

THERMOELASTIC PROPERTIES PREDICTION OF 3D TEXTILE COMPOSITES

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SUMMARY: Predictive methodology for effective thermoelastic properties of 3D orthogonal and multiaxial woven composites is developed. Based on a generic stochastic geometric characterization of a 3D fiber reinforcement, this methodology allows one to predict effective properties of composites with random deviations of the reinforcement paths from the designed, "perfect" ones. This enables to incorporate certain types of possible but hardly predictable processing/manufacturing flaws and imperfections (for example, fiber waviness, misalignment, and misplacement) in the material performance evaluation. Numerical results obtained for the effective properties of two novel classes of 3D woven composites are compared to the experimental data. Sensitivity analysis is performed to study the effect of reinforcement imperfections on the mean values and standard deviations of the effective elastic characteristics.

KEYWORDS: textile composites, 3D weaving, stochastic mechanics, stiffness averaging, effective properties, manufacturing flaws, sensitivity analysis.

INTRODUCTION

Two innovative technologies of processing 3D woven (orthogonal and multiaxial) textile preforms developed at North Carolina State University and licensed to 3TEX, Inc. offer a revolutionary style of 3-D weaving [1], [2]. A variety of recently developed, experimentally proven preform designs confirm a substantial performance improvement when these types of 3D preforms are used in engineering structures either as dry fabrics or as reinforcements for thick composites. Particularly, ballistic resistance over traditional 2D and 3D woven laminated textile materials is significantly increased. An innovative 3D multiaxial weaving technology (this incorporates two sets of bias yarns) shows significant improvement in the shear stiffness and shear strength characteristics. Generally, thick woven panels assure not only considerable weight reduction of the product, but also improved wear resistance at elevated temperatures, higher level of comfort, design flexibility, and reduced manufacturing cost.

Owed to certain specific features of the aforementioned 3D weaving technologies, the preform designs are characterized by perfectly straight yarns (zero crimp) in the warp direction. The weft and Z-yarns (as well as the bias yarns in the case of 3D multiaxial weaving) are only curved in a very small boundary regions, near outer surfaces of the manufactures preform. The

absence of crimp within all major part of this type 3D woven preforms substantially improves the in-plane mechanical properties against all other existing textile reinforcements. Also, these textile preforms fully eliminate delamination, which is the most critical failure mode in laminated composites. It is also important to note that the processes provided by this type 3D weaving are gentler on fibers, thus reducing processing damage and, respectively, increasing performance of the product. These weaving technologies enable creating not only thick plain fabrics but also complex integrally woven shapes (I-beams, T-sections, box-beams, etc.) in a single-step process. The weaving process allows one using various fiber types and sizes (hybrid reinforcements) within the same fabric. Further, complex fabric architectures, which use functionally graded reinforcement designs, can be purposefully tailored for achieving the optimal material performance. Due to the multiple insertion approach, these weaving technologies are capable of providing superior manufacturing rates, unmatched even with 2D weaving. This feature enables manufacturing of thick and complex shaped preforms at a lower cost.

Consolidation of the textile preform with resin, using traditional RTM or more recent advanced resin infiltration approaches, unavoidably results in a significant change of the fiber volume fraction within textile composite as compared to the dry preform (see, for example [3]). This well-established effect implies that the preform consolidation process may introduce considerable fiber waviness (especially in the Z-direction) into the reinforcement architecture. The waviness, in turn may significantly affect the consolidated composite performance.

In this work a generic theory developed in [4] for predicting elastic properties of composite materials with random imperfections of the reinforcement paths, is utilized to study the thermoelastic response and also perform sensitivity analysis, considering local imperfections of the reinforcement architecture in 3D woven composites.

PREDICTIVE ANALYSIS APPROACH FOR EFFECTIVE THERMOELASTIC CHARACTERISTICS

Prediction of effective thermoelastic properties of composites with 3D textile reinforcements includes two major steps. In the first step, effective properties of the respective unidirectional composite are analyzed, based upon properties of its constituents (fiber and matrix), the reinforcement arrangement, and fiber volume fraction. It should be noted that a vast variety of micromechanics approaches are available for predicting elastic characteristics of unidirectional composites, see for example review in [5]. Also, predictive methodologies for coefficients of thermal expansion are well established. In the second step, a spatial orientation averaging procedure (so-called stiffness or compliance averaging) is commonly applied to account for a complex 3D reinforcement architecture.

Let us introduce local orthonormal basis $\{\mathbf{e}'_i\}$ related to the principal directions of the reinforcement and orthonormal basis $\{\mathbf{e}_i\}$ related to the global coordinate system $\{x_i\}$, as shown in Fig. 1. Then, directional cosines characterizing the reinforcement orientation are defined as

$$e'_{ij} = \mathbf{e}'_i \cdot \mathbf{e}_j \quad (1)$$

The stiffness C_{ijkl} , compliance S_{ijkl} and thermal expansion α_{ij} characteristics of a unidirectional composite material, which are referred to the "global" coordinate system, are

related to the respective stiffness C'_{ijkl} , compliance S'_{ijkl} and thermal expansion α'_{ij} characteristics referred to the "local" coordinate system through the following tensor transformation law:

$$C_{ijkl} = C'_{mnop} e'_{mi} e'_{nj} e'_{ok} e'_{pl}, \quad S_{ijkl} = S'_{mnop} e'_{mi} e'_{nj} e'_{ok} e'_{pl}, \quad \alpha_{ij} = \alpha'_{mn} e'_{mi} e'_{nj} \quad (2)$$

Here, directional cosines e'_{ij} are defined by Eqn (1). Thermoelastic characteristics of a transversely anisotropic material can be readily obtained by using some micromechanics model. The micromechanics model of Hashin [6] is one of the most popular; it will be used in this analysis to predict stiffness C'_{ijkl} and compliance S'_{ijkl} tensors of the unidirectional composites.

Many different analysis approaches exist, with various degrees of complexity, for predicting the coefficients of thermal expansion of unidirectional composites. Summary of the work in this field can be found in [7], where results obtained with various analysis approaches were mutually compared and also checked with experimental data. Following [8], the tensor of thermal expansion is expressed in terms of the coefficients of thermal expansion of fiber and matrix, their elastic constants, as well as effective elastic properties of the composite:

$$\alpha'_{ij} = \alpha_{ij}^{(f)} V_f + \alpha_{ij}^{(m)} (1 - V_f) + (\alpha_{kl}^{(f)} - \alpha_{kl}^{(m)}) P_{klmn} (S_{mni} - S'_{mni}) \quad (5)$$

where V_f is fiber volume fraction. A fourth rank tensor, P_{klmn} , is defined by the following equation

$$P_{klmn} (S_{mni}^{(f)} - S_{mni}^{(m)}) = I_{klji} \quad (6)$$

Here, $S_{mni}^{(f)}$ and $S_{mni}^{(m)}$ are elastic compliances of fiber and matrix, respectively, and I_{klji} is a fourth rank unity tensor.

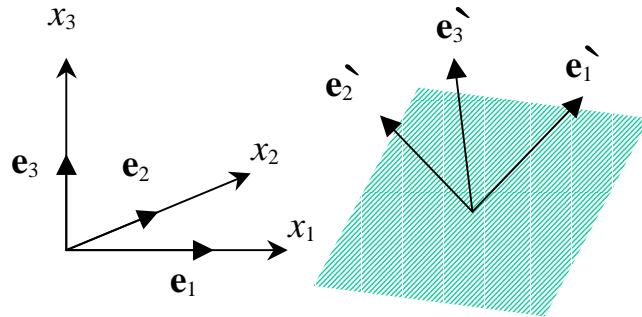


Fig. 1: Local basis $\{\mathbf{e}'\}$ related to the principal axes of the reinforcement, and global basis $\{\mathbf{e}_i\}$ related to coordinate system $\{x_i\}$.

Thermoelastic characteristics of a composite with any type of 3D textile reinforcement can be, in principle, evaluated by applying the orientation averaging technique originated in [9], [10]:

$$\mathbf{C}^* = \sum_k \mu_k \mathbf{C}^{(k)}, \quad \mathbf{S}^* = \sum_k \mu_k \mathbf{S}^{(k)}, \quad \boldsymbol{\alpha}^* = \mathbf{S}^* \sum_k \mu_k \mathbf{C}^{(k)} \boldsymbol{\alpha}^{(k)} \quad (7)$$

where $\mathbf{C}^{(k)}$, $\mathbf{S}^{(k)}$, and $\boldsymbol{\alpha}^{(k)}$ are stiffness, compliance, and thermal expansion tensors of the composite due to the k^{th} reinforcement system; μ_k is the volumetric fraction of the k^{th} reinforcement system. The above Eqs (7) are rather generic in nature, however after some specification, they allow one to predict thermoelastic properties of a composite with any complex 3D reinforcement architecture.

FABRICATION AND CHARACTERIZATION OF 3D MULTIAXIAL WOVEN COMPOSITES

An innovative 3D multiaxial weaving technique described in [2], [3] enables to fabricate woven preforms at different yarn orientations. In the preforms, five sets of yarns are used as the warp (axial), filling (crossing), Z-yarns (in the thickness direction), and $\pm\vartheta$ bias. The reinforcement architecture of this type textile preform is illustrated in Fig. 2. The $\pm\vartheta$ bias yarns are positioned on the back and front faces of the preform and locked to other sets of yarns by the Z-yarns.

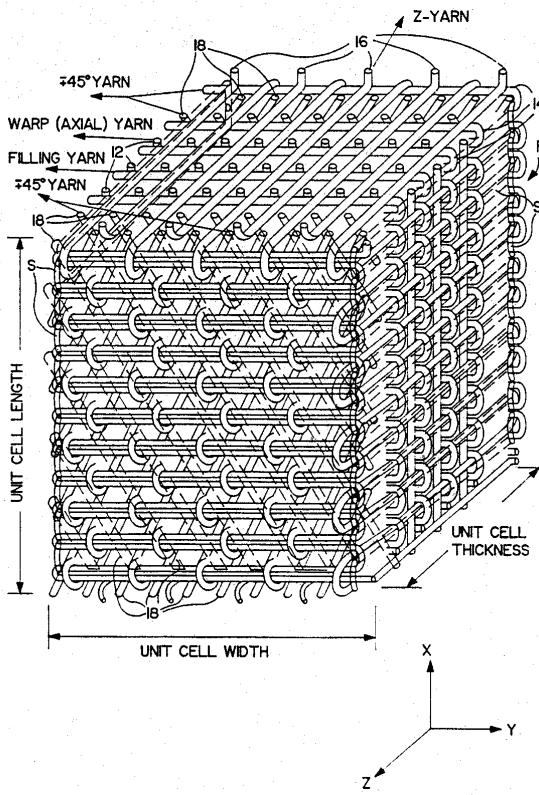


Fig. 2: Reinforcement architecture of the multiaxial 3D woven preform.

The multiaxial 3D woven preform structure is created from three warp layers, six weft layers, two layers of $+\vartheta$ bias yarns, two layers of $-\vartheta$ bias yarns, and Z-yarns (one Z-yarn for every warp raw). The yarn tows are processed from carbon fibers (Celion G30-500). The measured volume fractions of each set of yarns in the preform are: $V_x = 15.49\%$ (warp yarns, 12K denier), $V_y = 12.13\%$ (doubled weft yarns, 6K denier), $V_z = 2.60\%$ (Z-yarns, 3K denier),

$V_{\pm\vartheta} = 5.33\%$ ($\pm\vartheta$ bias yarns, 12K denier). The total fiber volume fraction in the preform is $V_{tot} = 40.86\%$.

The preforms were consolidated with Epoxy resin (Tactix 123, 85% and Catalyst Melamine 5260, 15%). Elastic characteristics of the carbon fibers taken from [11] are $E_f = 230 \text{ GPa}$, $\nu_f = 0.3$. Elastic properties of the matrix reported in [12] are $E_m = 230 \text{ GPa}$, $\nu_m = 0.35$.

Experimental coupons of this textile composite material have been fabricated and tested for their mechanical characterization. The Iosipescu test method was used to determine the in-plane shear properties. Results in Fig. 3 present experimental and predicted elastic moduli E_{11}^* and G_{12}^* . It is seen that the predicted characteristics are slightly lower than the respective experimental values. The difference can be explained by the change of fiber volume fractions caused by RTM consolidation process. Indeed, the total fiber volume fraction in the dry preform is $V_{tot} = 40.86\%$ (this value has been used in the predictive analysis), while the measured total fiber volume fraction in the consolidated composite is 51.8% [3].

For the comparison purpose, shear moduli of 3D orthogonal preform reported in [3] and analytical predictions obtained in [13] are also presented in Fig. 3. It is seen that the bias yarns substantially enhance the in-plane shear properties of the composite. This performance improvement, achieved by incorporating bias yarns in the 3D woven preform, opens new areas of applications for 3D woven composites, where the shear/torsion resistance is of a primary importance. Also, it is seen in Fig. 3 that the predicted in-plane shear modulus of the composite made with 3D orthogonal woven preform, is very close to the respective experimental value. This can be explained by the fact that in this case total fiber volume fractions measured in the preform and in the consolidated composite are 47% (this value has been used in the predictive analysis) and 52%, respectively. So, a discrepancy between them is significantly smaller (only 5%) then in the case of a multiaxial woven preform.

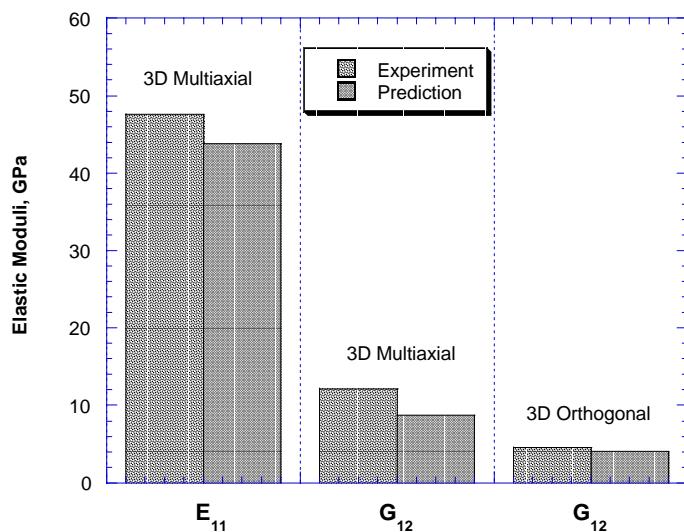


Fig. 3: Experimental and predicted elastic moduli of 3D woven composites.

SENSITIVITY ANALYSIS WITH RESPECT TO THE REINFORCEMENT IMPERFECTIONS

Various types of manufacturing flaws and/or imperfections of the reinforcement are commonly observed in 3D textile composites. A rather small deviation from the assumed "perfect" composite reinforcement architecture can be caused by the preform fabrication, RTM process, material handling and many other technological reasons. The imperfections can significantly affect mechanical properties and thus should be properly quantified and incorporated in the structural analysis and design practices. However, it is difficult to exactly quantify and model any specific type of imperfections, and thus the approach used in this work is to account them in a stochastic sense.

Although 3D textile preforms manufactured with the weaving technology [1], [2] do not show any visible deviations from the straight paths of the yarns, considerable curvatures (especially of the Z-yarns) can appear in the final composite product. A general theory of continuously reinforced composites with account for random imperfections in the reinforcement architecture has been recently developed in [4]. The theory enables to estimate the effect of imperfect (locally curved) reinforcement architecture on the mechanical properties of textile composites. Following this theory, local basis $\{\mathbf{e}'_i\}$ is tied to each point of the reinforcement

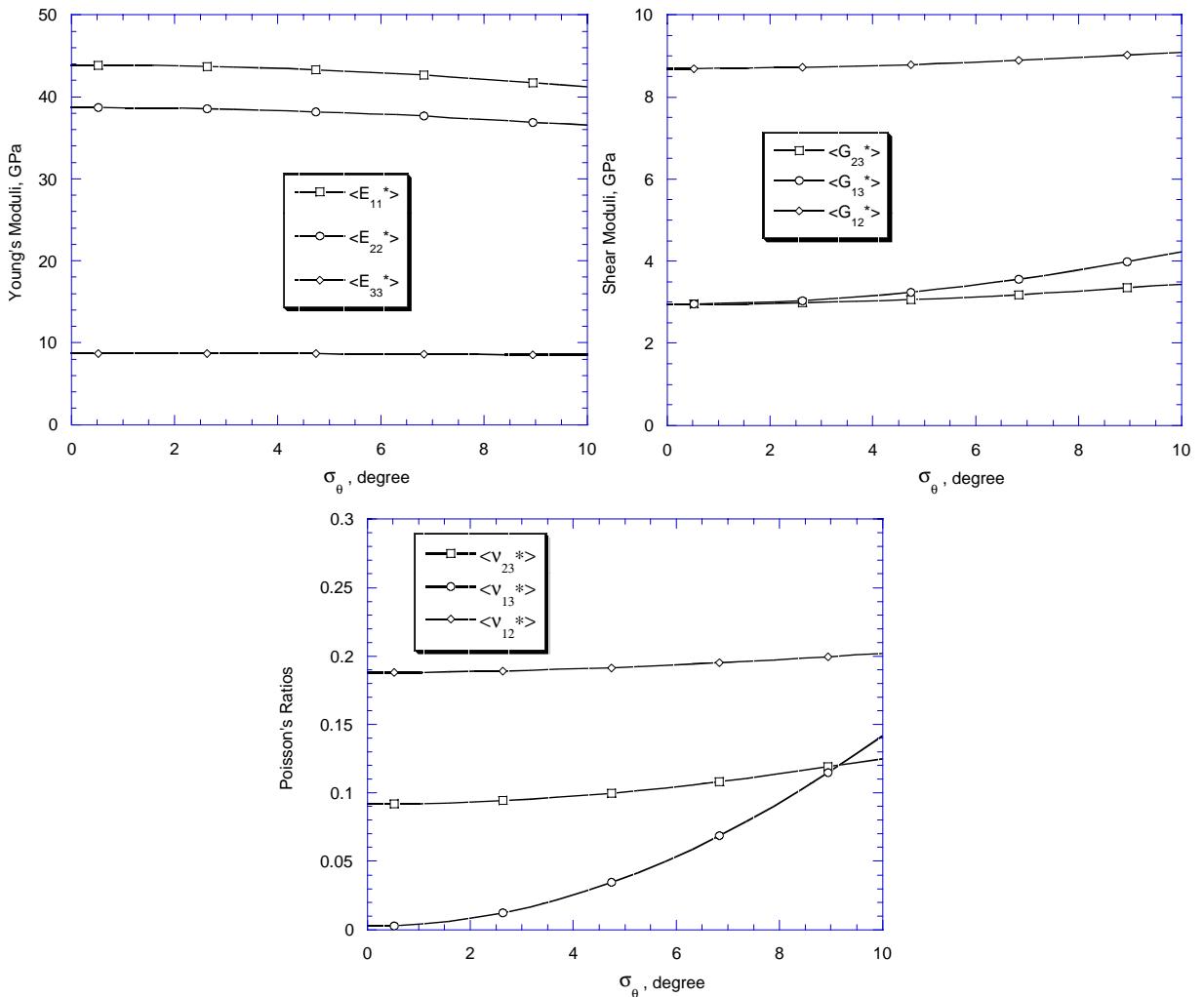


Fig. 4: Dependencies of mean values of the effective elastic characteristics of 3D multiaxial weave composite on standard deviation of the reinforcement path σ_θ .

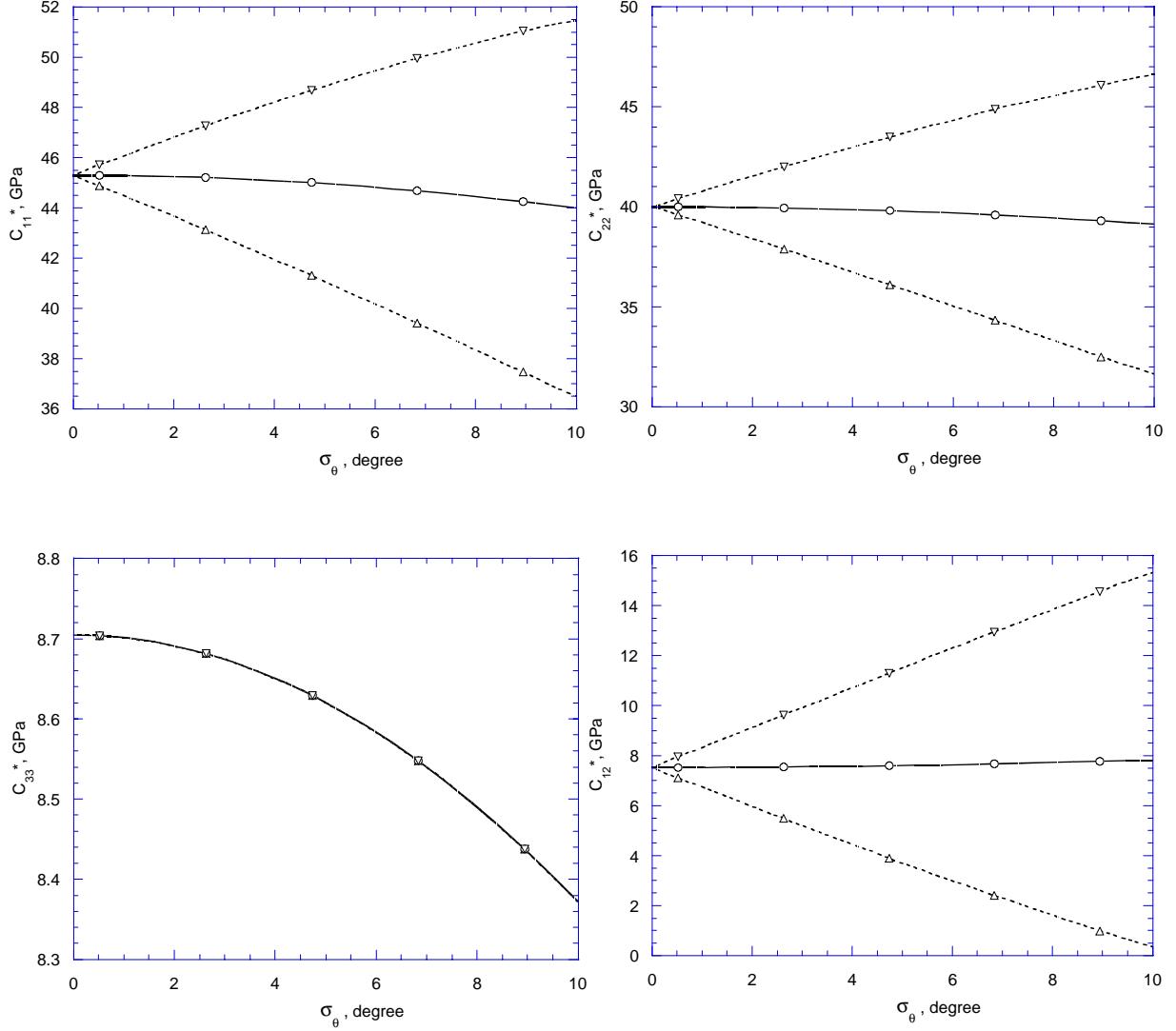


Fig. 5: Dependencies of mean values $\langle C_{ij}^ \rangle$ (solid lines) and standard deviations $\langle C_{ij}^* \rangle \pm \sigma_{C_{ij}^*}$ (dotted lines) of the effective stiffnesses on standard deviations of the reinforcement path σ_θ .*

path. Considering some specific reinforcement path, its imperfections result in a variation of the local basis orientation. Since local reinforcement imperfections are assumed random, the local basis $\{\mathbf{e}'_i\}$ has random orientation along the reinforcement path. The stochastic characteristics of the random local basis can be expressed in terms of experimentally measurable standard deviations of the in-plane and out-of-plane local deflection angles of the reinforcement path. The statistical averaging of Eqs. (2) and (7) provide the mean values and standard deviations of the effective thermoelastic characteristics of a composite with random imperfections in the reinforcement architecture. Further mathematical details of the procedure applied in this study can be found in [4].

Results of the sensitivity analysis, which quantifies the effect of imperfections in reinforcement architecture on the effective properties of multiaxial 3D woven composite, are presented in Figs. 4 and 5. In this sensitivity analysis, it was assumed that local variation of the reinforcement direction for each set of the reinforcing yarns is a random variable with its standard deviation σ_θ . It is seen in Fig. 4 that the *mean values* of all effective elastic

characteristics, except for the Poisson's ratio $\langle v_{13}^* \rangle$, are almost insensitive to the local reinforcement imperfections. However, the analysis shows that *standard deviations* of the effective stiffnesses are sensitive to the local reinforcement imperfections. This is illustrated in Fig. 5, where dependencies of the standard deviations of stiffnesses, $\sigma_{C_{ij}}$ are plotted versus standard deviation of the reinforcement orientation. One characteristic, which is most sensitive to the reinforcement angle variation, is the stiffness component C_{12}^* . At the same time the stiffness component C_{33}^* shows no visible variation, what can be explained by a rather small fiber volume fraction associated with the Z-yarns in this fiber preform.

The sensitivity analysis results were presented here for one special class of 3D woven composites, which are *free of crimp* in a dry preform. Nevertheless, these results may be useful, due to they allow one to evaluate how much variation of the composite properties can be expected if some random reinforcement imperfections are introduced in the other steps of composite fabrication.

CONCLUSIONS

Predictive stochastic theory developed in [4] and applied in this work is capable of considering any type of 2D or 3D textile composites: woven, braided, knitted, etc. Most of them possess considerable tow crimp even in a dry preform. An example of stochastic property prediction and sensitivity analysis presented here considers one special class of 3D woven composites, which are *free of crimp* in a dry preform. The results show that the effective characteristics of this class of 3D woven composites are low sensitive to possible local imperfections in the reinforcement architecture. However, some of the effective stiffnesses reveal noticeable variation about their mean values caused by random reinforcement imperfections.

The predicted elastic modulus and shear modulus of the 3D orthogonal and multiaxial woven composites are in a good agreement with the respective experimental data. Some discrepancy between the theoretical and experimental results is explained by uncontrollable change in the fiber volume fraction (densification) occurring during the preform consolidation.

Our other studies concerned 2D woven, 2D braided and 3D braided composites. Those showed that within a reasonable (from a real material fabrication conditions) range of scatter in the reinforcing yarn orientations, this stochastic effect may be significant not only for the standard deviations of the effective thermoelastic characteristics, but also for their mean values. This effect is especially severe when considering complex shape composite structural parts made with biaxial braided fabrics. Results of those studies will be reported elsewhere.

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