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Short Communication

Compensating process-induced distortions of composite structures: A short communication

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A R T I C L E I N F O

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A B S T R A C T

Dimensional non-conformance of fabricated parts is an issue in composite manufacturing. Numerous studies have been performed, focusing on simulation-based distortion prediction. In these studies it is implicitly assumed that a simple update of the nominal tool shape leads to parts in nominal shape. However, unsatisfactory little effort has been spent to prove this assumption experimentally.

The present paper reports on the experimental validation of a prediction-based tool compensation process for an integral box structure which showed a complex distortion behavior in an earlier study. The nonlinearity of a spring-in compensation is analytically demonstrated and its relevance is discussed.

1. Introduction

“Composite parts never have the same dimensions as the tool on which they are processed” [1]. This holds true for autoclave, closed-mold and out-of-autoclave fabrication techniques. The sources for this behavior have been addressed in several studies [2–8]. A good distinction is provided by Albert and Fernlund [5] who separate into intrinsic and extrinsic sources. The relevance of the latter is limited to certain parts, processes and tool configurations. In contrast intrinsic sources are material related. They occur inevitably and need to be considered early on in the part design for any composite product.

The present paper focuses on spring-in, representing an intrinsic, material-related phenomenon and uses it to outline the nonlinearity of the compensation process. Fig. 1 illustrates the typical scenario often experienced in practice, where the shape of a manufactured composite structure deviates from the tool it was processed on. In early studies on the topic, Radford [4] and later Nelson and Cairns [3] provided the following analytical relation to describe shape changes of circularly curved composite sections as a function of strains and the initial section angle, as the composite is considered as a homogeneous orthotropic media.

$$\Delta\varphi_{specimen} = \frac{\varepsilon_T - \varepsilon_R}{1 + \varepsilon_R} \cdot \widetilde{\varphi}_{specimen} \tag{1}$$

Even though recent studies show that this equation does not capture all relevant aspects, as for example the effect of part thickness and laminate stacking [9,10], it allows for a quick assessment. One can directly see that inhomogeneous strains $\varepsilon_T \neq \varepsilon_R$ lead to distortion $\Delta\varphi \neq 0$.

They are a result of the ply-based laminate architecture which induces a globally anisotropic material behaviour. In-plane properties of the composite are dominated by the fibers while through-thickness properties are dominated by the resin. Volumetric resin cure shrinkage and the resin’s high thermal expansion lead to inhomogeneous strains in the different material directions, which in turn induce distortions (see Eq. (1)). As distortions occur inevitably they need to be accounted for within the design process in order to avoid assembly issues and costly and time-consuming iterative tool-rework loops.

2. Tool compensation procedure

Compensating the tool geometry is considered the most promising way to address the issue within today’s CAE supported part development processes, even though other approaches, such as local layup variations [4] or the avoidance of curved composite sections [5] have been suggested in the literature as well.

The phrase ’compensation’ is used here as a synonym for a target-oriented modification of the tool’s functional surfaces, in a way, that occurring material- and process-induced distortions (PID) are compensated by this geometrical modification. In an ideal design process, the following six- step procedure should be applied in order to produce composite parts which fulfill tight dimensional tolerances.

1. Design the part in nominal dimensions
2. Perform PID analysis
3. Feed results to CAD model and compensate the part
4. Design the tool based on the compensated part shape

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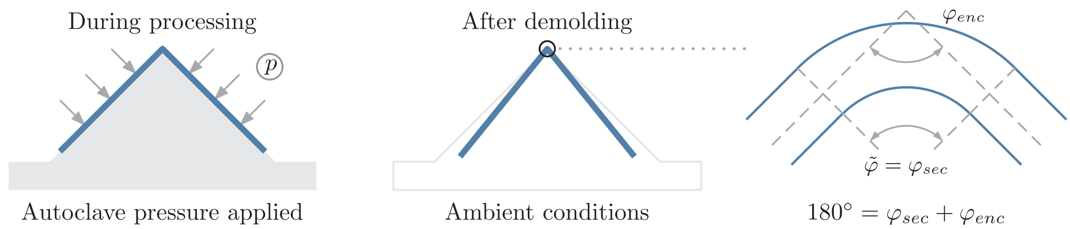

Fig. 1. Spring-in distortions appear after demolding. The relation between the enclosed angle (flange-to-flange) φ_{enc} and the section angle φ_{sec} is shown more detailed on the right.

5. Manufacture the part on the compensated tool
6. Demold a part in nominal shape

Thorough screening of the literature on the topic reveals a significant disproportion. A considerable number of studies has been performed focusing on the simulation-based prediction of process-induced distortions of composite structures. Svanberg [11,12], Wucher et al. [13], Garstka [6] and Hartmann [14], for example, focus on distortions of straight and curved frame structures with C- and I-shaped cross section profiles. Brauner [15] focuses on a long and slender complex integral flap structure. Fernlund et al. [16,17] focus on a fairing and a door structure which are composed of monolithic and sandwich zones. Fiorina et al. [18] focuses on a CFRP rib structure, coming from a recent Airbus A350 design. Liebisch et al. [19] performed probabilistic analyses in order to assess the effect of input-parameter scattering on the final part shape. Kappel et al. [20,21] focuses on process-induced distortions of different integral stiffened panels and an integral composite box structure.

The studies provide valuable insights and outline complex distortion modes for the investigated composite components. Many of the studies conclude with a comparison of predicted distortions and experimentally obtained ones, while more or less satisfying results were found.

However, with respect to the six-step procedure, outlined above, predicting PID represents only a fraction of the compensation task. Knowing how to implement the result into the tool design process and being sure that a compensation, based on this knowledge, will end up successful is the even more important fraction. Wucher et al. [13] provide a guiding statement in their conclusions: "The approach still needs to be validated experimentally".

The present paper addresses this directly by providing an additional example for the application of a simulation-based compensation procedure. In the literature, only two similar studies have been identified, wherein the whole six-step compensation process is performed. In Kappel et al. [24] the authors performed a simulation based-tool compensation for a linearly extruded stringer geometry. The compensated mold has been designed based on predictions derived with the phenomenological-numerical simulation technique, which is denoted as P-approach [22]. Evaluations of the manufactured stringers proved their excellent dimensional conformance. Given geometric tolerances were fulfilled and distortions were compensated almost completely. The same approach has also been used to update the tool geometry for the C73 frames, which are components of the MAAXIMUS shell demonstrator structure [23]. Evaluations of manufactured parts revealed satisfying quality as well, while shim-free assembly could be achieved.

The present paper reports on the simulation-based tool compensation for the integral box structure, which has been in focus of an earlier study [20]. In comparison to the aforementioned studies [22–24] the prepreg-made box structure represents a use case, with a more complex distortion behavior, which necessitates a full 3D tool compensation. In theory, the compensation of process-induced distortions is a nonlinear problem, a fact which often remains disregarded. The sources for this nonlinearity are analytically derived hereafter and their relevance is discussed with respect to the structure at hand. A compensated tool has been designed and fabricated based on simulation results and two box structures have been manufactured subsequently. Their manufactured shapes are subject of the following evaluation.

3. Nonlinearity of tool compensation

The compensation of spring-in for composite structures is a non-linear problem. Here is why! – According to Eq. (1), the ratio of the angle change of a circular arc and its initial enclosed angle $\Delta\varphi_{specimen}/\widetilde{\varphi}_{specimen}$ is defined by the anisotropic strains acting in tangential (in-plane) and radial (through-the-thickness) directions. Thus, a change of the enclosed angle $\widetilde{\varphi}_{specimen} \rightarrow \widetilde{\varphi}_{comp}$ will induce a change in distortion magnitude $\Delta\varphi_{specimen} \rightarrow \Delta\varphi_{comp}$ as shown by Eq. (2). In short: Different geometries produce different amounts of spring-in!

$$\frac{\Delta\varphi_{specimen}}{\widetilde{\varphi}_{specimen}} = \frac{\Delta\varphi_{comp}}{\widetilde{\varphi}_{comp}} \tag{2}$$

The section angle for the compensated part is derived based on the predicted or measured specimen's distortion $\widetilde{\varphi}_{comp} = \widetilde{\varphi}_{specimen} - \Delta\varphi_{specimen}$. Hence, the corresponding distortion of a part manufactured on the compensated tool is derived to

$$\begin{aligned} \Delta\varphi_{comp} &= \frac{\Delta\varphi_{specimen}}{\widetilde{\varphi}_{specimen}} \cdot (\widetilde{\varphi}_{specimen} - \Delta\varphi_{specimen}) \\ &= \Delta\varphi_{specimen} - \frac{\Delta\varphi^2_{specimen}}{\widetilde{\varphi}_{specimen}} \\ &= \Delta\varphi_{specimen} - D \\ &= \Delta\varphi_{specimen} \cdot \left(1 - \frac{\Delta\varphi_{specimen}}{\widetilde{\varphi}_{specimen}}\right). \end{aligned} \tag{3}$$

A quadratic relation between $\Delta\varphi_{comp}$ and $\Delta\varphi_{specimen}$ is found. It allows for the cognition that a part manufactured on a compensated tool will always produce smaller distortions than an identical part cured on an uncompensated tool, as it is illustrated in Fig. 2.

By definition, the part's section angle after manufacturing φ_{part} equals the sum of its initial section angle $\widetilde{\varphi}_{part}$ and its spring-in angle $\Delta\varphi_{part}$. Thus, for an L-profile with a distortion of 1.5° it is found that the section angle after manufacturing is smaller than the intended 90°.

$$\begin{aligned} \varphi_{part} &= \widetilde{\varphi}_{part} + \Delta\varphi_{comp} \\ &= (\widetilde{\varphi}_{specimen} - \Delta\varphi_{specimen}) + \left(\Delta\varphi_{specimen} - \frac{\Delta\varphi^2_{specimen}}{\widetilde{\varphi}_{specimen}}\right) \\ &= 88.\,50° + 1.\,475° = 89.\,975° \end{aligned} \tag{4}$$

The applied compensation measure overcompensates the distortion. When instead, the observed nonlinearity is considered and the initial section angle of the part is derived to $\widetilde{\varphi}^*_{part} = \widetilde{\varphi}_{specimen} - \Delta\varphi_{specimen} + D$ the compensation can be improved.

$$\begin{aligned} \varphi^*_{part} &= \widetilde{\varphi}^*_{part} + \Delta\varphi^*_{comp} \\ &= \widetilde{\varphi}^*_{part} \cdot \left(1 + \frac{\Delta\varphi_{specimen}}{\widetilde{\varphi}_{specimen}}\right) \\ &= 88.\,525° + 1.\,47542° \\ &= 90.\,00042° \approx 90.\,00° \end{aligned} \tag{5}$$

The section angle of the part after manufacturing derives to 90.00°, which corresponds to the aim of compensating distortions completely.

The observed difference D between the initial compensation $\Delta\varphi_{specimen}$ and the distortion of a specimen manufactured on the