CURE SHRINKAGE AND SHAPE DISTORTION OF L-SHAPED COMPOSITES WITH INTERLAMINAR TOUGHENED LAYERS

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Keywords: Spring-in, in-situ strain monitoring, optical fiber sensor

Abstract

L-shaped composites are fundamental parts for complex-shaped structures. It is well known that chemical-cure- and thermal-shrinkage decreases the enclosed angle (i.e., spring-in) due to the orthotropic nature of composites. This residual deformation significantly increases manufacturing cost, so the mechanisms of spring-in deformation have been widely studied in previous researches. Meanwhile, recent aerospace-grade carbon fiber reinforced plastics (CFRPs) utilize interlaminar toughened layers to enhance the interlaminar fracture toughness for impact resistance. Even though interlaminar layers have possibilities to affect residual deformations, their effects have not been evaluated. Therefore, this study conducted fiber-optic-based internal strain measurement and residual deformation evaluation of L-shaped parts with interlaminar toughened layers. The through-thickness cure shrinkage strain at the corner part relaxed and the spring-in angle decreased by holding the cured parts at the cure temperature, implying that viscoelasticity of the interlaminar resin layer plays an important role. Viscoelastic finite element analysis supported this finding and the results obtained indicated that the effect of toughened layers on the residual deformation should be taken into account to determine the optimized cure process.

1. Introduction

CFRPs have been intensively applied to aircraft structures due to its weight reduction advantage and environmental stability. L-shaped composites are fundamental parts for those complex-shaped structures and it is well known that residual deformation (i.e., spring-in) occurs after curing due to the orthotropic nature of composites (Figure 1). When the spring-in deformation is corrected during assembly, significantly high out-of-plane stress is generated at the corner part, which leads to strength reduction, so cost-intensive manual shimming is necessary during assembly. For this reason, optimization of tools and curing cycles has been carried out based on trial and error. However, the cost for trial manufacturing is very high, so understanding these phenomena and predicting the residual deformation based on its mechanism are quite important to determine an appropriate process in a reasonable manner with minimal trial and error.

So far, various researches on spring-in have been carried out. Radford and Diefendorf [1] predicted spring-in angles based on geometric calculations by the following equation,

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

where θ is the angle of the corner part, ε is the strain, α is the thermal expansion coefficient, ΔT is the temperature change, φ is the cure shrinkage strain, and the subscripts I and T indicate the in-plane and through-thickness directions. However, this formula could not explain the effect of thickness as

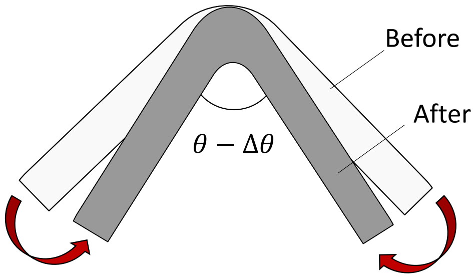


Figure 1. Spring-in deformation.

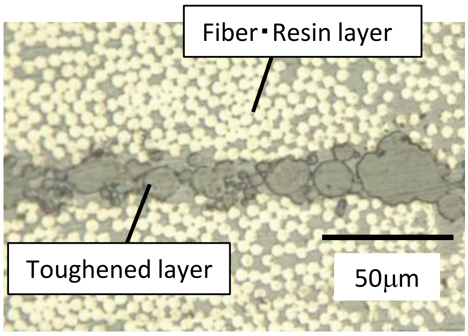


Figure 2. Interlaminar resin layer constituted by thermoplastic particles and epoxy resin. (T800S/3900-2B (Toray Industries, Inc.)).

measured in most experiments. Therefore, Wisnom et al. [2] proposed a new model for C-shaped parts where through-thickness shear deformation was taken into account. The theoretical model successfully predicted the effect of thickness as obtained in the corresponding experiment. Our research group expanded this model to practically relevant L-shaped parts and clarified their behavior in detail by employing in-situ monitoring of internal strain [3].

Meanwhile, recent aerospace grade CFRPs utilize interlaminar toughened layers to enhance the interlaminar fracture toughness for impact resistance (Figure 2). Albert and Fernlund [4] measured spring-in angles using a material with interlaminar resin layers while changing stacking sequence, thickness, flange length and cure cycle. However, the influence of interlaminar resin layers on the spring-in deformation was not evaluated. Although it is expected that the internal stress/strain change during curing is influenced by resin layers, sufficient knowledge has not been obtained at present. Therefore, this study evaluates their effect using fiber-optic-based in-situ strain monitoring and shape measurement.

2. Experiment

2.1 Internal Strain Measurement using Optical Fiber Sensors

Cure-induced strain monitoring was conducted using fiber Bragg grating (FBG) sensors embedded in the L-shaped corner part (Figure 3). T800S/3900-2B (Toray Industries, Inc.) with interlaminar resin layers was used to be compared with the result of a material without interlaminar resin layers (T800S/Model epoxy S1 (Toray Industries, Inc.)). The stacking sequence was $[90_4/0_4]_{2S}$ (90° was the longitudinal direction), the corner radius 6.4 mm, the flange length 60 mm, and the width 75 mm. Prepreg sheets were first laid up on a tool made of aluminum and vacuum bagging was applied. A small hole was then introduced into the prepreg sheets and the bag film using an ultrasonic horn and a metal needle (ϕ = 0.5 mm), and finally an FBG sensor (grating length: 1 mm) was inserted [3]. The

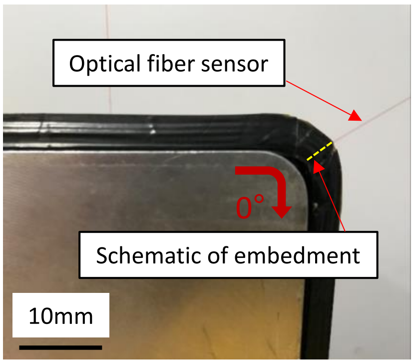


Figure 3. L-shaped specimen with embedded optical fiber sensor.

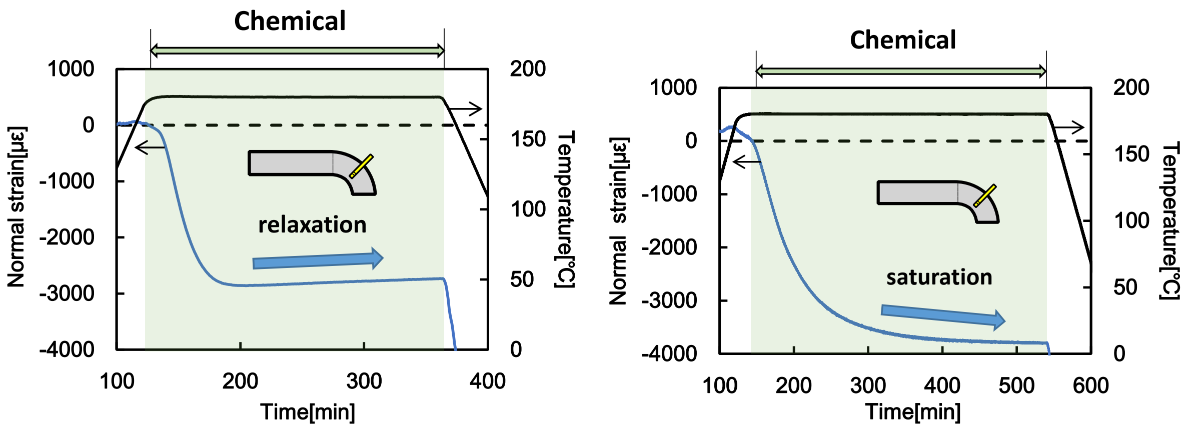
FBG sensor was cut at 2 mm from the grating and the sensing part was located at the center in the thickness direction of the laminate. After embedding, sealant tape was used to cover the hole in the bagging film. The curing was conducted in an autoclave under 0.6 MPa pressurization with 2°C/min heating, holding at the cure-temperature of 180°C and 2°C/min cooling. The cure-temperature holding time was 4 hours for T800S/3900-2B and 7 hours for T800S/Model epoxy S1 because their resins were different and different holding time was necessary to fully cure them.

Figure 4 shows the strain change measured during curing. The FBG sensors started to measure chemical-cure shrinkage after gelation and the strain changing rate gradually decreased as the cure reaction proceeded. It is important to note that, in the case of the specimen with interlaminar toughened layers (Figure 4(a)), the compressive strain relaxed during the cure-temperature hold. This strain relaxation is attributed to the viscoelastic nature of the interlaminar resin layers constituted by thermoplastic particles and an epoxy resin [5]. This result implies that the internal strain and stress changed complicatedly due to the interlaminar resin layers.

2.2 Spring-in Angle Measurement

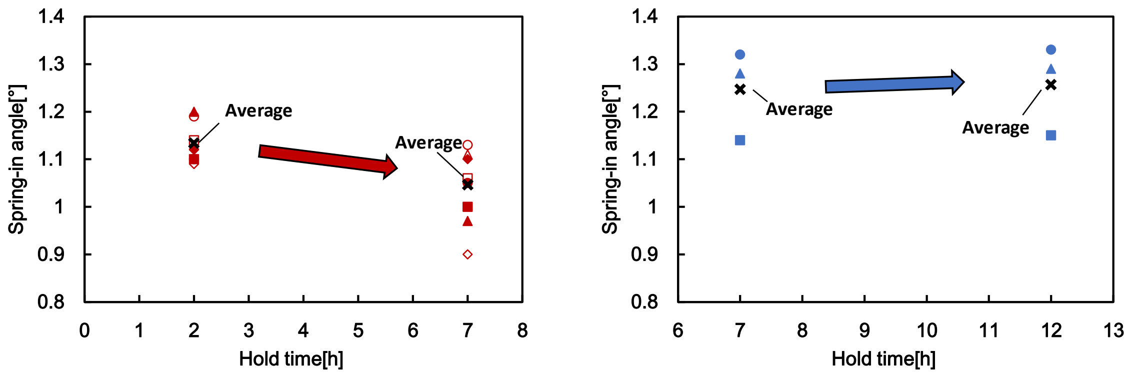
The strain relaxed in the latter part of the cure-temperature hold was small compared to the whole cure strain (Figure 4 (a)), but it was expected that the relaxed stress was non-negligible because the material was vitrified and had a high stiffness at this stage. In order to investigate the effect of this stress relaxation on the final shape, spring-in angles of L-shaped parts were measured at different cure-temperature holding time.

Figure 5 shows the spring-in angle depending on holding time at the cure temperature of 180°C. Measurement was conducted using a 3D scanner ATOS (GOM mbH). The spring-in angle decreased in the specimens with interlaminar toughened layers as the holding time increased. In contrast, the angle did not change in the case of the specimens without interlaminar layers. This result indicates that the strain relaxation due to the viscoelasticity of the interlaminar resin layers actually affects the final part shape. This angle change is relatively small but cannot be neglected as aerospace-grade components must meet tight tolerances. In case that dimensional tolerance is 0.25 mm, acceptable deformation is exceeded at a position 350 mm away from the corner part. It is important to note that in this study the cure temperature holding time was intentionally changed, but temperature history actually differs within a large-scale part under a practical manufacturing process as the part and tool thickness is non-uniform and each area has different heating rate and cure temperature holding time. So it is expected that the deformation amount may be non-uniform even in actual manufacturing.



(a) (b)

Figure 4. Strain development during curing. (a) With interlaminar toughened layers (T800S/3900-2B). (b) Without interlaminar toughened layers (T800S/Model epoxy S1).



(a) (b)

Figure 5. Spring-in angle depending on holding time at cure temperature. (a) With interlaminar toughened layers (T800S/3900-2B). (b) Without interlaminar toughened layers (T800S/Model epoxy S1).

3. Finite Element Analysis

Finite element analysis was conducted to clarify the deformation mechanism caused by the strain relaxation. Figure 6 shows the finite element model used. One quarter of the L-shaped part was modeled using appropriate boundary conditions and frictionless contact was defined between the L-shaped part and the tool. The interlaminar resin layer was modelled using a viscoelastic material property determined from a rule of mixtures in order to simulate the stress/strain change during holding at the cure-temperature.

Figure 7 shows the through-thickness strain development calculated at the corner part. After the change due to autoclave pressurization and cure reaction, the compressive strain relaxed in the interlaminar toughened layer during temperature holding as in the experiment (Figure 4 (a)). This was because high through-thickness tensile stress was generated due to geometrical constraint on the cured part and creep deformation occurred in the interlaminar layers. Figure 8 depicts the deformation mechanism. The cured L-shaped part had reduced corner angle due to the orthotropic cure shrinkage but the autoclave pressure constrained the cured part to the tool shape, which generated the end-opening bending moment and through-thickness tensile stress in the corner part. This stress induced creep deformation of the interlaminar layers and consequently decreased cure-induced spring-in deformation.

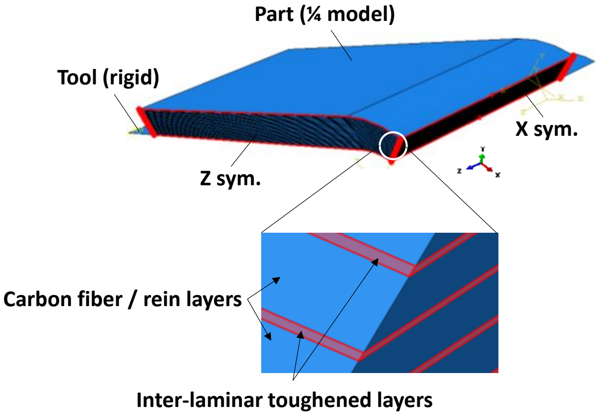


Figure 6. Finite element model of L-shaped part with inter-laminar toughened layers.

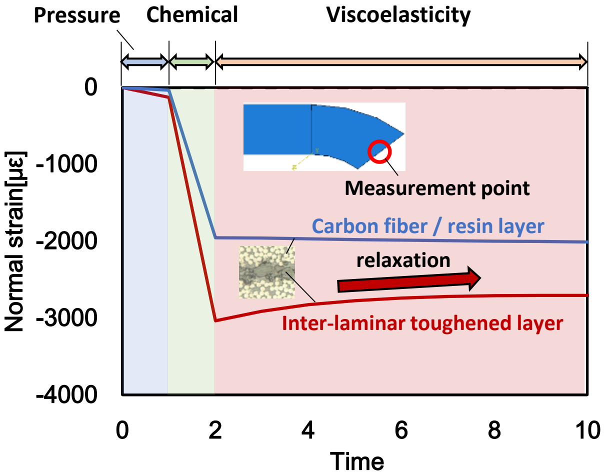


Figure 7. Through-thickness strain development at center of corner part.

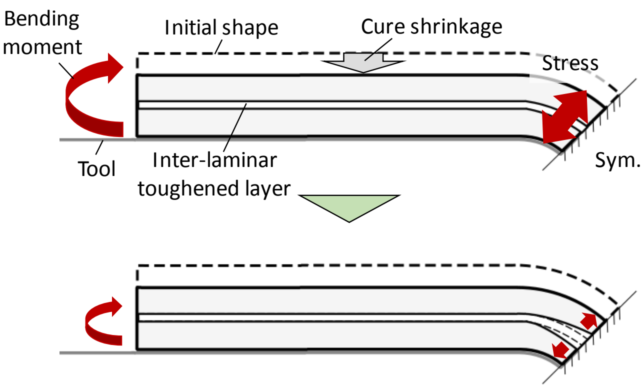


Figure 8. Spring-in deformation mechanism of L-shaped part with inter-laminar toughened layer.

4. Conclusions

This study conducted fiber-optic-based internal strain measurement and residual deformation evaluation of L-shaped parts with interlaminar toughened layers. The through-thickness cure shrinkage strain at the corner part relaxed and the spring-in angle decreased by holding the parts at the cure temperature, implying that viscoelasticity of the thermoplastic particles plays an important role. Viscoelastic finite element analysis supported this finding and the results obtained indicated that the effect of toughened layers on the residual deformation should be taken into account to determine the optimized cure process.

Acknowledgments

This study was supported by SIP (Cross-ministerial Strategic Innovation Promotion Program) – SM4I (Structural Materials for Innovation) by the Council for Science, Technology and Innovation (CSTI), Japan.

References

[1] Radford D.W, R.J. Diefendorf. 1993. “Shape instabilities in composites resulting from laminate anisotropy.” J. Reinf. Plast. Compos., 12(1):58-75.
[2] Wisnom M.R., K.D. Potter, and N. Ersoy. 2006. “Shear-lag analysis of the effect on thickness on spring-in of curved composites” J. Compos. Mater., 41(11): 1311-1324.
[3] Takagaki, K., Minakuchi, S., & Takeda, N. (2017). Process-induced strain and distortion in curved composites. Part II: Parametric study and application. Composites Part A: Applied Science and Manufacturing, 103, 219-229.
[4] Albert C., and G. Ferlund. 2002.“Spring-in and warpage of angled composite laminates.” Compos. Sci. Technol., 62(14):1895-1912.
[5] Niwa, S., Takagaki, K., Minakuchi, S., & Takeda, N. (2015). Cure shrinkage monitoring and process analysis of CFRP laminates with interlaminar-resin layers. Journal of the Japan Society for Composite Materials, 41(5), 168-175.