%
	24	30	2.46	2.50	1.9%
		45	2.24	2.30	2.7%
		90	1.69	1.68	0.9%
	28	30	2.33	2.37	1.9%
		45	2.10	2.17	3.0%
		90	1.48	1.55	4.7%

DATA ANALYSIS OF SPRING-BACK

In the dataset presented in this paper, three parameters (size, thickness, and corner angle) are considered as the factors correlated to the spring-back of the curved specimens. The following graphs depict the correlation between each parameter and the spring-back.

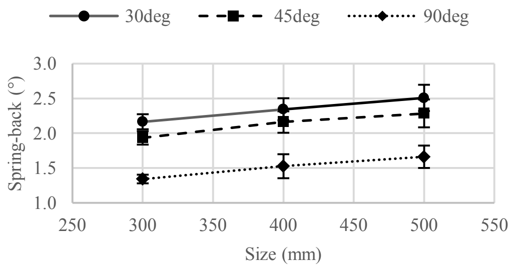

Fig. 6: Plot of the effect of specimen size on the spring-back for different corner angles.

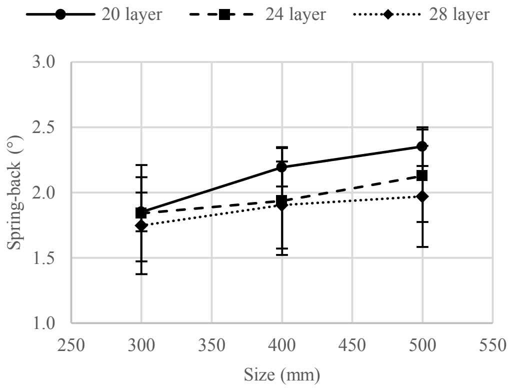

Fig. 7: Plot of the effect of specimen size on the spring-back for different thicknesses.

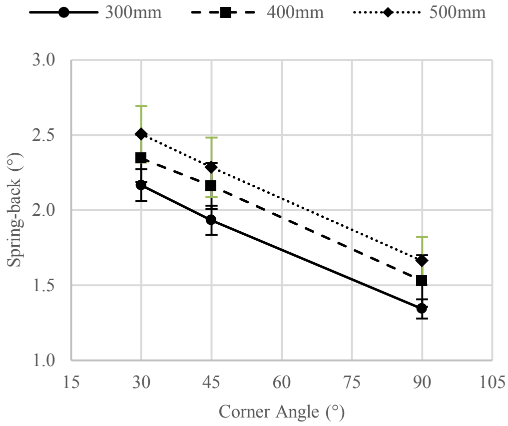

Fig. 8: Plot of the effect of specimen corner angle on the spring-back, for different sizes.

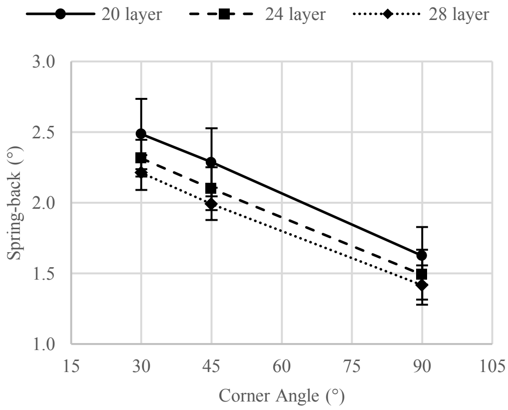

Fig. 9: Plot of the effect of specimen corner angle on the spring-back, for different thicknesses.

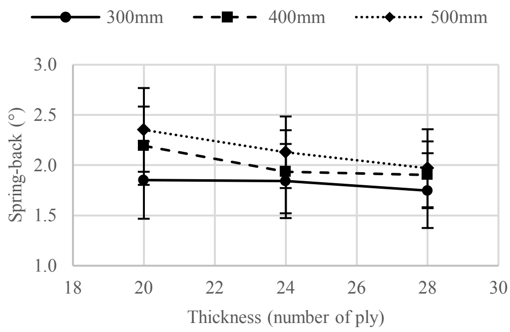

Fig. 10: Plot of the effect of specimen thickness on the spring-back, for different sizes.

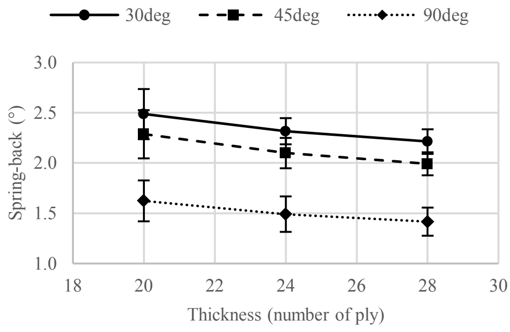

Fig. 11: Plot of the effect of specimen thickness on the spring-back, for different corner angles.

Each data point in all graphs above represents an average value of three measurement data points from the three duplicates of specimen as previously mentioned. The error bars indicate the positive and negative standard deviation for the respective data points. For the size factor, the spring-back value increases with an increment in size. However, for the remaining two factors (thickness and corner angle), the spring-back value decreases with an increment of each factor. A mathematical model that describes the correlation between the spring-back and the three factors was derived from a multiple linear regression analysis.

Table 2. Regression statistics of the spring-back dataset.

Multiple R	0.985442968
R-squared	0.971097843
Adjusted R-squared	0.967327997
Standard error	0.073125821
Observations	27

Table 3. Significance of each parameter or factor to the regression of the spring-back.

	Coefficients	Standard error	t-stat	P-value
Intercept	2.8495189	0.1287157	22.138068	5.22E-17
Size	0.0016847	0.0001723	9.7748054	1.17E-09
Thickness	-0.0323111	0.0043089	-7.4985515	1.27E-07
Corner Angle	-0.0137556	0.0005519	-24.920137	3.81E-18

From the output of the regression analysis as shown in Table 2, the value of the R-squared of 0.97 signifies a good fit. The t-statistics, as listed in Table 3, also indicate significant correlation of each factor to the spring-back value. In terms of distribution of errors, the residual plots as in Fig. 12, Fig. 13, and Fig. 14 show no obvious pattern, suggesting fairly random and unbiased distribution of errors.

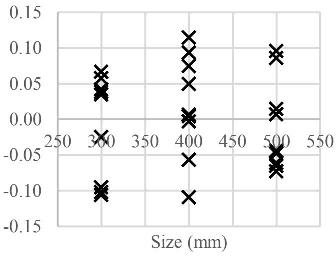

Fig. 12: Plot of distribution of residuals against specimen size.

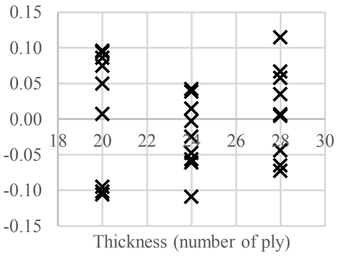

Fig. 13: Plot of distribution of residuals against specimen thickness.

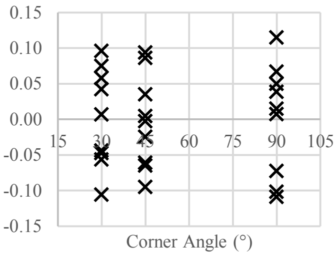

Fig. 14: Plot of distribution of residuals against specimen corner angle.

From the regression analysis, the mathematical model yielded is as follows:

$$S(L,t,\theta) = 2.85 + 0.00168 \cdot L - 0.0323 \cdot t - 0.01380 \cdot \theta \quad (1)$$

where S is the spring-back (in °), L is size (in mm), t is thickness (number of ply, dimensionless), and θ is corner angle (in °). Using this equation, any combination of values of the parameters can be substituted to obtain a predicted value of the spring-back, within an average error of 3%, with a maximum error of 8%. The comparison between the actual measurement and the predictive model is shown in Table 1.

CONCLUSION AND FUTURE WORKS

All three parameters which are size, thickness, and corner angle are found to have significant correlation with the amount of spring-back of thick curved laminates. The statistical model used is of linear regression with the parameters being in linear form. This model has been able to predict the amount of spring-back with satisfactory accuracy, at least within the experimental ranges. A follow-up from this finding is the development of predictive numerical models 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 arising from multiple iterations of mold tool fabrication and modification.

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