A RAPID METHOD FOR RESIDUAL CURE STRESS ANALYSIS FOR OPTIMIZATION OF CURE INDUCED DISTORTION EFFECTS

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Abstract

Within this paper, the authors present a rapid method for residual cure stress analysis. The method uses a high-fidelity path-dependent cure kinetics analysis subroutine implemented in Abaqus to calibrate values for a linear elastic analysis. The path dependent model accounts for the tool-part interaction, forming pressure, and the changing composite modulus during the rubbery region of matrix curing during an arbitrary cure cycle. Results are used to calculate equivalent lamina-wise coefficients of thermal expansion (CTE) in 3 directions for a linear temperature analysis. The goal is to accurately predict distortions for large complex geometries with a single linear temperature load as rapidly and accurately as possible for use in an optimization framework. A carbon-epoxy system is studied. Simple parts are manufactured using unbalanced layups and out-of-autoclave methods. The resulting distortions are scanned with a 3D scanner and compared with simulation results for the same geometries. Further, a more complicated part is studied to compare the two methods using complex geometry. Results are presented and the accuracy and limitations of the rapid simulation method are discussed with particular focus on implementation in a numerical optimization framework.

1. Introduction

Cure induced distortion due to residual stresses is a major cost and risk driver within composite manufacture in aerospace. Traditional aeronautical composites usually consist of carbon fibre reinforcement and epoxy cured at 180°C in an autoclave. This is excellent for obtaining high glass transition temperatures in resin materials, but creates other significant challenges in the form of high built-in thermal stresses, and challenges with miss-matches in CTE between parts and tooling. This is especially true in the trend towards large integrated structures. Distortions can cause delays in production, require late phase re-working of tooling, cause damage during assembly, and lead to expensive scrappage. For these reasons, avoiding or controlling the distortion in manufacture is critical to cost control in composite production in both the short and long term. In the long term, simulation, prediction, and control of distortion will become even more important at an earlier stage as unbalanced and non-symmetric layups become of interest for highly weight critical applications.

1.1 Residual stress analysis- background and state-of-the-art

Over the years several methods have been developed for the purpose of residual stress analysis by assuming either elastic or viscoelastic material behavior of the curing matrix. In an early work, White and Hahn [1] developed a methodology to predict residual stresses in composites using a viscoelastic approach. Subsequently Zobeiry [2] and Prasatya [3] developed similar methodologies to predict residual stresses taking into account the full viscoelastic behavior of the matrix. In [1-3], linear viscoelasticity is assumed. While there exists other work that assumes non-linear viscoelasticity, it is much more complicated and the literature suggests that a linear viscoelastic approach is sufficient to model curing induced residual stresses [4, 5], since the strains developed during processing are thought to be infinitesimally small. Regardless, a full viscoelastic implementation, linear or otherwise, is currently not feasible for industrial applications due to the extensive material characterization and computational costs required.

One of the most frequently used approaches in use today is the Cure Hardening Instantaneously Linear Elastic (CHILE) model [6]. In this model the properties are assumed linear elastic within each material phase. Under certain conditions, both spring-in angles and warpage can be predicted for a composite part reasonably accurately using this approach. This approach has been implemented e.g. in the commercial software COMPRO by Convergent.

A simplified approach is proposed by Svanberg and Holmberg [7] in the form of a path dependent model (as opposed to rate dependency) based on the incrementally written differential form of viscoelastic relaxation formulated by Zocher et al. [8]. The proposed method is a pseudo-viscoelastic formulation which is an improved form of the CHILE model taking viscoelasticity into account. The path dependent model can predict residual stresses and shape distortions relatively accurately and is robust in nature. It has been implemented in various commercial tools for process simulations (PAM-DISTORTION and LUSAS HPM) of industrial relevance. Several different works [4, 5, 9] have implemented the path dependent model in various commercial softwares for simulating manufacturing processes ranging from RTM to prepreg layup and concluding reasonable accuracy of the model for the stated purposes. In fact, recent reviews [10] have pointed out that the CHILE model and the path dependent models are the most widely used models for the computation of residual stresses.

Recently, new studies have emerged [11-14] that have proposed an improvement over the path dependent model taking into account thermorheologically complex materials and also the dependency of the glassy and rubbery stiffnesses on temperature. For the work within this paper, these improvements have been added to the existing path dependent model.

For the sake of brevity, the reader is directed to [6, 13, and 14] for a detailed description of the path dependent model and the improvements employed in the present work. The emphasis of the current paper is to explain the rapid simulation methodology proposed to simplify the distortion prediction process.

2.0 The rapid methodology

The methods described above are well known and accepted for process simulation of aerospace composites. While accurate, none of these approaches is well suited to optimization with large models of highly integrated structures with many design variables due to the relatively long computational times. Herein lies the motivation for the rapid methodology proposed in this paper.

Here an equivalent value of CTE for the UD lamina is calculated using a path dependent model including effects of tool-part interaction and forming forces for an arbitrary material and cure cycle. A single temperature load for the linear model equivalent to the total ΔT of the path dependent model is used as shown in Figure 1.

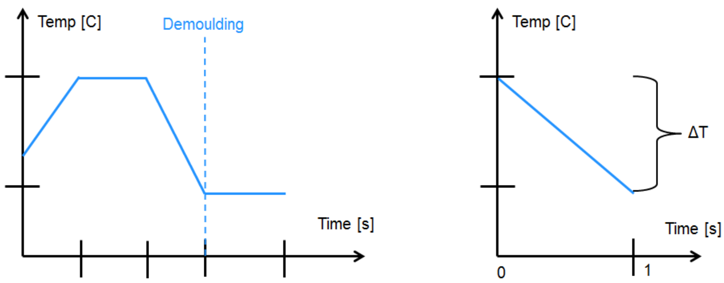

Figure 1: The full cure cycle (left) v/s the linear temperature step for the rapid method (right)

The rapid method can be summarized in three steps.
Step 1: Calculate the shape distortion of two reference parts using the path dependent cure model. For the path dependent model, the tooling and bag pressure are included during the curing phase, and then

removed after the cure cycle at demoulding, see Figure 1, to yield total deformation. One reference part with tooling and bag pressure is presented in Figure 2a.
Step 2: Calibrate a linear model of the same parts by adjusting the values of CTE-22 and CTE-33. Nodal displacements for points at the extremities of these virtual calibration coupons, see Figure 2b, are calculated and compared with the results from the path dependant model. The same mesh is used for both simulations. The values of CTE22 and CTE33 for a UD ply are iteratively adjusted using a python script until distortion in the linear elastic simulation matches that of the path dependent model to within a tolerance specified by the user for both coupons. Tooling and bag pressure is excluded from the linear analysis.
Step 3: Use the new artificial CTE values to calculate shape distortions in an arbitrary model

The first calibration coupon is a long, slender, flat plate with a cross ply layup [0_4,90_4] to maximise the out-of-plane warpage and thus isolating the effect of CTE_{22}. The second coupon is a quasi-isotropic L-profile. The quasi-isotropic layup minimises the in-plane thermal strains, meaning the deformation will be primarily limited to out of plane deformations due to matrix shrinkage-both chemical and thermal thus isolating CTE_{33}. Use of these geometries and layups allows for relatively simple experimental validation of the model.

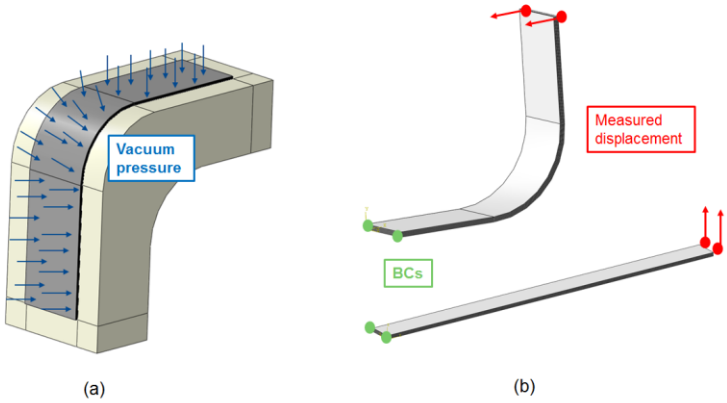

Figure 2: Geometry and boundary conditions for the virtual calibration coupons. a) The bag pressure and the tool in the full path dependant L-shape model. b) Location of the boundary conditions and measuring points for both the linear and the full path dependant models.

The aim of the rapid method is not to predict distortions to the same level of accuracy as the high-fidelity model, but rather to create an extremely fast and efficient way of predicting the most important deformation modes for a complex component accurately enough, so that pro-active design optimization can be performed early on in the design process.

3. Application of method and results

For the sake of brevity within this paper, only coupons presented in Table 1 will be discussed here. To provide a basis for validation and comparison of the two numerical methods, these coupons were manufactured, and the distorted geometry was measured with a GOM Atos 3D laser scanning system. Simulation results are presented below, along with comparisons to as-manufactured geometry.

Table 1. Coupons analyzed in the current paper

Coupon Type	*Layup*	*Dimensions(mm)*
Cross-ply	[0,0,0,0,90,90,90,90]	400 x 100
L-Shape	$[0,45,-45,90]_S$	100 x 100 (flanges), R=10
L-Shape	[0,45,0,45,0,45]	100 x 100 R=10

3.1 Crossply plate

Figure 3 below shows the predicted distortions for the full path-dependent method on the upper left, the rapid model on the upper right, and the result of a 3D scan of a manufactured specimen at the bottom of the figure. Distortion in the FE model is given from a plane through the two ends of the specimen. This is comparable to measuring vertical displacement from a table top where a specimen would rest on its ends after removal from the tool. For the path dependent model, the maximum distortion is calculated as 28.25mm, and for the rapid method, 27.75mm. For the measurement, the maximum distortion is given as 27.45 mm. Clearly, both models give a very good representation of the distortion trend, and magnitude.

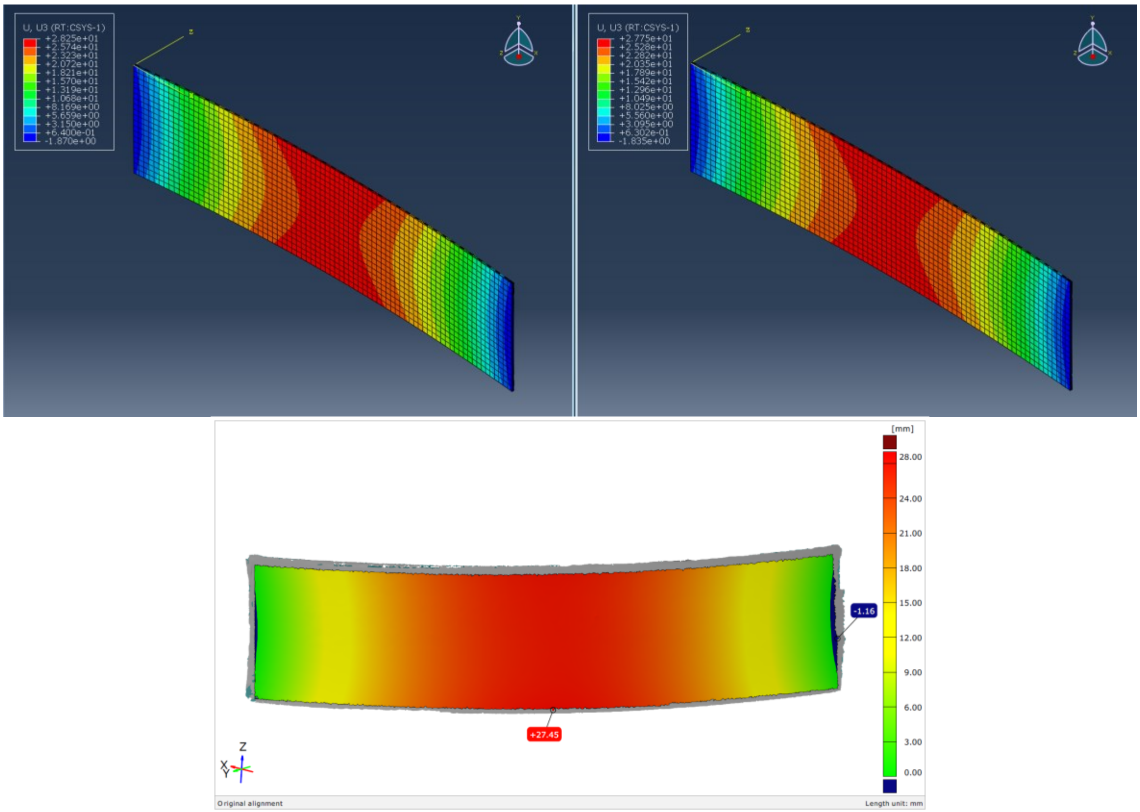

Figure 3: Simulated distortions in cross-ply laminate for path-dependent model (left) and rapid method (right)

3.2 L-profiles

For the Quasi-isotropic L-profile, the distortions for the path-dependent model and the rapid model are shown to the left and right respectively in Figure 4. Displacement in the figure shows the displacement of one flange in the x direction, i.e. the spring-in distance. As can be seen, the two results show very good agreement with each other, differing only on the order 0.04 mm.

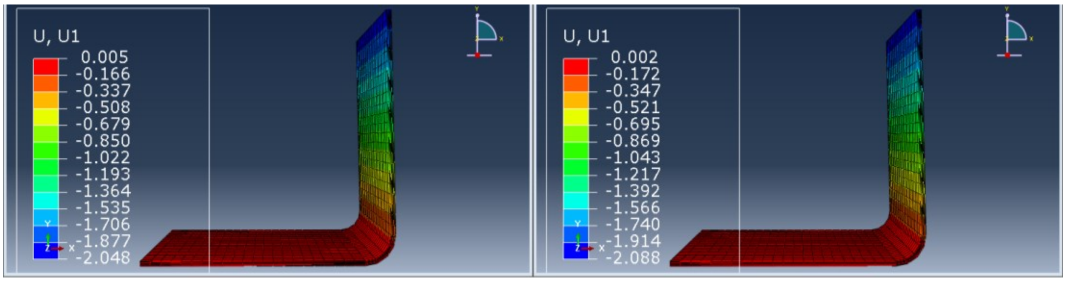

Figure 4: Distortion prediction for symmetric L-profile laminate for path-dependent model (left) and rapid method (right)

Figure 5 shows the results for the two simulations for the unbalanced L-profile. Again, the path dependent model is to the left, and the rapid model to the right. As can be seen in the figure, the rapid model captures the same distortion mechanisms- i.e. twisting of the flange. The magnitude of predicted distortion is approximately 0.3 mm less. This corresponds to approximately 0.2 degrees in spring-in angle for a 100 mm flange.

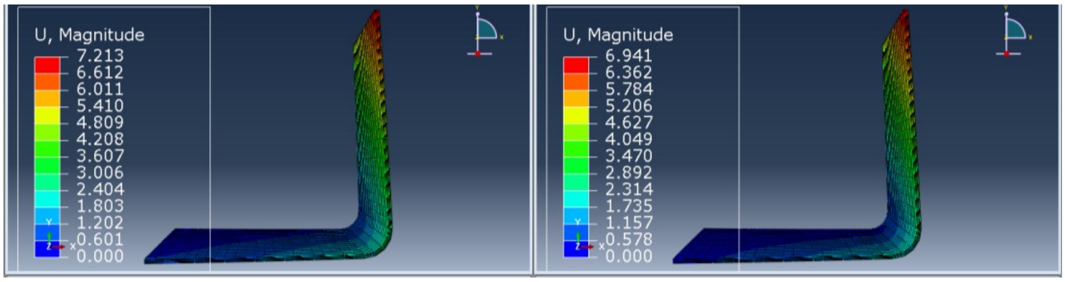

Figure 5: Distortion prediction of un-balanced L-profile for path-dependent model (left) and rapid method (right).

Spring-in angle was chosen as the most reasonable method of comparing the distortion shown in Figures 4 and 5 with those measured on manufactured parts. Parts were scanned, and the angle between tool-side surfaces at 3 different sections along the length of the profile were measured using GOM Correlate software, see Figure 6. The distorted nodal coordinates from the simulation results were exported in a format compatible with GOM Correlate, and the exact same measurements were performed. A comparison of the measured angles from manufacture, and simulation is given below in Table 2.

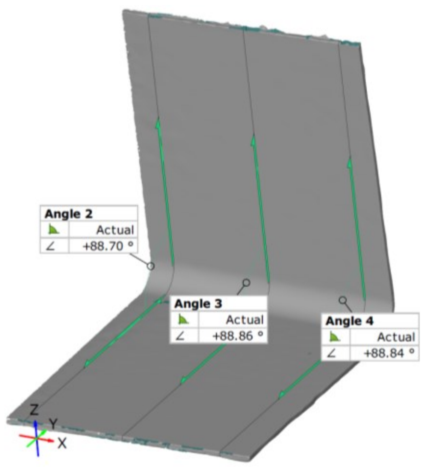

Figure 6: Angle measurements for L-profile

Table 2. Measurements vs simulation results.

L-profile Type	*Measured Angle (see fig 6)* *Angle 2*	*Angle 3*	*Angle 4*	Simulation *Angle 2*	*Angle 3*	*Angle 4*
Sym 1	88.06	88.03	88.0	88.94	88.93	88.94
Sym 2	88.70	88.86	88.84			
Average angle 2-4		*88.4*			*88.94*	
Non-sym1	87.88	87.87	87.94	88.18	88.08	88.23
Non-sym2	87.83	87.68	87.74			
Non-sym3	88.06	88.09	88.05			
Non-sym4	88.94	89.03	88.99			
Average	*88.18*	*88.17*	*88.18*			

As can be seen in Table 2, the simulation results agree very well with the measurements for the L-profiles in both cases. Interestingly, for the L-profile, the unbalanced layup appears to have little effect on the overall distortion. Variation between samples of the same layup is as large as variation between the different layup types. Simulation data, taken from the path-dependent model, show a good agreement with the measurements. The variation in spring-in angles for the parts is larger than the error between the predicted value and the measured average value.

4. Applications to complicated geometry

To evaluate the method properly, a more realistic part geometry was necessary. A curved z-profile was used to incorporate male and female radii and double curvature. The part was approximately 500 mm long, 100mm high and 175mm wide, and 3.5mm thick. A single layer of elements was used for each layer of material. In total 14 layers were used with the orientation $[0,90,\pm45,0_2,45]_S$. Below, a comparison of the model size and simulation time is given. Figure 7 shows a comparison of the distortion predicted using both methods.

Table 1. Validation Z-profile model data.

Modelling Approach	*Model Size* Part Elements	Tool Elements	Analysis Time (6CPUs)
Path Dependent	66611	85191	1168
Rapid	66611	-	~1

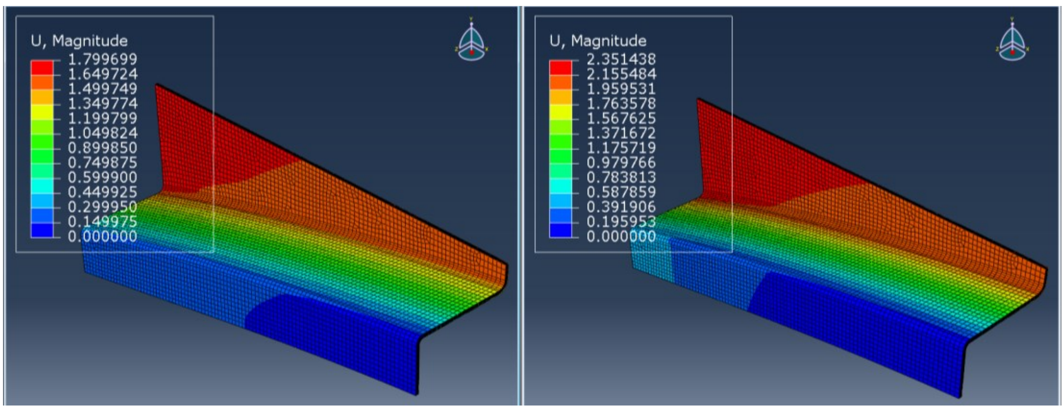

Figure 3: A comparison of the path-dependent (left) and rapid method (right) for distortion of a curved z-profile

The distortion in Figure 7 clearly shows that the rapid method and the path-dependent model capture the same general distortion modes. The rapid method does however appear to slightly over-estimate the distortion that does occur. This is not necessarily a problem. The motivation for the development of this method was to enable simulation in an optimization framework to alter layup shape and stacking sequence in an effort to minimize the effects of cure induced distortion. Overestimation of distortion may act as a built in amplification factor for otherwise very small distortions. Whether this is an advantage or disadvantage remains to be proven. For this particular component, the simulation time was approximately 1 minute for the rapid model as opposed to 1168 minutes for the path dependent model, i.e. 0.09% of the computational time. For this vast reduction in computational time, the accuracy reduction should hopefully prove acceptable.

At the time of writing, the validation profile was not yet manufactured and measured. This is planned for the immediate future and will be included in any future publications.

5. Conclusions

Within this paper, a rapid method for analysing cure induced distortion has been presented. The method builds upon using a high-fidelity path dependent cure model to predict distortions of carefully selected virtual calibration coupons in order to calculate equivalent values of linear CTE for a UD ply. Simulations are performed using both methods for simple geometries, and a more complicated validation part. Comparison with manufactured specimens shows a very good agreement for both methods. For the validation part, the rapid method appears to overestimate cure induced distortion somewhat, but for the present case represents more than 1000 times reduction in computational time. For the intended purpose of early stage design alterations, the rapid method shows significant promise. The efficacy of the method will be further evaluated and results presented in a future publication.

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