CURVED COMPOSITE STRUCTURES AND COMPROMISE BETWEEN PROCESS-INDUCED DEFORMATIONS AND STRUCTURAL PERFORMANCE

H. Ghiasi[1*], M. Rahmat[2], P. Hubert[3], L. Lessard[3]
[1, 2] Department of Mechanical Engineering, McGill University, Montreal, Canada
[1] Postdoctoral fellow, [2] PhD Candidate, [3] Associate Professor
[*] Corresponding author (hossein.ghiasi@mail.mcgill.ca)

Keywords: *Polymer composite, Process-induced deformation, Curved structures, Performance*

1 Introduction

Advanced composite materials usually undergo a significant variation in temperature during the manufacturing process and are generally cured at a temperature different than their service temperature. Because of anisotropic material properties and the mismatch between the thermal properties of the part and the mold, the temperature variations can create significant residual stresses and undesired deformations. Magnified by the effect of resin volumetric chemical shrinkage during the cure process, the process-induced deformations can produce major changes in geometry and structural performance of a curved structure.

Experimental, analytical and numerical studies are available on modeling of the process-induced deformations, demonstrating the contribution of several parameters including cure process [1, 2, 3], tool material [4, 5, 6], tool and part geometries [1, 3] and laminate stacking sequence [5]. To achieve a high level of dimensional fidelity required for aerospace applications, a design procedure is required to minimize the undesired process-induced deformations and stresses by controlling these parameters.

Thus far, minimizing the process-induced deformations is realized mainly through mold design and deformation compensation [5]. However, this method can compensate for process-induced deformations; it is not able to reduce process-induced stresses. Residual process-induced stresses reduce structural performance of the final structure. In this paper several test cases are studied, demonstrating that it is possible to reduce the undesired process-induced deformations and residual stresses by simultaneous consideration of structural and processing stresses during the stacking sequence design and by adjusting processing parameters, such as tool material and thickness, cure cycle and autoclave heat conduction rate.

Both structural and processing parameters are studied in order to design a curved structure with maximum dimensional fidelity and minimum weight. Deformations and stresses created by different mechanisms such as mechanical loads, thermal loads, chemical shrinkage during cure and tool-part interactions are taken into account. It is shown that with a proper tailoring of the stacking sequence and processing parameters, undesired distortions can be reduced significantly without a considerable deterioration in structural functionality of the part.

2 Structural Design and Processing Parameters

A common design approach, usually practiced in design of composite and non-composite structures, includes several iterations between the structural design team and the manufacturing team. The moderately weak interconnection between the two fields in metallic materials results in an acceptably efficient design process that converges to a reasonably good design within a small number of re-iterations; however, in composite structures because of anisotropic material properties and significant effect of processing parameters on internal material properties, this link is stronger. In this case convergence may require larger number of iterations and yet the final design may not be the optimum possible structure. Case-studies presented in this paper demonstrate examples where the re-iterative approach leads to a non-optimal solution because of a compromise between process-induced deformation and structural performance.

Two design approaches are practiced and compared. In *“Approach A”*, shown in Figure 1, the lamination sequence of a composite structure with a given geometry is designed such that it realizes a structure with minimum weight while satisfying given strength and deflection requirements under certain mechanical loads. The optimum structural design is then analyzed for process-induced deformations. Processing parameters are adjusted in order to minimize undesired deformations. The remaining process-induced stresses are tolerated by strengthening (i.e. adding layers to) the current laminate until the final design satisfies strength and deformation requirements under mechanical and process-induced stresses.

In *“Approach B”* structural analysis and process simulation are used in a single optimization process. Thus the iterative part in the flowchart shown in Fig.1 is excluded. This approach considers process-induced deformations at the stage of laminate stacking sequence design. *Approach B* has this advantage of using process-induced stresses to compensate for some stresses due to mechanical loads and thus can lead to a lighter and stronger structure compared to *Approach A*.

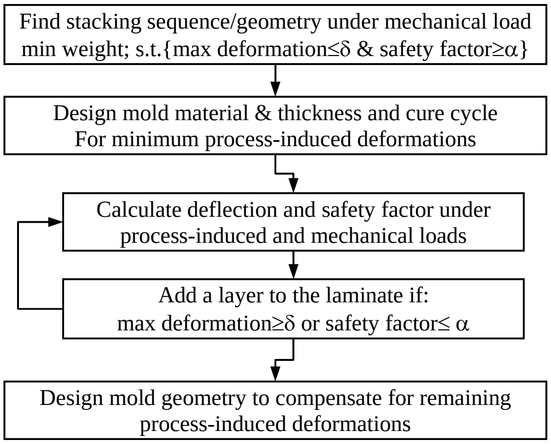

Fig.1. A common design approach includes re-iteration between structural and process design, while an integrated approach exclude the iterative loop in this flowchart by considering both mechanical and processing stresses in the first block

2.1 Simulations

The effect of the cure cycle, resin shrinkage and tool-part interaction on process-induced deformations are simulated using COMPRO [7], a composite processing analysis and design software. COMPRO simulates the cure process considering full processing parameters such as changes in material stiffness, temperature, viscosity, degree-of-cure, volumetric cure shrinkage, tool-part interaction, etc.

For structural analysis, including the stress and strain field due to mechanical, thermal and chemical shrinkage a semi-analytical code or a commercial finite element package is used depending on the geometry of the part, which is discussed at the corresponding section.

2.2 Optimization

Approach A requires separate optimization of stacking sequence and processing parameters. For design of the stacking sequence, depending on the number and continuity of the design variables, a constrained Nelder-Mead simplex optimization technique [8] or a Branch-and-bound method [9] is used. For the processing parameters, where the objective function is smoother and the choices for variables are limited, a design of experiments method, i.e. Tagouchi method [10], is used. The results from this method are employed to find the best combination of processing parameters.

3 Case-Studies and Discussion

3.1 Z-shaped bracket

As a first case-study, a Z-shaped composite bracket shown in Fig.2 is studied. The design problem consists of finding three geometrical variables, fiber orientations for a 20-ply composite laminate and four processing parameters as described in Fig.3. The bracket is made of carbon/epoxy, Hexcel AS4/8552, whose properties and cure kinetics model are shown in Table 1. The bracket is designed for minimum vertical deflation under the specified load and the minimum spring-in (change in angles after demolding) due to the thermal loads and chemical shrinkage during cure.

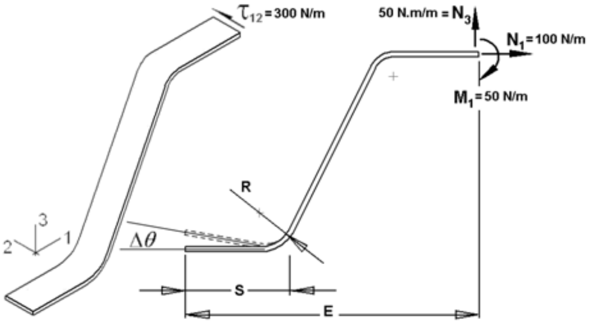

Fig.2. A Z-shaped bracket is designed for minimum vertical deflection and process-induced deformations

Table 1. Cure kinetics model for Hexcel epoxy 8552

<table>
<tr><td colspan="2">KINETIC MODEL [11] (α IS THE DEGREE OF CURE)
$$\frac{d\alpha}{dt} = \frac{K\alpha^{m}(1-\alpha)^{n}}{1+e^{C\{\alpha-(\alpha_{c0}+\alpha_{CT}T)\}}}\ ;\ \ K = Ae^{(-\Delta E/RT)}$$</td></tr>
<tr><td>Parameter</td><td>Value</td></tr>
<tr><td>Activation energy, ΔE</td><td>66.50 kJ/gmol</td></tr>
<tr><td>Cure rate coefficient, A</td><td>1.528×10^{5} s^{-1}</td></tr>
<tr><td>m , n</td><td>0.8129, 2.736</td></tr>
<tr><td>Diffusion constant, C</td><td>43.09</td></tr>
<tr><td>α_{C0} , α_{CT}</td><td>-1.684, 5.475×10^{-3} k^{-1}</td></tr>
<tr><td>Degree of cure at gel point</td><td>0.31 [14]</td></tr>
<tr><td>Volumetric cure shrinkage after gel point (%)</td><td>2.8 [15]</td></tr>
</table>

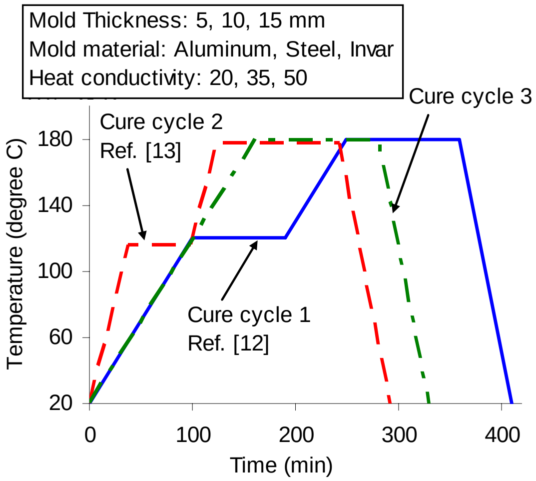

Fig.3. Cure cycle, mold thickness, mold material and heat conductivity are the processing parameters studied, each at three different levels

According to *approach A*, the initial step is to find the geometrical and lamination sequence that returns the minimum vertical deflection. This optimization problem is solved using a Nelder-Mead method [9]. Taking advantage of the geometry of the bracket (consisting of two curved corners whit inverse laminate sequence), it is possible to find a stacking sequence and geometry with close-to-zero vertical deflection under the specified mechanical load (see the results labeled “min defl.” in Fig.4.

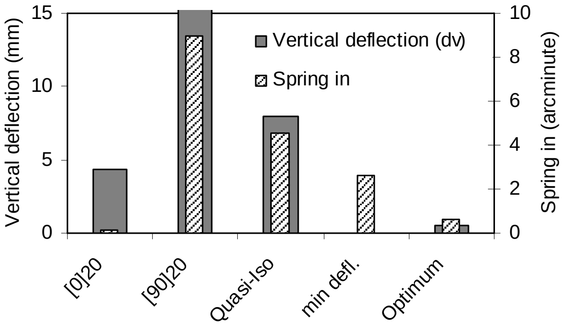

Fig.4. Contribution of laminate stacking sequence in structural and process-induced deformations

The next step is to calculate and minimize process-induced deformations by adjusting the processing-parameters. In order to reduce the number of process simulations, yet thoroughly study the effect of four selected processing parameters, Tagouchi Design of Experiments method is used. Using an L_9 orthogonal table, only nine analyses are required to study this system (instead of 81 full factorial combinations). Accordingly, a set of nine analyses is carried out in COMPRO. The results, shown in Fig.5, suggest that the mold material is the most influential parameter, yet its contribution in overall process-induced deformation (i.e. spring-in) is less than 5%. Other processing parameters with around 1% contribution are ranked after the mold material.

Process-induced deformations are caused by the differences in deformation in different layers and directions. Thus, anisotropic thermal and chemical shrinkage are the main source of such deformations. The cure map of the resin in Fig. 6 shows that in the three suggested cure cycles, the maximum temperature is the same. Also the temperature at gel point is similar and between 166ºC and 176ºC.

Thermal residual stresses are formed after the gel point. Since the gel point and the peak temperature are similar in three suggested cure cycles, it is expected to see small effect from cure cycle on the process-induced deformations. Similarly, it was observed that the mold material and thickness did not have a considerable effect on temperature at gel point and at the peak temperature.

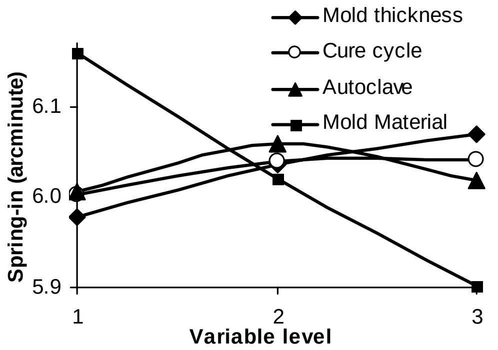

Fig.5. Effect of processing parameters on spring-in observed in a Z-shaped bracket

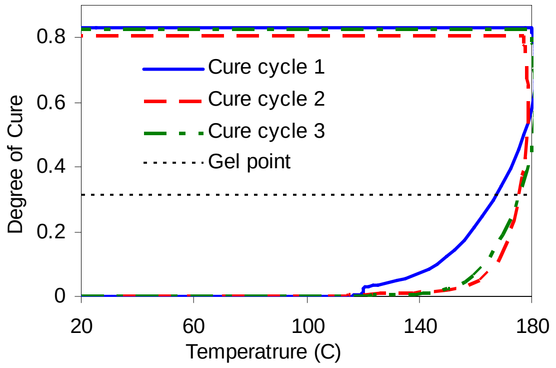

Fig.6. Degree-of-cure versus temperature in three cure cycles suggested in Fig.3

This study suggests that the process-induced deformations are mainly controlled by anisotropy due to lamination sequence; hence consideration of process-induced deformations during the laminate design is required. In this particular case, it is not possible to improve the bracket by simply adding more layers to the current laminate; therefore, the Nelder-Mead optimization method is used to minimize a weighted sum of the spring-in and the vertical deflection by adjusting geometry and fiber orientations.

Fig.4 compares the “optimum” solution found from the integrated design with the one obtained from *Approach A* (labeled as “min defl.”). It also shows some common lamination sequences such as quasi-isotropic and unidirectional laminates. The structure designed for minimum vertical deflection (“min defl.” in Fig.4) resulted in a notable amount of spring-in; however, by taking into account the compromise between structural and process-induced deformations, a solution was achievable (labeled as “optimum” in this figure) with considerably less spring-in and a small penalty on vertical deflection. This figure also shows that with a proper design approach it is possible to design laminates which are more efficient than commonly used quasi-isotropic or uni-directional laminates both in processing and performance.

3.2 Cylindrical Shell

The second case-study is that of a half-cylindrical composite shell shown in Fig. 7 made of the similar material as that used in the first case-study. The lamination sequence is specified as $[0_n/\pm 45_n/90_n]$ where number of layers at each fiber orientation can vary between 1 and 3 layers each at 0.25 mm thickness. The laminate can be placed such that the 0°-layer(s) is (are) located at the inner or the outer side of the curvature. A structure with this geometry can be a cover for precise rotary equipment. The shell must be designed for minimum weight while the safety factor is kept above 2 and the total deformation less than 1.5 mm. The design parameters include laminate stacking sequence, cure cycle, tool material, tool thickness, heat conduction rate and mold geometry.

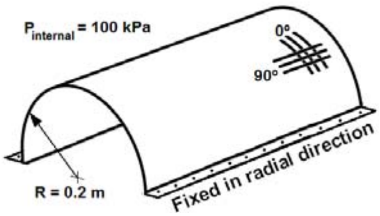

Fig.7. A half-cylindrical shell is designed for minimum deformation under internal pressure and process-induced deformations

Based on the results of the previous case-study, mold thickness, mold material, heat conduction rate and cure cycle are independently adjusted for minimum process-induced deformations. The mold geometry is designed to compensate for process-induced deformations such that the composite shell after being removed from the mold at the room temperature provides the exact required geometry.

A finite element model in ANSYS is used to calculate the deformation and stresses due to the internal pressure, the temperature difference between the gel point and the room temperature, and the volumetric shrinkage during cure. To model the latter, the coefficient of thermal expansion (CTE) of the composite laminate is modified as follows:

$$CTE_i' = CTE_i - \frac{Shrinkage_i}{(T_{gel} - T_{room})}$$

where, subscript “i” shows the fiber or matrix direction. Using the modified CTE, the total deformation under the thermal load of $T_{gel} - T_{room}$ is equivalent to the sum of the thermal expansion and the cure shrinkage. The process-induced stresses are calculated while the half-cylinder is not constrained, simulating the demolding process at room temperature. Process-induced deformations, as high as 30 mm, were observed in some cases (compensated by mold geometry). The structure is analyzed under pressure with and without process-induced stresses as initial stress state and the safety factors are plotted in Fig. 8

A Brach-and-Bound optimization method is used to find the lightest possible shell structure that can satisfy strength and deformation criteria under the internal pressure (*Approach A)*. Point (A) in Fig. 8 and Fig. 9 shows this structure with the lamination sequence of [0/±45/90$_2$], safety factor of 3.19 and maximum deformation of 1.34 mm. But this structure exhibits excessive deformation when the process-induced stresses are considered (see Fig. 9). To reduce the total deformation, the laminate is modified by adding new layers. Each new layer is added in the direction that makes the most reduction in deformation. The modified laminate is labeled with letter “B” in Fig. 9 and has the laminate sequence of [0$_3$/±45$_3$/90$_2$] with a safety factor of 3.35 and deflection of 1.25 mm. This laminate has a total thickness of 2.75 mm.

In *Approach B*, similarly an optimum design is found but considering the process-induced stresses as initial stress-state. The best laminate found with this approach is [0$_3$/±45/90], with the safety factor of 2.77 and deformation of 1.14 mm (labeled with a letter “C” in Figs. 8 and 9). The total thickness of the new laminate is only 1.5 mm, which is significantly lighter than design “B”. The trade-off is visible in Fig. 9, as the laminates that showed lower deformation without process-induced stresses, acted the opposite under the combined pressure and process-induced stresses.

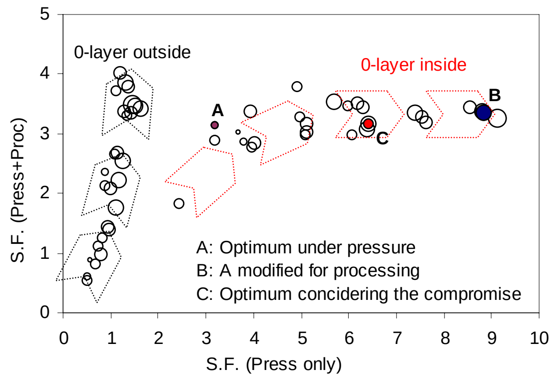

Fig. 8. Safety factor under internal pressure with and without process-induced stresses; Laminates with 0º–layer inside are safer under internal pressure; however, the inverse arrangement is safer when process-induced stresses are considered. Marker size shows the laminate thickness.

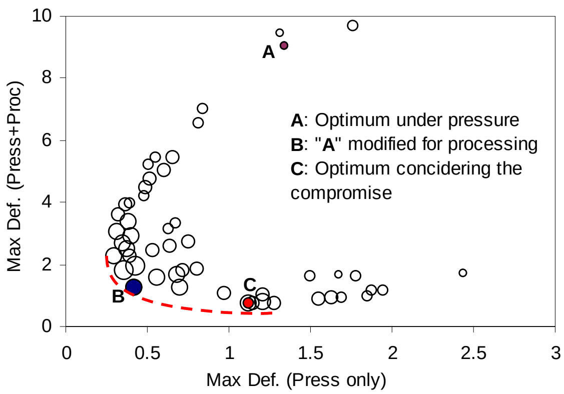

Fig.9. Maximum deformation calculated under internal pressure, with and without consideration of process-induced stresses. The red dash-line, shows the line of trade-off between the two types of deformations (marker size shows thickness)

3 Conclusions

The significance of process-induced stresses and deformations in overall performance of two demonstrative composite structures are studied and it was shown to have a considerable effect on structural performance. Different processing parameters including mold material, thickness and geometry and the cure cycle are studied for their effect on controlling undesired process-induced deformations. Different sources for process-induced stresses were considered, including thermal loads, chemical shrinkage and tool-part interaction. It was shown that the processing parameters generally provide a window of less than 10% adjustment in process-induced deformations. The major contribution in process-induced deformation and stresses is from the laminate stacking sequence. Therefore, it is necessary to take into account process-induced deformations during the early stage of laminate design.

In line with the last recommendation, two design approaches were explained and compared. The first approach, *"Approach A"*, finds a laminate with the best structural performance, which then undergoes modifications in lamination sequence in order to compensate for process-induced stresses. In contrast, *"Approach B"* considers structural and process-induced stresses in an integrated design approach. Demonstrative curved structures studied showed that the compromise between processing and structural stresses exists and hence an integrated design approach is necessary. One case revealed that the integrated design led to 50% weight reduction.

The coupling between processing and structural performance would be more evident if structures with double-curvature were considered. In such structures fiber draping and deviation of fiber angles from an ideal design orientation can add to the undesired process-induced deformations. A truncated cone, spherical structures and structures with funnel or nuzzle shape are the future case-studies for this work.

References

[1] Dong C. "A parametric study on the process-induced deformation of composite T-stiffener structures". *Composites: Part A*, Vol. 41, pp 515–20, 2010.

[2] L. Khoun, P. Hubert. "Investigation of the dimensional stability of carbon epoxy cylinders manufactured by resin transfer moulding". *Composites: Part A*, Vol. 41, pp 116–124, 2010.

[3] C.S. Dong, S. Lynch and J Li. "Mold development for resin transfer molding with dimension variation and deformation compensation". *Advanced Materials Research*, Vol. 123 - 125, pp 491-494, 2010.

[4] D.A. Darrow and L.V. Smith. "Isolating components of processing induced warpage in laminated composites". *Composite Materials,* Vol. 36, No. 21, pp 2407–19, 2002.

[5] K.J. Yoon and J.S. Kim. "Effect of thermal deformation and chemical shrinkage on the process induced distortion of carbon/epoxy curved laminates". *Composite Materials*, Vol. 35, No. 3, pp 253-63, 2001.

[6] M.P. Koteshwara and J. Raghavan. "Parametric study of process induced deformation in composite laminates", Proceeding of SAMPE 2001, Long Beach, CA May 6 - 10, 2001.

[7] A finite element composite processing analysis and design software, *Convergent Manufacturing Technologies Inc.*, http://www.convergent.ca.

[8] H. Ghiasi, D. Pasini, L. Lessard. "Constrained globalized Nelder-Mead method for simultaneous structural and manufacturing optimization of a composite bracket". *Composite Materials, Vol.* 42, No. 7, pp 717-36, 2008.

[9] *"Engineering optimization: theory and practice"*, S.S. Rao, Third edition, John Wiley & Sons Inc. New York, 1996.

[10] *"Design and analysis of experiments"*, D.C. Montgomery. Third edition, Hoboken, NJ: John Wiley & Sons, 2005.

[11] A. Johnston, "An integrated model of the development of process-included deformation in autoclave processing of composite structures", *PhD thesis, University of British Columbia*, April 1997.

[12] Hexcel Composites Company, Product Data Sheet for Epoxy 8552, *Publication FTA 072a* (May 2003).

[13] N. Hager III, and R. Domszy. "Time-domain-reflectometry cure monitoring", *SAMPE 2001*, Long Beach CA, May 6-10, 2001.

[14] N. Ersoy,T. Garstka, K. Potter, M.R. Wisnom, D. Porter, M. Clegg, G. Stringer. "Development of the properties of a carbon fibre reinforced thermosetting composite through cure", *Composites: Part A*, Vol. 41, pp 401-409, 2010.

[15] T. Garstka, N. Ersoy, K.D. Potter, M.R. Wisnom. "In situ measurements of through-the-thickness strains during processing of AS4/8552 composite", *Composites: Part A*, Vol. 38, pp 2517–26, 2007.