Jurnal
Teknologi

Full paper

Proposed Parameter Investigation Based on Design of Experiment for Woven Fabric Composites Deformation

Mohd. Razali Muhamad[a]*, Mohammad Hamdan Mohd. Sanusi[b]

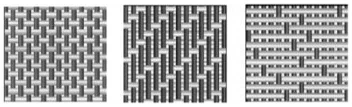
[a]*Faculty of Manufacturing Engineering, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka*
[b]*CTRM Aero Composites Sdn. Bhd., Composites Technology City, Batu Berendam Airport, 75250, Melaka*

*Corresponding author: mohdrazali@utem.edu.my

Article history

Received : 29 March 2012
Received in revised form : 16 June 2012
Accepted : 30 October 2012

Graphical abstract



Abstract

Advanced composite laminate and honeycomb core sandwich structure depict process induced geometrical and dimensional deformations after end of curing process. 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 geometrical shape of the mould tool prior to mass production, which is very costly, uneconomical and time consuming. Alternatively a better method is sought to predict shape deformations considering the elements of material properties, tool-part interaction and processing factors. Based on previous studies, there is still lacking of experimental data and studies on the effect of weavings styles and honeycomb core material properties in affecting shape deformations of flat and L-angled composite parts. Hence, it is proposed to perform a design of experiment with a fractional factorial of 2^{8-4}, Resolution IV, to investigate the parameters that affect the shape deformations of composite parts.

*Keywords:*Shape deformation; warpage; spring-in; composite; design of experiment

Abstrak

Struktur komposit termaju yang terdiri daripada lapisan dan bahan berbentuk indung madu akan mengalami kecacatan geometri dan dimensi selepas proses pengawetan. Kecacatan bentuk ini sukar diramalkan dan ianya menyebabkan ralat pemadanan, rupa bentuk dan fungsi semasa proses pemasangan. Teknik percubaan berulang-kali yang lazim digunakan untuk memperbaiki bentuk geometri acuan sebelum pembuatan berskala besar menelan kos yang tinggi, tidak menguntungkan dan membuang masa. Sebagai alternatif, satu kaedah yang lebih baik diperlukan untuk meramalkan kecacatan bentuk dengan mengambil kira elemen-elemen komposisi bahan, hubungan peralatan dan komponen, dan faktor pemprosesan. Berdasarkan kepada kajian lalu, masih terdapat kekurangan data eksperimen dan maklumat kajian terhadap kesan corak anyaman gentian dan bahan berbentuk indung madu yang mempengaruhi kecacatan bentuk komponen komposit berbentuk leper dan sudut. Oleh itu, dicadangkan satu rekabentuk ujikaji dijalankan dengan faktorial pecahan 28-4, Resolusi IV, untuk menyiasat parameter yang menjadi punca kepada kecacatan bentuk komponen-komponen komposit.

Kata kunci:Kecacatan bentuk; melengkung; kelengkungan ke dalam; komposit; rekabentuk kajian

■1.0 INTRODUCTION

Advanced composite laminate and sandwich structures depict process induced geometrical and dimensional deformations after autoclave curing process. Even a simple flat laminate part tends to warp; meanwhile an angled or curved laminate part indicates spring-in distortions when removed from its moulding tools. These shape deformations are unpredictable and contribute to fit, form and functional error at production assembly stage if not troubleshot and rectified at the early design and development phase. In some cases, some shims had to be added to fill-up the gap between the distorted composite part and its counterpart during an assembly stage [1]. Often inefficient trial-and-error method is employed in resolving process induced shape deformation; however, this traditional iterative technique is very costly and time consuming for aerospace composite manufacturers.

There have been many studies carried out before by various researchers [2-14] 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. There is also a lack of experimental data in understanding the effect of fiber weaving styles and honeycomb core material properties in inducing shape deformation of composite parts. Therefore, the objective of this study is to investigate the relationship and effects of internal and external variables in influencing shape deformations of composite parts using design of experiment methodology.

2.0 COMPOSITE MATERIAL PROCESSING DEFECTS

Unlike metals advanced composite materials indicate anisotropic behaviour. They are widely selected and used for high performance aerospace parts due to its high temperature serviceability, lower density, high strength-to-weight ratio and design flexibility. Generally the polymer-matrix of advanced composite materials has higher thermal expansion than the fibers at the micro scale level. A unidirectional carbon fiber tends to have lower 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 the laminate. This results in warping of flat laminate when lay-ups are not symmetrical and balanced [2].

During an autoclave curing process, residual stress is developed due to strain from chemical shrinkage and the mismatch between coefficient of thermal expansion of longitudinal and through thickness. Figure 1 illustrates the change in spring-in angle before and after the curing process.

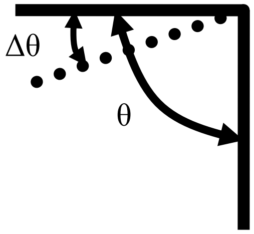


Figure 1 Spring-in of an angled shape part before and after curing process

Eq. (1) is a mathematical formula to calculate the spring-in angle of L-angled and curved laminate which takes into account the chemical shrinkage and the coefficient of thermal expansion (CTE) of the material [3].

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

In the equation, $\Delta\theta$ is spring-in angle after curing process, θ is initial part angle before curing process, ΔT is the change 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 which is a thermo-analytical method for measuring the CTE of thermal expansion and volumetric expansion over a controlled temperature regime.

Eq. (1) assumes 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 is dominated by thickness of cure shrinkage [4].

The interface between the tool and composite part is considered as an 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 [5]. 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 produces lesser warpage and spring-in angle than a male (convex) mould tool [6]. Hence, the design and the type of material selected for fabricating or machining the tool can influence the shape deformations of composite parts.

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 [7]. However, a three-dimensional model of thermo-chemo-viscoelastic indicated otherwise, that the autoclave curing cycle parameters such as dwell temperature, pressure and cooling rate have lesser effect on shape deformations [8].

Simple instrument such as a flatbed document scanner was used to scan the distorted part on a traceable paper for shape deformation analysis [1]. Besides that, a digital hand calliper had also been used to measure the distortion [9]. Nowadays researchers tend to use advanced and sophisticated measuring equipment which can give better accuracy within few microns such as laser beam [10] and Coordinated Measuring Machine (CMM) [11].

3.0 RECENT STUDIES

Previously many researchers opted to use unidirectional carbon fiber together with thermoset resin system in their studies as summarized in Table 1. 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 types of fabric woven 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 [12]. Nonetheless, the degree and magnitude of fabric woven styles and honeycomb core material properties are relatively unknown in affecting shape deformations of composite parts.

Table 1 Recent studies on factors affecting composite shape deformation

Part Geometry	**Fabric Weaving Style**	**Part Configuration**	**Material Type**	**Processing Tech.**	**Reference**
Flat	Unidirectional	Monolithic	Carbon	Autoclave	[13]
Angled	5HS, 8HS	Monolithic	Glass	RTM	[14]
	Unidirectional	Sandwich	Carbon	Autoclave	[12]
Curved	Plain weave	Monolithic	Carbon	Autoclave	[15]
	2x2 Twill	Monolithic	Carbon	RTM	[16]
	Unidirectional	Monolithic	Carbon	Autoclave	[17]

Using higher satin weave style and pattern in the composite fabrication should further reduce process induced shape deformations [18]. Figure 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 indirectly limiting the shape deformation errors.

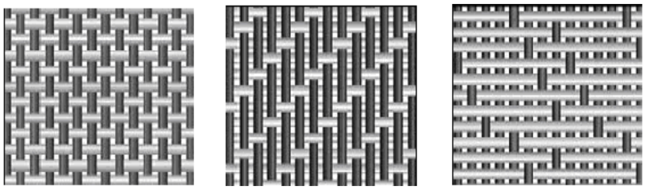

Plain Weave Twill Weave 8HS Weave

Figure 2 Examples of different weaving styles and patterns for fabrics [19]

4.0 THE PROPOSED STUDY

Based on the literature review and recent studies, there are still existing gaps in experimental data and studies on 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, in the current work carried out by the authors, it is proposed to perform a 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 parameters 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 [20].

All the parameters shown in Table 2 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 such as pressure, vacuum and temperature are kept constant. CMM 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 Proposed 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	Aluminium	Advanced Composite Tool

5.0 CONCLUSIONS

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 the 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 factors defined 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 solid laminate and sandwich composite components.

References

[1] Twigg, G., A. Poursartip and G. Fernlund. 2003. An Experimental Method for Quantifying Tool-Part Shear Interaction During Composites Processing. *Composites Science and Technology*. 63: 1985–2002.

[2] Hyer, M. W. 1981. Some Observations on the Cured Shape of Thin Unsymmetric Laminates. *J. Compos. Mater*. 15: 175–94.

[3] Radford, D. W., and R. J. Diefendorf. 1993. Shape Instabilities in Composites Resulting from Laminate Anisotropy. *J. of Reinforced Plastics and Compos*. 12: 58–75.

[4] Darrow Jr., D. A., and L. V. Smith. 2002. Isolating Components of Processing Induced Warpage in Laminated Composites. *J. of Compos. Mater*. 36: 2407–2419.

[5] Alam, M. K., and M. S. Anghelescu. 2009. Analysis of Deformation and Residual Stresses in Composites Processed on a Carbon Foam Tooling. *J. of Compos. Mater*. 43: 2057–2070.

[6] Radford, D. W. 1995. Volume Fraction Gradient Induced Warpage in Curved Composite Plates. *Compos. Eng*. 5: 923–934.

[7] Genidy, M. S., M. S. Madhukar, and J. D. Russell. 2000. A New Method to Reduce Cure-Induced Stresses in Thermoset Polymer Composites, Part

II: Closed Loop Feedback Control System. *J. of Compos. Mater*. 34: 1905–1925.

[8] Zhu, Q., P. H. Geubelle, M. Li, and C. L. Tucker III. 2001. Dimensional Accuracy of Thermoset Composites: Simulation of Process-Induced Residual Stresses. *J. of Compos. Mater*. 35: 2171–2205.

[9] Fernlund, G., K. Karl Nelson, and A. Poursartip. 2000. Modelling of Process Induced Deformatıons of Composıte Shell Structures. *45th International SAMPE Symposium.* 169–176.

[10] Radford, D. W., and T. S. Rennick. 2000. Separating Sources of Manufacturing Distortion in Laminated Composites. *Journal of Reinforced Plastics and Composites.* 19: 621–641.

[11] Capehart, T. W., N. Muhammad, and H. G. Kia. 2007. Compensating Thermoset Composite Panel Deformation using Corrective Molding. *Journal of Composite Materials*. 41: 1675–1701.

[12] Fernlund, G. 2005. Spring-in of Angled Sandwich Panels. *Compos. Sci. and Tech*. 65: 317–323.

[13] Arafath, A. R. A., R. Vaziri, and A. Poursartip. 2008. Closed-Form Solution for Process-Induced Stresses and Deformation of a Composite Part Cured on a Solid Tool: Part I – Flat Geometries. *Compos. Part A.* 39: 1106–1117.

[14] Golestanian, H., and A. S. El-Gizawy. 2001. Modeling of Process Induced Residual Stresses in Resin Transfer Molded Composites with Woven Fiber Mats. *J. of Compos. Mater*. 35: 1513–1528.

[15] Sweeting, R., X. L. Liu, and R. Paton. 2002. Prediction of Processing-Induced Distortion of Curved Flanged Composite Laminates. *Compos. Structures.* 57: 79–84.

[16] Svanberg, J. M., C. Altkvist, and T. Nyman. 2005. Prediction of Shape Distortions for a Curved Composite C-Spar. *J. of Reinforced Plastics and Compos*. 24: 323–339.

[17] Ersoy, N., T. Garstka, K. Potter, M. R. Wisnom, D. Porter, and G. Stringer. 2010. Modelling of the Spring-in Phenomenon in Curved Parts Made of a Thermosetting Composite. *Compos. Part A*. 41: 410–418.

[18] Tuttle, M. E. 2004. *Structural Analysis of Polymeric Composite Materials.* USA: Marcel Dekker.

[19] Hexcel Technical Fabric Handbook. 2010. www.hexcel.com.

[20] Montgomery, D. C. 2009. *Design and Analysis of Experiments.* USA: John Wiley and Sons, Inc.