THE EFFECT OF WOVEN FABRIC STYLES AND HONEYCOMB CORE PROPERTIES COMPOSITE PARTS: A REVIEW

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(Advanced Processes & System in Manufacturing (APSIM2011), 14-15 December 2011, Kuala Lumpur)

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

The Effect of Woven Fabric Styles and Honeycomb Core Properties on Composite Parts: A Review

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Keywords: Shape Deformation, Warpage, Spring-In, Composite, Design of Experiment

Abstract.
Advanced composite laminate and honeycomb sandwich structure depict process induced geometrical and dimensional deformations after end of curing process and when removed from its mould tools. A simple flat part tends to warp while an angled or curved part indicates spring-in phenomenon due to the anisotropic material properties. These shape deformations are unpredictable and contribute to fit, form and functional error during an assembly stage. Often a conventional trial-and-error method is deployed to correct the mould tool shape prior to mass production, which is very costly, uneconomical and time consuming. Alternatively a better method is sought to intelligently predict shape deformations considering the material properties, tool-part interaction and processing factors through analytical model, experiments and numerical analysis. However, experimental data is lacking in understanding the effect of fiber weaving styles and honeycomb core material properties in inducing shape deformations. Using higher satin weave style in the composite fabrication is believed to reduce the shape deformations. While adding a honeycomb core between solid laminate skins reduces shape deformation due to its high stiffness to weight ratio. The degree and magnitude of both factors in influencing shape deformations are unknown. Hence, it is proposed to perform design of experiment using Design Expert software with eight key process parameters such as lay-up orientation, number of layers, part geometry, part size, fiber volume, part configuration, weaving style and tool material to provide more insights of process induced shape deformations of monolithic and honeycomb sandwich composite structure.

Introduction

Advanced composite laminate and honeycomb core sandwich parts illustrate process induced shape deformations after end of autoclave curing process and when removed from its mould tools. A simple flat laminate part tends to warp, while an angled or curved laminate part indicates spring-in phenomenon. Advanced composite material indicates anisotropic behaviour unlike metals but widely selected and used in high performance aerospace parts due to its high temperature serviceability, lower density, high strength-to-weight ratio and design flexibility. However, the shape deformations are unpredictable and contributes to fit, form and functional error at production assembly stage if not rectified at the early development phase. Often inefficient trial-and-error method is employed in resolving process induced shape deformations; however, this traditional iterative technique is very costly, uneconomic and time consuming for aerospace composite manufacturers.

There have been many studies carried out before by various researchers [1-13] focusing on internal variables such as material constituents, mechanical properties, and/or external variables such as processing and tool-part interaction factors that affect process induced shape deformations. However, the relationship between the internal and external factors is difficult to be examined, analyzed and simulated accurately. Also, there are lacking of experimental studies on the effect of woven fabric styles and honeycomb core material properties on flat and angled composite parts.

Material Properties. Generally the polymer-matrix of advanced composite materials has higher thermal expansion than the fibers at the micro scale level. As an example, the unidirectional carbon fiber tends to have very low coefficient of thermal expansion in the fiber direction and higher values at the transverse direction. The difference leads to residual stresses to occur during curing process. Meanwhile at the ply-level interface, the difference of coefficient of thermal expansions causes in-plane stresses in laminate. This results in warping of flat laminate when lay-ups are not symmetrical and balanced [1]. During autoclave curing process, residual stress is also developed due to strain from chemical shrinkage and the mismatch between coefficient of thermal expansion of longitudinal and through thickness. Eq. (1) is a mathematical formula to calculate the spring-in angle of L-angled and curved laminate which taking into account the chemical shrinkage and the coefficient of thermal expansion (CTE) of the material [2]. Fig. 1 illustrates the change in spring-in angle before and after the curing process.

$$\Delta\theta = \theta\left(\frac{(\alpha_I - \alpha_T)\Delta T}{1 + \alpha_T \Delta T}\right) + \theta\left(\frac{\phi_I - \phi_T}{1 + \phi_T}\right). \quad (1)$$

Where $\Delta\theta$ is spring-in angle after curing process, θ is initial part angle before curing process, ΔT is changed in temperature, α_I is in-plane CTE, α_T is through-thickness CTE, Φ_I is longitudinal chemical shrinkage and Φ_T is through-thickness chemical shrinkage. The CTE and chemical shrinkage values can be measured using dilatometer equipment.

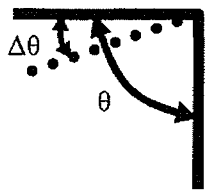


Fig. 1 Angled shape

The Eq. (1) assumes for a simple linear elastic model of laminate construction and the through thickness properties are uniform. However, the formula does not consider the effect of laminate thickness, corner radius, tool-part interaction, part size, weaving styles and honeycomb core material properties such as cell size, density, thickness and ribbon direction.

Material fiber volume fraction can vary in laminate when the resin is bled out during curing process when using a bleeder material. The laminate surface at the bagging area typically indicates higher fiber volume but less resin content due to the area adjacent to bleeder material and vacuum port. On the contrary, the laminate surface adjacent to the tool surface indicates lower fiber volume but higher resin content. This variation of material fiber volume fraction through the thickness induces shape deformations. For thinner parts (<2 mm), the shape deformations of L-angled part indicates spring-in distortion dominated by fiber volume gradient and mould stretching effect whereas for thicker parts (>2 mm), the spring-in was dominated by thickness of cure shrinkage [3].

Tool-Part Interaction. The interface between the tool and composite part is considered as external factor that induces shape deformations of composite parts. The differential thermal expansion between the fully cured composite part (negative CTE) and tooling (positive CTE) generates a compressive stress in composite part at the end of curing cycle before the part is removed from its mould tool [4]. This compressive stress causes shape deformations. Aluminum tool has the largest CTE if compared with other tool materials such as Steel, Invar, Nickel and Advanced Composite Tool. Thus, tool made from a material which has higher CTE tool value such as Aluminum relatively will exhibit worse shape distortions than other lower CTE tool values.

Apart from the tool-part interface, the shape of mould tool also can have an adverse effect on composite parts. A female (concave) mould tool produced less warpage and spring-in angle than a male (convex) mould tool [5]. Hence, the design and the type of material selected for fabricating or machining the tool can influence the shape deformations of composite parts.

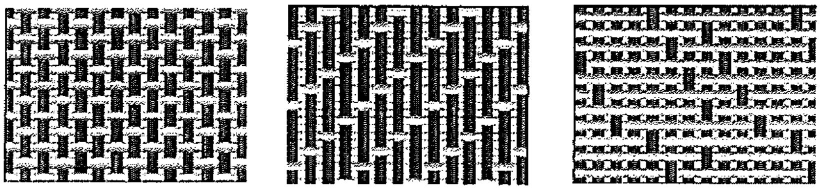
Processing Factors. Other external variables are those parameters e.g. temperature, pressure and vacuum applied during the curing process of the composite parts using equipment such as autoclave or out-of autoclave machine e.g. resin transfer moulding (RTM), resin infusion etc. The autoclave curing at low temperature for a long time seems to increase the total effective thermal expansion, which counteracts the effect of chemical and cooldown shrinkage [6]. However, a three-dimensional model of thermo-chemo-viscoelastic indicates otherwise, that the autoclave curing cycle parameters such as dwell temperature, pressure and cooling rate have less effect on shape deformations [7].

Recent Studies. Based on Table 1, historically most parts were fabricated using unidirectional carbon fiber and thermoset resin system. Other fiber weaving styles and patterns had also been used before such as Plain Weave, 2x2 Twill, Five Harness Satin (5HS) and Eight Harness Satin (8HS). The results of warpage and spring-in angle from previous researchers in Table 1 are not correlated to conclusively state that there is a significant relationship between shape deformations with different usage of weaving fabric styles and honeycomb core material properties. The inclusion of honeycomb core in L-angled parts reduced spring-in effect due to its stiffness to weight ratio [8].

Table 1: Recent studies of composite shape deformation using different part geometries, weaving styles, part configuration, type of materials and processing technology

Part Geometry	Fabric Weaving Style	Part Configuration	Material Type	Processing Tech.	Reference
Flat	Unidirectional	Monolithic	Carbon	Autoclave	[9]
Angled	5HS, 8HS	Monolithic	Glass	RTM	[10]
	Unidirectional	Sandwich	Carbon	Autoclave	[8]
Curved	Plain weave	Monolithic	Carbon	Autoclave	[11]
	2x2 Twill	Monolithic	Carbon	RTM	[12]
	Unidirectional	Monolithic	Carbon	Autoclave	[13]

Using higher satin weave style and pattern in the composite fabrication should further reduce process induced shape deformations [14]. Fig. 2 illustrates the examples of different weaving styles and patterns for fabrics. The satin weaves patterns provide better drapeability and flexibility in conforming to complex curved geometries. However, there is unknown analytical, experimental or finite element study to validate this belief.



Plain Weave Twill Weave 8HS Weave

Fig. 2 Examples of different weaving styles and patterns for fabrics [15]

Discussions

Based on the literature review and recent studies, there are still limited experimental data and studies in the effect of weaving styles and honeycomb core material properties in affecting shape deformations of flat and L-angled composite laminate and sandwich structure. Hence, it is proposed to perform design of experiment as a scientific and statistical approach methodology. The response variables and interactions of materials properties, processing and tool-part factors can be investigated and the results can be analyzed and synthesized. Design Expert software will be used to study the eight key process factors such as lay-up orientation, number of layers, part geometry, part size, fiber volume, part configuration, weaving style and tool material listed in Table 2. A full two-level factorial design of 2^8 with 8 factors will require 256 number of experiments, however, with a fractional factorial design of 2^{8-4} with Resolution IV, the experiments can be reduced to 16 runs only [16].

All the parameters are considered internal variables representing material constituents except the tool material which acts as an external factor. Other external elements such as autoclave processing parameters are kept constant. Coordinated Measuring Machine will be used to measure the warpage and spring-in angle of parts. The inspection results of spring-in angle of L-angled laminated parts will be compared against Eq. (1) to determine whether the formula can accurately predict the spring-in values when applied with different variables as specified in Table 2.

Table 2: Design of experiment parameters with high and low settings

No.	Parameter	+1 (High Level)	-1 (Low Level)
1	Lay-up Orientation	Quasi-isotropic	Axial
2	Number of Layers	8 layers	16 layers
3	Part Geometry	Flat	L-shaped
4	Size (mm)	100 x 100	300 x 300
5	Fiber Volume	Bleed out resin	No bleed out resin
6	Part Configuration	Monolithic	Sandwich
7	Weaving Style	Carbon PW	Carbon 8HS
8	Tool Material	Aluminum	Advanced Composite Tool

Conclusion

Previous studies indicated that material constituent properties, tool-part interaction and processing mechanism can influence the warpage of flat and spring-in angle of composite parts. Nonetheless, the degree and magnitude of woven fabric styles and honeycomb core material in affecting shape deformations are unknown. In this proposed research that will be carried out by the authors is to investigate these variables influence in affecting the geometric and dimensional changes of composite parts. Design of experiment method is chosen together with Design Expert software in analyzing the significant relationship of eight key parameters in **Table 2**. This proposed experimental study will provide additional insights and information of the effect of weaving styles and honeycomb core material properties in affecting the process induced geometrical and dimensional changes of monolithic and sandwich composite components.

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