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Process-Induced Deformations on Composite L-Shaped Part: Numerical Prediction and Compensated Mould Design

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Abstract. This work investigates the formation and control of residual deformations in composite L-shaped parts manufactured by autoclave curing. An experimental study is first conducted to characterize spring-in for different stacking sequences. Dimensional measurements are performed using stereo digital image correlation to quantify spring-in and to assess the presence of warpage along the flanges. A numerical study is then carried out to develop a simulation method for process-induced deformation prediction. The influence of the main mechanisms involved is analyzed, and a modeling strategy for the tool-part interaction is proposed. Finally, compensated mould design is addressed. The convergence of the optimization problem is investigated, and an optimized mould geometry is determined for each part considered in this study.

Introduction

Composite materials play a key role in the aerospace industry. They account for more than 50% of the mass of modern commercial aircraft and constitute a large proportion of primary structural parts. In this context, reducing manufacturing costs represents a major industrial challenge [1]. The total cost of high-performance composite structures is strongly linked to the manufacturing process. Beyond raw material costs and the autoclave curing cycle [2], mould design and manufacturing represent a significant expense. Indeed, the fabrication of composite parts inevitably leads to the development of residual deformations, which generate spring-in and warpage of the part and may compromise geometric tolerances [1].

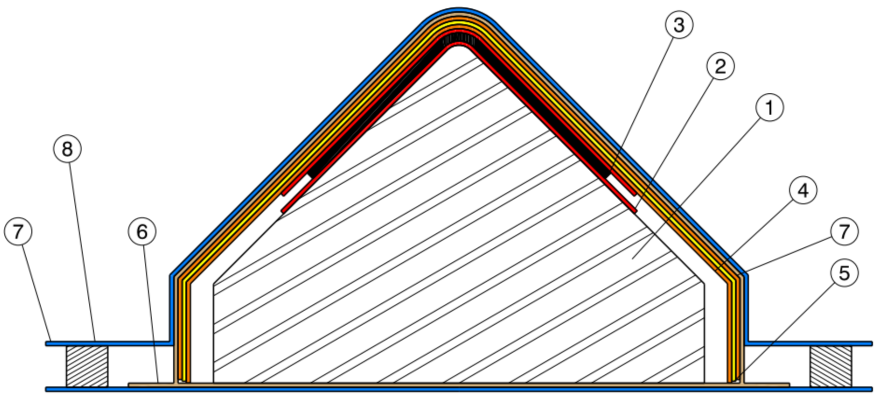
The autoclave curing of thermoset composite parts involves multiphysics mechanisms due to the polymerization of the resin in a constrained environment [3], [4]. The heterogeneous nature of the composites generates intrinsic residual stresses [5]. The main mechanisms involved are thermal expansion, chemical shrinkage of the resin [6], and the development of thermal gradients during the cure [7]. In addition, the part interacts with the mould, release films, and peel plies under the autoclave pressure. These phenomena are referred to as extrinsic mechanisms. The main extrinsic mechanism is the tool-part interaction [8], which plays a significant role for thin composite parts [9]. Depending on the manufacturing method used process-induced deformation can be linked to other phenomenon as shown for example in refs. [13, 14] with pultruded L-shaped composites.

As a consequence, the final geometry of a composite part never exactly matches that of the mould. To address geometrical tolerances, the best way is to design a compensated mould [10]. This designing process can be time-consuming and costly, as it often relies on successive experimental trial-and-error iterations. In a competitive industrial environment, reducing the number of experimental iterations is a key objective [1]. To this end, a digital mould design method must be implemented, and accurate numerical tool has to be developed. The objective of this study is to develop a numerical method for the design of a compensated mould for composite L-shape parts, with a particular focus on spring-in compensation.

The paper is organized as follows. First, the experimental study of process-induced deformations is presented. Then, the numerical methodology for predicting residual deformations is detailed and validated. Finally, a compensated mould design approach is introduced, and the convergence of the associated optimization problem is studied.

Experimental Study of Process Induced Deformations

The first part of this work focuses on the experimental investigation of residual deformations in composite L-shaped parts. Two stacking sequences are considered: $[0,90]_{2s}$ and $[0,90]_{4s}$. The material used is a unidirectional carbon/epoxy prepreg (AS4/8552). The L-shaped parts have dimensions of 150 x 50 mm, with a fillet radius of 2 mm. The vacuum bagging is illustrated in Figure 1.



1 - Aluminium mould	2 - Peel ply	3 - Composite laminate	4 - Perforated release film
5 – Bleeding plies	6 - Breather fabric	7 - Vacuum bag	8 - Vacuum tape sealant

Fig.1. Vacuum bagging and mould used for this study

The aluminum mould is treated with a release agent, and two peel plies are placed on both sides of the laminate to avoid additional spring-in effects by layup asymmetry during curing. The laminate coordinate system is defined such that the x-direction is parallel to the fillet axis of the part. Curing is performed in an autoclave according to the composite manufacturer's recommended cycle. For each stacking sequence, three identical specimens are manufactured. The manufactured parts are dimensionally characterized using Digital Image Correlation (DIC). This technique provides full-field displacement measurements over the entire upper surface of the part, allowing accurate determination of the fillet radius, the spring-in value and possible warpage along the flanges. The experimental setup is shown in Figure 2 as well as the displacements measured by DIC on an L-shaped part.

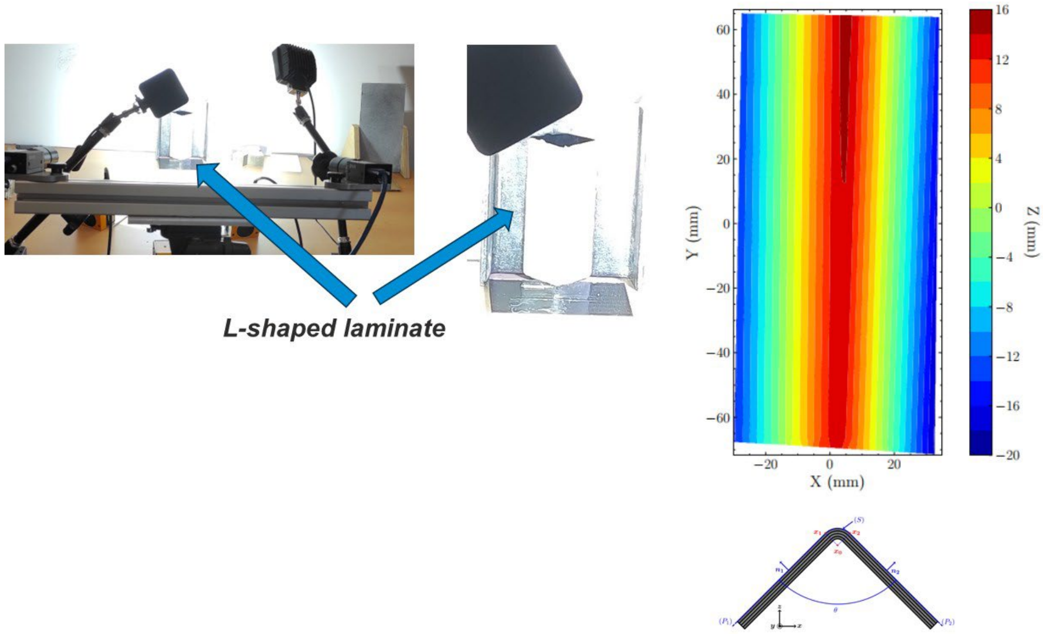


Fig. 2. Experimental setup for the dimensional monitoring. Displacements measured by DIC on a L-shaped part.

After dimensional inspection using DIC, the point cloud corresponding to the upper surface of the L-shaped part is extracted. A post-processing procedure based on a least-squares fitting algorithm is used to compute the spring-in angle and the fillet radius. Additionally, thanks to this control method, the presence of warpage along the flanges is investigated. For the parts considered in this study, no significant warpage is observed. The final geometry of the L-shaped part can therefore be accurately described by the spring-in angle only. The results are reported in Figure 3. For each part, three measurements are performed:

- With both peel plies in place,
- With only a single peel ply in contact with the mould,
- After removal of both peel plies.

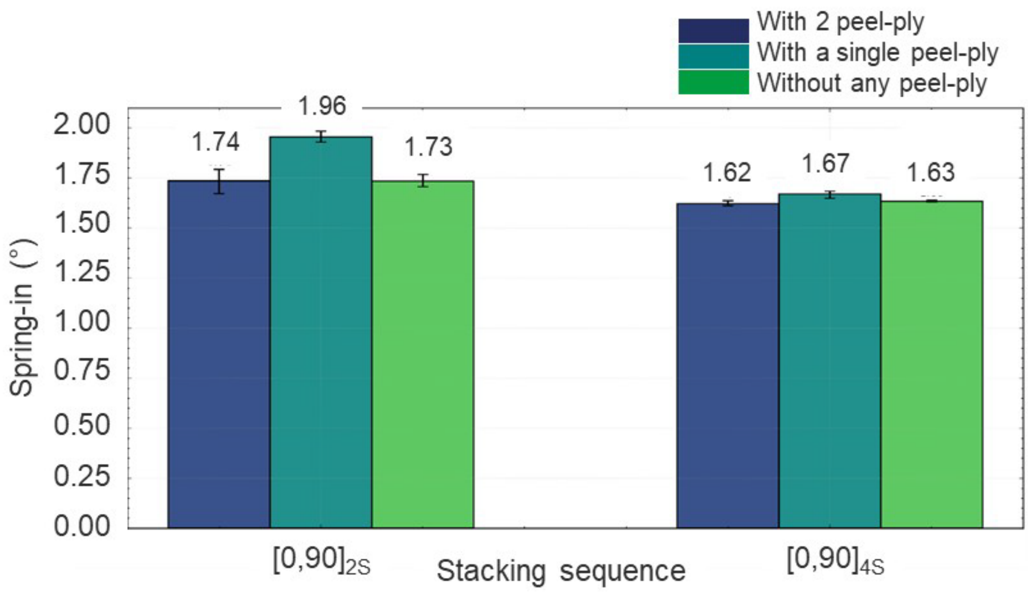


Fig. 3. Experimental spring-in angle measurements of [0,90] laminates

Figure 3 first shows that no significant difference is observed between the spring-in angle measured with both peel plies in place and the angle measured after their removal. This observation indicates that when two peel plies are placed on both sides of the part, no significant asymmetry is introduced in the shear stresses transmitted to the part under these configurations. This effect is therefore neglected in the remainder of this study, and peel plies are no longer considered. In addition, a larger spring-in angle is observed for the thinner part, highlighting the influence of part stiffness on the magnitude of residual deformations.

Numerical Study of Process Induced Deformations

Beyond the prediction of process-induced deformations, which constitutes the primary objective of this section, understanding the influence of the underlying mechanisms is essential. To this end, a progressive increase in model complexity is adopted. A first simplified model, accounting only for intrinsic mechanisms, is introduced and its limitations are discussed. The influence of the mould is then added, first by considering geometric constraint effects, and subsequently, by introducing the frictional interaction between the part and the mould. Owing to the small thickness of the manufactured parts, thermal gradients are neglected in the present modelling framework. The numerical simulations are performed using Abaqus and reproduce a portion of the vacuum bagging configuration presented in Figure 1. Based on the experimental observations regarding the peel plies, only the mould and the composite part are modelled.
The interaction between the mould and the composite part is described using a frictional contact interaction, with properties evolving as a function of the degree of cure. The curing cycle is applied uniformly to all components; therefore, no coupled thermal analysis is performed. An autoclave pressure of 0.7 MPa is applied to the upper surface of the L-shaped part. The material properties are taken from the literature [11], [12]. Resin curing is modelled using the CHILE (Cure Hardening Induced Linear Elastic) model. A known limitation of this approach is the neglect of viscoelastic effects, particularly in the rubbery stage. The CHILE model is implemented through a dedicated UMAT subroutine.
During the cure, minimal boundary conditions are applied to the mould to suppress rigid body motions. For the demoulding, the mould is removed, and isostatic boundary conditions are applied to the L-shaped part to eliminate rigid body motions without generating additional stresses. Twenty-node quadratic brick elements (C3D20) are used. The mesh is locally refined in the fillet region to accurately capture bending effects in this critical area (see Figure 4).

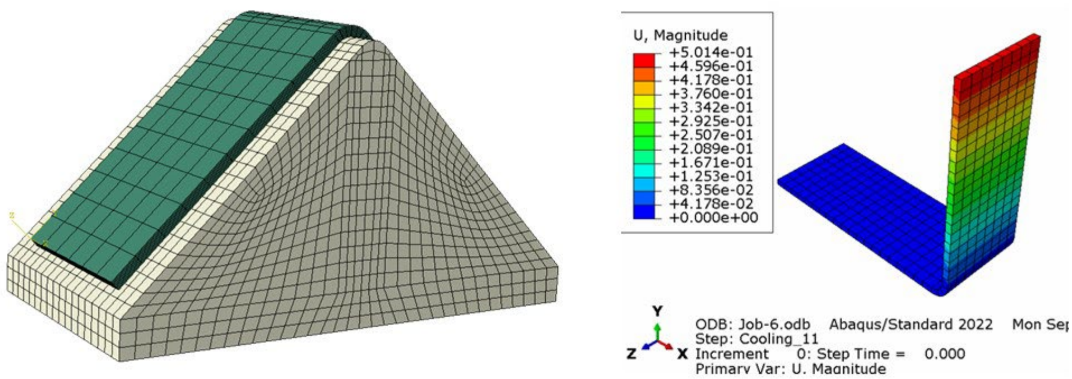


Fig. 4. Example of the numerical simulation on ABAQUS for the curing of a L-shaped laminate.

The simulation results (Figure) obtained without accounting for mould effects are first examined. Thermal deformations alone account for around 30 % and 34 % of the experimentally measured spring-in for the 8 plies and 16 plies L-shaped parts, respectively. The introduction of the chemical shrinkage significantly improves the prediction accuracy, leading to predicted values corresponding to 78 % and 87 % of the total spring-in, respectively. Nevertheless, this initial study shows the necessity of accounting for extrinsic mechanisms, in particular the autoclave pressure and mould effects such as the interactions between the mould and the part.

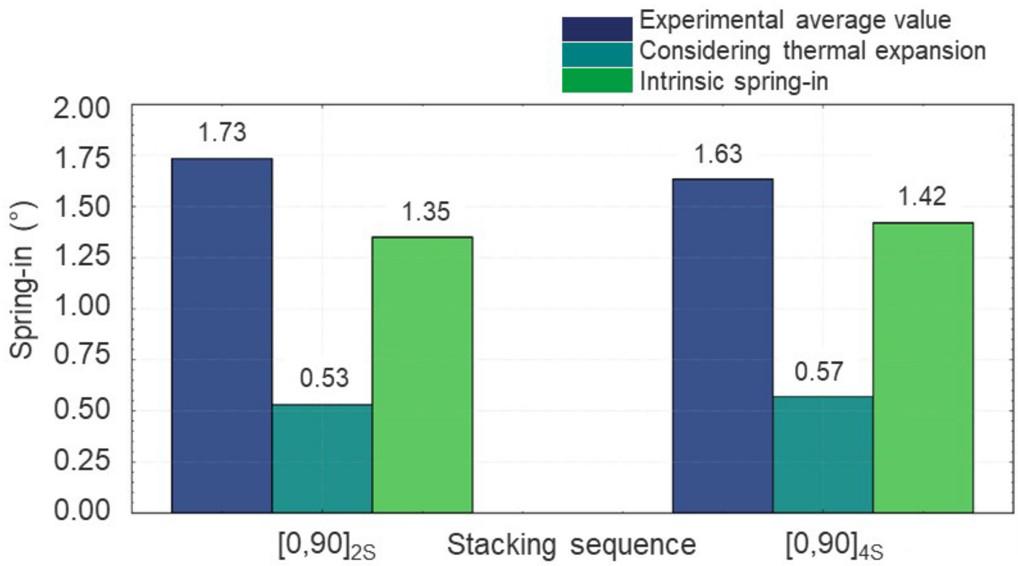


Fig. 5. Comparison between experimental spring-in values and numerical predictions accounting for intrinsic mechanisms

The mould effect is then introduced, and a first analysis focuses on the influence of the friction coefficient during the rubbery stage. Figure shows that the introduction of friction between the mould and the laminated part bottom surface leads to an increase in spring-in for both configurations. It is observed that the influence of friction becomes more pronounced as the part stiffness decreases. It can be seen in Figure 6 that calculating the spring-in angle value without considering any friction (f = 0) leads to slightly underestimated values. Using higher values of f such as f = 0.25 or f = 0.5 gives theoretical values overestimating the experimental ones. A friction coefficient of f = 0.15 provides a satisfactory prediction for 16-ply L-shaped part. In contrast, if keeping f = 0.15 for the 8-ply configuration, the spring-in is clearly overestimated. It therefore does not appear possible to identify a single friction coefficient that is numerically admissible for both configurations. This observation suggests that accounting for friction only during the rubbery stage is insufficient, and that a non-zero friction coefficient must be applied during the viscous stage.

By considering a friction coefficient of 0.1 during the viscous stage and 0.15 during the rubbery stage, the prediction is improved, with predicted spring-in angle values of 1.80° and 1.64° for 8-ply and 16-ply parts, respectively. This result indicates that shear stress transfer occurring during the viscous stage contributes to a reduction in spring-in. This behaviour is not unexpected in the present configuration, since the ply adjacent to the mould is a 0° ply, which is mainly loaded in longitudinal tension. Through Poisson's effect, transverse compressive strains are stored, which are released during demoulding and result in a reduction of the spring-in.

This numerical study makes it possible to identify a set of parameters that account for the dominant mechanisms governing spring-in and to achieve predictions consistent with the experimental results. The magnitude of the shear stresses generated at the tool-part interaction interface is consistent with values reported in the literature [11]. However, this analysis also highlights the difficulty of unambiguously identify the influence of individual mechanisms. While some mechanisms tend to increase spring-in, others contribute to its reduction, and experimental data required for parameter identification remain difficult to access. Further investigations are therefore required to improve the understanding of these mechanisms, notably by considering additional stacking sequences and different part shapes.

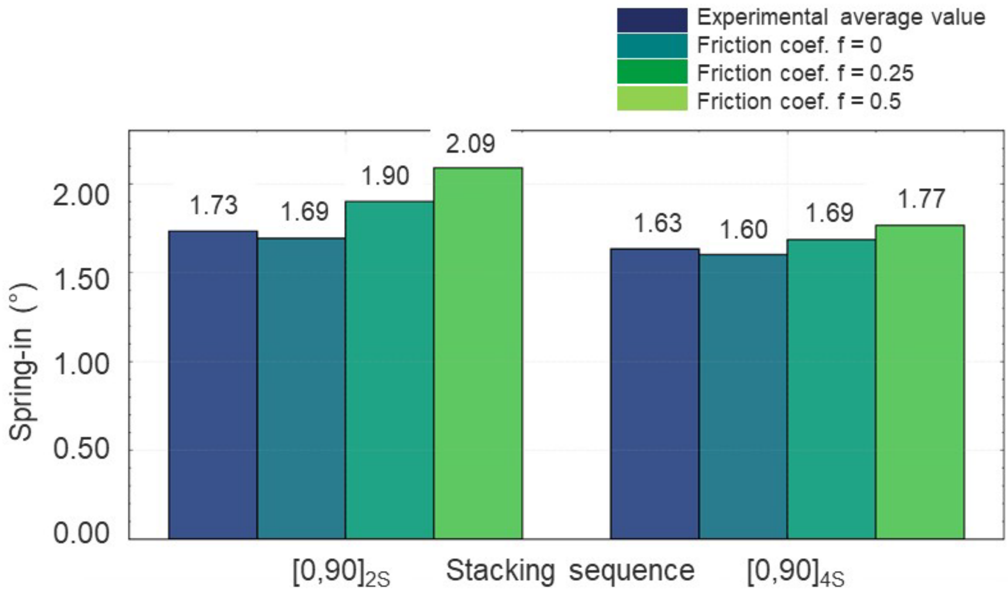


Fig. 6. Comparison between experimental spring-in values and numerical predictions including rubbery friction interaction effects

Compensated Mould Design

The validation of the prediction approach makes it possible to consider the use of the model for compensated mould design. The objective is to design the mould geometry such that the final shape of the manufactured part matches the desired geometry after demoulding. For the composite L-shaped parts in this work, this consists in determining the mould angle that leads to a final angle equal to 90°. To this end, the configuration using the friction coefficients identified as optimal in the previous section is retained. The same numerical model is employed, and the initial mould angle is parameterized in order to identify the optimal mould angle.

Figure presents the evolution of the angular error of the L-shaped part as a function of the initial mould angle. The relationship is found to be linear, indicating that the optimization problem is straightforward for L-shaped parts without warpage. Only two simulations are required to identify the optimal angle. The optimal angle is 91.83° for 8-ply, and 91.65° for the 16-ply part.

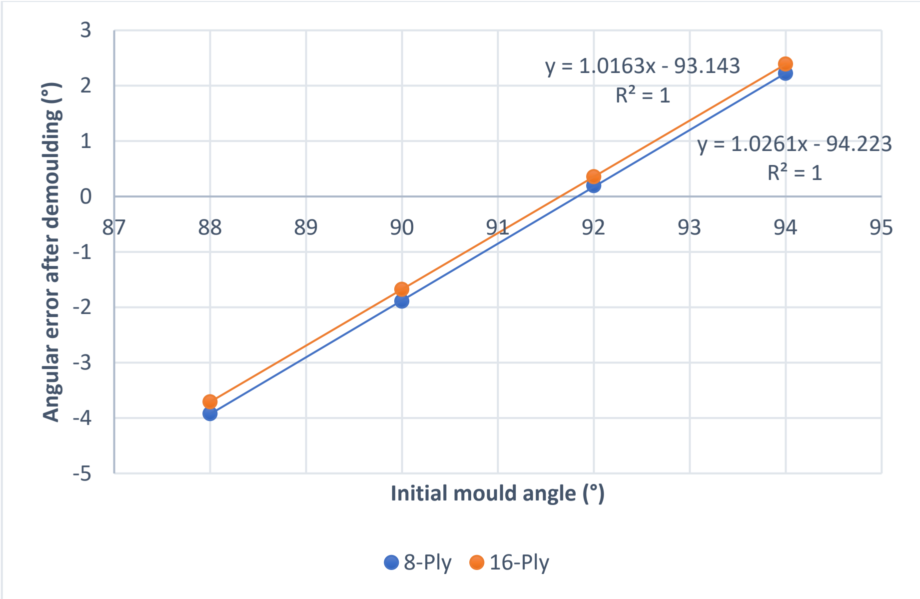


Fig. 7. Linear relationship between angular error and initial mould angle for compensated mould design

Conclusion

This study led to the development of a numerical prediction method for previously manufactured composite L-shaped parts. The progressive numerical analysis made it possible to assess the influence of the dominant mechanisms involved in spring-in formation and to identify a set of parameters allowing tool-part interaction to be accounted for. The numerical tool was then applied to the design the compensated moulds for the two configurations investigated. The convergence analysis showed that the angular error varies linearly with the mould angle.

This analysis also highlights the inherent difficulty of reliably modelling curing-induced deformation mechanisms. Some effects contribute to an increase in spring-in, while others tend to reduce it, making the individual validation of each mechanism challenging. Additional experimental investigations are required to better isolate and quantify these effects. For example, the use of male and female moulds, variations in the orientation of the ply in contact with the mould, or the study of flat laminates would provide valuable insight. A numerical approach validated over such a range of configurations could then be considered sufficiently reliable for the individual modelling of the main mechanisms.

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