Modelling of the Residual Stress State in a New Type of Residual Stress Specimen

J. Jakobsen[a*] and J. H. Andreasen[a]

[a] *Department of Mechanical and Manufacturing Engineering, Aalborg University, Fibigerstraede 16, DK-9220 Aalborg, Denmark*

Keywords: Residual stresses, Experimental testing, Fibre Brag Grating sensor.

Abstract

The paper presents a study on a new type residual stress specimen which is proposed as a simple way to conduct experimental validation for model predictions. A specimen comprising of a steel plate with circular hole embedded into a stack of CSM glass fibre and further infused with an epoxy resin forms the experimental case which is analysed. A FE model of the specimen is used for analysing the curing history and the residual stress build up. The model is validated against experimental strain data which are recorded by a Fibre Brag Grating sensor and good agreement has been achieved.

1. Introduction

Processing of fibre composite parts may occur at an elevated temperature and together with the matrix solidification the process is challenging to characterise. This further makes predictions of part quality due to a given set of process conditions a difficult engineering task.

Shape distortions and residual stresses in fibre composite parts are some consequences of the chosen process conditions and these may compromise quality requirements and in service performance of the part. Shape distortions and residual stresses induced by the curing process have been investigated by several researchers. Some of the first to model the curing history and residual stress build up during the process were Hahn et al [1, 2], Bogetti et al. [3] and White et al. [4, 5]. Based on their findings and methodology models were gradually improved.

The understanding of material behaviour during the curing process is another area which has been given vast attention during the years. The chemical conversion which is when the molecular structure sets within the matrix is typically modelled using a phenomelogical approach. A review of cure kinetic models has been given by Yousefi et al. [7]. These models are typically based on the reaction enthalpy measured by Differential Scanning Calorimetry (DSC). Another measuring technique that may be used to characterize the chemical conversion is electrical impedance spectroscopy which has been investigated by Skordos et al. [8].
Other important material properties needed in the attempt to model curing stress and/or distortions are the dimensional changes in the material. These changes arise from the thermal expansion and chemical shrinkage in the material constituents. The behaviour may be strongly depended on temperature and chemical conversion. The chemical shrinkage may be measured in a dilatometer however this technique is limited to post gelled samples. Li et al. [9]

proposed a new method where the shrinkage could be measured in the entire range of chemical conversion and the gel-point could be identified as a change in slope in the shrinkage strain. The characterisation of thermal expansion due to temperature change may be done in various ways. Similar to the chemical shrinkage a dilatometer can be used or strain gauges. Bing et al [10] used digital image correlation (DIC) to capture the deformation field of film subjected to a temperature change. A modelling approach was taken by Craft and Christensen [11] to predict the coefficient of thermal expansion (CTE) of a randomly orientated fibre composite material.

Shape distortions of composite parts do occur and it is the consequence of the material characteristics and manufacturing process. Some of the authors to address this were among others Amato [12], Svanberg et al. [13, 14] and Sweeting et al. [15]. These authors analysed different composite elements fx. a U-Channel and the L-shape and measured the distorted geometry and compared with model predictions. Wisnon et al. [16] studied the distortion/spring-in effect of an unsymmetric laminate and argued that the main contribution to the spring-in is caused by the cooling process after vitrification has occurred.

Modelling the process and predicting the consequence of the manufacturing process involve solving a multi-physic problem which describe the thermal, liquid/solid transition and structural behaviour of the problem. However due to the complexity and vast amount of input data needed, the validity of model predictions may often be questioned.

Contributing to bridge the gap between predicted residual stresses from models of fibre composite parts and actual measurements the paper presents a study on residual stresses induced into a glass/epoxy composite using a test specimen capable of introducing an equal biaxial stress field. This study presents both numerical and experimental results on the in situ strain development during curing.

2. Method

The paper presents both numerical analysis of the curing process for the tested experimental setup and actual strain measurements to validate the numerical model.

2.1 Experimental setup

An experimental setup using a steel plate with circular hole placed in between six layers of Chopped Strand Mat (CSM) glass fibre forms the specimen. This stack was then infused with an epoxy resin at room temperature. The specimen was then brought to approximately 90℃ so curing of the epoxy resin could take place. After 160min the heater was turned off and the specimen was cooled back to room temperature by natural convection.

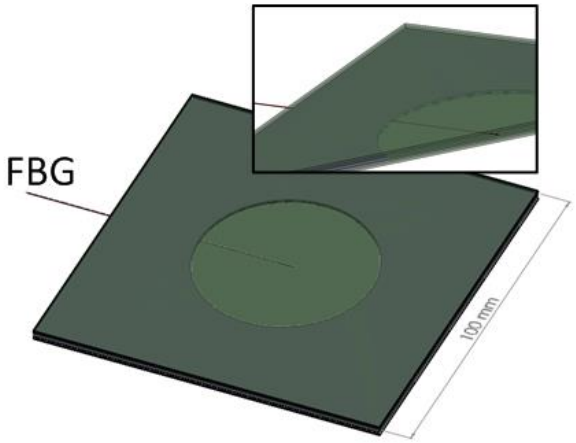

Figure 1. A sketch of the specimen is seen in the figure. A Fibre Brag Grating (FBG) sensor is placed just below the steel plate. The magnification illustrates the position of the FBG.

A Thermo couple was placed on the specimen to monitor the temperature history during the entire process. In addition a Fibre Brag Grating (FBG) sensor is placed between the CSM layer and the steel plate with its Brag Grating area in the centre of the circular part of the specimen. The FBG is used to record the strain in the material as it is processed. The Grating length is 5mm. The FBG sensoring technique has been known for some years and has recently been used by Parlevliet et al. [17] to monitor curing strain. The strain monitoring presented here will be used to estimate the associated residual stress magnitude.

2.2 Numerical Analysis

The numerical analysis was conducted in Comsol Multi-physic®; a commercial software package. The numerical analysis is setup as a 3D model. However due two symmetry axis existing in the specimen only one quarter of the model has been analysed. Thermal heat transfer was not included in the model of the in situ strain development, since it was verified from pre-analysis of temperature distribution that the spatial uniformity was within a few degrees over the entire process, and therefore a uniform temperature within the model is a good approximation.

In the structural analysis the material behaviour is assumed to be isotropic. The Chemical strain is modelled as being linear depended on the chemical conversion [18]. The thermal strain is modelled with a bi-linear law with its transition at the in situ glass transition temperature [18]. The Young's modulus is depending on both temperature and the chemical conversion and is described further in [19].

The model analysed consisted of second order triangular elements and the model was further discretised with 6 elements in it thickness direction giving a total of 2688 elements. This gives a model with 48.000 degrees of freedoms (see Figure-2).

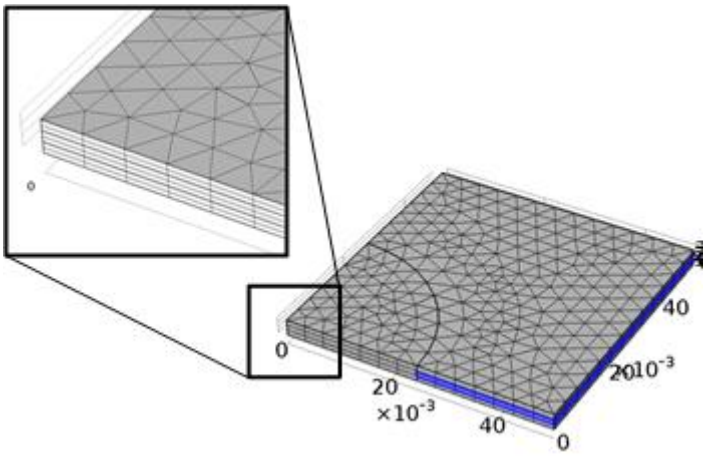

Figure 2. The model is meshed with triangular 2nd order elements. The blue shaded volume indicates the steel late. The grey volume is occupied by CSM glass/epoxy material.

3. Materials

A CSM glass/epoxy material was tested. The CSM glass mat consisted of 50mm fibre chops and its area weight was 450g/m^2. The epoxy was a Bisphenol-A with an Amine hardening agent. The steel plate was assumed to take typical values for steel. However since the accuracy of its coefficient of thermal expansion is important for the residual stress build-up in the composite material it was measured. Values are given in Table-1.

	***E* [GPa]**	**ν [-]**	**α [µm/(m C)]**
Steel	210	0.3	11.5
CSM glass/epoxy	E(T,c) E_{ult} = 13.1	0.34	18.5 ($c > c_{gel}$ and $T < T_g$) 6.0 ($c > c_{gel}$ and $T > T_g$)

Table 1. Young's modulus (E), Poisson's Ratio (**ν**) and Coefficient of thermal expansion (**α**) of steel.

The fibre volume fraction was estimated to 0.25. Details on the resin cure kinetics, thermal- and chemical strains, and modulus of elasticity can be found in [19, 20]. The coefficient of thermal expansion for the CSM glass/epoxy material is reduced slightly compared to the nominal value stated in [19]. The reduction is done to obtain a better comparison with experimental data and the reduction is still within a standard deviation of the nominal value reported in [19]. The modulus is modelled as being elastic and dependent on temperature (T) and the chemical conversion (c). For a fully cured CSM glass/epoxy material at room temperature the Young's modulus is set to 13.1GPa.

4. Results

The temperature history is recorded with a thermo-couple and the strain in the centre of the specimen is monitored with an FBG (see Figure-3). From the strain response before the heater is turned on resin arrival can be seen as a peak in the signal as it causes a pressure release in the vicinity of the FBG grating area. Moreover the resin arrival peak is followed by a smooth strain decrease which corresponds to the pressure increase behind the resin front, as it can be seen in the magnification in Figure-3. An additional pressure adjustment "increase pressure" was included in the process as this is common practise when fabricating fibre composite parts. However it can be seen that this pressure change did not affect the strain response further. The heater is then turned on to reach the curing temperature of 93℃.

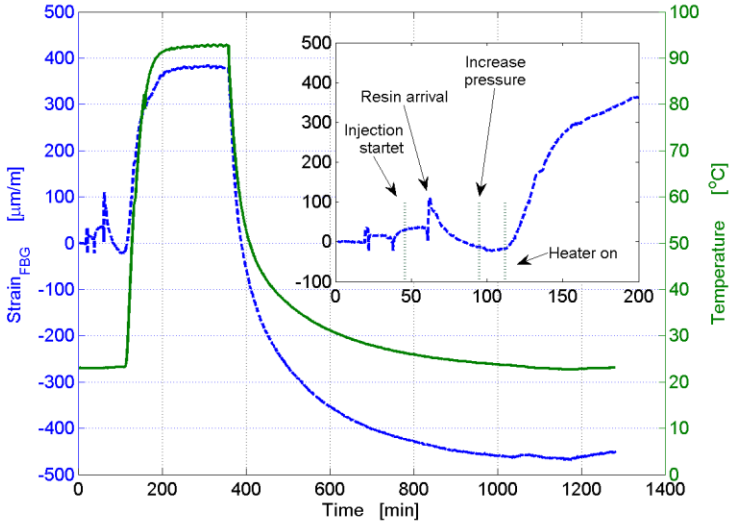

Figure 3. Recorded temperature history (-) together with measured radial strain (--) in the centre of the specimen is shown in the figure. Process steps made during the injection are indicated in the magnification.

Analysing the measured strain response further it may be seen from Figure-4 that the slopes during heating and cooling in the temperature domain are different. During heating a slope (CTE) are found to 5.5µm/(m℃). The thermal expansion of the FBG itself has been compensated out and it is thereby assumed that expansion is related to the expansion of neat glass fibre. The 5.5µm/(m℃) agrees well with measured values for neat glass fibre [19].

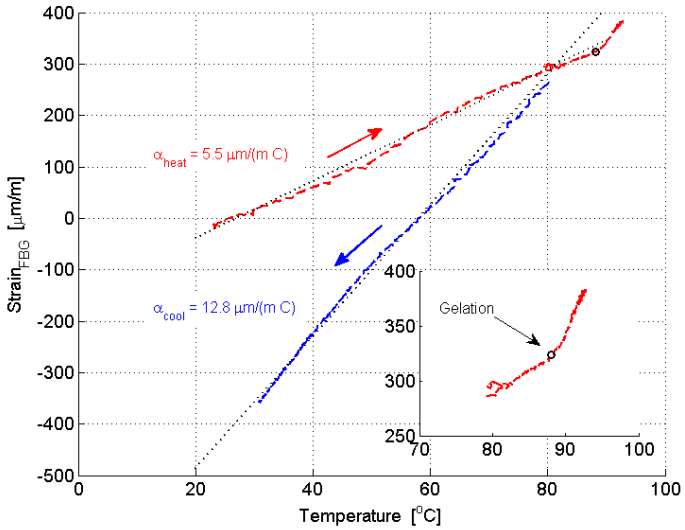

Figure 4. Different CTE's are observed during heating and cooling. A significant kink at the end of the heating is noticed. This kink corresponds well to the occurrence of resin gelation (o).

Gelation may be observed as an abrupt change in the slope during heating of the specimen. After gelation the fibre and epoxy bond to the steel plate and act as a united material with different expansion behaviour. This kink further agrees well with model predictions of the occurrence of gelation. As the specimen cools the material near the FBG follows a curve with a slope of 12.8µm/(m℃) (see Figure-4). This value is recognised to be in close agreement with CTE for steel (see Table-1). Due to the higher modulus of steel compare to the CSM glass/epoxy makes the steel plate controlling the deformation of the CSM glass/epoxy material in the centre of the specimen.

Initially both the chemical and thermal strain was included in the model (see Figure-5). However the chemical shrinkage taking place at the elevated temperature was not observed in the measured strain. Moreover the final strain state was heavily overestimated. It can be argued that stress relaxation at the elevated temperature may balance the chemical shrinkage and therefore it can be justified to only include the thermal strain in the model. This further gave a good correlation between the modelled and measured strain response. The agreement with measured strain was within 50µm/m at the final strain state.

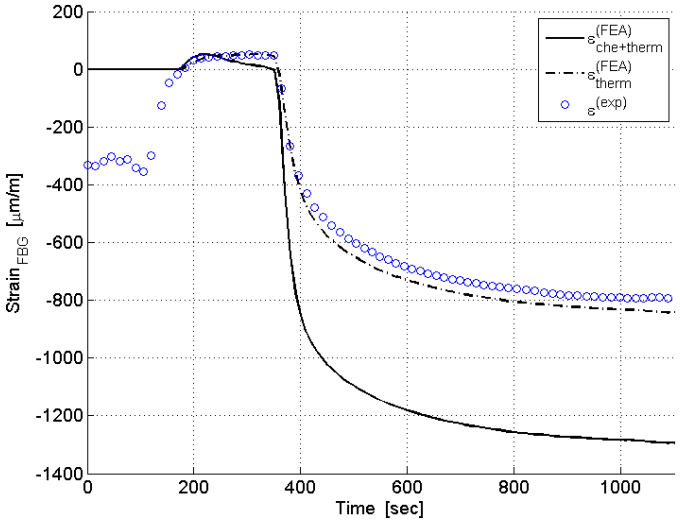

Figure 5. A comparison between model predictions and experimental measurements is shown. It may be seen that omitting the chemical shrinkage strain and only considering the thermal strain gives a better comparison with experimental measurements.

The mismatch in CTE between the steel plate and the CSM glass/epoxy material generate a tensile bi-axial residual stress state in the centre of the specimen. The stress state will primarily develop during cooling of the specimen because the modulus of the CSM glass/epoxy material during this stage increases significantly. The stress state in the centre of the specimen after cooling is determined to 3.5MPa. The magnitude of the generated residual stress state is rather low compared to its failure strength. However even small magnitudes of induced residual stresses could have an influence on fx. the fatigue behaviour of the material.

Conclusion

A specimen consisting of a steel plate with a circular hole is embedded into a stack of CSM glass fibre preform has been investigated. Using VARTM the stack is infused with an epoxy resin. The temperature history and strain development is monitored during the curing of the laminate.

From the measurements it was possible measure different expansion/contraction behaviour during heating and cooling of the specimen. Gelation was identified as a sudden change in CTE of the specimen. After gelation the expansion and contraction of the specimen was highly controlled by the CTE and modulus of the steel plate. Chemical shrinkage was expected to be identified during curing but it was not that significant. Since the curing primarily took place above Tg the chemical shrinkage is likely to be subjected to a neutralising creep.

A FE model of the specimen was analysed and material properties has been measured from previous studies. The model stated the occurrence of gelation in good agreement with the sudden change in CTE for the specimen during heating. In addition the model yielded good agreement with the experimental measured strain response if the chemical shrinkage was omitted from the model.

Acknowledgements

The work presented has been sponsored by the Danish Council for Independent Research | Technology and Production Sciences (FTP, Grant Agreement 10-093339, "Mechanical Property Characterisation of Fibre Composites with Focus on Thermal Cure Conditions". In addition, the test materials were sponsored by Siemens Wind Power. The received support is gratefully acknowledged. Moreover the authors would like to acknowledge Dr. Alex Skordos, Dr. Stephen James and Dr. Ricardo Correia for their fruitful collaboration and assistance during the experimental part of the work presented.

References

[1] Hahn, H. & Pagano, N. (1975), 'Curing Stresses in Composite Laminates', *Journal of Composite Materials* **9**(1), 91-106.
[2] Hahn, H. T. (1976), 'Residual Stresses in Polymer Matrix Composite Laminates', *Journal of Composite Materials* **10**(4), 266-278.
[3] Bogetti, T. A. & Gillespie, J. W. (1992), 'Process-Induced Stress and Deformation in Thick-Section Thermoset Composite Laminates', *Journal of Composite Materials* **26**(5), 626-660.
[4] White, S. & Hahn, H. (1992), 'Process Modeling of Composite Materials: Residual Stress Development during Cure. Part I. Model Formulation', *Journal of Composite Materials* **26**(16), 2402-2422.
[5] White, S. & Hahn, H. (1992), 'Process Modeling of Composite Materials: Residual Stress Development during Cure. Part II. Experimental Validation', *Journal of Composite Materials* **26**(16), 2423-2453.
[6] Cadenato, A.; Salla, J.; Ramis, X.; Morancho, J.; Marroyo, L. & Martin, J. (1997), 'Determination of gel and vitrification times of thermoset curing process by means of TMA, DMTA and DSC techniques', *Journal of Thermal Analysis and Calorimetry* **49**, 269-279.
[7] Yousefi, A.; Lafleur, P. G. & Gauvin, R. (1997), 'Kinetic studies of thermoset cure reactions: A review', *Polymer Composites* **18**(2), 157--168.
[8] Skordos, A. A. & Partridge, I. K. (2004), 'Determination of the degree of cure under dynamic and isothermal curing conditions with electrical impedance spectroscopy', *Journal of Polymer Science Part B: Polymer Physics* **42**(1), 146--154.
[9] Li, C.; Potter, K.; Wisnom, M. R. & Stringer, G. (2004), 'In-situ measurement of chemical shrinkage of MY750 epoxy resin by a novel gravimetric method', *Composites Science and Technology* **64**(1), 55 - 64.
[10] Bing, P.; min, X. H.; Tao, H. & Asundi, A. (2009), 'Measurement of coefficient of thermal expansion of films using digital image correlation method ', *Polymer Testing* **28**(1), 75 - 83.
[11] Craft, W. J. & Christensen, R. M. (1981), 'Coefficient of Thermal Expansion for Composites with Randomly Oriented Fibers', *Journal of Composite Materials* **15**(1), 2-

20.

[12] Amato, E. D. (2007), 'Numerical modeling and experimental studies for shape and dimensional control in the curing process of textile composites ', *Composite Structures* **81**(1), 11 - 20.

[13] Svanberg, J. & Holmberg, J. (2004), 'Prediction of shape distortions. Part II. Experimental validation and analysis of boundary conditions ', *Composites Part A: Applied Science and Manufacturing* **35**(6), 723 - 734.

[14] Svanberg, J. M. & Holmberg, J. A. (2004), 'Prediction of shape distortions Part I. FE-implementation of a path dependent constitutive model ', *Composites Part A: Applied Science and Manufacturing* **35**(6), 711 - 721.

[15] Sweeting, R.; Liu, X. & Paton, R. (2002), 'Prediction of processing-induced distortion of curved flanged composite laminates ', *Composite Structures* **57**(1вЂ“4), 79 - 84.

[16] Wisnom, M.; Gigliotti, M.; Ersoy, N.; Campbell, M. & Potter, K. (2006), 'Mechanisms generating residual stresses and distortion during manufacture of polymerâ€“matrix composite structures ', *Composites Part A: Applied Science and Manufacturing* **37**(4), 522 - 529.

[17] Parlevliet, P. P.; Bersee, H. E. & Beukers, A. (2010), 'Measurement of (post-)curing strain development with fibre Bragg gratings ', *Polymer Testing* **29**(3), 291 - 301.

[18] Jakobsen, J.; Andreasen, J. & Thomsen, O. (2013), 'A comparison of gel point for a glass/ epoxy composite and a neat epoxy material during isothermal curing', *Journal of Composite Materials*.

[19] Jakobsen, J.; Jensen, M. & Andreasen, J. (2013), 'Thermo-mechanical characterisation of in-plane properties for CSM E-glass epoxy polymer composite materials- Part 1: Thermal and chemical strain', *Polymer Testing* **32**(8), 1350 - 1357.

[20] Jakobsen, J.; Jensen, M. & Andreasen, J. (2013), 'Thermo-mechanical characterisation of in-plane properties for CSM E-glass epoxy polymer composite materials - Part 2: Young's modulus', *Polymer Testing* **32**(8), 1417 - 1422.