Spring-back simulation of flat symmetrical laminates with angled plies manufactured through autoclave processing

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Abstract. This paper presents a non-linear finite element analysis (FEA) method to predict the spring-back deformation for composite structures manufactured using autoclave processing. It is a progression from previous accompanying study on flat unidirectional samples and the aim is to observe spring-back warpage on laminates consisting of angled (±45°) plies compared to unidirectional (0°) laminate. Three samples for each of the symmetrical laminates with angled plies [45/0]S and [45/-45]S are manufactured and the warpage form is observed. FEA model that was utilized in the previous study, along with the physical mechanisms of spring-back such as the first ply stretching and tool-part interaction mechanisms, are maintained with only changes in material orientation for the part and the tool-part interface components. Upon comparison, the data shows that the spring-back form for symmetrical laminate becomes more complex to predict.

1. Introduction

Composite usage within the aerospace industry has increased significantly over the past 30 years, led by original equipment manufacturers (OEMs) such as Airbus that have been incorporating composite structures into their aircraft designs. The recent A350 project has seen 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 in an autoclave. Those residual stresses pre-stress the composites, resulting in strength degradation. The apparent consequence of this is the deviation of the final product from what is initially designed. This phenomenon is known as spring-back deformation. Other weaknesses of laminate composite structures also include impact strength and hygrothermal loading [1].

Spring-back deformation can be attributed to a multitude of factors. One of them is the change in mechanical properties of the laminate during curing process whereby fibre reinforcement properties essentially remain constant but the matrix/resin properties evolve with respect to the curing process. Another source of the deformation is the difference in fibre orientation between individual plies, which results in non-uniform in-plane stresses through the laminate thickness. The severity of the warpage is more for an asymmetrical and unbalanced layup due to the multiple constraints that has been imposed [2]. Several studies have highlighted the contribution from the autoclave curing cycle. For example, a
study showed that a 2-hold cure cycle yields significantly higher spring-back than a 1-hold cure cycle if there is no release film sheet between the laminate part and tool [3]. This is because in a 2-hold cure cycle, temperature of the autoclave is raised after a period of time that induces more resin shrinkage inside the laminate, hence greater thermal stresses. Other studies have also stated that a 2-hold cure cycle, with a first lower temperature hold and a second temperature hold, is designed such that the resin gels during the first hold. As a result, spring-back is more severe compared to a 1-hold cure cycle [4, 5]. Another study has demonstrated that by optimizing the cure cycle, the quality and strength of the part can be enhanced [6]. Nevertheless, tool-part interaction is seen as the most critical mechanism [7, 8, 9]. The difference in stretching between the tool and laminate during heat-up creates interfacial shear stresses, which generate a stress gradient through the laminate thickness that creates the bending moment [10]. The varied stacking sequence of a laminate results in in-plane stresses within the plies due to the disparity in thermal expansions in both the fibre and resin directions at the ply level [11, 12]. With cross-ply composites [0/90], the 90° fibres will impose a mechanical constraint on the 0° fibres during the processing phase [13]. The geometry after curing for the non-unidirectional laminate varies depending on the stacking layup as shown in Figure 1.

![Figure 1. Part warpage due to asymmetrical layups: (a) original, (b) saddle, (c) and (d) cylindrical, (e) and (f) spherical [2]](image)

The goal of this study is to develop a robust numerical method that can accurately predict spring-back warpage on flat symmetrical laminates via finite element analysis (FEA). Previous accompanying study has managed to predict spring-back warpage by utilizing the same FEA model for unidirectional flat laminates [14]. In that study, the two critical parameters in providing accurate results were the in-plane stress generated collectively by the first ply stretching and fibre volume fraction gradient, and the out-of-plane shear stress via tool-part interaction. In real life manufacturing, the in-plane stresses are due to resin polymerization that occurs during cure, so the composite law behaviour of the FEA model is modelled as a function of the degree of cure of the laminate. The law behaviour is obtained by integrating the elastic-linear law behaviour with respect to the three different resin polymerization stages: viscous, rubbery and glassy. Meanwhile, the tool-part interaction behaviour is modelled with a layer of solid elements associated with isotropic elastic property. For the current symmetrical laminate study, the mechanisms established for unidirectional are retained with the variables being the layup configuration and the corresponding material modulus.

2. Experimental
The current study employs a tool machined from S275JR carbon steel to manufacture the laminate composites made from IMA/M21E, which were symmetrically configured. Both were fabricated as per industry standards by CTRM, the leading supplier of aerospace composite structures in Malaysia. For proprietary reasons, the material property values of the steel tool and laminate together with its curing...
profile will not be provided in this paper. The laminate has an area of 300 x 300 mm$^2$ with a thickness of four plies and laid up at [45/0]$_S$ and [45/-45]$_S$ configurations. For repeatability, three samples were manufactured for each layup.

The resulting warpage for both [45/0]$_S$ and [45/-45]$_S$ laminates was different compared to that of the unidirectional, i.e. [0]$_S$ laminate from previous study [14], such that the warpage form is maximum in two diagonal corners as opposed to the symmetrical distortion of the unidirectional stacking. This is shown in Figure 2. Additionally, the direction of the warpage followed the fibre orientation, i.e. longitudinal direction, of the first ply. The maximum points were measured from the respective vertices of the warped sample to the reference plane and averaged as in Table 1. If based purely on the yielded spring-back warpage, the best configuration is the unidirectional layup. However, in real life aerospace applications, load path of the structure needs to be accounted for and this may require the use of symmetrical laminates with angled plies, especially $\pm 45^\circ$, to account for the shear stresses [15].

![Figure 2. Spring-back warpage for: (a) [0]$_S$, (b) [45/0] and [45/-45]$_S$](image)

| Laminate layup | Averaged maximum warpage |
|---------------|--------------------------|
| [0]$_4$       | -5.2 [mm]                |
| [45/0]$_S$    | -13.3 [mm]               |
| [45/-45]$_S$  | -6.2 [mm]                |

At the laminate level, having a symmetrical layup uncouples the in-plane (membrane) and out-of-plane (bending) responses should theoretically eliminate the spring-back warpage due to the difference in thermal expansion between longitudinal and transversal directions. This is not the case as evident from Table 1. Nonetheless, the warpage can be minimized if the layup configuration is balanced aside from being symmetrical through two mechanisms. Firstly, the membrane coupling between the in-plane normal and shear behaviours is removed as a result of the membrane stiffness coefficients $A_{16}$ and $A_{26}$ being zero. Secondly, the laminate bending response is simplified when the bending stiffness coefficients $D_{16}$ and $D_{26}$ that couple bending and twisting are non-zero for symmetrical configuration, e.g. [45/0]$_S$. Of course, the application of a bending moment will generate twisting and the twisting moment produces a bending curvature. However, if the angled plies are dispersed in $\pm$ orientation, the $D_{16}$ and $D_{26}$ will be relatively less compared to the other terms in the $D$ bending matrix [16].

Having a balanced configuration still does not eliminate the spring-back warpage, which brings into question the fabricating tool. There exists a great disparity (several orders of magnitude) of the thermal expansion between the tool and the laminate. It is this manufacturing reality that forms the basis of the first ply stretching that creates the in-plane through thickness stress and the out-of-plane shear stresses from the tool-part interaction mechanism. Both mechanisms are detailed in the following section.
3. Finite element analysis

3.1 Hypothesis and model characteristics
As mentioned earlier, this study is a progression from previous study that was done for unidirectional flat samples in [14]. Therefore, the methodology is maintained with only differences in the material orientation to reflect the various fibre orientations in a symmetrical laminate. The FEA model for the unidirectional study was constructed based on several assumptions. Considering that the goal was to develop an efficient but robust model, only the cool-down phase (180°C to 25°C) was simulated based on a study that observed inconsequential effects in terms of spring-back deformation from the strain gage readings during cure and only seeing an exponential rise in the contribution during the cool-down phase [17]. The temperature loading started at 180°C, which was the maximum curing temperature that the samples underwent during the cure cycle and ended at 25°C, the room temperature at which the samples were cooled to when it had achieved full vitrification. In tandem with that, the autoclave pressure was also neglected. Like in the unidirectional study, the FEA model for the symmetrical study comprised of the tool, interface and laminate part modelled using solid elements (refer to Table 2 and Figure 3). Both the tool and laminate components were respectively assigned isotropic and orthotropic thermal-mechanical elastic laws while the interface properties were input via a user-defined subroutine file (VUMAT) compiled using FORTRAN.

Table 2. Material property input for the FEA model components

| FEA Model Component | Material Properties |
|---------------------|---------------------|
| Tool                | As per for S275JR carbon steel |
| Interface           | User defined subroutine (orthotropic linear with failure criterion) |
| Laminate part       | Rest of the laminate: As per for carbon fibre IMA/M21E prepreg and the properties oriented in the ply angle direction |
|                     | First ply: As per for carbon fibre IMA/M21E prepreg except the coefficient of thermal expansion in the longitudinal direction modified to simulate the ply stretching effect and the properties oriented in the ply angle direction |

![Figure 3](image)

3.2 Laminate part (IMA/M21E) 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 cure cycle [3]. Integrating all three phenomena would condense the FEA model and complicate the simulation, not to mention that the
required material data would be difficult to obtain. The resin shrinkage is considered to have a minimal effect on the warpage [7]. Moreover, laminates made out of carbon fibres and M21 epoxy resins were observed to not exhibit any fibre volume fraction gradient effects [8]. Thus the in-plane stress gradient was initiated through the ply stretching component only. As only the cool-down phase was modelled, the in-plane stress created by the stretching of the laminate plies during the heat-up phase of the cure cycle was initiated by assigning a specific longitudinal coefficient of thermal expansion (CTE), $\alpha_{11}$ to the first ply (see Figure 3b) as it is hypothesised that only the closest ply to the tool bears most of the stress transfer from the tool [3].

For both $[45/0]_S$ and $[45/-45]_S$ layups, the longitudinal coefficient of thermal expansion of the first ply that was determined for the unidirectional laminate ($3.06 \times 10^{-6}$ $^\circ$C$^{-1}$) in [14] to accurately capture the spring-back form and magnitude for 300 x 300 mm$^2$ and 4 plies, was maintained with only differences in the material orientation to reflect various fibre orientations in the symmetrical laminate. Table 3 shows the resultant modulus and principal material direction of the laminate samples relative to the unidirectional ($0^\circ$) laminate as calculated using Classical Laminate Analysis (CLA). Examining both Table 1 and Table 3, the $[45/0]_S$ layup possesses a longitudinal modulus, $E_{11}$ of approximately 0.5 times smaller but has a displacement value of approximately 2.6 times larger than the unidirectional laminate. Meanwhile, the $[45/-45]_S$ layup possesses a longitudinal modulus 12.6 times smaller but still yields a maximum displacement greater only by 1 mm to the unidirectional laminate. This situation is most probably due to the quasi-isotropic nature of $[45/-45]_S$ layup compared to $[45/0]_S$ (see Figure 4).

Table 3. Resultant modulus and principal fibre direction of IMA/M21E laminate samples with 300x300 mm$^2$ and 4 plies thickness

| Laminate layup | Longitudinal modulus | Transversal modulus | Principal material direction relative to the unidirectional laminate |
|----------------|----------------------|---------------------|---------------------------------------------------------------------|
| $[0]_4$        | 154000 [MPa]         | 8500 [MPa]          | $0^\circ$                                                            |
| $[45/0]_3$     | 83100 [MPa]          | 10300 [MPa]         | $10^\circ$                                                          |
| $[45/-45]_3$   | 12200 [MPa]          | 12200 [MPa]         | $45^\circ$                                                          |

Figure 4. Evolution of the laminate material modulus

3.3. Out-of-plane shear (interface) properties

The interface component in the FEA model represents the polytetrafluoroethylene (PTFE) release film and has significantly less rigidity compared to other two components above and below it. Therefore, to
ensure that the laminate component does not penetrate the interface and tool, i.e. effective out-of-plane shear stress transfer, the transversal through thickness Young’s modulus of the interface was assigned the same value as the tool while the in-plane modulus was maintained from the release film (PTFE) properties. Therefore, a single layer of elements was assigned with orthotropic linear coupled with an out-of-plane shear stress failure criterion, $\tau_{xz,\text{failure}}$, which was developed from previous unidirectional study [14]. The transferred stress from the interface to the laminate part can be controlled via the out-of-plane shear modulus, $G_{xz}$ and the out-of-plane shear stress failure, $\tau_{xz,\text{failure}}$. The FEA model maintains the same interface properties as before, using the same values of 56 MPa and 3.8 MPa for the out-of-plane shear modulus and out-of-plane shear stress failure, respectively, with the exception of the orientation being parallel to the principal material direction (refer to Table 3).

4. Result and discussion

Table 4 shows the comparison between the FEA results and the experimental data of the [45/-45]$_S$ and [45/0]$_S$ laminates (refer also to Figure 5). The FEA results illustrate the complexity in predicting the geometry and modelling the non-linear analysis that is instrumental in capturing spring-back behaviour using a numerical model. The deviation is correlated to the severity of the warpage. From the results, having a 45° fibre direction at the first ply will generate more warpage compared to a layup having 0° fibre direction at the first ply adjacent to the tool. The significant difference of the maximum warpage magnitude between the two layups is most probably due to the balanced laminate of [45/-45]$_S$, which provides the laminate with more uniform properties compared to the [45/0]$_S$ layup (see Figure 4).

| Laminate layup  | Longitudinal coefficient of thermal expansion | Spring-back warpage | Error deviation |
|-----------------|---------------------------------------------|--------------------|----------------|
| [0]$_S$         |                                             | -5.2 [mm]          | -5.2 [mm]      | 0 [%]          |
| [45/0]$_S$      | $3.06 \times 10^{-6} \text{[°C}^{-1}]$      | -13.3 [mm]         | -7 [mm]        | 47.37 [%]      |
| [45/-45]$_S$    |                                             | -6.2 [mm]          | -5.74 [mm]     | 7.42 [%]       |

Figure 5. Experimental (left) vs FEA (right) for: (a) [45/0]$_S$ and (b) [45/-45]$_S$ layups
5. Conclusions and future work
The objective of this study is to develop an FEA model capable of predicting spring-back warpage for symmetrical laminates, i.e. \([45/0]_S\) and \([45/-45]_S\). Several main conclusions that can be made are listed as follow:

- Having an angled ply as the first ply in contact with the tool will significantly increase the severity of the warpage
- The FEA model has close proximity with the experimental data for the \([45/-45]_S\) layup, which is balanced and quasi-isotropic in behaviour
- For the unbalanced \([45/0]_S\) layup, the disparity between the FEA simulation and experimental measurement is great but the spring-back form is accurate in the simulation. With that, an FEA model refinement study which involves the bending strength properties of the laminate and its first ply specific longitudinal CTE might be performed to close the gap

This study has increased the understanding on the part design parameters affecting spring-back and illustrates the many forms of spring-back deformation. However, the conclusions drawn should be used with caution outside the scope of this study. There is also a need to study the various symmetrical configurations and their corresponding warpage patterns.

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