Process-induced distortions in CFRP manufacturing: A bottleneck for high-rate production scenarios

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Undesired process-induced distortions (PID) are an inherent issue in today's CFRP manufacturing scenarios. Distortions are inevitable due to an interaction of composite-specific and process-specific parameters. In academia it is distinguished in three main phenomena Spring-in, Warpage and Forced-interaction while their specific relevance depends on the part shape at hand. As process distortions remain widely unconsidered in current partdevelopment chains, they induce considerable difficulties and costs in assembly. Time consuming rework of tools and manual shimming becomes necessary what adulterates efficient automated assembly processes.

Consequently, industry demands for reliable prediction capabilities in order to overcome today's experiencebased compensation strategies and to end up with a sophisticated design process.

In particular, efficient approaches are demanded in industry, which are able to predict PID with satisfying accuracy while their application should be as close as possible to industrial practice. The present paper introduces the acting mechanisms inducing PID, while comments on their technical relevance are given. Subsequently, a novel phenonumerical simulation strategy that focuses on PID is compared with state-of-the-art process simulation. The phenonumerical simulation strategy promises significant advantages in terms of reduced modeling and characterization efforts as available models from structural analysis (SA) can be used to predict PID.

Introduction

World-wide aviation traffic is predicted to increase about 4-5% per year [1] while even higher growth rates are announced for Asia and the Middle East. Boeing and Airbus react to this trend and announced a significant 'ramp up' of their production rates for next-generation aircrafts. High-rate scenarios, aiming towards 50 aircrafts per month, need to be realized in order accommodate the growing demand.

This challenge is accompanied by an even more challenging aim of reducing CO_2 emissions about 75% as formulated in Flightpath2050 [1]. Lightweight design and in particular the full utilization of high-performance CFRP materials can contribute to achieve those aims. In particular, realizing more integrated structures, such as integral frames for example, lead to a direct weight reduction of the overall structure as thousands of rivets can be saved. Even more important, the reduction of riveting efforts by reducing the number of parts shortens the assembly time and corresponding costs. Thus, an acceleration of the overall process chain can be achieved. This is necessary as high-rate production implies high-rate assembly.

Nowadays, as illustrated in Figure 1, the assembly process often decelerates the overall CFRP process chain as undesired process-induced distortions need to be compensated manually by shimming. Those PID are an inherent issue in composite manufacturing.

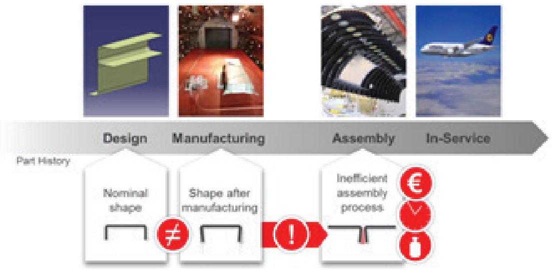


Fig.1: PID impede the overall CFRP process chain

The composite's through-thickness anisotropy and the manufacturing boundary conditions are sources of those undesired deviations between the nominal design and the manufactured part shape.

In summary PID are inevitable for laminae-based CFRP structures.

Consequently, there is a strong demand for prediction capabilities in industry which can be beneficially utilized and integrated into existing part-design processes.

Figure 2 depicts a sophisticated part-development chain, which combines structural analysis and process simulation.

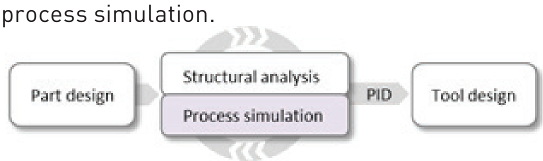


Fig. 2: A sophisticated design process considers PID as early as possible

The ability to predict PID with satisfying accuracy at an early state of the overall design process enables the derivation of tool-compensation measures while no prototype information is necessary. This represents another indirect cost-saving potential as cost-intensive prototypes and time consuming tool rework loops can be saved.

Relevant mechanisms

According to the definition of Fernlund [2, 3] the sources of PID are divided into intrinsic and extrinsic. Former ones are driven by the composite's constituents, resin and fibers, while latter ones are driven by external affectations, such as the tool properties or the bagging arrangement. In academia it is distinguished in three different mechanisms Springin, Warpage and Forced-interaction [4, 5]. Figure 3 depicts the acting phenomena, their characteristic distortion modes and specific sources.

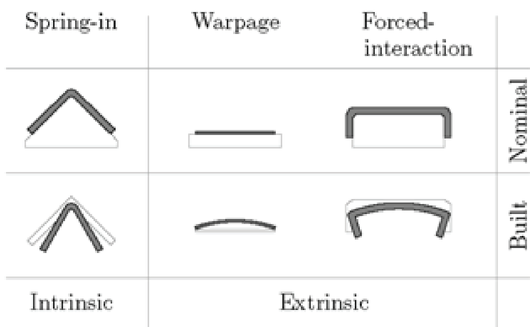


Fig.3: Phenomena inducing PID and their sources

Spring-in is an intrinsic source as it is mainly driven by the resin's considerable chemical shrinkage [6, 7] and its high thermal expansion compared to the fibers. Warpage and forced-interaction are extrinsic sources. Both are typical-ly driven by a mismatch of thermal expansion between the tool and the composite material. Warpage is driven by a friction connection be-tween the part and the tool, while the Forced-interaction is driven by form closure. Experiments show that Warpage is relevant for thin laminates fabricated with single-sided tool concepts only [3, 8]. In contrast, Forced-interaction affects thin as well as thick laminates [4, 5].

Technical relevance

From an industrial point of view Spring-in is the most relevant phenomenon as it affects all non-flat composite structures and even composite toolings no matter whether they are manufactured with prepreg, RTM or out-of-autoclave techniques. While Warpage is less relevant due to its limitation to flat and thin laminates, Forced-interaction can induce considerable part distortions even for comparably thick laminates [4].

However, it must be remarked that Forced-interaction hasn't been in focus of experimental studies available in the literature. Therefore, the DLR currently performs an experimental study that accounts for the essential parameters laminate thickness and layup. High scrap rates and even the necessity to manufacture new toolings are the consequences of PID nowadays.

Prediction via simulation

Due to the inevitability of PID in composite manufacturing considerable effort has been undertaken in recent years to develop process-simulation (PS) tools accounting for the complex physical processes of the CFRP manufacturing process [7, 9, 10, 12, 15, 17].

On the one hand, those comprehensive models claim increased accuracy due to the multiplicity of considered physical effects. On the other hand, complex models typically require increased com-putational, characterization and in particular modeling efforts.

In industry the manufactured shape of a composite structure is of particular importance. Its knowledge can be beneficially used to improve manufacturing processes. Tool compensation measures can be derived prior to the first prototype is manufactured. Moreover, assembly efforts or required shimming can be assessed at an early state of the part development chain. Recalling the challenges of high-rate production, considerable cost-saving potential is related to PID.

The department Composite Design of the DLR Institute of Composite Structures and Adaptive Systems picked up this challenging task and pursues a twofold strategy. On the one hand, experimental studies are performed to further characterize the acting mechanisms in order to increase confidence and establish profound knowledge of the main drivers. In parallel, efficient simulation strategies are in scope which focuses on PID while their application is close to industrial practice.
As outlined in the following section, a pheno-numerical simulation strategy turned out to be a promising concept to overcome limitations and disadvantageous mannerisms of state-of-the-art process-simulation tools.

Exemplary C-profile use case

Figure 4 shows a set of CFRP C-profiles which serve as an example to outline advantages and shortcomings of the different simulation ap-proaches.

Fig.4: CFRP C-profile specimens manufactured with single-sided tool concept

Due to nature of CFRP parts, which are commonly thin and/or slender, shell-element models are used within the structural analysis while radii are seldomly modeled discretely. Figure 5 shows a representative structural model of the C-profile as it is typically used in industry.

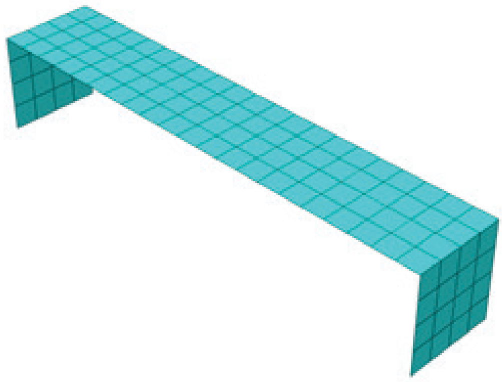


Fig. 5: Typical structural analysis model of the C-profile structure in focus

State-of-the-art process simulation

The resin undergoes complex state changes during the curing process. Hence, material models of the resin have been in focus in academia. [10, 11, 12, 13]. Typically, state-of-the-art (SoA) PS utilizes a sequential simulation process while a thermo-chemical analysis is followed by a stress-deformation analysis. Those models are called incremental. However, even full viscoelastic material models of the resin have been developed as outlined in [14].

The typical dependencies within the simulation are indicated by the following expression.

$T(t) \rightarrow \alpha \rightarrow V_f \rightarrow \varepsilon \rightarrow \sigma_{res} \rightarrow \Delta\varphi$

Therein, $T(t), \alpha, V_f, \varepsilon, \sigma_{res}, \Delta\varphi$ denote the temperature profile of the manufacturing cycle, degree of cure, fiber-volume fraction, strain on ply level, residual stress and part deformation, respectively.

In summary, SoA process-simulation models provide information on fiber-volume fraction, degree of cure, residual stress and finally part deformation. Nevertheless, it should be noted that a selective output of only one of those parameters, for example part deformations, is not possible due to their direct dependence on each other.

Figure 6 shows a representative process-simulation (ComPro CCA) model for the single-sided manufacturing strategy of the C-profiles in focus while the degree of cure at the end of the process is illustrated.

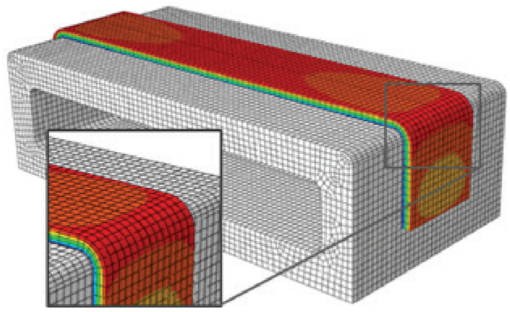


Fig. 6: Thermo-chemical model of the C-profile in ComPro

As curing induces strain in the in-plane and through-thickness directions, solid-element mod-eling is mandatory within process modeling. Moreover, discrete radii need to be modeled in order to calculate PID as those are driven by a strain mismatch between the in-plane and the through-thickness direction [6]. In addition, commonly the tool geometry needs to be modeled in order to consider effects of an inhomogeneous temperature distribution or specific heat-conduction properties of the tool (metal, CFRP). When comparing Figures 5 and 6 it is obvious that extensive modeling is necessary to set up a process-simulation model based on a shell-element-based model available from the structural analysis. Although this step can be supported by scripting, it remains a labor-intensive step when it comes to full-scale parts of complex geometry.

For tasks which predominantly need information on PID, such as the tool design or tool compensation for example, PS-related effort is disproportional. Even for the part design, the number of necessary parameters and the considerable modeling hampers a wide application of PS. Detrimental aspects of SoA tools from an industrial point of view are:

- Extensive modeling is necessary to transfer structural models to adequate process-simulation models (shell->solid)

- Resin- and fiber-specific material parameters need to be characterized
- Model-size limitations due to aspect ratio limitations of solid elements
- Disproportional calculation times due to transient modeling

Pheno-numerical approach

As outlined before, the DLR strives for simulation strategies which predict PID with satisfying accuracy while their application should be as close as possible to industrial practice. Figure 7 illustrates the aim of the proposed strategy. In particular, a significant reduction of modeling and parameter efforts is aspired.

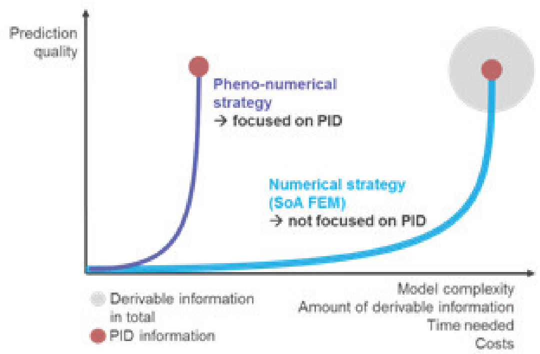


Fig. 7: Cost-saving potential of a pheno-numerical strategy accounting for PID

The pursued strategy is called pheno-numerical as phenomenological parameters, such as L-profile distortions are used as input variables. The analytically transferred parameters are afterwards used in combination with conventional numerical models utilizing linear-elasticity. This is in contrast to SoA process-simulation tools which demand fiber- and resin specific material characterization. The validity of this approach is supported by findings of comprehensive experimental studies on L-profile level [3,16] which reveal a direct dependence between relevant processing parameters of a part and obtained distortions after manufacturing. Thus, the measured process-induced distortion of an L-profile $\Delta\varphi=\tilde{\varphi}-\varphi$ is representative for a certain manufacturing scenario [16] as it is indicated in Figure 8. Investigations on geometrical scattering of part's PID support this thesis as low scattering is observed.

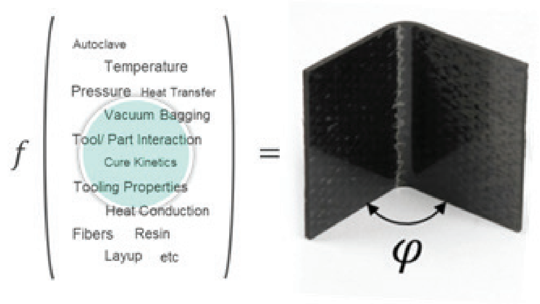


Fig. 8: Fabricated part shape depends on all manufacturing parameters

However, each simplifying approach is based on simplifying assumptions. The pheno-numerical one presented here is based on the following ones.

- Manufacturing conditions of the L-profile specimens, in particular composite material, tool material and processing conditions, should be identical with the ones of the final part
- Homogeneous curing is assumed throughout the part
- Layup variations are slight and can be accounted for based on experimental knowledge

Due to the structure of the pheno-numerical approach, expectable PID of the regarded C-profile structure can be predicted utilizing the available structural analysis model shown in Figure 5. This is due to the key-fact that out-of plane distortions are generated by a target-oriented modification of in-plane strain parameters.

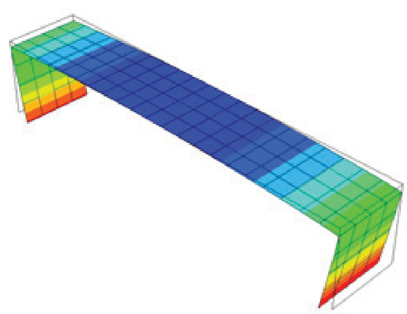


Fig. 9: PID calculated with the pheno-numerical approach utilizing the structural analysis FE model

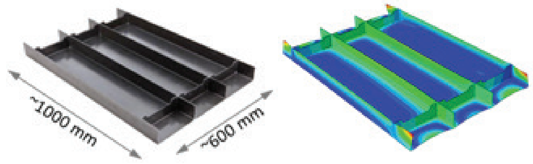
Thus, shell-element models can be used which significantly reduce modeling and computational effort.

Regarding the C-profile structure use case, the spring-in angle of a single manufactured L-profile specimen needs to be measured and analytically transferred to an equivalent simulation parameter. Other parameter-determine techniques are conceivable as well, as outlined in [4]. Within the simulation linear-elastic ply properties are used for modeling the laminate. Figure 9 shows calculated PID of the C-profile, while the manufactured part shows shape changes due to spring-in and Forced-interaction [4, 5]. However, in particular modeling of the Forced-interaction phenomenon needs further attention as this mechanism is widely uninvestigated. In particular the contribution of the tool's thermal expansion needs to be investigated thoroughly.

Shell-element and solid-element-based modeling techniques can be used in combination with the pheno-numerical strategy [4]. Thus, even parts showing severe double curvature can be modeled.

Additional application examples

It should be noted that the proposed pheno-numerical simulation strategy has already been successfully applied for the prediction of PID of an integral CFRP box structure [18]. Furthermore, PID of even more complex structures such as an integrally stiffened two-stringer and four-stringer panel have been predicted with satisfying accuracy, see Figure 10.



The applicability to structures containing double-curved areas has been verified based on comparison of solid-element-based and shell-element-based models. This has been performed for a circumferential Z-frame with varying web-heigt depicted in Figure 11.

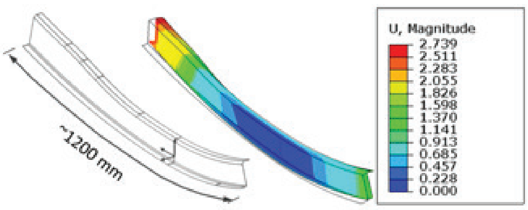


Fig. 11: PID prediction for a frame sections of varying web height, displacements are shown in [mm]

However, an experimental validation by means of comparing manufactured parts with predicted part shapes is still in progress.

Conclusion

Process-induced distortions occur inevitably when laminae-based composite structures are manufactured. Three main phenomena are distinguished in academia, namely Spring-in, Warpage and Forced-interaction.

Spring-in, which represents the most relevant phenomenon, has been investigated in multiple studies. However, industrially relevant aspects such as effects of AFP manufacturing or ply drop-offs have not been addressed satisfactorily.

While low relevance of Warpage for industrial applications has been elaborated in experimental studies, Forced-interaction is sparsely investigated, although it can be a show-stopper for relevant part geometries as frames for example.

Commercially available state-of-the-art process simulation is able to provide comprehensive process-relevant information.

However, claimed accuracy advantages in terms of prediction quality of PID have not been demonstrated satisfactorily. Moreover, necessary application efforts are high and not in-line with industrial practice.

A novel simulation-strategy focusing on PID is briefly presented in this paper. It is called pheno-numerical as it combines phenomenological pa-rameters with conventional numerical simulation. The aim of the strategy is to predict PID with satisfying accuracy while application efforts are minimized.

The potential of the pheno-numerical strategy as a tool to assist part and tool designers is elaborated based on an exemplary CFRP C-profile structure.

Summarizing it is concluded that further experimental studies on the acting PID-inducing phenomena are necessary to elevate the confidence level and to extent the phenomena-specific state of knowledge. Moreover, prediction quality of state-of-the-art numerical process simulation and the novel pheno-numerical approach should be compared to full-field measurements in order to assess prediction quality and modeling efforts in equal measure.

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