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Predicting process-induced distortions in composite manufacturing – A pheno-numerical simulation strategy

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ABSTRACT

Process-induced distortions (PID) of high-performance CFRP structures lead to problems with dimensional control if the distortions are not accounted for by compensating the process tool accordingly. There is a need to predict PID via simulation in industry rather than relying on less reliable information such as past experience or measurements on prototype structures. PID are caused by many phenomena, which can make detailed simulation complex and time consuming. This paper presents three simplified techniques for prediction of PID with sufficient accuracy but that are much faster and cheaper to run than traditional complex process models. The three techniques use solid or shell finite elements and use inputs based on measured spring-in of simple L-angles made of the same material and process conditions as the larger scale structures to be simulated. Application of the three techniques to example structures show that the predictions agree well with each other and that they give good predictions compared to experimentally measured distortions of a CFRP box. Given their speed and simplicity they have the potential to be useful for predicting PID for simpler composite structures, particularly early on in the design cycle where quick approximate calculations are of great value to evaluate different design concepts.

1. Introduction

Dimensional fidelity of manufactured carbon fiber reinforced plastics (CFRP) parts is of particular importance in aerospace and automotive industries. A lack of dimensional precision induces significant costs due to increasing assembly efforts. When high-performance structures are assembled of multiple sub-components, manual shimming is required to fill gaps between mating parts. In addition, tool redesign and rework loops induce longer lead times and deceleration of the overall process chain. There is a need in industry for fast and cost-efficient process-induced distortion (PID) prediction methodologies that can be used early in the design process to assess dimensional fidelity.

1.1. Relevant phenomena

Considerable effort has been undertaken to investigate the main driving mechanisms of PID for composite structures. Albert and Fernlund [1] distinguish between intrinsic and extrinsic sources. Intrinsic sources are resin and fibers, lay-up and part geometry, parameters that are defined by the design engineer. Extrinsic sources are directly related to the manufacturing process: tool design and tool material, or the bagging arrangement and process equipment (e.g. ovens, autoclaves and presses), and cure cycle. Extrinsic sources are generally controlled by the process engineer and can be altered without involving design engineers and/or stress analysts. Both intrinsic and extrinsic sources contribute to PID. The intrinsic ones are often dominant and determined in part design and material selection, whereas the extrinsic ones tend to be of lesser importance and can often be mitigated by modifying the manufacturing process.

Process-induced distortion is divided into three different phenomena in this paper: spring-in, warpage and forced-interaction [2,3]. Fig. 1 illustrates these phenomena, their characteristic deformation modes and their sources (intrinsic and extrinsic).

Spring-in, which is the common term for closure of angles and increase of curvature of any curved section, is mainly driven by the anisotropy of the laminate shrinkage in-plane versus through thickness. This laminate anisotropy is largely driven by the resin's considerable chemical shrinkage [3–5] and its high coefficient of thermal expansion (CTE) compared to the fibers. The distinct through-thickness anisotropy of lamina-based composites inevitably leads to PID in curved laminate areas as shown by Radford [6]. Warpage and forced-interaction are caused by extrinsic sources. Both phenomena are magnified by high autoclave pressure but

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they are typically caused by a CTE mismatch between the tool and the composite material, causing stretching of the part at tool-part interface. Warpage is driven by friction between the part and the tool, while forced-interaction is believed to be caused by mechanical interaction due to geometrical locking [3]. Experiments have shown that warpage is relevant for thin laminates fabricated with single-sided tools [7–9], whereas forced-interaction affects thin as well as thick laminates [10,11,2,3]. Forced-interaction is not well understood and has not been investigated thoroughly for structures of technically relevant laminate thicknesses. Experimental studies need to be performed to increase the confidence of the nature of forced-interaction and its effect on PID. The relevance of each PID mechanism is part specific. However, due to its intrinsic nature, spring-in represents the most critical phenomenon as it impacts almost every CFRP structure. Therefore, prediction of PID due to spring-in is the focus of this paper.

1.2. Prediction of PID via simulation

Considerable effort has been invested to develop process simulation (PS) models that account for the complex chemical and physical processes during composite manufacturing [5,12–14]. In particular, the resin has been the focus in academia [15–21] as it is the main driver of PID. Available PS tools such as COMPRO CCA, utilizes a sequential simulation process starting with a thermo-chemical analysis followed by a stress-deformation analysis [22]. Although these numerical PS tools promise high model fidelity due to the wide range of considered physical effects they have drawbacks in terms of speed and cost of simulation when used in a traditional engineering environment:

- Model set up can be time consuming, if not special automation tools are used, as surface based-design models need to be transferred into a solid-element process model.
- Resin- and fiber-specific material parameters that are not part of standard linear-elastic parameters on ply-level need to be characterized.
- Transfer of simulation results from the solid-element-based process model back to the surface-based design model or shell-element mesh can be time consuming if not special automation tools are used.
- The model-size for solid-element process-models is often very large requiring substantial computational resources and long run times.

1.3. Aim of this paper

The aim of this paper is to develop and verify an efficient PID-prediction methodology that provides sufficient accuracy while application efforts are reduced to a minimum.

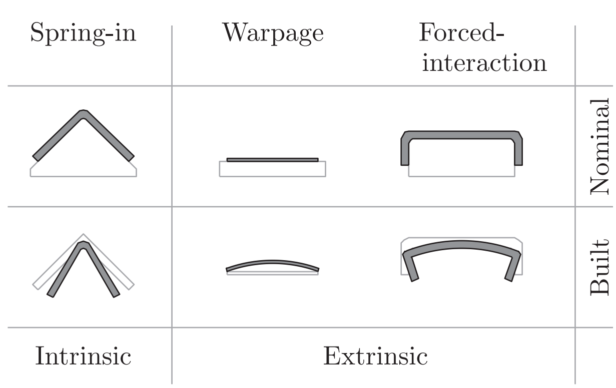

Fig. 1. Relevant phenomena inducing PID: specific deformations and sources.

To overcome the drawbacks with state-of-the art process simulation in terms of speed and cost an alternate strategy will be pursued. Comprehensive experimental studies on the spring-in phenomenon [3,25,1,23] have shown that occurring PID of laboratory-scale L-profile specimens depend on the manufacturing process, layup, tooling properties as well as the composite material itself. Thus, distortions measured on test samples can be used to characterize the spring-in phenomenon. The simulation strategy proposed in this paper is called *pheno-numerical* as it uses phenomenological parameters, in form of measured spring-in distortions of L-profile samples, as input parameters for large-scale finite-element-based numerical simulation. Within this paper this methodology is denoted with *p-approach*.

Different modeling techniques, in particular solid- and shell-element based ones, can be used in combination with the *p-approach* presented in this paper. The ability to use shell-element-based FE models for the prediction of PID has significant cost-saving potential as extensive solid–element modeling is avoided. The *p-approach* enables prediction of PID using linear-elastic numerical simulation with conventional shell elements [2,3] analogous to what is used for stress analysis in industrial practice.

The perfect PID methodology is: good (high fidelity of predictions, robust, generally applicable), fast (short set-up time, short run time, and quick processing of results), and cheap (low software cost, limited training required, low cost of input data). In order to increase speed and lower cost, some compromises have to be made in terms fidelity of predictions, robustness and general applicability. The concept of extracting and transferring deformation characteristic of an experimental L-profile sample to another more complex geometry is based on a set of assumptions:

- Manufacturing conditions, in particular composite material, manufacturing technique, tool material and bagging arrangement of the fabricated specimens should be identical with the ones of the final part.
- There are no scaling effects with extrinsic parameters.
- Homogeneous heating and curing is assumed throughout the whole part.
- Layup variations are accounted for based on experimental experience such as effect of increasing part thickness or layup modifications. Otherwise, multiple L-profiles are necessary in order to derive locally varying simulation parameters.

It should be noted that the shell-element-based modeling techniques presented in the following can potentially be combined with existing PS tools such as COMPRO CCA or Raven as indicated in Fig. 2. However, this is out of the scope of the research presented here and will be addressed in an accompanying paper.

The aims of the present paper are addressed in four main sections:

1. Extension of the shell-element-based modeling technique developed by Kappel [3] in order to apply it for PID predictions when no radii are provided by the design model.
2. Comparison of the three modeling techniques with different level of simplification for an L-profile use-case for sake of verification
3. Application of three modeling techniques to the prediction of PID for a CFRP box structure investigated earlier [2] and comparison to obtained experimental results.
4. Application of the presented modeling techniques to a circumferential Z-frame with varying web height to verify applicability to parts of realistic complexity.