VALIDATION AND INDUSTRIAL IMPLEMENTATION OF AN ANALYSIS METHOD FOR PREDICTING DISTORTIONS INDUCED BY COMPOSITE CURING PROCESS

Daniel Hartung[1], Matthias Hartmann[2]

[1]Premium AEROTEC GmbH Augsburg, 86136 Augsburg, Germany
Email: daniel.hartung@premium-aerotec.com, Web Page: http://www.premium-aerotec.com
[2]Institute for Carbon Composites, Technische Universität München, Faculty of Mechanical Engineering, Boltzmannstr. 15, D-85748 Garching b. München, Germany
Email: hartmann@lcc.mw.tum.de , Web Page: http://www.lcc.mw.tum.de

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Abstract

The manufacture of composite parts subject to aerospace processing requirements (high temperature curing thermoset resin systems) results in curing induced residual stresses and induced deformations of the structure. Analysis methods for simulating and predicting Process Induced Deformations (PID) of composite components whilst curing are essential to manufacturing to within acceptable assembly tolerances. The results of the publically funded project: MAI Design founded by by the German Federal Ministry of Education and Research (BMBF), of which the Institute for Carbon Composites and Premium Aerotec GmbH cooperated are presented in this paper. An aerospace qualified material, characterized at the Institute for Carbon Composites, was analyzed with respect to thermo-mechanical curing sensitive properties. A method of simulating the process induced deformations with finite elements was developed at Premium AEROTEC GmbH based on previous work [1, 2]. Good correlation between predicted and measured deformation of serially manufactured components was established. Additionally it was confirmed that the stochastic deviation between all serial components was insignificant. With a consistent manufacturing process producing serial components of little deviation, it enabled the simulation to easily predict the structural modifications needed to better satisfy assembly and manufacturing tolerances. How the simulation method could be incorporated within the design and manufacturing process is described in this paper.

1. Introduction

Processing and curing of composite parts generates curing induced distortions that affect the accuracy with which a part can be manufactured. Utilization of high temperature epoxy resin systems in the aerospace industry results in thermally induced strains that can lead to a shrinkage or spring-in deformation of the cured composite part. The serial production of parts that lie outside manufacturing tolerances can lead to an increase in manufacturing lead-time. Assuming the induced distortions are consistent throughout the same composite part the geometry of the curing tool can be adapted to take account of the spring-in deformation. Nevertheless, to predict the impact of adapting the curing tool the existing distortions must first be simulated by a thermo-mechanical finite element analysis. The transient thermal and mechanical material behaviours are defined using material models hard-coded into subroutines of the finite element analysis software Abaqus. The material model is based on test data for unidirectional composite specimens. The simulation process has been validated by comparing the predicted distortions

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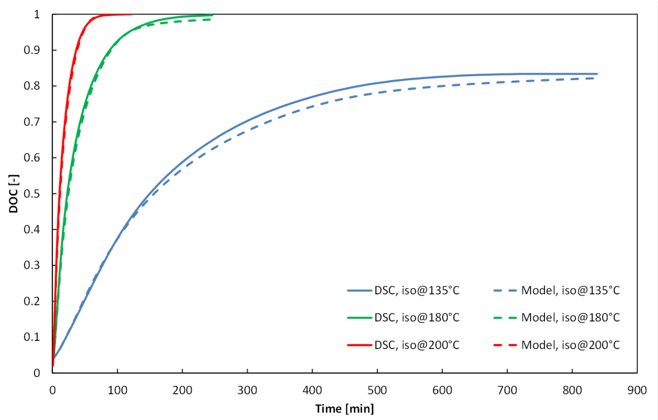

Figure 1. Experimental DSC data and cure kinetics model predictions: isothermal.

to the measured distortions of serially produced composite A350XWB-1000 frames.

2. Material characterization

The important input parameters to feed various material property development models for the thermo-mechanical modelling of a curing composite during processing are [1]:

- Resin cure kinetics and transition from liquid to solid state.
- Specific heat capacity and thermal conductivity.
- Young's modulus and Poisson's ratio of the resin defined as a function of temperature and Degree Of Cure (DOC).
- Coefficient of Thermal Expansion (CTE).
- Volumetric resin shrinkage and DOC at gelation.

Additionally, fiber mechanical and thermal properties are needed. Fiber and matrix mechanical properties at room temperature were fit to ply property data provided by PAG utilizing appropriate micromechanics models [3] with a least-squares method. Temperature dependent conductivity and specific heat capacity of the fibers have been taken from literature [1]. A modulated Dynamic Scanning Calorimetry (DSC) test campaign was carried out to quantify the total heat of reaction, glass transition temperatures, cure progress as well as the specific heat capacity on isothermal and constant temperature ramp scans. Weighted least-squares methods were applied to fit the material parameter λ of the DiBenedetto equation, a two-stage reaction cure kinetics model adopted from Dykeman [4] and a heat capacity model from Shakarami [4, 5] to the experimental data. The cure kinetics model reflects the DOC progression with sufficient accuracy, see Figure 1 and Figure 2. Appropriateness of the DOC and T_g predictions was validated on intermitted cure cycles. The thermal properties including an estimate of the resin conductivity based on literature data was validated via a comparison between simulated and measured temperature history in the middle of an approximately 20 mm thick laminate plate during cure. The maximum difference during the relevant portion of the cure cycle including temperature ramps was 2°C.

Due to the significant difference between the uncured and cured thicknesses of a typical laminated plate, a bi-material beam (BMB) test typically employed to characterise transient Young's modulus development

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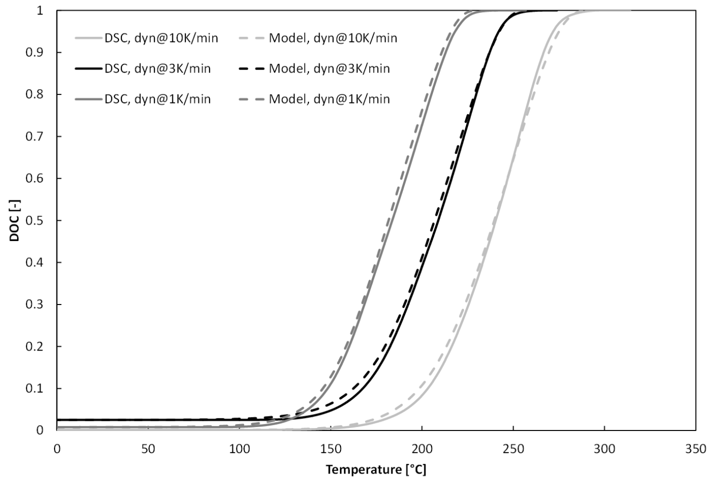

Figure 2. Experimental DSC data and cure kinetics model predictions: dynamic (constant ramp rate).

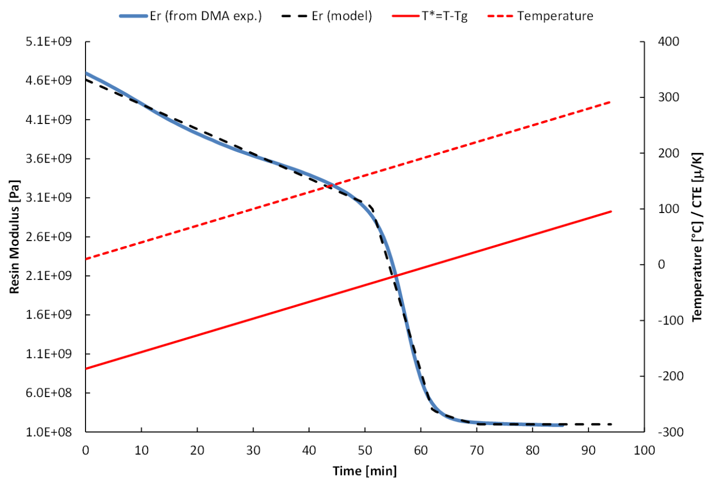

Figure 3. Resin modulus progression from DMA tests and model fit.

[6], was not found to be applicable for the current material system. Consequently, fully cured 6-ply unidirectional samples were subjected to a temperature gradient in the Dynamic Mechanical Analysis (DMA) test machine and oscillatory 3-point bending with plies laid perpendicular to the loading direction only. The resin storage modulus was back-calculated from the dynamic force / displacement response and an appropriate modulus development model [5] was fit to the experimental data projecting the modulus development on the critical temperature

$$T^* = T - T_g \tag{1}$$

Modulus data derived from DMA tests and the model adapted are shown in Figure 3. The bulk modulus of the resin has been assumed constant during processing [1].

To determine the CTE of the resin in glassy and rubbery state, the curvature change of a bi-material beam, consisting of a steel shim co-cured with 4 unidirectional plies, was measured as temperature was increased in the DMA test machine. The material function was employed to calculate an assumed uniform temperature dependent transverse ply modulus and equivalent mechanical properties to quantify

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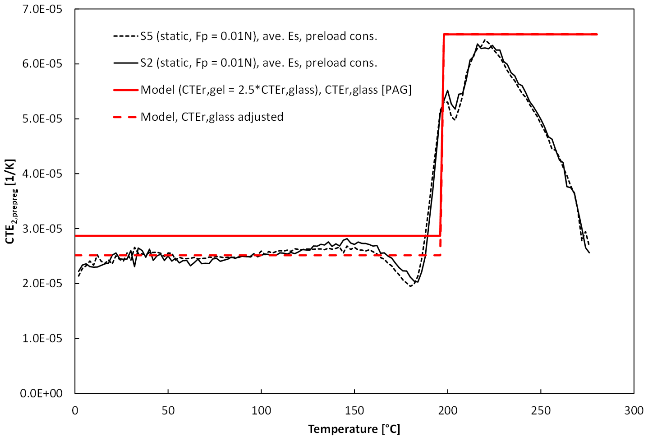

Figure 4. Variation in composite fibre transverse CTE from DMA tests and model fit.

the bending stiffness of the BMB. Clyne's formula [7] relating curvature change of a bi-material beam, due to temperature increase, to the thermal strains of substrate and deposit was adapted for different laminate widths to determine the transverse CTE. The experimentally observed behaviour of the transverse composite fibre CTE from the DMA experiments and material model are illustrated in Figure 4. From Shimbo [8] the ratio between the CTE value of the resin in glassy state and CTE value of the resin in a rubbery state has been assumed to be 2.5. The maximum predicted CTE values of the ply in a rubbery state correlate well with the maximum experimentally determined CTE values. Equally, the predicted CTE values of the ply in a glassy state correlate well with the experimentally determined CTE values. The ratio between the CTE values of the glassy and rubbery states, for both experimental and predicted CTE values, is approximately 2.5. A drop in the rubbery experimentally determined CTE is assumed to result from some combination of slippage between the shim and laminate, and steel shim oxidation. DOC at gelation and the total volumetric curing induced shrinkage have been taken from Msallem [9] for a similar material system.

3. Finite Element Simulation

The curing induced distortions are simulated with a thermo-mechanical finite element analysis. Heat fluxes generated by heating or cooling the part in the autoclave generate temperature fields in the tool, composite part and production auxiliaries. In an uncontrolled environment any transient increase in temperature is generally heterogeneous and unsteady during successive heating and cooling phases. In the aerospace industry curing processes are carefully controlled to ensure low temperature gradient throughout the heating and cooling phases. Since the transient temperature gradients are comparatively low the temperature throughout all analysed parts, at a given time, is assumed constant. The temperature and heat fluxes are calculated by a thermo-mechanical finite element solver. Once the temperature is known the curing behaviour of the resin can be determined. With curing equations derived empirically from DSC tests describing the phenomenological behaviour of the resin – specifically the exothermic heat flux generated by polymerization of the resin, the curing kinetic of the complete composite part can be described.

The mechanical material properties are calculated based on temperature and curing state. The anisotropic material properties of the fibre are assumed to be constant throughout. For the current analysis, it is assumed that the resin is in a liquid state below the gelation temperature and stress free. During solidification the material properties of the resin increase generating residual stresses that induce distortion.

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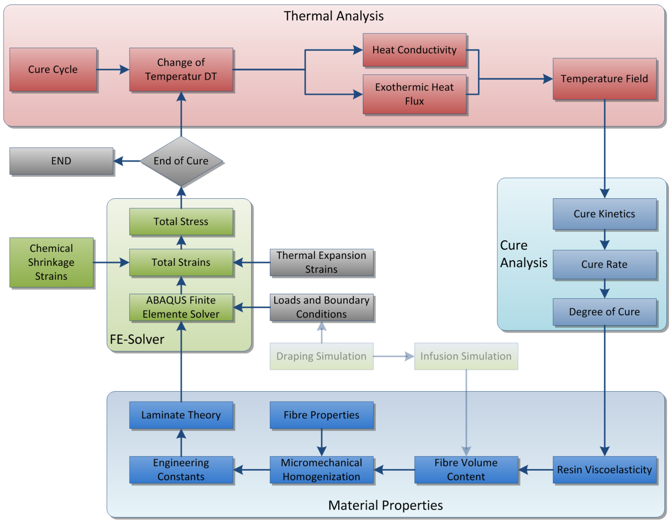

Figure 5. Finite element simulation work flow for the determination of curing induced distortions.

The resin conversion is simulated with a user defined subroutine in the thermo-mechanical finite element analysis. Both fibre and recently gelated resin material properties are combined to update the composite material properties for the unidirectional single ply. During polymerization the resin changes from liquid to solid and consequently contracts. The updated anisotropic composite material properties lead to different resin shrinkage in in-plane and out-of-plane directions which is simulated by considering effective shrinkage strains in the strain tensor.

The thermal and mechanical behaviour of the manufactured composite part are, in reality, generally dependent upon one another, not least because of the change in thermo-mechanical properties throughout the curing process. However, given that the deformations are minimal the 2nd order behaviour describing the heat flux affected by mechanical motion alone has been assumed to be negligible. Indeed in the investigated literature [1–3] the same assumption has been made. Both simulations are therefore sequentially run. Figure 5 demonstrates the principle work flow of the simulation.

4. Validation

The distortions simulated by the finite element analysis are compared to the deformation measurements of composite frames produced with automated fibre placement process. The distortions of pre-production parts as well as different types of serially produced frames were analysed. The frames distort in a combination of torsion, bending and spring-in deformation modes that were measured with an automated optical measurement system applicable for different frame types. The distortions are present in each frame type and ever present in serial production. A comparison of the actual distortions and simulated distortions is illustrated in Figure 6 – showing very good correlation. The difference between the measured and simulated distortions are within the magnitude of distortion variations for serially produced frames, which are limited in a range of tenth of a millimetre. The simulation is capable of predicting approximately 95% of distortions that exist in serially produced frames. Therefore, the simulation is used to compensate the distortions in the curing tool by redesigning the curing tool geometry which in turn is validated by the simulation. This virtual curing tool development cycle is cost effective and enables the rapid development of curing tools.

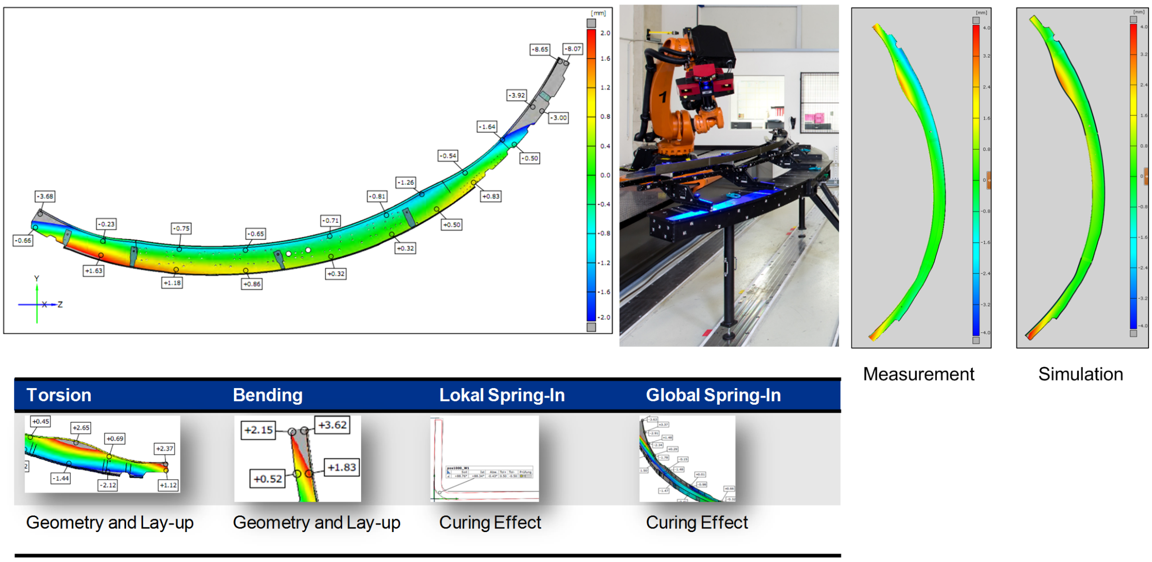

Figure 6. Measured distortions and deformation modes of composite frames (left), comparison of simulated and measured distortions (right)

5. Conclusion

The presented finite element simulation of curing induced distortion is based on a material characterisation from which the phenomenological thermo-mechanical behaviour has been identified. The material models are defined within Abaqus subroutines and accessed when running the thermal-mechanical analyses. Generally the simulation of process induced distortion of composite frames shows very good correlation with serially produced frames. The deviation in distortion across all hitherto serially produced frames is comparatively small. Given the consistency of frame distortions, curing tools have been designed to take account of these curing induced distortions to produce composite parts that are geometrically closer to the nominal geometry. This process is currently being implemented at Premium AEROTEC GmbH for the design of future curing tool geometries.

Acknowledgments

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