WARPAGE PREDICTION IN OVER-INFUSION PROCESS OF GLASS/POLYESTER COMPOSITE LAMINATES

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ABSTRACT

Over-infusion is a manufacturing process in which a pre-fabricated composite is co-molded with an uncured laminate during the vacuum assisted resin transfer molding (vaRTM) process. One of the applications of this process is to produce wind turbine blade components such as root section. A complex shear interaction between the pre-fabricated laminate and over-infused part play a crucial role in the final shape distortions, residual stresses and bonding quality of the interface. In order to have more reliable over-infusion processes and improve the product quality, a predictable process modelling tool is necessary to understand and describe some of the challenges such as residual stresses and shape deformations. The current work presents a combined experimental and modelling effort to develop a fundamental understanding of the warpage formation during the over-infusion process which has not considered up to now. A unidirectional (UD) glass/polyester laminate plate (~200×200 mm) with a thickness of 2 mm is first fully cured using the vaRTM at room temperature. Another UD layer is over-infused on top of the already cured laminate using same processing conditions. Due to the chemical shrinkage of the matrix and the shear interaction between the two laminates, a warpage occurs after the curing process. To predict this deformation mechanism, a fully coupled thermo-chemical-mechanical process model is developed in ABAQUS. Two different models are employed at the interface to capture the shear interaction during the process: a shear layer model and a traction-separation model. The interface model mimics the load-transfer from the infused laminate to the pre-fabricated laminate. A parametric analysis is performed based on the properties defined in the proposed interface models. A good agreement between the predicted and measured warpage formation is found using a soft resin stiffness at the interface.

1 INTRODUCTION

The wind turbine blades are generally manufactured using the vacuum assisted resin transfer molding (vaRTM) technique. One of the main challenges in composite wind turbine production is having a reliable root section connected to the main hub via metal bushings. In order to tackle this challenge, prefabricated pultruded blade root reinforcements have been recently used in the wind turbine root sections in order to have a reliable design for the root, high precision for the location of the embedded metal bushings and reduce the vaRTM process time [1]. The laminated blade structure is infused over the prefabricated pultruded components at the root section using the vaRTM process [2]. The pultruded components are placed between the steel bushings which enables mounting of the blade structure to the wind turbine rotor hub. The hybrid blade root joint can then be co-molded into a wind turbine blade root section. It is crucial to secure the bushings in place to uphold the tolerances necessary for eased installation of the final blade assembly on the rotor hub on site. The analysis of the over-infusion processes is a comprehensive task due to the diverse interactions between involved fiber and matrix (resin) material, along with the physical and chemical phenomena mainly related to the resin flow, heat transfer, chemical curing reaction and solid mechanics. One of the main challenges is the process induced residual stresses which inevitably arise causing dimensional variations in the composite part such as warpage and spring-in [3,4].

The process-induced stresses and distortions in fiber reinforced polymer composites have been studied numerically and experimentally in the literature [5-16] considering different manufacturing processes of composites. The major sources of residual stresses and shape distortions are the material anisotropy, a mismatch in coefficient of thermal expansion (CTE) of tool and part, a mismatch in ply-level CTE and the through thickness temperature and cure gradients. The tool-part interaction was found to have a crucial influence on the residual distortions in [17] using a shear layer between the tool and composite part. It was found in [17] that an increase in shear layer modulus resulted in an increase in part warpage.

Although there have been several studies carried out to investigate the residual shape distortions in composites, at present, there is a lack of information on the warpage formation in co-molded composites manufactured using over-infusion process. The main challenge is the mechanics and constitutive behavior of the interface between the prefabricated composite and the infused laminate which are not described well for the bonding. This paper presents experimental and numerical modelling approach to address the warpage formation during the over-infusion process. Firstly, a fully cured base laminate in plate form is manufactured using the vaRTM process. Another laminate is co-molded with the prefabricated laminate to have a bonded structure. The observed warpage is predicted using a thermo-chemical-mechanical process model in which the constitutive behavior of the interface is modelled using the shear layer approach as proposed in [17] as well as traction separation law using a cohesive surface in ABAQUS. The multi-physics process model predicts the curing behavior, temperature distribution during curing and residual stresses and deformations develop during the over-infusion process.

2 EXPERIMENTS

The co-molded flat plate laminates (200×200 mm) were manufactured using the vaRTM technique using a flat glass mold. The resin system was a pre-accelerated orthophthalic polyester resin. A peroxided based hardener was used in this resin system. The glass reinforcement layer was a 750 g/m2 unidirectional (UD) roving reinforced (660 g/m2) with random filament and stitching (90 g/m2). The fiber volume content of the laminate was approximately 54 %. For the co-bonding experiment, a prefabricated composite part or prefab serves as the base plate. The layup of the prefab was consisting of four UD layers. The vacuum pressure was set to 0.6 bar during the infusion. The base plate (prefab) was cured at room temperature for approximately 30 hours and post-cured at 110 °C for 2 hours in order to have a fully cured state. The total thickness of the fully cured base laminate was approximately 2.25 mm. The same layup (four UD layer) was stacked on top of the base prefab and the resin was infused. The curing took place for the over infused laminate at room temperature for 30 hours. A schematic view of co-molding is depicted in Fig. 1. The total laminate thickness was approximately 4.5 mm with 8 UD layers. Due to the chemical shrinkage during curing of the over infused laminate and bonding at the interface between the prefab and over infused laminate, a warpage formation is expected to occur as seen in Fig. 1 after the curing cycle.

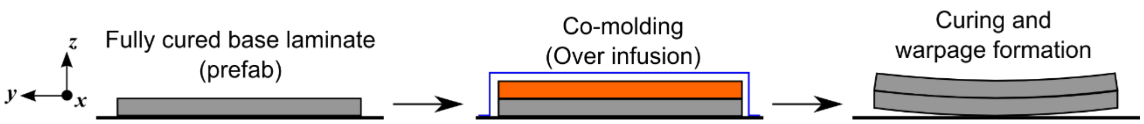

Figure 1: Schematic view of the co-molding process. Note that the fiber direction of the laminates is in the *x*-direction.

The picture of the of the vaRTM setup is shown in Fig. 2. A total of two over-infusion experiments was conducted to manufacture the co-molded laminates. The curvature of the laminate after infusion process was measured using Mitutoyo Coordinate Measurement System, type Crysta-PlusM 544.

The utilized polyester resin was characterized and necessary material models were developed as in. The cure kinetics model was developed based on the isothermal dynamic scanning calorimetry (DSC) measurements. The temperature and cure dependent resin modulus were developed using the dynamic mechanical analyzer (DMA). The glass transition temperature was found to be approximately 45 °C from the DMA. The chemical shrinkage and the gelation point of the pure resin were obtained using a rheometer (Anton Paar MC501 with a CTD450 oven) in the plate-plate mode as done in [18]. The total volumetric shrinkage was found to be approximately 9.45 % for the pure polyester used in the experiments. The thermal properties needed for the process model was taken from [19] in which a polyester resin system was studied.

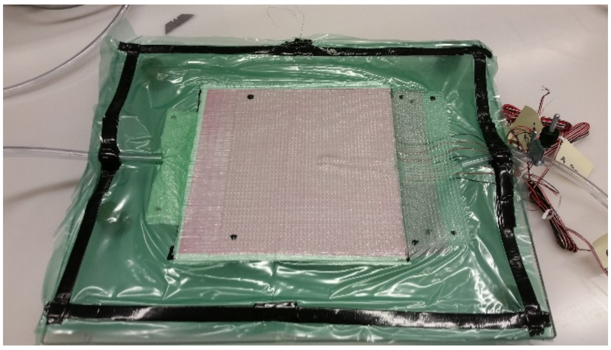

Figure 2: The vaRTM setup for the over-infusion (co-bonding) experiments prior to the resin infusion.

3 PROCESS MODEL

A process simulation tool was developed using ABAQUS by the author [20-21] to predict the residual stresses and shape distortions in composites parts. This tool was modified to simulate the co-bonding process. The tool is based on a thermochemical model sequentially coupled with a quasi-static mechanical model. The temperature and degree of cure are predicted in the thermochemical analysis and the process induced strains and stresses are calculated in the mechanical analysis. The details of the developed process model can be found in [21]. The developed model was modified and adapted to simulate the co-molding or over-infusion process schematically seen in Fig. 1. A user interface seen in Fig. 3 was developed in MATLAB in order to modify the material parameters which are put into ABAQUS. The process parameters used in the material models (cure kinetics, cure hardening instantaneous linear elastic (CHILE) model, glass transition temperature, chemical shrinkage and thermal expansion/contraction) and the material properties can be seen in Fig. 3.

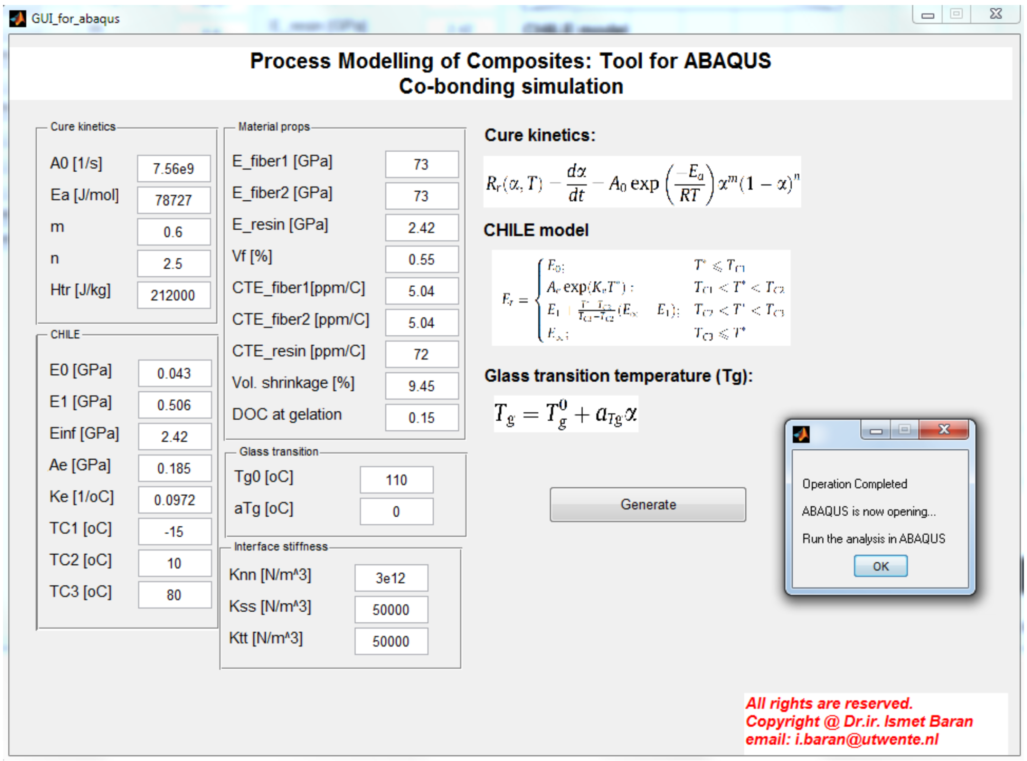

Figure 3: Screenshot of the developed user interface for the process simulation of co-bonding (over-infusion).

A two-dimensional (2D) model was developed in ABAQUS for the over-infusion of 200×200 mm laminate with 4.5 mm thickness (8 UD layers). Only the half of the plate was modelled due to the symmetry. The schematic view of the process model domain together with dimensions is seen in Fig. 4. Since the curing of the laminate over the prefab took place at room temperature (25 °C), the temperature kept constant at 25 °C in the simulations. The internal heat generation due to the exothermic reaction during curing was included in the model. The variation in the material properties of the fully cured prefab as a function of temperature was also taken into account. The glass mold was modelled as a rigid surface as seen in Fig. 4. Any expansion of the base laminate beyond that rigid surface was restricted, however, any separation was allowed without taking the friction into account between the base laminate and rigid surface. The constitutive behavior of the interface between the base laminate (prefab) and the over-infused laminate was defined using two different approaches:

- Shear layer: A shear layer was defined at the interface with a thickness of 0.01 mm. The shear layer modulus (E_r [Pa]) was defined using a parametric analysis based on the warpage prediction.
- Cohesive surface: A cohesive surface was defined at the interface using the traction separation law in the cohesive. The interface shear stiffness (K_s [N/m^3]) was determined using a parametric analysis based on the warpage prediction. The interface strengths used in the traction separation law in ABAQUS were set to 30 MPa and 60 MPa for the opening and shear mode, respectively [22].

Total of 1600 plane strain elements were used in the thermo-chemical-mechanical process model.

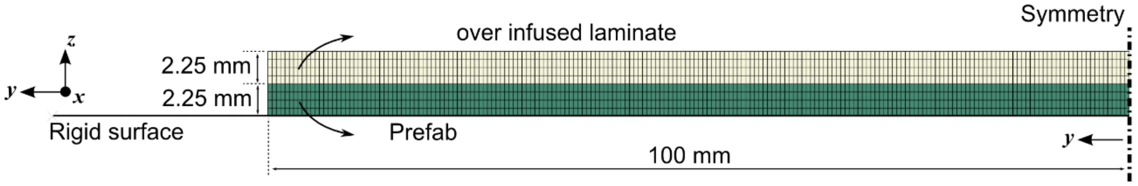

Figure 4: Schematic view of the co-molding (over-infusion) process model domain.

4 RESULTS AND DISCUSSIONS

The picture of a warped co-molded laminate is shown in Fig. 5. The warpage formation was due to the chemical shrinkage of the over-infused laminate during co-molding. The radius of the curvature seen in Fig. 5 was measured for two co-molded laminates approximately as 1791 mm and 1926 mm using the Mitutoyo coordinate measurement system before the post curing. The temperature and degree of cure developments were predicted using the numerical process model. There was the negligible effect of exothermic heat generation on the temperature development was observed since the temperature remained almost constant due to the relatively thin laminate.

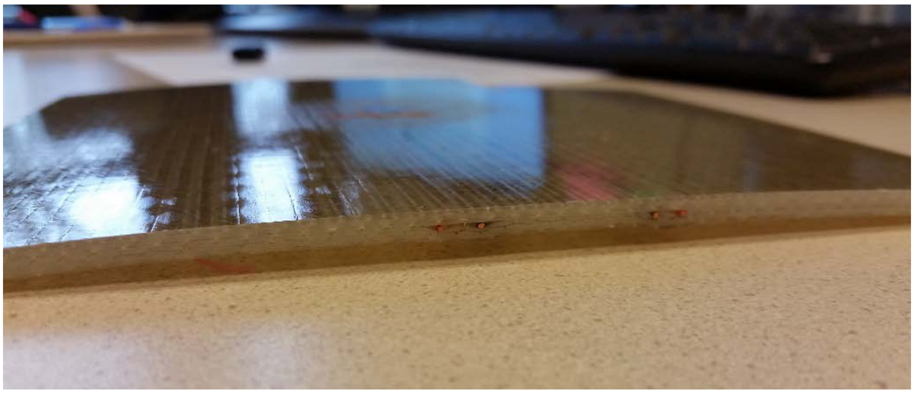

Figure 5: A picture showing the warpage in the co-bonded composite part. The side facing the table is the over infused part.

Since the bonding conditions such as initiation and progression of bonding were not known exactly during processing, 5 different values were employed for the resin elastic modulus (E_r = 1e3 Pa, 3e3 Pa, 5e3 Pa, 1e4 Pa and 2.42e9 Pa) used in shear layer approach and for the interface stiffness (K_s = 1.0e4 N/m^3, 1.5e4 N/m^3, 2.0e4 N/m^3, 2.5e4 N/m^3 and 1e12 N/m^3) used in traction separation law. The highest values considered in both cases, i.e. E_r = 2.42e9 Pa and K_s = 1e12 N/m, were employed in order to simulate the perfect bonding case, i.e. only stick situation, during the over-infusion process. The measured and predicted curvatures are shown in Fig. 6 and 7 for the shear layer approach and traction separation law, respectively. The maximum deflection of the warpage from the experiments was obtained approximately as 2.7 mm in the *z*-direction at *x* = 100 mm. It is seen that the perfect bonding conditions for both approaches used in the process simulations highly overestimated the curvature of the warpage as compared with the measurements. This indicates that a lower interface stiffness should be used during the process simulations. This is due to the fact that the bonding probably takes place somewhere after gelation during curing. A good agreement was found between the predicted and measured warpage for E_r = 5e3 Pa and K_s = 2e4 N/m. The predicted interfacial shear stresses were way below the interfacial strength defined in the traction separation law. The corresponding contour plots of the warpage are depicted in Fig. 8 and 9 for the shear layer and traction-separation case, respectively.

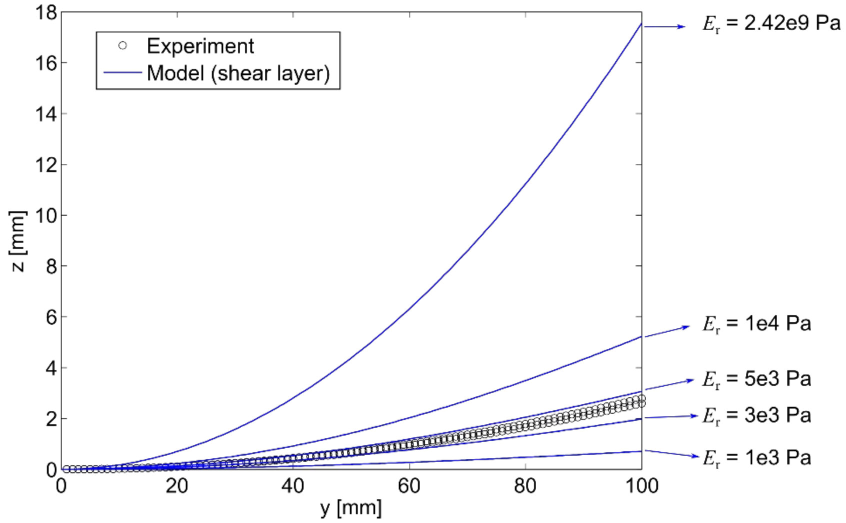

Figure 6: The measured and predicted curvature using the shear layer approach with different shear layer moduli (E_r [Pa]) for the warped laminate.

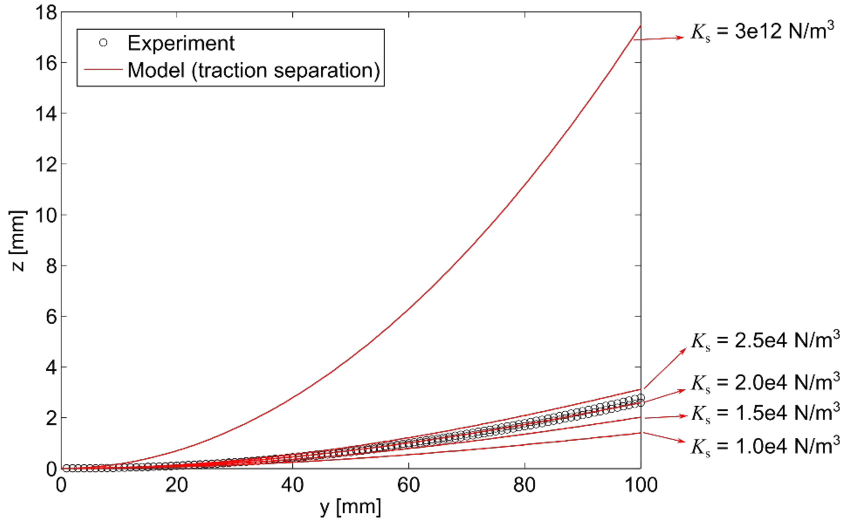

Figure 7: The measured and predicted curvature using the traction separation approach with different interface stiffness (K_s [N/m^3]) values for the warped laminate.

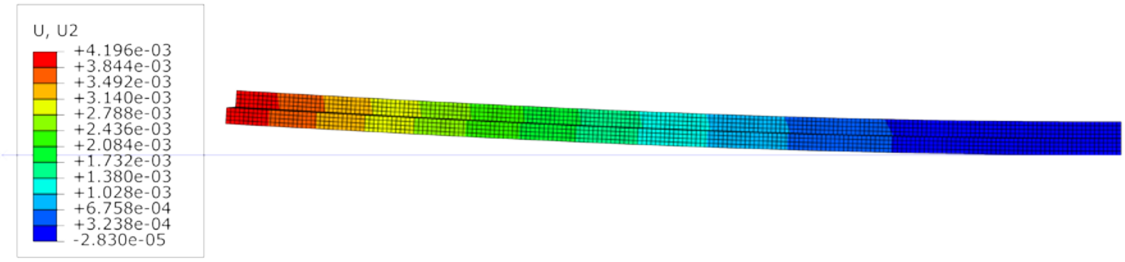

Figure 8: The predicted warpage formation using the shear layer at the interface with resin elastic modulus E_r = 5e3 Pa.

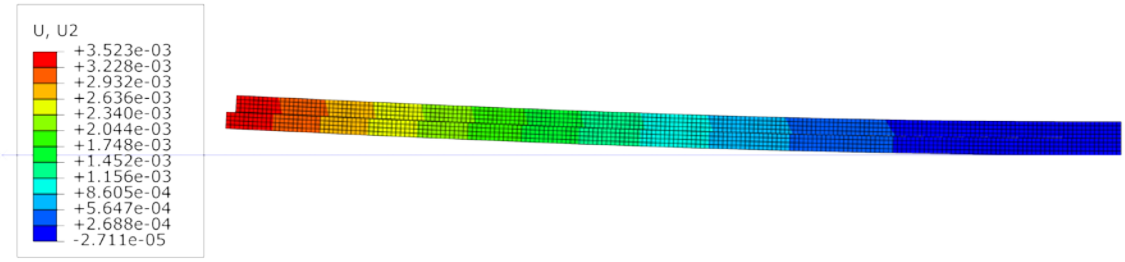

Figure 9: The predicted warpage formation using the traction separation law at the interface with resin interface stiffness K_s = 2e4 N/m^3.

5 CONCLUSIONS

The warpage formation in co-molded glass/polyester laminates was analyzed experimentally and numerically. An uncured part was infused over a fully cured laminate using the vaRTM technique. The co-molded plate was 200×200 mm with a thickness of approximately 4.5 mm (8 UD layers). The warpage was measured after the infusion process by using Mitutoyo coordinate measurement system. A thermo-chemical-mechanical process model was developed to simulate the co-molding of the laminates. A dedicated material characterization of the polyester resin was carried out and corresponding material models were developed for the multi-physics process model. The constitutive behavior of the interface was modelled using two different approaches, i.e. the shear layer approach and traction separation law. Reasonable agreement between the process model and experimental results was achieved using soft resin stiffness at the interface. This suggests using a comprehensive constitutive behavior of the interface during curing.

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REFERENCES

[1] I. Baran, *Pultrusion: state-of-the-art process models*, Smithers Rapra, Shropshire, UK, 2015.

[2] M.W. Nielsen, *Predictions of process induced shape distortions and residual stresses in large fibre reinforced composite laminates*, Ph.D. Thesis, Technical University of Denmark, Lyngby, Denmark; 2012.

[3] I. Baran, K. Cinar, N. Ersoy, R. Akkerman and J.H. Hattel, A review on the mechanical modeling of composite manufacturing processes, *Archives of Computational Methods in Engineering*, **24(2)**, 2017, pp. 365-395.

[4] M.R. Wisnom, M. Gigliotti, N. Ersoy, M. Campbell and K.D. Potter, Mechanisms generating residual stresses and distortion during manufacture of polymer-matrix composite structures, *Composites Part A: Applied Science and Manufacturing*, **37**, 2006, pp. 522-529.

[5] H.T. Hahn and N.J. Pagano, Curing stresses in composite laminates, *Journal of Composite Materials*, **9(1)**, 1975, pp. 91-106.

[6] R.H. Nelson and D.S. Cairns, Prediction of dimensional changes in composite laminates during cure, *34th International SAMPE symposium and exhibition*, **34**, 1989, pp. 2397-2410.

[7] H. Sarrazin, B. Kim, S.H. Ahn and G.S. Springer, Effects of processing temperature and lay-up on springback, *Journal of Composite Materials*, **29(10)**, 1995, pp. 1278-1294.

[8] M. Gigliotti, M.R. Wisnom and K. Potter, Development of curvature during the cure of AS4/8552 [0/90] unsymmetric composite plates, Composites Science and Technology, **63**, 2003, pp. 187-197.

[9] M. Svanberg and J.A. Holmberg, An experimental investigation on mechanisms for manufacturing induced shape distortions in homogeneous and balanced laminates, *Composites Part A: Applied Science and Manufacturing*, **32**, 2001, pp. 827-838.

[10] N. Ersoy, K. Potter, M.R. Wisnom and M.J. Clegg, Development of spring-in angle during cure of a thermosetting composite, *Composites Part A: Applied Science and Manufacturing*, **36**, 2005, pp. 1700-1706.

[11] D.W. Radford and T.S. Rennick, Separating sources of manufacturing distortion in laminated composites, *Journal of Reinforced Plastics and Composites*, **19(8)**, 2000, pp. 621-640.

[12] T. Garstka, *Separation of process induced distortions in curved composite laminates*, Ph.D. thesis, University of Bristol, UK, 2005.

[13] I. Baran, C.C. Tutum, M.W. Nielsen and J.H. Hattel, Process induced residual stresses and distortions in pultrusion, *Composites Part B: Engineering*, **51**, 2013, pp. 148-161.

[14] I. Baran, J.H. Hattel, R. Akkerman and C.C. Tutum, Mechanical modelling of pultrusion process: 2D and 3D numerical approaches, *Applied Composite Materials*, **22**, 2015, pp. 109-118.

[15] I. Baran, J.H. Hattel and R. Akkerman, Investigation of process induced warpage for pultrusion of a rectangular hollow profile, *Composites Part B: Engineering*, **68**, 2015, pp. 365-374.

[16] I. Baran, R. Akkerman and J.H. Hattel, Modelling the pultrusion process of an industrial L-shaped composite profile, Composite Structures, **118**, 2014, pp. 37-48.

[17] G. Twigg, A. Poursartip and G. Fernlund, Tool–part interaction in composites processing. Part II: numerical modelling, *Composites Part A: Applied Science and Manufacturing*, **35(1)**, 2004, pp.135-141.

[18] H. Mohsan,P. Hubert and L. Lessard, Cure Shrinkage Characterization and Modeling of a Polyester Resin Containing Low Profile Additives, Composites Part A: Applied Science and Manufacturing, 38(3), 2007, pp. 994-1009.

[19] I. Baran, R. Akkerman and J.H. Hattel, Material characterization of a polyester resin system for the pultrusion process, *Composites Part B: Engineering*, **64**, 2014, pp. 194-201.

[20] I. Baran, *Pultrusion processes for composite manufacture*, in 'Advances in Composites Manufacturing and Process Design, (ed. P. Boisse) ', Cambridge, UK, Woodhead Publishing, 2015.

[21] I. Baran, *Modelling the pultrusion process of off shore wind turbine blades*, Ph.D. Thesis, Technical University of Denmark, Lyngby, Denmark; 2014.

[22] A. Turon, P.P. Camanho, J. Costa and J. Renart, Accurate simulation of delamination growth under mixed-mode loading using cohesive elements: Definition of interlaminar strengths and elastic stiffness, Composite Structures, 92, 2010, pp. 1857-1864.