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Effect of Stacking Layup on Spring-back Deformation of Symmetrical Flat Laminate Composites Manufactured through Autoclave Processing

M N M Nasir[1], M A Seman[2], L Mezeix[3], Y Aminanda[4], A Rivai[5] and K M Ali[6]

[1, 4]Department of Mechanical Engineering, International Islamic University Malaysia, 50728 Kuala Lumpur, Malaysia
[2, 5]Faculty of Mechanical Engineering, Universiti Teknikal Malaysia Melaka, 76100, Durian Tunggal, Malaysia
[3]Faculty of Engineering, Burapha University, 20131, Chonburi, Thailand
[6]Aerospace Malaysia Innovation Centre, 63000 Cyberjaya, Malaysia

E-mail: yulfian@iium.edu.my

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 symmetrical layup effect on spring-back for flat laminate composites. Plies stacked at various symmetrical sequences were fabricated to observe the severity of the resulting warpage. Essentially, the experimental results demonstrated that the symmetrical layups reduce the laminate stiffness in its principal direction compared to the unidirectional laminate thus, raising the spring-back warpage with the exception of the $[45/-45]_S$ layup due to its quasi-isotropic property.

1. 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

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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 layups which results in in-plane stresses within the laminate. The severity of the warpage is more for an asymmetrical and unbalanced layup 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.

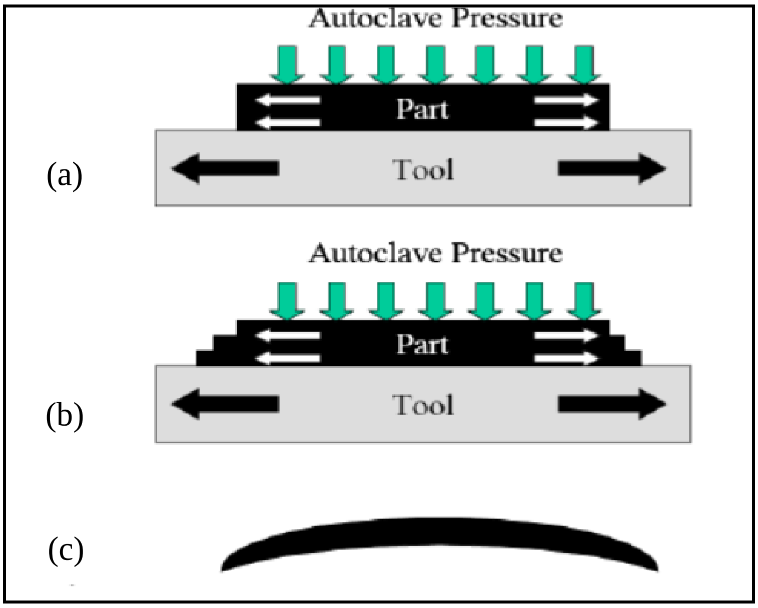

Figure 1. Part warpage due to tool-part interaction [6].

However, these are simply natural behaviors 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 manufacturing process. The current study investigates the effect of having a symmetrical ply layup which is an intrinsic parameter.

The varied stacking sequence of a laminate results in in-plane stresses within the plies due to the difference in the coefficients of thermal expansion in both the fibre and resin directions at the ply level [8]-[10]. With cross-ply composites [0/90] as shown in

figure **2**, the 90^o fibres impose a mechanical constraint on the 0^o fibres during the processing phase as in where σ represents the residual stresses [11].

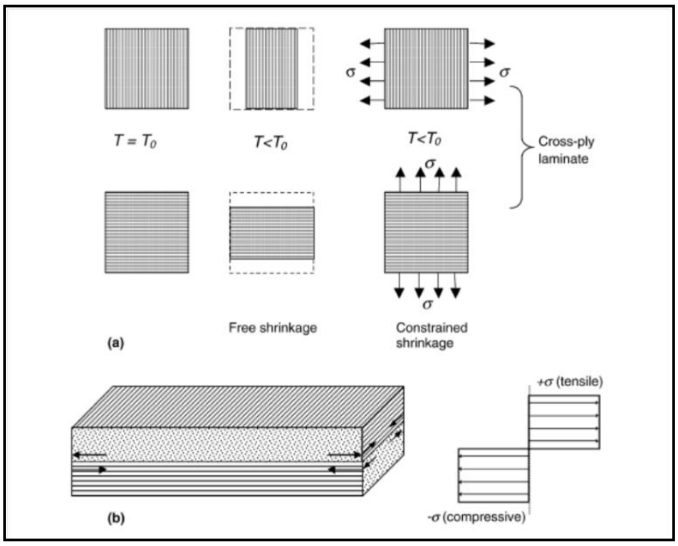

Figure 2. Schematic view of the (a) residual stress formation in an asymmetrical cross-ply laminate and the (b) residual thermal stresses when the laminate is constrained [11].

For the [0/90] layup, various stable geometries exist after curing as shown in figure 3 [2]. While laminates with a small in-plane to thickness ratio lead to saddle shapes i.e. (a) and (b), laminates with larger in-plane dimensions show cylindrical shapes i.e. (c) and (d). For angled laminates, angled cylindrical shapes are formed i.e. (e) and (f). These effects reduce with increasing laminate thickness and can be avoided using symmetrical laminates. This paper therefore describes and analyses the resulting warpage produced by symmetrically stacked laminates manufactured through autoclave processing.

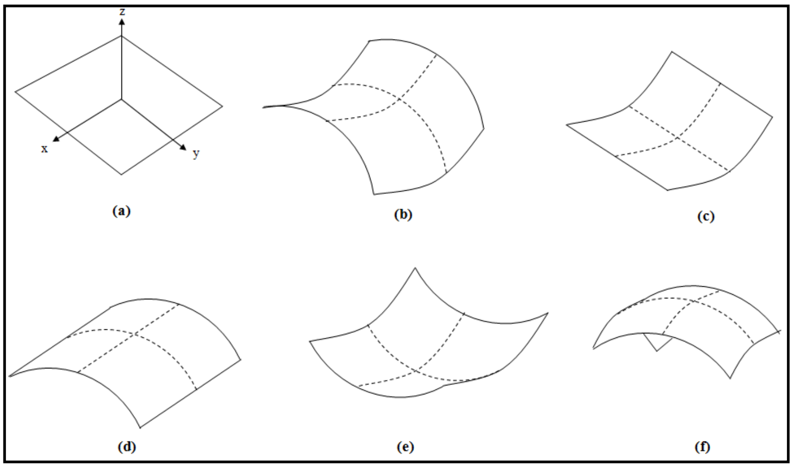

Figure 3. Part warpage due to asymmetrical layups; (a) original; (b) saddle-shaped; (c) and (d) cylindrical-shaped; (e) and (f) rotated cylindrical [2].

2. Experimental

2.1. Materials and parameter
The current study will employ tool made from S275JR carbon steel to manufacture laminate composites made from IMA/M21E of various symmetrical layups and observe the 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 300x300 mm^2 and laid up to a thickness of 4 plies with symmetrical sequences. The sequences are $[0/90]_S$, $[0/45]_S$, $[45/0]_S$ and $[45/-45]_S$ (see figure 4). The symmetrical configurations are for the purpose of keeping the research relevant to the aerospace manufacturing industry as it is recommended to manufacture aircraft structures with symmetrical and balanced stacking [12].

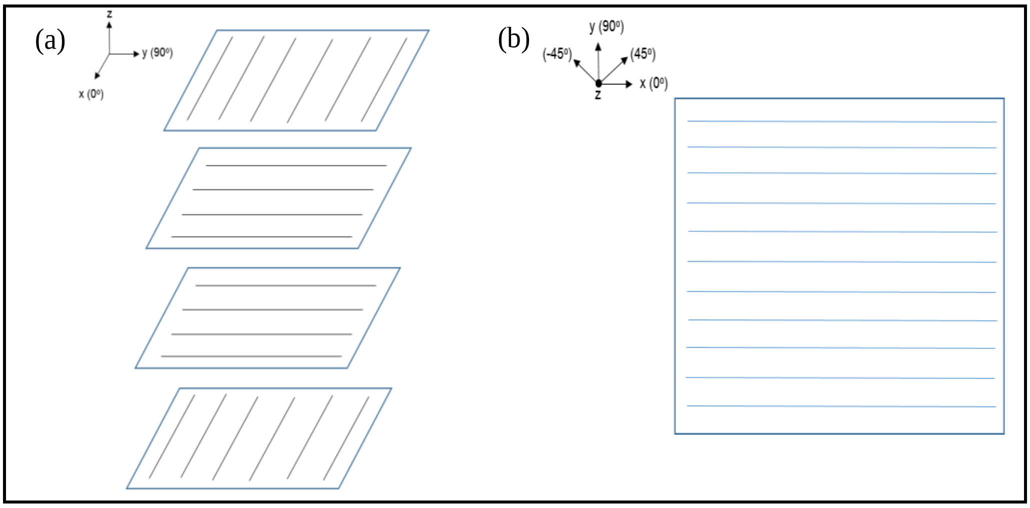

Figure 4. (a) Laminate stacking layup for $[0/90]_S$ and (b) fibre orientation of a ply.

2.2. 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 **5** was placed inside the autoclave and cured to the respective pressure and temperature profile.

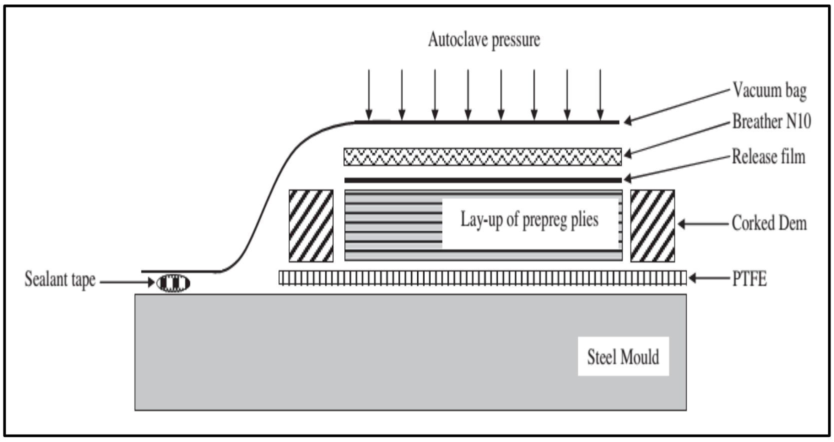

Figure 5. Final bagging system for autoclave curing.

The resulting warpage for a symmetrically-stacked laminate differs from a unidirectional laminate in that the warpage pattern is non-uniform (see figure 6). The spring-back warpage is measured as the maximum point of warpage relative to the reference point as shown in figure 6.

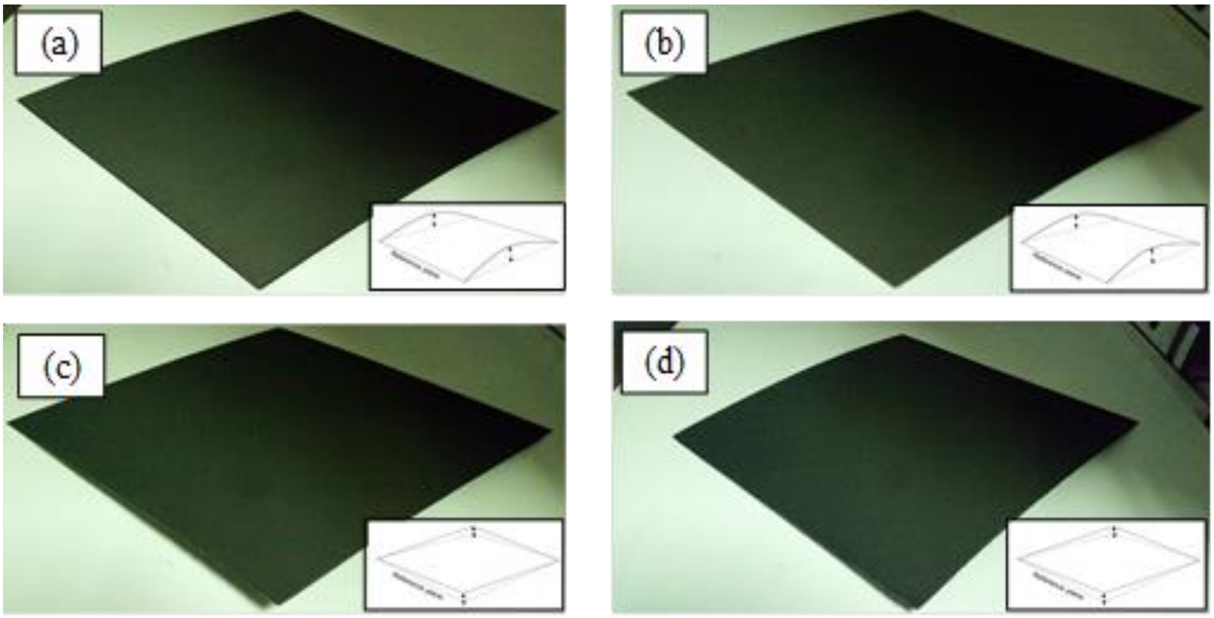

Figure 6. Laminate part warpage for (a) $[0/90]_S$; (b) $[0/45]_S$; (c) $[45/0]_S$ and (d) $[45/-45]_S$.

3. Results and discussion

A plot of the maximum warpage for all the tested samples is provided in figure 7. The author has also included the maximum warpage for the unidirectional laminate i.e. 0° from a previous accompanying study [13] as the baseline. The maximum warpage of all 5 configurations are tabulated in table 1 .

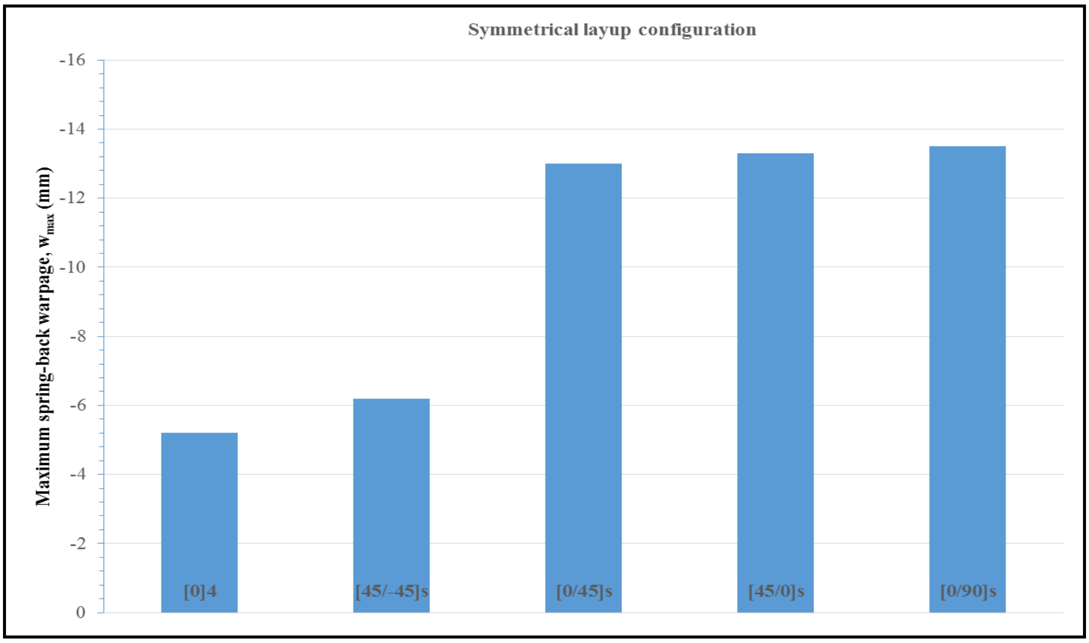

Figure 7. Maximum warpage for 300x300 mm^2 and 4 plies thickness with symmetrical configurations.

Table 1. Maximum warpage of the 300x300 mm^2 and 4 plies thickness laminate samples.

Laminate layup	Maximum warpage
$[0]_4$	-5.2 mm
$[45/-45]_S$	-6.2 mm
$[0/45]_S$	-13 mm
$[45/0]_S$	-13.3 mm
$[0/90]_S$	-13.5 mm

As mentioned earlier, it is standard practice to lay up the laminates symmetrically because it uncouples bending and the membrane response thereby preventing twisting of the laminates. Another reason is to supposedly prevent spring-back warpage during temperature cool-down but as shown in figure 6, figure 7 and table 1, there still exists warpage and in various forms depending on the ply layup configuration.

Table 2. Maximum warpage of the 300x300 mm^2 and 4 plies thickness laminate samples.

Laminate layup	Longitudinal stiffness	Transversal stiffness	Principal material direction
$[0]_4$	154 GPa	8.5 GPa	0^o
$[45/-45]_S$	12.2 GPa	12.2 GPa	45^o
$[0/45]_S$	83.1 GPa	10.3 GPa	10^o
$[45/0]_S$	83.1 GPa	10.3 GPa	10^o
$[0/90]_S$	81.3 GPa	81.3 GPa	10^o

Table 2 shows the resultant stiffness and principal material direction of the laminate samples calculated using Classical Laminate Analysis (CLA). By relating the values with the experimental data in table 1, the layups that yield approximately the same warpage also possess close longitudinal stiffness and have the same principal material direction i.e. $[0/45]_S$, $[45/0]_S$ and $[0/90]_S$. The warpages of all 3 layups are also approximately 2.5 times greater than the $[0]_4$ layup which is a direct consequence of the longitudinal stiffness being almost 50% of the unidirectional laminate. However, the $[45/-45]_S$ layup possesses a lower longitudinal stiffness but still generated the same magnitude of warpage for a unidirectional laminate which might be due to the quasi-isotropic nature of $[45/-45]_S$ layup compared to the others which are significantly anisotropic. This is shown in figure 8 where the laminate stiffness is mapped at every angle between 0^o to 90^o for all the symmetrical layups.

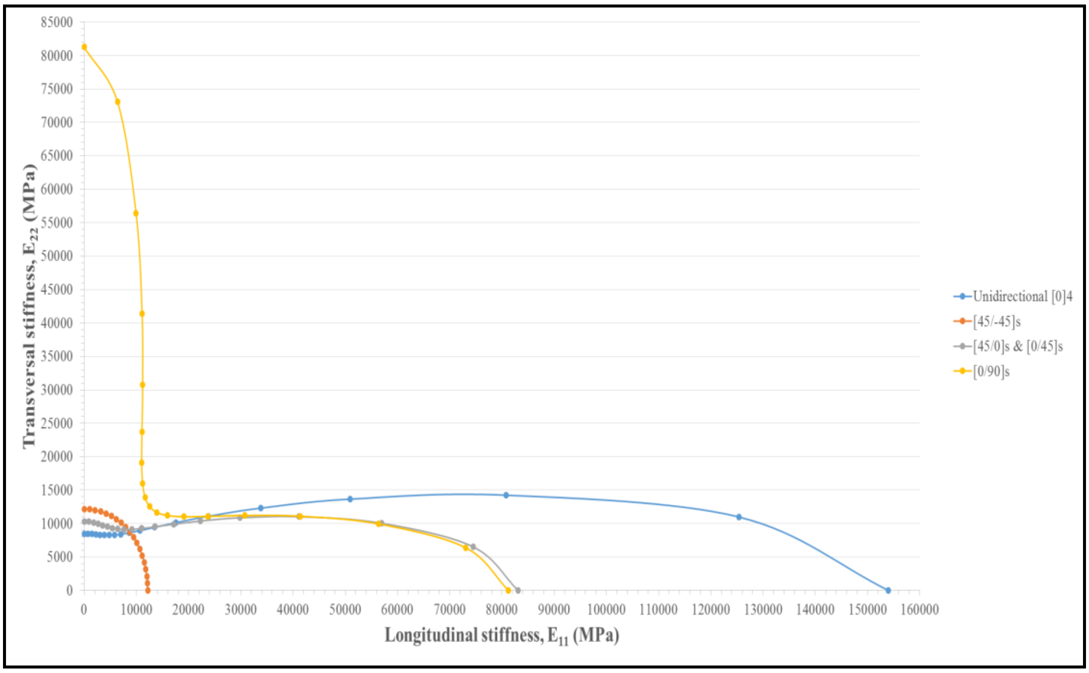

Figure 8. Laminate stiffness between 0° to 90°.

4. Conclusions and future work

The objective of this study was to investigate the effect of the stacking layup on the warpage of flat IMA/M21E laminates. The main conclusions are as follow:

- The stiffness reduction in laminate principle direction will significantly increase the severity of the warpage by more than 150% especially for orthotropic laminate.
- The severity of the warpage in a symmetrical layup could be greatly reduced if the laminate is quasi-isotropic in behaviour.

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 symmetrical laminates. 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.

Finally, the detailed study on the mechanism triggered by the 45° fibre direction ply can be simulated using the FEA previously developed in the accompanying study of unidirectional laminates [13]. The analysis on the macromechanical stress distribution obtained from the FEA model would provide more understanding on the influence of the ply stacking sequence in the spring-back warpage especially the effect of the tool-part interaction.

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