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EFFECT OF THE CORNER ANGLE ON SPRING-BACK DEFORMATION FOR UNIDIRECTIONAL L-SHAPED LAMINATE COMPOSITES MANUFACTURED THROUGH AUTOCLAVE PROCESSING

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ABSTRACT

The residual stresses that develop within fibre-reinforced laminate composites during autoclave processing lead to dimensional warpage known as spring-back deformation. A number of experiments have been conducted on flat laminate composites with unidirectional fibre orientation to examine the effects of both the intrinsic and extrinsic parameters on the warpage. This paper extends the study on to the corner angle effect on spring-back for L-shaped laminate composites. Tools with corner angles of 30°, 45° and 90° were fabricated and its influence on the magnitude and final deformation shape of unidirectional L-shaped laminates were observed. Essentially, the experimental results proved that the corner angle parameter has a significant impact on spring-back deformation.

Keywords: spring-back, CFRP, autoclave processing, intrinsic parameters.

INTRODUCTION

The usage of composites in the aerospace industry has increased significantly in the past 30 years where leading manufacturers e.g. Airbus have been integrating composite-made structures into their latest airliners. The most recent has been with the A350 which saw more than 50% application of composite materials due to its higher specific stiffness compared to metals.

As with any other material, composites induce residual stress as a result of the manufacturing process which in this case involves curing at high temperatures inside an autoclave. The residual stresses will pre-stress the composite and decrease its overall strength. An observed consequence of this is a deviation of the final product from what was initially designed. This phenomenon is known as spring-back deformation. This issue will cause problems during the assembly stage because of poor fit-up between the mating structures which will compel the technicians to force fit the parts. Such practice will increase the internal stress levels of the structure and reduce its span life.

There are many factors to spring-back deformation. One is the change in mechanical properties of the laminate during the curing process. While fibre properties remain essentially constant, the matrix resin properties evolve as the resin polymerizes. The correlation between the development of residual stresses and the resulting warpage is more pronounced during the cool-down stage as observed in an experiment [1] when the thermal stresses that had been accumulated during the ramp and hold stages, were relieved. Another source of spring-back warpage is the difference of fibre orientation between individual plies i.e. anisotropic lay-ups which results in in-plane stresses within the laminate. The severity of the warpage is more for an asymmetrical and unbalanced lay-up as discovered in another study [2] due to the multiple constraints that had been imposed as a result.

Nonetheless, tool-part interaction is seen as the most critical mechanism [3]-[6]. As illustrated in

Figure-1, interfacial shear stresses will develop from the difference in stretching between both components during heat-up, generating a stress gradient through the part thickness that finally yields the spring-back warpage.

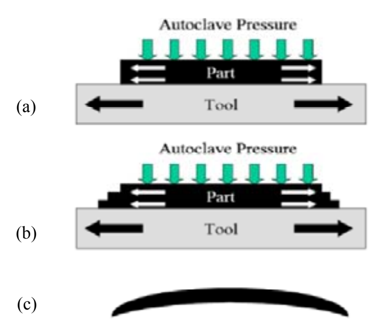

Figure-1. Part warpage due to tool-part interaction [6].

However, these are simply natural behaviours of laminates and are difficult to control. A study [7] categorized the controllable parameters of spring-back deformation into intrinsic and extrinsic parameters whereby intrinsic relates to part geometry and material properties whereas extrinsic parameters are facets of the

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manufacturing process. The current study investigates the corner angle effect which is an intrinsic parameter.

For the corner angle effect, a study [8] manufactured laminates with the dimensions 100x50 mm^2 and 8 plies thickness on aluminium male tools of varying angles (45^o, 75^o, 90^o 135^o and 165^o) as shown in

Figure-2a. The results from the study showed that the spring-in warpage increases as the tool corner angle decreases (see

Figure-2b). Generally, parts produced on male tools have thin corners [9] which means there is considerable inconsistency in the fibre and matrix distribution through the corner thickness. Another study [5] postulated that when the plies are imperfectly laid up due to curvature of the tool, there will be slippage between the individual plies which initiates tensile stresses in the tows close to the inner radius if the plies do not fully slip (see

Figure-2c). This is supported by a separate study [10] where the stresses in the plies closer to the inner radius act over a smaller area due to its shorter circumferential length which results in a force imbalance and yields bending.

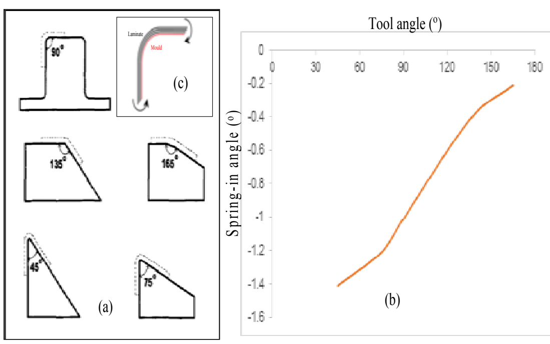

Figure-2. (a) (b) Spring-in warpage in function of the tool angle [8] and (c) fibre stresses due to corner consolidation (inset) [10].

EXPERIMENTAL

Materials and parameter

Similar to the previous study [8], the current study will employ tools with various corner angles, θ_n, (30^o, 45^o and 90^o) as in

Figure-3 made from S275JR carbon steel to manufacture unidirectional laminate composites made from IMA/M21E and observe the corner effect on spring-back deformation. Both components are fabricated by CTRM, the leading supplier of aerospace composite structures in Malaysia, based on the industry standards. The part samples were cut to dimensions of 500x500 mm^2 and laid up to a thickness of 4 plies on tools of 30^o, 45^o and 90^o. For repeatability, 3 samples from each tool angle were manufactured.

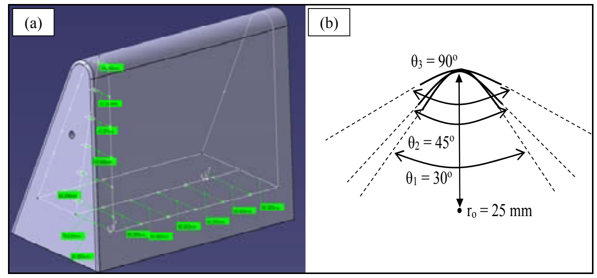

Figure-3. (a) S275JR carbon steel tool geometry and (b) the various corner angles.

Manufacturing process and measurement procedure

Firstly, polytetrafluoroethylene (PTFE) was placed on the surface of the tool to serve as release agent that allows easy separation of the laminate composite part from the tool after processing. Next, the prepreg was laid up on the tool according to the designed stacking and the release film was placed on top of the prepreg and consolidated for 5 minutes. Afterwards, the breather cloth was placed on top of the release film for final bagging. Once the vacuum test was performed during the final bagging stage, the system in

Figure-4 was placed inside the autoclave and cured to the respective pressure and temperature profile.

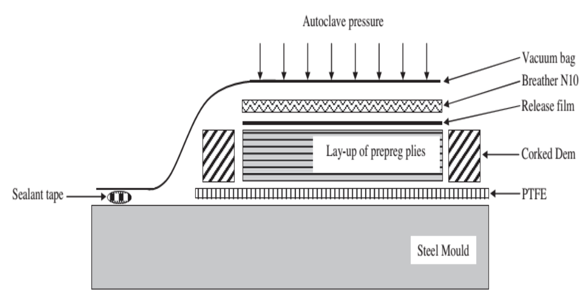

Figure-4. Final bagging system for autoclave curing.

To measure the resulting warpage, a non-contact measuring method using a 3D scanner was implemented. Fundamentally, the warped sample is positioned on a level surface that serves as reference and the scanner is swept through it. For L-shaped samples, the spring-back warpage, w_{max}, is defined as the displacement from the initial external flange profile to the reference line drawn between the 2 extremities of the deformed flange (see

Figure-5).

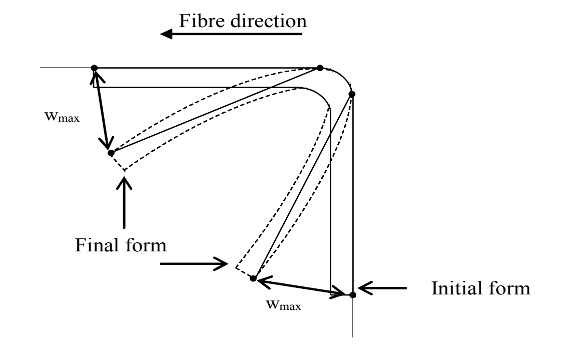

Figure-5. The part warpage generated from the angled tool.

Using the 3D scanner, the sample model was generated by dispersing 11 measurement points and the warpage is the distance from the initial point on the periphery to the displaced point (see **Figure-6**). For this project, the warping profile is along the y-axis i.e. points 6 to 11 (see **Figure-7**).

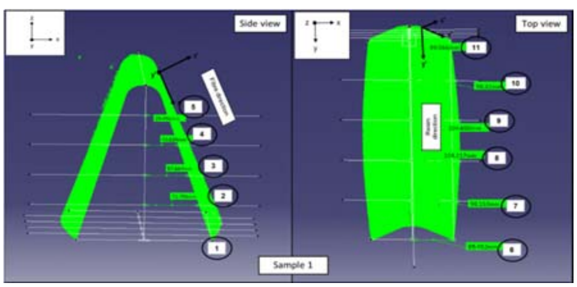

Figure-6. Displacements of the measuring points on a part sample from a 45° tool.

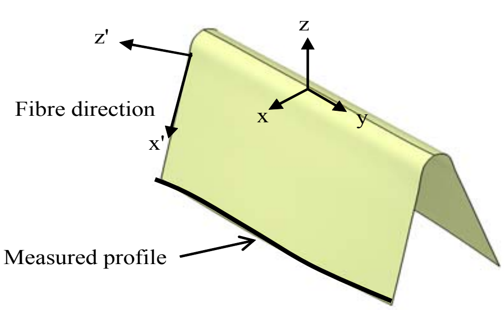

Figure-7. Warpage profile of the part sample.

RESULTS AND DISCUSSIONS

A plot of the warpage profiles for all tool angles is provided in **Figure-8**. The author has also included the warpage for the 180° tool angle i.e. flat tool from the previous accompanying study [11]. The mean warpage of all the measurement points along the measured profile for all 4 tool corner angles are calculated and tabulated in Table-1.

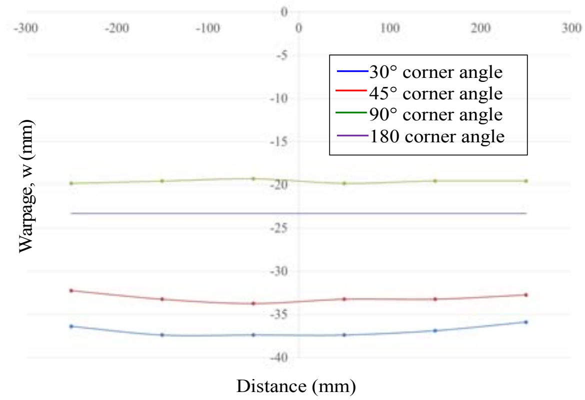

Figure-8. Warpage profile along the y-axis for 500x500 mm^2 with 4 plies thickness.

Table-1. Mean warpage of the part samples.

Tool corner angle	Mean warpage
30°	-36.88 mm
45°	-33.07 mm
90°	-19.6 mm
180°	-23.3 mm

From the plotted distributed warpage data in **Figure-8** and the normalized warpage results in **Figure-9**, acute angles (< 90°) were observed to yield higher warpages. From both figures, the warpage from 90° and flat (180°) tools are in close proximity to one another which indicates that tools with corner angles 90° < θ_n < 180° would have minimal impact on the evolution of part warpage. The difference in warpage between both respective tool corner angles is ~4 mm and considering the possibility of an error during the warpage measurement, the claim that there would be no significant contribution to the warpage is true.

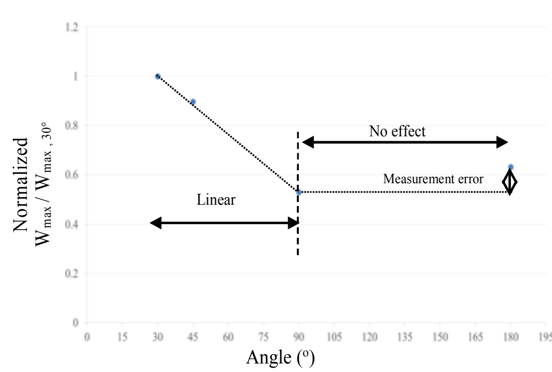

Figure-9. Evolution of the normalized mean warpage in function of the tool angle.

CONCLUSIONS

The objective of this study was to investigate the effect of the corner angle on the warpage of unidirectional IMA/M21E laminates. The main conclusions drawn are:

- From 30º to 90º, the spring-back warpage is inversely proportional to the tool corner angle.
- The impact of the tool corner angle is significant from 30º to 90º only. Beyond that and approaching 180º, the warpage plateaus.

This study has increased the understanding on the part design parameters affecting spring-back warpage of laminate composites and demonstrates the importance of how warpages are defined and measured on L-shaped samples. However, the conclusions drawn should be used with caution outside the scope of this study. There is also a need to investigate the effects of extrinsic i.e. process parameters e.g. cure cycle, tool material, tool surface conditions etc. as this is more practical in the aerospace manufacturing industry.

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