DEVELOPMENT OF A FE DESIGN FRAMEWORK TO PREDICT THE RESPONSE OF DISCONTINUOUS COMPOSITE STRUCTURES WITH HETEROGENEOUS MICROSTRUCTURES

Y. Li[1], S. Pimenta[1]

[1]meComposites, Department of Mechanical Engineering, Imperial College London,
South Kensington Campus, London, SW7 2AZ, UK
Email: yizhuo.li10@imperial.ac.uk

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Abstract

Tow-based discontinuous composites (TBDCs) are a growing class of high performance discontinuous composites used in structural applications. These materials have significant spatial variability in their microstructure and mechanical properties, which adds complexity to structural design using TBDCs. This study proposes a FE Monte-Carlo simulation framework to predict the mechanical response of a TBDC structure, while accounting for the variability in the microstructure of TBDCs. The simulation framework calculates a stochastic distribution of the modulus and strength of TBDCs; it then defines a characteristic spacing between uncorrelated material property points, at which the stochastic distributions of modulus and strength are assigned to a structure. The structure is then analysed in a Finite Element (FE) software, whose results are mesh-independent.

1. Introduction

Tow-Based Discontinuous Composites (TBDCs) are a growing class of high-performance materials for high-volume production of structural components. These materials are composed of carbon-fibre tows randomly oriented and distributed in a polymeric matrix; therefore, they have a large intrinsic variability in the local tow orientations and, consequently, local modulus and strength.

In the literature, there are a number of models attempting to predict the effect of this variability. Harper *et al.* [1] and Selezneva *et al.*'s [2] models explicitly generate the location of each tow in a Finite Element (FE) simulation, and predict the local stiffness and strength fields of the TBDC material in a structure; however, the tow placement method limits the application of these frameworks to structures with simple 2D geometries and requires heavy computational power. Feraboli *et al.* [3] proposed another FE simulation framework to predict the variability in the modulus of TBDCs based on a stochastic laminate analogy, but this does not predict failure initiation in a structure.

Therefore, this study aims to develop a simulation framework to predict the effect of variability in a TBDC structure, by (i) generating *statistical distributions of local mechanical properties* for TBDC materials (see Section 2), (ii) identifying the characteristic distance between points with *uncorrelated material properties* in a TBDC structure (see Section 3), and (iii) assigning stochastic property fields to FE models of TBDC structures in a *mesh independent* way (see Section 4). Section 5 presents the main conclusions.

2. Stochastic distributions of mechanical properties for TBDC materials

The local modulus and strength properties of TBDCs are predicted based on a ply-by-ply Equivalent Laminate (EL) analogy which has been used in the literature [4]. The EL consist of N_{ply} Uni-Directional (UD) plies, and each ply consists of UD discontinuous tows with the same dimensions of the randomly-oriented TBDC. In contrast with previous literature [4] (where the ELs have a Quasi-Isotropic (QI) lay-up to calculate the average properties of the randomly-oriented TBDC), we use *Stochastic* ELs (SELs) to predict the local properties of randomly-oriented discontinuous composites. The in-plane orientation θ of each ply in the SEL is assumed to be a random number between 0 and π. Classical Laminate Theory (CLT) is used in combination with Pimenta *et al.*'s shear-lag model [5] to calculate the local modulus of each SEL, whereas an in-house developed strength model is used to calculate the local strength [6] of each SEL.

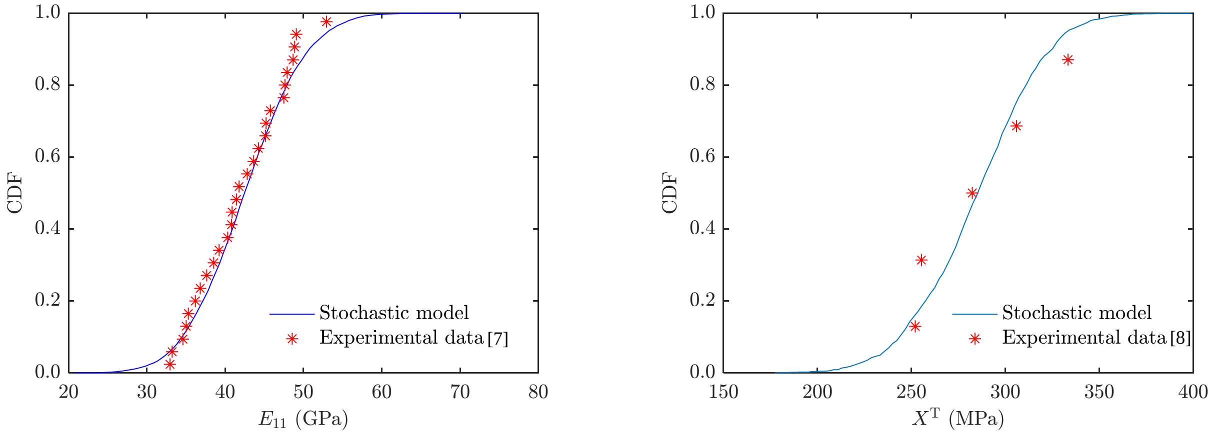
Figure 1 shows the stochastic modulus and strength distributions of TBDCs predicted by the SEL model, and shows a good agreement with experimental data for both the mean value and the spread of the modulus and strength of TBDCs.

3. Characteristic spacing between uncorrelated material points in random fields

In the TBDC material, the spatial variability of mechanical properties will be dictated by the spacing between uncorrelated SELs, which needs to be determined. We assume that this spacing — hereafter named *characteristic seed spacing*, ζ — can be estimated as the harmonic mean between the tow length l_{t} and tow width w_{t}:

$$\zeta = \frac{2}{1/l_{\text{t}} + 1/w_{\text{t}}}. \tag{1}$$

It was confirmed [10] that this definition of the characteristic seed spacing generates random modulus fields with a cross-correlation function similar to the one calculated from an explicit representation of each individual tow.



(a) Modulus.

(b) Strength.

Figure 1: CDF of the modulus and strength of TBDCs, compared to experimental data [7, 8].

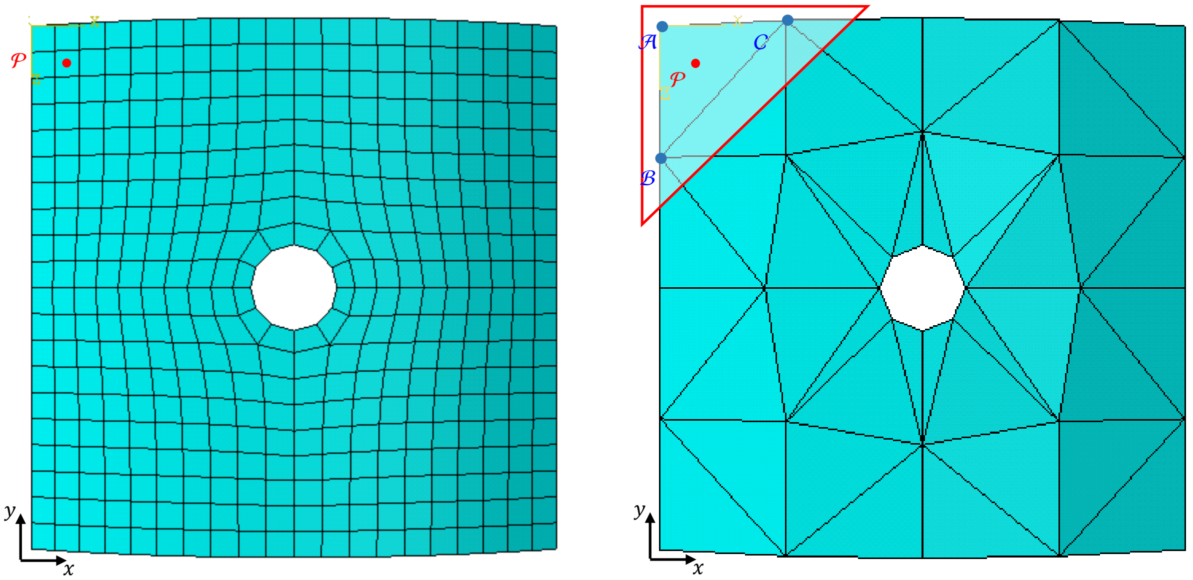
4. Mesh-independent FE formulation

To assign a random field to a structure in an FE analysis at the uncorrelated material points determined in Section 3, and to generate a mesh-independent analysis, two steps are required: (i) to generate a map of uncorrelated material points — hereafter named "seeds" — in a structure, and (ii) to interpolate the properties of the seeds to the integration points of the FE mesh used for structural analysis.

The first step is addressed by creating a triangular "seed mesh", which is assigned to the structure with an element size equal to the seed spacing ζ calculated in Section 3. The seed mesh is unstructured to avoid creating a structured pattern of uncorrelated material properties. The *seeds* are taken as the nodes of the triangular mesh as shown in Figure 2a; each seed is then assigned a SEL lay-up, with a random orientation assigned to each ply. Note that the seed mesh is not the one used for running FE simulations (as explained below).

The mechanical properties at each seed are calculated using the stochastic models described in Section 2. However, in the FE analysis of the TBDC structure, the simulation will be carried out on a *structural mesh* (Figure 2a) — different from the seed mesh — which means it is necessary to interpolate the material properties at the *integration points of the structural mesh* (see Figure 2b) from the material properties at the *nodes of the seed mesh* (see Figures 2a and 2b). This is done using the shape function method (which is widely used in FE simulations [11]).

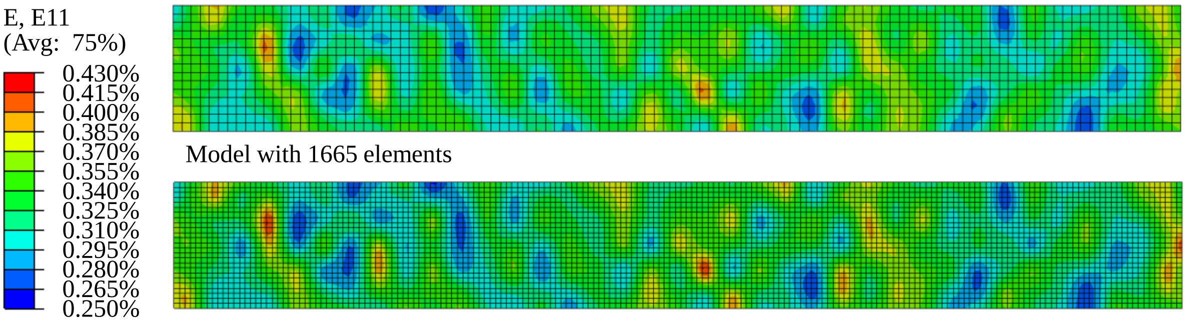
Figure 3 shows the strain field of a rectangular tensile specimen predicted by the FE framework, considering two different sizes of structural mesh but the same stochastic modulus field. It is clear that the interpolation method mentioned above allows for a mesh-independent implementation of the framework.



(a) Structural mesh with integration point $\mathcal{P}$ highlighted by red point.

(b) Seed mesh with element $\mathcal{ABC}$ highlighted (seeds $\mathcal{ABC}$ highlighted by blue points).

Figure 2: Structural mesh and seed mesh of a curved panel.



Model with 1665 elements

Model with 4625 elements

Figure 3: Mesh-independent implementation of the simulation framework, demonstrated in a specimen simulated under tension. The maps shown corresponds to horizontal strain.

5. Conclusions

This study proposed a simulation framework that accounts for the intrinsic variability in the microstructure of TBDCs, and predicts the effect of this variability on the mechanical response of a structure. This simulation framework is suitable for large structures and hence can be used to improve the efficiency in designing TBDC structures. The simulation framework is able to:

1. Predict the mean value and variability of the modulus and strength of TBDCs, with a good agreement with experimental data;
2. Estimate the spacing between uncorrelated material property points in a TBDC structure, according to the microstructure of the TBDC material used;
3. Conduct a mesh-independent stress/strain/failure analysis of a TBDC structure in a FE software.

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