# DEVELOPMENT OF A NUMERICAL APPROACH TO PREDICT PROCESS INDUCED DEFORMATIONS DURING CURE OF FIBRE-REINFORCED STRUCTURES

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**Abstract**
Shape distortions of prepreg structures occurring during autoclave curing cycles are a common problem, which often impairs the ability to achieve required manufacturing tolerances. Today, an excessive procedure of testing and reshaping of moulds is commonly used in order to compensate these deformations. To reduce the additional costs involved in this process, reliable predictive methods are required. The finite element method is commonly used as a numerical tool in a 2-step approach to predict the spring-in and warpage of structural components during autoclave curing processes. The implication of this method requires correct material properties of both steps in order to be effective. To avoid excessive experimental measurements and to increase the accuracy a new calibration method has been developed, where the best fitting set of material properties is determined by means of evolutionary algorithms. Validation of the defined method on airplane structural components show that the method can successfully be applied to practical problems with reasonably good accuracy.

## 1. Introduction

Prepreg structures usually deform during autoclave curing cycles, making it difficult to reach defined tolerances. To reduce time and costs, the currently applied procedure of testing and reshaping of moulds should be replaced by reliable predictive methods. However, prediction of the deformation magnitude is a very complex task. Whereas flat sections tend to warp, angles tend to spring-in (Fig.1). Because this research is related to curved aircraft structures with relative short flanges, the spring-in phenomenon has more impact on the final geometry and will therefore be subjected to further investigation.

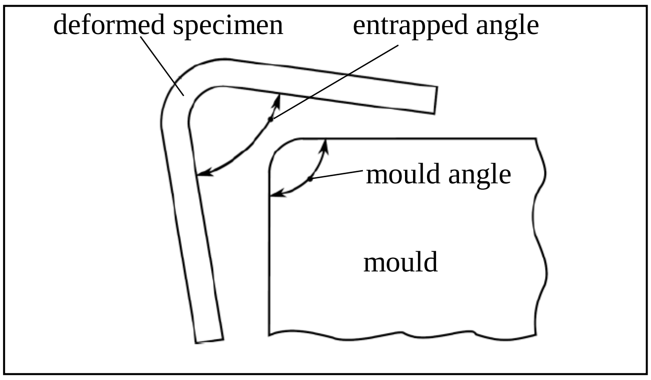


**Figure 1:** Spring-in of a 90° angular specimen

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Extensive research has already been done in order to analyse the deformation behaviour. Whereas some researchers investigated different factors influencing the spring-in behaviour, others developed methods to predict the spring-in [1-8].

The main origin for the deformations can be found in the difference between in-plain and through-the-thickness expansion properties. Although most researches confirmed that chemical and thermal shrinkage are the main intrinsic effects influencing the deformation behaviour, many suggested that other factors also play a crucial role [1,5,7]. Because most of them are linked to one and another, a predictive method including all effects is almost impossible to create. Therefore, the results of predictive methods will always deviate from the reality. The overall aim of this study remains developing a method, which is capable to predict the spring-in more accurate than current procedures.

Radford et al. [8] developed a simple analytical formula to define the spring-in magnitude, Wiersma et al. [1] came up with a visco-elastic simulation approach and Yoon et al. [5] based their approach on the classical laminate theory. Eventually, the thermo-elastic 2-step approach proposed by Ersoy [3] has been chosen for further research. This numerical method offers a fast prediction and is proven to be most accurate. To increase the accuracy and to reduce the experimental effort and costs, a new calibration process has been developed. For comparability purposes with other investigations, angular brackets have been used for this research.

## 2. The spring-in phenomenon

A typical autoclave cycle can be divided in a certain amount of phases. The amount of phases is depending on the analysed parameter (stiffness, through-the-thickness strain, ...). When analysing the degree of cure, a typical cycle can be divided into 3 phases. Each phase represents a specific matrix state of matter. Figure 2 visualises the temperature change of a typical autoclave cycle with two hold periods, showing the three phases. Because of the liquid state in phase 0, the matrix can shear freely. That means no stresses can remain in the material. During phase 1, material properties change drastically over a short time period to an almost complete cured state (gel-phase). There are multiple effects competing against each other but chemical shrinkage will dominate. As the material is in a rubber state, a thickness reduction causes stresses to occur. Because the manufactured part is still pressed onto the tool, almost no deformation is possible. This means that the stresses are frozen until phase 2 is reached. During phase 2, after the part is fully cured, the pressure is relieved allowing the part to deform freely (glass-phase). Together with the residual stresses of the second phase, thermal stresses occurring during cool down cause the part to deform.

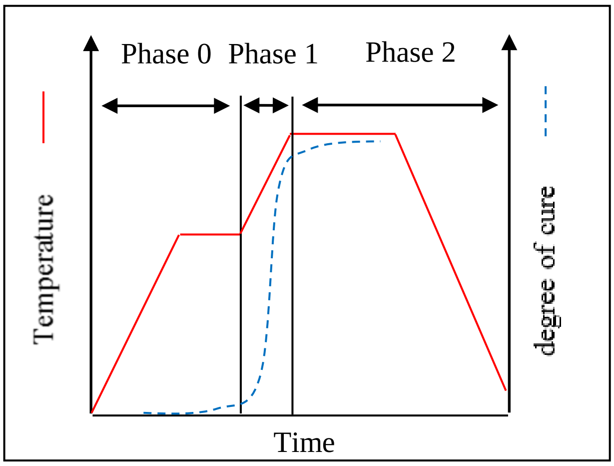


**Figure 2:** Temperature change of a typical autoclave cycle



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In contrast to the in-plane shrinkage behaviour, through-the-thickness shrinkage is strongly present. As a result, through-the-thickness shrinkage will lead to a reduction of the thickness ($t_0 \rightarrow t_{th}$), causing the outer and inner arc length ($S_o$, $S_i$) to decrease (Fig.3). Because of limited in-plain straining possibilities, a change in arc length will induce stresses that cause the part to spring-in ($\Delta\theta_{th}$).

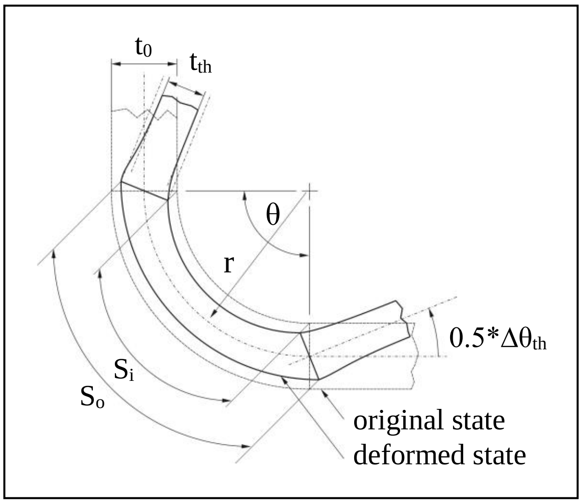


**Figure 3:** 2D visualization of the spring-in phenomenon of a simple angular specimen

## 3. Predictive method

### 3.1. Numerical approach

The finite element approach developed to predict process induced deformations is based on a 2-step method defined by Ersoy [1]. The material behaviour during cure is idealized by a step transition from a rubber to a glassy state with constant material properties in every step. The first step represents the gel-phase (phase 1). During this phase the resin properties change drastically over a very short period, obtaining enough stiffness to sustain internal stresses. The stresses imposed by the chemical shrinkage effect are frozen and transferred to the second step, which represents the glass phase (phase 2). During this phase the part cools down, causing it to shrink thermally. Stresses occurring in both phases force the part to deform as shown in figure 4**.**

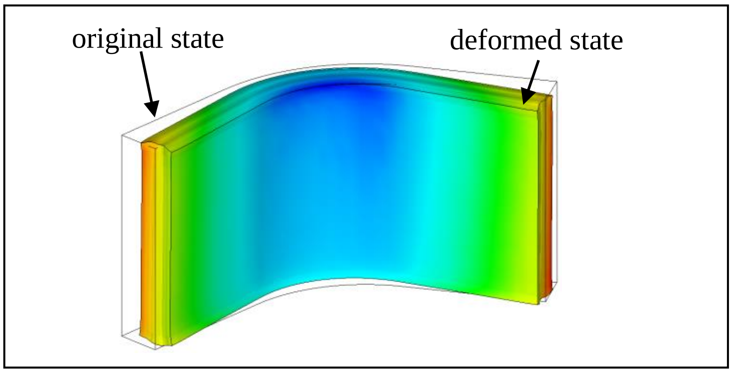


**Figure 4:** Deformation of a simple angular specimen

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In addition to the effects of chemical and thermal shrinkage, other intrinsic and extrinsic factors influence the deformation behaviour of composite parts. Temperature gradients, scatter in fibre volume fraction and differences in expansion coefficients between tool and part are examples of such effects. Experimental investigations showed that these influences are limited and are therefore not included in the numerical analyses. Taking this in mind, the simulated results will deviate from the reality. Nevertheless, these deviations could be reduced by implying a newly developed calibration method.

### 3.2. Calibration method

The numerical approach described before can only be applied when correct material properties are available. As the manufactured parts are almost fully cured during the second step, the related properties can be obtained by testing. In contrast, the material properties of the first step change continuously and are therefore much more difficult to determine experimentally. This problem is solved by applying numerical calibration instead of conducting complex experiments. The calibration process is based on a comparison of the spring-in between experimental specimens and their corresponding finite element (FE) models. Therefore, a test campaign is required that consists of simple L-shaped brackets with different angles, stackings and amount of layers.

In the first step, gel properties are randomly chosen within a predefined design range. Together with the glass properties they are fed into the finite element models of the manufactured parts. The obtained results are then compared with corresponding experimental deformations, followed by an adaption of the gel properties. Optimal properties are achieved, when the minimal average angular error between theoretical and experimental spring-in is obtained (Fig.5). The best fitting set of material properties is determined by using evolutionary algorithms, which are inspired by biological evolution and use mutation, recombination and other genetic mechanisms to optimize the properties.

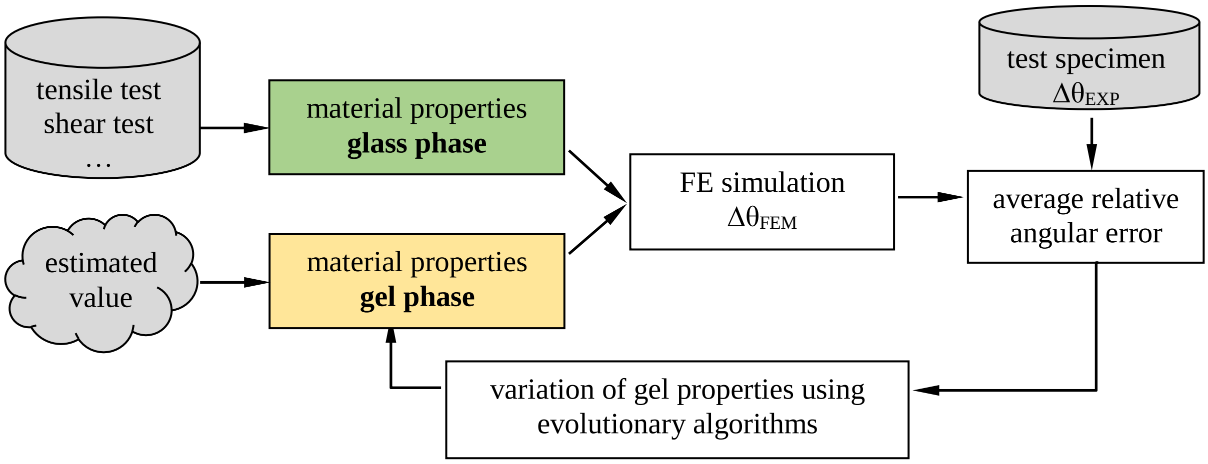


**Figure 5:** Calibration diagram

## 4. Results

### 4.1. Accuracy of calibration method

As mentioned before, only the most important factors are included in the simulation models. This means that a certain part of the spring-in effect cannot be predicted, resulting in differences between simulation and reality. In comparable studies (using similar test specimen) predicted spring-in values have a maximum deviation of 15% to 20% [1-4]. With the proposed calibration method this accuracy

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level can be considerably improved. Although only two effects were included, a maximum relative angular error of 11.2% was achieved. As the calibration technique tries to find optimal properties to reduce the relative angular error, these data will cover both known as well as unknown factors that have an effect on the spring-in. This means that portions of the spring-in angle, which can be attributed to other intrinsic effects, are compensated by adapting the properties. As a result, the obtained properties are no real physical material data but more like simulation parameters.

### 4.2. Validation of the prediction method

To validate the practical applicability of the developed 2-step approach together with the obtained simulation parameters, a real aeronautical structure was analysed. The part is a doubly curved L-shaped stiffener, fabricated for integration into an aircraft (Fig.6). The spring-in results obtained from the numerical analysis only deviate 3.2% from the averaged measured spring-in angle, proving the effectiveness of this method.

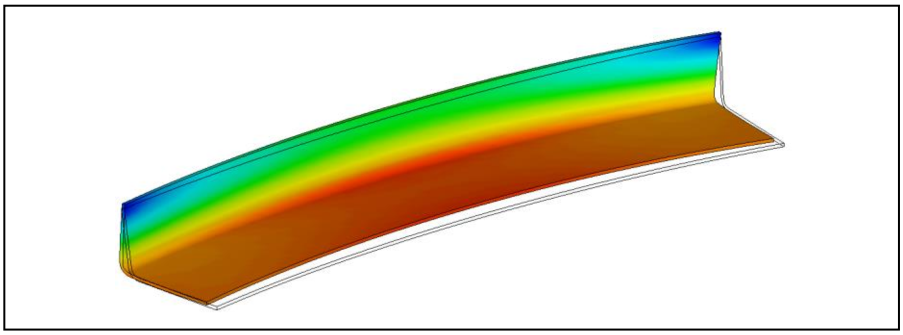

**Figure 6:** Deformation plot of curved L-shaped part

## 5. Conclusion

The outcome of this research shows that by using the described process, the spring-in of complex structures can be predicted very accurate, fast and without excessive experimental effort.

By calibrating optimal simulation parameters, also non explicit physical effects are taken into account, which increases the global prediction accuracy. To perform such a calibration, only a small amount of angular specimens is required. As a result, the experimental effort can be limited, reducing time and cost. Although only simple angular specimens were used for the calibration, the obtained simulation parameters do allow an accurate prediction of the spring-in of complex geometrical parts.

## Acknowledgments

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