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Spring-back simulation of unidirectional carbon/epoxy L-shaped laminate composites manufactured through autoclave processing

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Abstract. This paper presents an original method in predicting the spring-back for composite aircraft structures using non-linear Finite Element Analysis (FEA) and is an extension of the previous accompanying study on flat geometry samples. Firstly, unidirectional prepreg lay-up samples are fabricated on moulds with different corner angles (30°, 45° and 90°) and the effect on spring-back deformation are observed. Then, the FEA model that was developed in the previous study on flat samples is utilized. The model maintains the physical mechanisms of spring-back such as ply stretching and tool-part interface properties with the additional mechanism in the corner effect and geometrical changes in the tool, part and the tool-part interface components. The comparative study between the experimental data and FEA results show that the FEA model predicts adequately the spring-back deformation within the range of corner angle tested.

1. Introduction

In the last 30 years, composites have seen a significant rise in its implementation within the aerospace industry. Leading manufacturers such as Airbus have been integrating composite-made structures into their latest airliners, most recently with the A350 which saw more than 50% application of composite materials due to its higher specific stiffness compared to metals. Like 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 reduce its overall strength. An evident consequence of this is the deviation of the final product from what was initially designed. This phenomenon is referred to as spring-back deformation. This issue results in problems during the assembly stage because of poor fit-up between the mating structures which will

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compel the technicians to force fit the parts. Such practice increases the internal stress level of the structure and degrades 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.

Nevertheless, tool-part interaction is widely regarded as the key mechanism to initiate spring-back deformation [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.

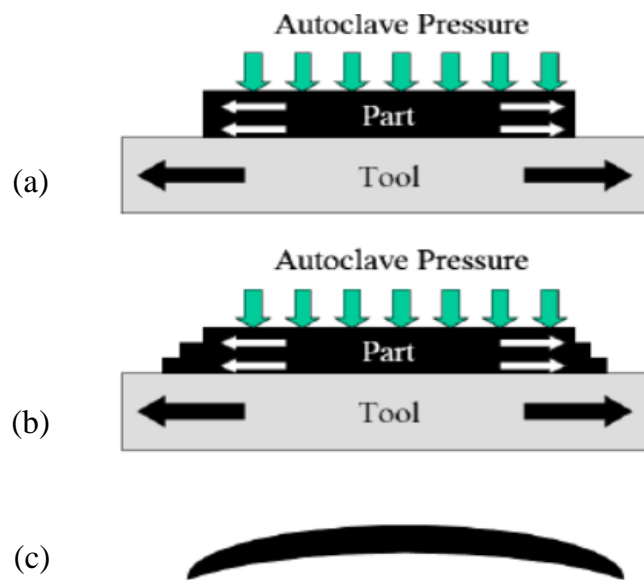


Figure 1. Part warpage due to tool-part interaction [6].

However, these are simply natural behaviours of laminates and are therefore 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 aspects of its manufacturing process. The current study investigates the corner angle effect which is an intrinsic parameter. A previous study [8] investigated the tool corner effect on laminates with dimensions $100 \times 50 \text{ mm}^2$ and 8 plies thickness manufactured on tools of various corner angles (45° , 75° , 90° , 135° and 165°) 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 angled tools have varied corner thicknesses in relation to its other areas [9] which means that 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 hypothesis is supported by a separate study [10] which states that 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.

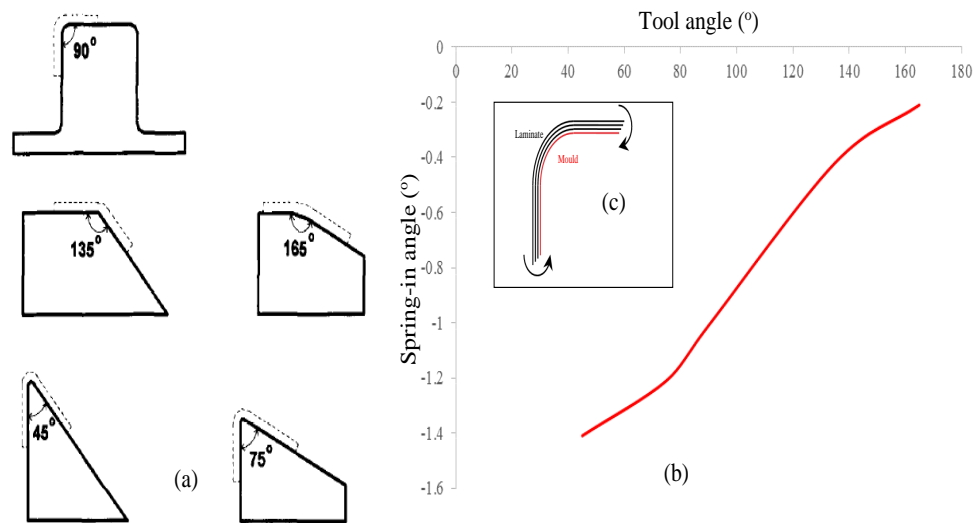


Figure 2. (a) (b) Spring-in warpage in function of the tool angle [8] and (c) fibre stresses due to corner consolidation (inset) [5].

To emphasize on the criticality of the corner effect, a study [11] managed to control the spring-back warpage by manipulating the corner radius of the part whereas for flat unidirectional samples, the proposed method is to redesign the tool [12]. For the current study, the goal is to develop a robust method that can accurately predict the spring-back warpage on unidirectional L-shaped laminate samples via Finite Element Analysis (FEA). A previous accompanying study managed to predict the spring-back warpage using FEA model on unidirectional flat laminates [12]. In that study, the 2 parameters that were crucial in yielding accurate results were the in-plane stress generated collectively by the first ply stretching and fibre volume fraction gradient [13] and the out-of-plane shear stress via the tool-part interaction [7][14]-[15]. The in-plane stresses are due to the resin polymerization that occurs during the cure cycle so therefore, the composite law behaviour of the FEA model was modelled in function of the degree of cure of the laminate. The law behaviour was obtained by integrating the elastic-linear law behaviour with respect to the 3 different resin polymerization stages i.e. viscous, rubbery and glassy [16]. Meanwhile, the tool-part interaction behaviour was modelled with a layer of solid elements associated with an isotropic elastic property [17]. For the L-shaped laminates, the author will develop the model used for the flat samples [12] and integrate the corner effect into it. Details are described in section 3.

2. Materials and parameter

The laminate composite material used in the current study is unidirectional carbon fibre IMA/M21E prepreg and the tool is made from S275JR carbon steel. Both materials are aerospace graded and manufactured as per the guidelines set by Airbus and CTRM Aero Composites Sdn. Bhd. The properties of the materials used are not disclosed in this paper due to it being proprietary information. The laminate samples were cut to a size 500x500 mm² and laid up to a thickness of 4 plies on tools with corner angles of 30°, 45° and 90° (see figure 3). To ensure that the resulting warpage is established with a high degree of confidence, 3 samples from each tool angle were manufactured, totalling 9 overall. The specimen configurations are shown in table 1.

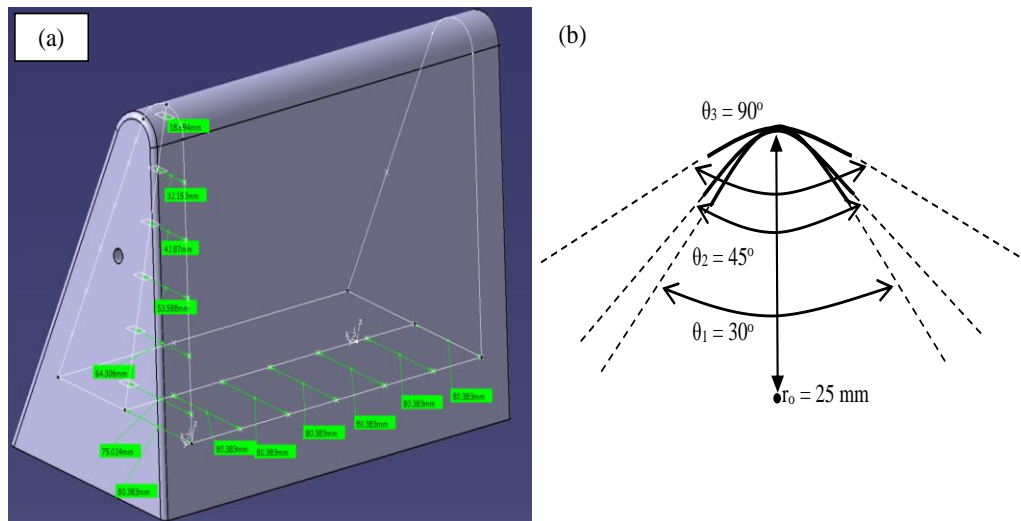


Figure 3. (a) S275JR carbon steel tool geometry and (b) the various corner angles.

After curing, the warpage was measured using a non-contact method i.e. 3D scanner. Essentially, the deformed sample is positioned on a level plane with the scanner being swept through. 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 final flange profile (see figure 4a) and along the y-axis (see figure 4b).

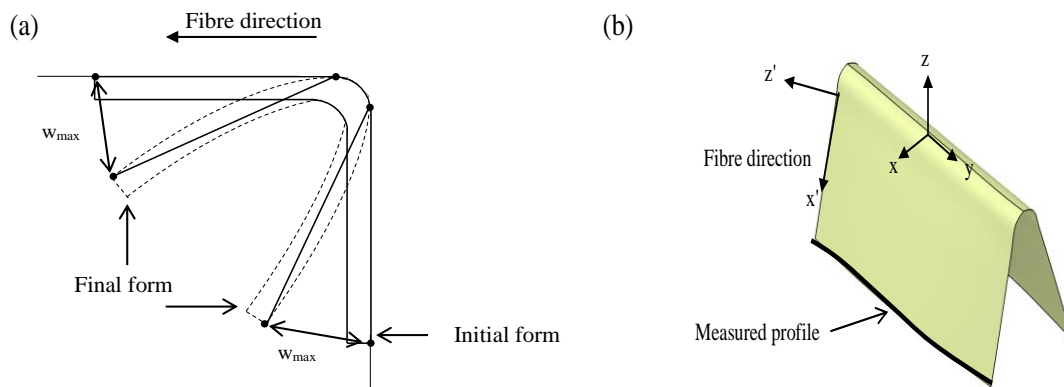
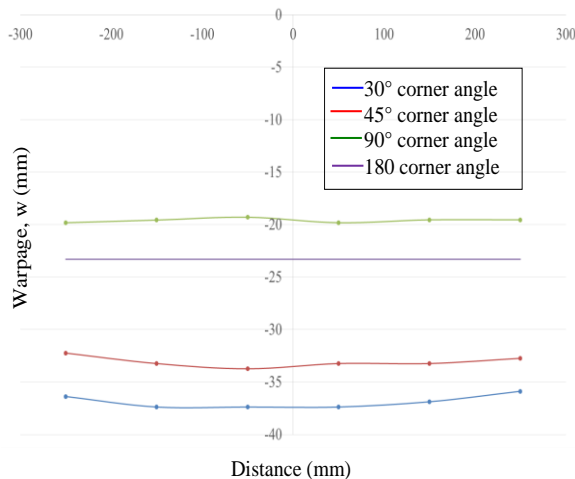
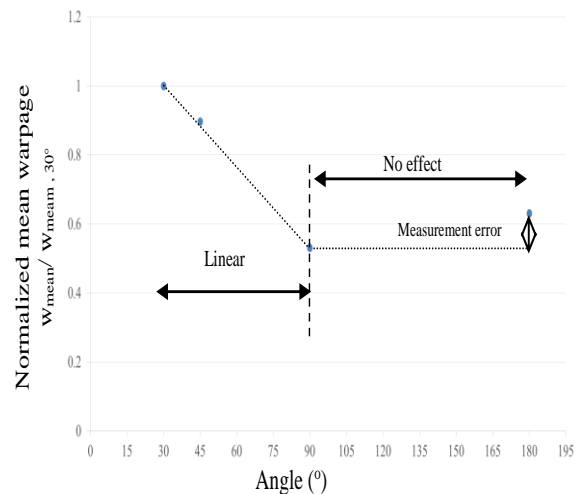


Figure 4. (a) Laminate part warpage generated from an angled tool and (b) the measured profile of the laminate part.

A plot of the measured warpage profile for all the tool angles is provided in figure 5. The author has also included the warpage obtained for an 180° tool angle i.e. flat tool from the previous accompanying study on unidirectional flat samples [12]. The mean warpage of all the measurement points along the y-axis profile for all 4 tool angles are calculated and tabulated in table 1.

Table 1. Mean warpage of the laminate part samples.

Tool corner angle	Sample size and thickness: 500x500 mm ² and 4 plies
30°	-36.9 mm
45°	-33.1 mm
90°	-19.6 mm
180°	-23.3 mm

**Figure 5.** Warpage profile along the y-axis for 500x500 mm² with 4 plies thickness.**Figure 6.** Evolution of the normalized mean warpage in function of the tool angle.

From the plotted distributed warpage data in figure 5 and the normalized warpage results in figure 6, acute angles ($< 90^\circ$) were observed to yield higher warpings. From 30° to 90° , there is a considerable change in warpage even though the samples have the same dimensions ($500 \times 500 \text{ mm}^2$ and 4 plies). This highlights the additional bending initiating from the corner depending on its acuteness. However, beyond 90° and approaching 180° i.e. flat, the warpings are observed to be in close proximity to one another which indicates that the influence of the corner angle will decrease as the geometry starts to level. This is a logical trend given the tool geometry for all 3 angles (see figure 3b) where a lower angle would generate a higher in-plane stress around the corner bend due to its sharpness thus, giving more bending when the part stretches and contracts during autoclave processing. The difference in warpage between both 90° to 180° is $\sim 4 \text{ mm}$ 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.

3. Finite element modelling

Considering that the current study is an extension of the previous study done on unidirectional flat samples [12], the methodology that formed the basis for the development of the FEA model then is maintained with only a few slight changes given the difference in geometry of the laminate samples. The additional bending initiating from the corner will be modelled as another parameter on the first ply i.e. coefficient thermal expansion of the corner, $\alpha_{11, \text{corner}}$. Details on the development of the FEA model are given below.

3.1. Hypothesis and model characteristics

The FEA model is based on a number of simplifying assumptions. Existing manufacturing factors e.g. ply stretching, fibre volume fraction gradient and resin shrinkage occur during either the ramp-up or

dwelling period of the cure temperature cycle while the shear interaction between the tool and laminate part i.e. tool-part interaction is significant during the cool-down phase. Coupled with the goal of developing a simple and time efficient model, only the cool-down phase out of the entire curing cycle was simulated. Therefore, the laminate part is assumed to be fully cured by assigning linear-elastic behaviour in Abaqus. Besides the curing cycle, the autoclave pressure has a negligible influence on the laminate part properties during the cool-down step and is not included in the simulation. Thus, only thermal loading is applied in the simulation (initially from 180°C to 25°C at the end of the loading).

Similar to the one for flat samples [12], the FEA model comprises of the tool, interface and laminate part components modelled with solid elements (see table 2 and figure 7). Also, seeing that the spring-back warpage is symmetrical due to the orthotropic behaviour of laminate composites, the FEA model is reduced to a quarter of its actual size with symmetrical boundary conditions being assigned. Both the tool and laminate part components were assigned isotropic and orthotropic thermal-mechanical elastic laws, respectively while the interface properties were input in the form of a user-defined subroutine (VUMAT) written by FORTRAN.

Table 2. Material property input for the FEA model components.

FEA model component	Material properties
Tool	As per for S275JR carbon steel
Interface	As per for polytetrafluoroethylene (PTFE)
Laminate part	First ply: Coefficient of thermal expansion in the longitudinal direction modified by the author to simulate the ply stretching effect Rest of the laminate: As per for carbon fibre IMA/M21E prepreg

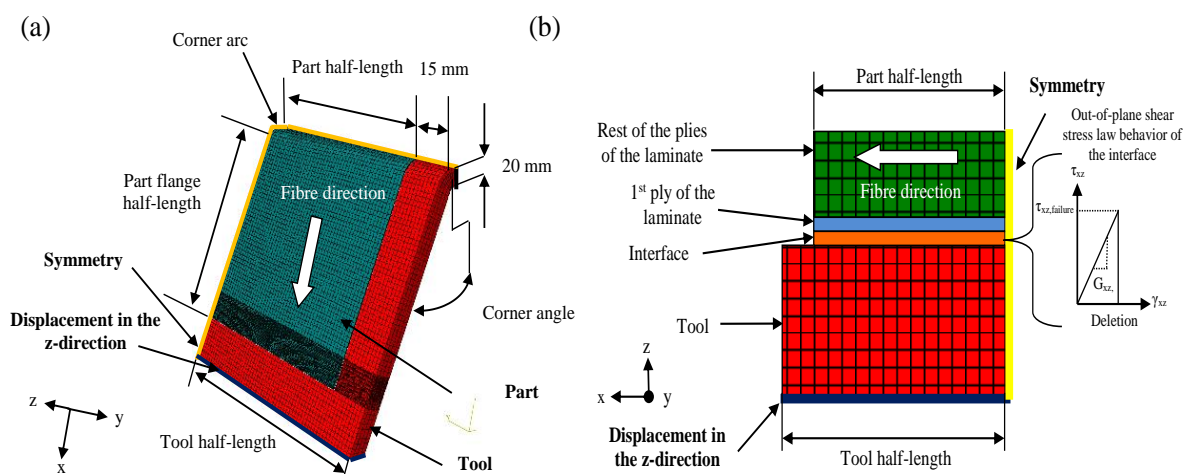


Figure 7. FEA model, 500x500 mm² (a) 3D view and (b) cross-sectional view and the out-of-plane shear stress law behaviour of the interface.

3.2. Laminate part properties

As mentioned earlier, ply stretching, fibre volume fraction gradient and resin shrinkage create an in-plane stress gradient through the laminate part thickness during the curing cycle [13][18][19]. Upon removal from the tool, the resultant bending moment warps the laminate. Integrating all 3 phenomena would complicate the FEA simulation and the required material data would be difficult to obtain. The resin shrinkage was seen to have a minimal effect on the warpage [1]. Moreover, laminates made from carbon fibres and an M21 epoxy resin that has been added with a thermoplastic resin are seen to not exhibit any fibre volume fraction gradient effects [20]. Therefore for this study, the in-plane stress gradient was initiated through the ply stretching only. As the cool-down phase was only modelled, the

in-plane stress created by the stretching of the laminate plies during the heat-up phase of the curing cycle was initiated by assigning certain longitudinal coefficients of thermal expansion (CTEs), α_{11} , to the laminate part. In detail, a different longitudinal coefficient of thermal expansion was assigned to only the first ply that is adjacent to the tool (see figure 7b) compared to the rest of the laminate. It is assumed that only the closest ply to the tool bears most of the stress transfer from the tool [13]. Furthermore, the current study only concerns unidirectional laminates for which the spring-back warpage occurs only in the longitudinal direction, which is why only the CTE in that respective direction is modified. The properties of the rest of the laminate is maintained as per the manufacturer specifications.

In the previous accompanying study concerning unidirectional flat laminates [12], the FEA model was mainly based on the assumptions made by another previous study [13] that considered the effects of resin shrinkage, fibre volume fraction gradient and ply stretching. In that study, the authors attributed 80% of the laminate spring-back warpage to the in-plane stress hence why the longitudinal CTE of the first ply was determined first without the interface and tool components. After that only both components were included to integrate the tool-part interaction mechanism that accounted for the remaining 20% of the spring-back warpage. For L-shaped laminates, the analysis is more complex with the addition of another mechanism that which is the corner effect. To accommodate this, the first ply of the laminate was split into the corner section and the flange section (see figure 8). Both sections possess different longitudinal coefficients of thermal expansion due to the imperfection of the ply when laid up on the curved tool, which will result in both areas having different resin content leading to tensile stresses from ply slippage that contributes to the increase of spring-back warpage [16]. The CTE for the flange section, $\alpha_{11,flange}$, is maintained from the flat sample study as for the laminate part configuration 500x500 mm² and 4 plies with only the CTE for the corner section, $\alpha_{11,corner}$, being varied.

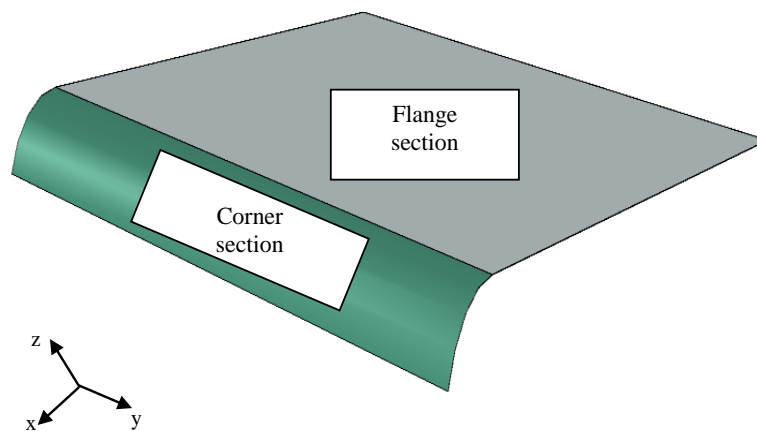


Figure 8. The corner section (green) and flange section (grey) of the first ply for a unidirectional L-shaped (30°) 500x500 mm² with a thickness of 4 plies.

3.3. Out-of-plane shear interface properties

The interface component in the FEA model represents the tool-part interaction that is initiated at the start of the cool-down phase. The current study employs the same interfacial behavior as the accompanying study for flat samples [12] whereby a single layer of elements is assigned with orthotropic linear coupled with an out-of-plane shear stress failure criterion, $\tau_{xz, failure}$, which will delete upon reaching the limit value. This interface characteristic was developed by an earlier study [21]. The interface in-plane properties are those of the polytetrafluorethylene (PTFE) film that acts as the release agent during the actual manufacturing of the samples although the transverse modulus value is the same as the S275JR tool to avoid the laminate part component from penetrating through the tool component [22]. The amount of stress that is transferable from the interface to the laminate part can be tailored based on the

assigned values for the out-of-plane shear modulus, G_{xz} , and the out-of-plane shear stress failure, $\tau_{xz, failure}$. With this, the laminate part warpage can be controlled. In the flat sample study [12], the FEA model was able to obtain accurate results when compared with experimental data using the combination of 56 MPa and 3.8 MPa for the out-of-plane shear modulus and the out-of-plane shear stress failure, respectively. The current study for L-shaped samples will employ the same interface properties.

3.4. Results and discussion

Table 3 shows the comparison between the obtained FEA results and experimental data of the IMA/M21E unidirectional L-shaped laminate parts manufactured on tools of various angles. As mentioned previously, the CTE for the flange section, $\alpha_{11, flange}$, is fixed and obtained from the corresponding flat sample study [12] of the configuration 500x500 mm² and 4 plies ($1.86 \times 10^{-5} \text{ }^\circ\text{C}^{-1}$) with only the CTE for the corner section, $\alpha_{11, corner}$, being varied until accuracy is achieved. The interface properties are fixed as per detailed in section 0.

Table 3. Comparison between the FEA simulation results and the experimental data.

Tool corner angle	Longitudinal coefficient of thermal expansion		Spring-back warpage		Error deviation
	Flange	Corner	FEA	Experimental	
30°		$1.97 \times 10^{-4} \text{ }^\circ\text{C}^{-1}$	-37.4 mm	-36.9 mm	1.27%
45°	$1.86 \times 10^{-5} \text{ }^\circ\text{C}^{-1}$	$1.67 \times 10^{-4} \text{ }^\circ\text{C}^{-1}$	-32.7 mm	-33.1 mm	1.21%
90°		$4.46 \times 10^{-5} \text{ }^\circ\text{C}^{-1}$	-19.8 mm	-19.6 mm	1.02%

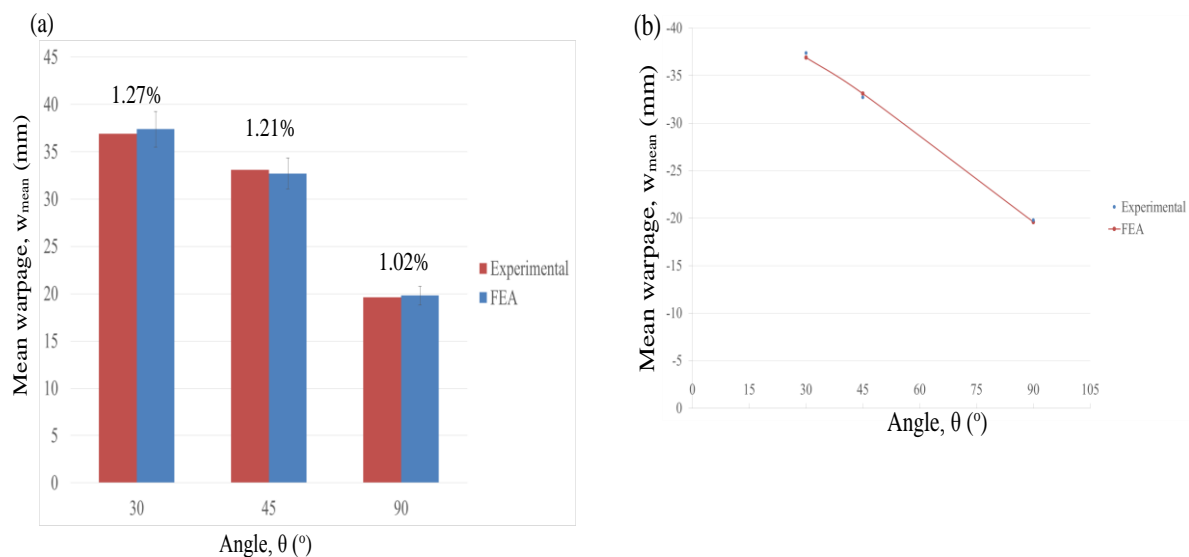


Figure 9. Comparison between the experimental data and the FEA simulation results of the mean warpage in function of the corner angle for the laminate configuration 500x500 mm² and 4 plies thickness in (a) bar and (b) line formats.

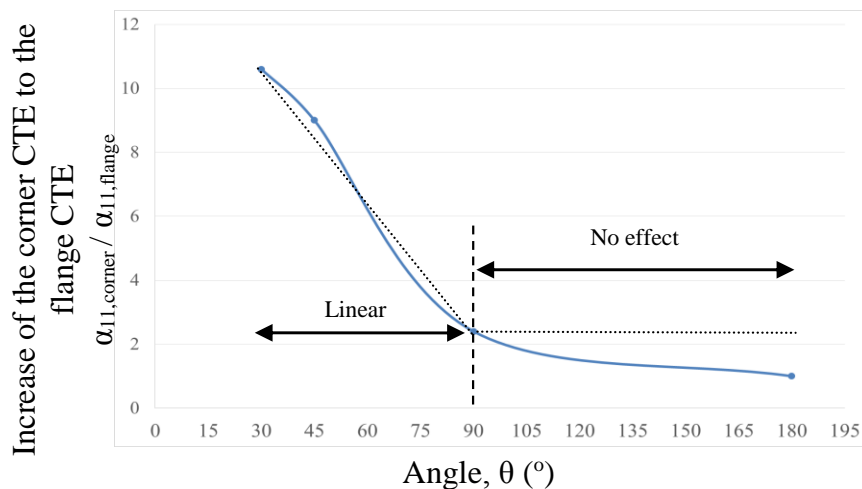


Figure 10. Increase of the longitudinal coefficient of thermal expansion of the corner section to the longitudinal coefficient of thermal expansion of the flange section in function of the corner angle for the laminate configuration 500x500 mm² and 4 plies thickness.

From modifying the CTE for the corner section, $\alpha_{11,corner}$, good agreement between the predicted FEA results and the experimental data based on figure 9a. There is also a linear relationship (from 30° to 90°) in terms of the warpage (see figure 9b). Another finding from the results is the evolution of the longitudinal coefficient of thermal expansion of the corner section $\alpha_{11,corner}$, to the longitudinal coefficient of thermal expansion of the flange section, $\alpha_{11,flange}$ (see figure 10). From both figure 9 and figure 10, it seems that the corner effect is more significant as the corner angle becomes more acute and beyond 90°, the warpage plateaus. This is a similar trend observed with the normalized experimental warpage in figure 6. To validate the FEA model, the author implemented the same model characteristics and methodology to compare against the experimental result of a previous study [23] that used a different laminate (3900-2/T800H) angled at 45° with the dimensions of 280x50 mm² and 8 plies (see table 4). Using the same approach as described in this section, the author was able to obtain a match between the FEA result and experimental data. Maintaining the same part dimensions, the author next tested the material used in the current study (IMA/M21E) and obtained a warpage value close to the one using 3900-2/T800H. Considering that the properties of 3900-2/T800H are similar to the properties of IMA/M21, this FEA validation is regarded as successful.

Table 4. Comparison between the FEA simulation results and the experimental data for the validation study.

Tool corner angle	Part thickness	Part length	Part width	FEA spring-back warpage		Experimental spring-back warpage
				IMA/M21E	3900-2/T800H	3900-2/T800H
45°	8 plies	280 mm	50 mm	-0.45 mm	-0.47 mm	-0.47 mm

4. Conclusions and future work

The objective of this study was to develop a predictive FEA model for the spring-back deformation of unidirectional IMA/M21E L-shaped laminates. The main conclusions are as follow:

- There is significant influence of the corner effect to the overall spring-back warpage for acute corner angles ($\theta_n < 90^\circ$).
- From 30° to 90° , the warpage is linear and inversely proportional to the corner angle.
- There is good agreement between the FEA results and the experimental data.
- The influence of the corner effect reduces as the part starts to take a more level geometry ($90^\circ < \theta_n < 180^\circ$).
- The developed process to predict the FEA warpage is workable with a previous study.

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 intrinsic effects in addition to the corner angle i.e. part size and part thickness as the findings from these investigations will give a more definitive assessment on the warpage affecting L-shaped laminates.

5. Acknowledgements

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