Numerical Evaluation of Reinforcement Morphology Contribution to Process-Induced Residual Stresses in 3D Woven Composites

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Abstract

3D woven composites, in particular carbon/epoxy, are being increasingly adopted in aerospace, wind energy, transportation and other industries due to their high strength, lightweight, good dimensional stability and delamination resistance. They are often produced by resin transfer molding with epoxy cured at elevated temperature. This process can result in high level of residual stresses due to the mismatch in thermal expansion coefficients of carbon and epoxy. In this paper, a numerical modeling in combination with blind hole drilling experiments is utilized to determine processing-induced residual stresses in 3D woven composites using the example of orthogonal reinforcement. In particular, the individual contributions of residual stress in the weft and binder tows as well as resin-rich pockets to the entire residual stress distribution are evaluated. Our studies show that these contributions are determined by both arrangement and orientation of the tows. The developed numerical modeling tool can be used in the design of reinforcement architectures with reduced levels of residual stresses.

1. Introduction

3D woven carbon/epoxy composite materials are prone to developing thermal curing-induced residual stresses. This phenomenon can lead to reduced strength, stiffness, and fatigue life or microcracking in the material [1]. Due to the complexity of the material reinforcement microstructure, non-uniform temperature and curing ratio distribution, chemical shrinkage in the epoxy resin and the mismatch between coefficients of thermal expansion (CTE) of carbon fibers and polymer matrix, the residual stress fields are not uniform and their experimental measurement present significant challenges. To fully predict the composite material behavior during service, the residual stress state has to be defined both qualitatively and quantitatively. It has been shown in [2] that the mesoscale finite element (FE) modeling of woven composites can be successfully utilized for mechanical analysis of these materials.

In this paper, a meso-scale FE models [3] are used to evaluate spatial distribution of the residual stresses in woven composite. The hypothesis is that the residual stresses occur in the material during cooling after curing mostly due to the mismatch between CTEs of carbon fibers and epoxy resin. To obtain a realistic evaluation of the residual stress distribution, the models are correlated to the experiments via comparing with the experimentally measured displacement fields around a drilled blind hole. Drilling of the hole causes displacement of the material around it due to the release of residual stresses. These displacements are then measured using electronic speckle pattern interferometry (ESPI), see [4]. Once the model is correlated to the actual measurements, the residual stress field distribution can be evaluated from the simulations. The residual stress field is not uniform and requires a thorough investigation to evaluate the contribution of each tow type of a given reinforcement architecture including its location and orientation.

2. FEA Modeling

Development of meso-scale 3D FE models for 3D woven composites is described in [3]. Because the material reinforcement is periodic, the model of the smallest repeatable portion of the material – unit cell (UC) is modeled. Geometrical representation of the material reinforcement is achieved with the Digital Fabric Mechanics Analyzer (DFMA), see [5]. As an example the orthogonal type of the reinforcement is used, see Figure 1.

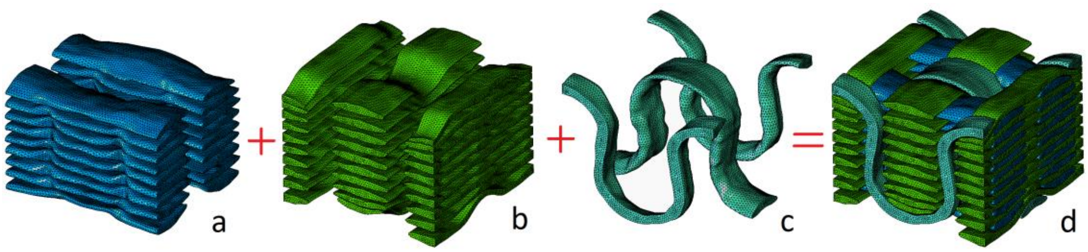

Figure 1. Orthogonal reinforcement (d). Tows: warp (a), weft (b) and binder (c).

The material properties of the reinforcement (each tow consists of 12,000 IM7 carbon fibers impregnated with RTM6 epoxy resin) and epoxy resin matrix (fully cured HEXCEL RTM6) are determined from micromechanical modeling and experimental data, as reported in [6]. Because the models do not include stress relaxation effects in the epoxy, they need to be correlated to the experiments. To correlate the models, the blind hole drilling experiment is simulated in MSC Marc Mentat software. The finite elements corresponding to the hole are deactivated after simulation of the cooling process ($\Delta T = -140^oC$), then the displacement fields around the hole are compared to those measured by ESPI. The effective temperature drop ΔT_{eff} is introduced for the model correlation, where $\Delta T = k\Delta T^{eff}$ and k is the correlation coefficient. This approach allows matching the simulated and measured displacements around the hole.

3. Evaluation of local residual stress fields

In the procedure, the orthogonal reinforcement architecture shown in Figure 1(d) is considered. Three hole locations are chosen to evaluate the contribution of each tow type. To correlate the models to the experiments, the displacements after the hole drilling along the horizontal (X) and vertical (Y) lines crossing the hole center (e.g. see Figure 2) obtained numerically are compared with experimental observations for each hole location. Based on this comparison, the effective temperature drop was found to be $\Delta T = 4.67\Delta T^{eff}$

or ΔT^{eff}=-30ºC. This result does not depend on the hole location and can be assumed to be constant for this particular composite.

3.1. Stresses around binder tows

Figure 2 illustrates displacements around the hole drilled in the binder tow. With the found value of ΔT^{eff}=-30ºC the model shows generally good agreement with the experiment. However, the model predicts more pronounced closure of the hole in horizontal direction than is seen in the experimental data. Generally, the hole opens in the direction normal to the binder tow but closes and shifts along its direction. The opening is driven by the tensile residual stress in the epoxy resin, and closure is due to the compressive stress in the binder tow along its central line.

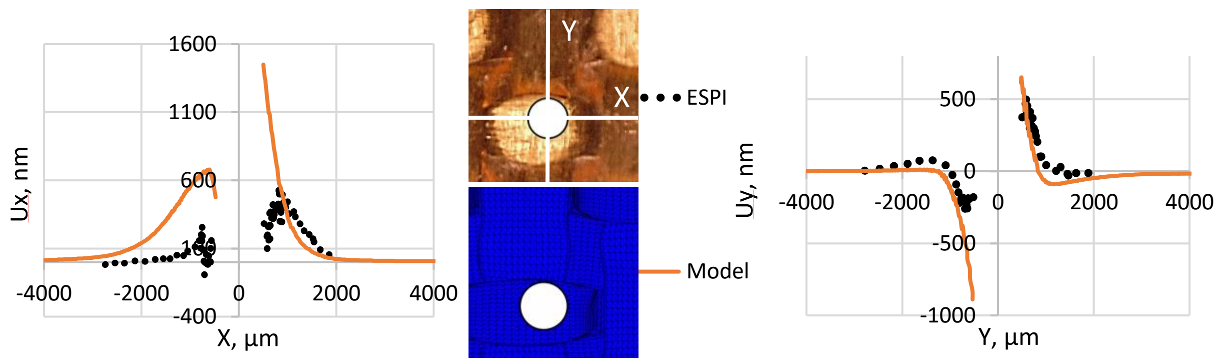

Figure 2. Horizontal and vertical displacements around the hole cutting a binder tow

3.2. Stresses around weft tows

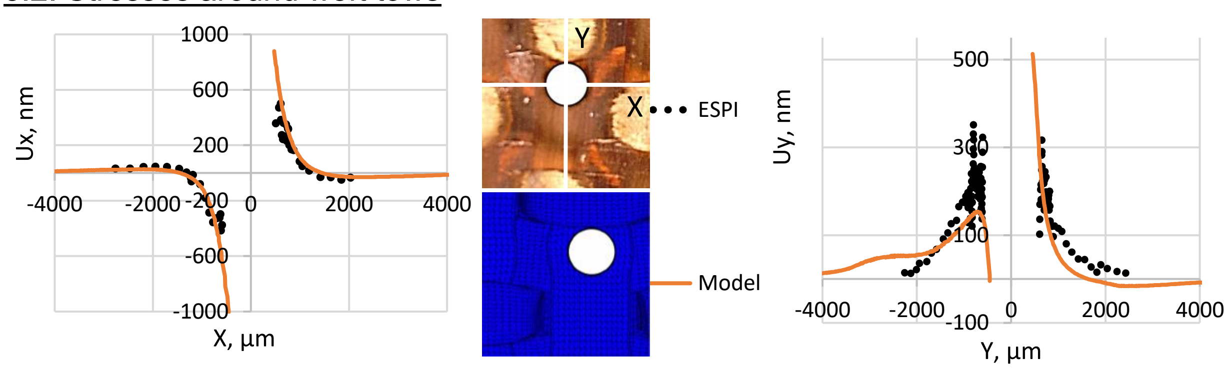

Figure 3. Displacements around the hole cutting a weft tow

For the hole cutting the weft tow, the same trend as for the binder is observed. Figure 3 shows that the hole opens in the transverse to the tow direction and closes and shifts towards the crossing binder tow along the weft (vertical) direction. This behavior is explained by the tensile residual stress in the resin matrix and compressive stress in the weft tows in vertical direction.

3.3. Stress in the epoxy resin

The third hole drilled does not cut any tows and mostly removes epoxy resin matrix material. Figure 4 illustrates the hole opening in both vertical and horizontal directions. This behavior is dictated by a significant level of tensile residual stress in the epoxy resin.

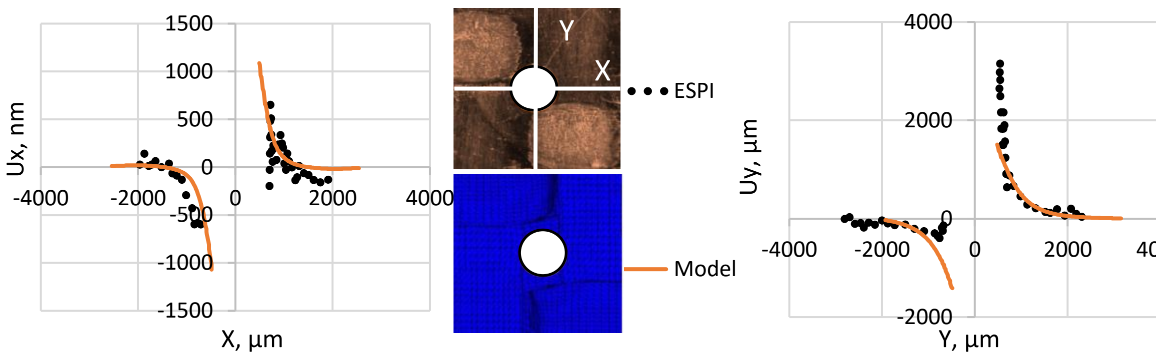

Figure 4. Displacements around the hole drilled in the epoxy resin matrix

4. Conclusions

The developed approach enables evaluation of the full-field distribution of the process induced residual stresses in 3D woven composites. Various blind-hole locations with respect to the reinforcement microstructure have been considered. The opening of the hole in the direction normal to the tows is caused by significant tensile stresses in the epoxy matrix. The closure of the hole in the direction along the central line of the tow being cut is dictated by the compressive residual stress in the tow along its direction. In the case when no tows are cut during the drilling, the hole opens in both directions due to the tensile residual stresses in the matrix. The numerical models are correlated to the ESPI experiments and the effective temperature drop ΔT^{eff} is found to be constant for the orthogonal reinforcement and equal to -30^{o}C regardless the hole location.

5. Acknowledgements

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6. References

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