# QUANTIFYING AND PREDICTING THE EFFECT OF HETEROGENENOUS MICROSTRUCTURES ON THE PERFORMANCE OF DISCONTINUOUS COMPOSITES

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**Abstract**
The heterogeneous microstructure of high performance Tow-Based Discontinuous Composites (TBDCs) leads to non-uniform stochastic fields of local mechanical properties; consequently, TBDC structures present a non-deterministic response, and may fail at locations that can only be predicted with stochastic methods. We have quantified the effect of the heterogeneous microstructure on the strength of unnotched and notched tensile specimens, using a range of hole sizes; we have then used an in-house developed FE Monte-Carlo framework to predict stochastic strain fields, critical locations, and critical loads in the specimens. The results from the FE Monte-Carlo analysis provide a good qualitative agreement with the experimental data, suggesting that our framework can be used for structural design of TBDC structures.

## 1. Introduction

High-performance Tow-Based Discontinuous Composites (TBDCs) are composed of randomly-placed and randomly-orientated chopped carbon-fibre tows, embedded in a polymeric matrix. The discontinuous and random microstructure of these materials allows TBDC components with complex 3D shapes to be moulded using fully automated processes. Moreover, the tow-based microstructure allows TBDCs to achieve a high content of carbon fibres (up to 60% in volume) and, consequently, to achieve high stiffness and toughness. Consequently, TBDCs are now being used to manufacture lightweight (semi-)structural components in the aeronautics, automotive and sports industries.

However, due to the large dimensions of the tows (up to 50 mm long and 10 mm wide), the local mechanical properties – e.g. stiffness and strength – of TBDCs vary significantly from one point of the microstructure to another. Consequently, a TBDC structure under a mechanical load will present non-deterministic strain fields, and may fail at unexpected locations. This makes it necessary to develop a stochastic framework to design TBDC structures considering the intrinsic variability of TBDC materials.

The goal of this work is to quantify the effects of variability in TBDC materials on the mechanical performance of structures, by using a combination of experimental testing and an FE Monte-Carlo framework that we have developed specifically for TBDCs [1]. Section 2 will present experimental results from unnotched and notched tensile tests, and Section 3 will provide an overview of the FE predictions; the main conclusions will be summarised in Section 4.

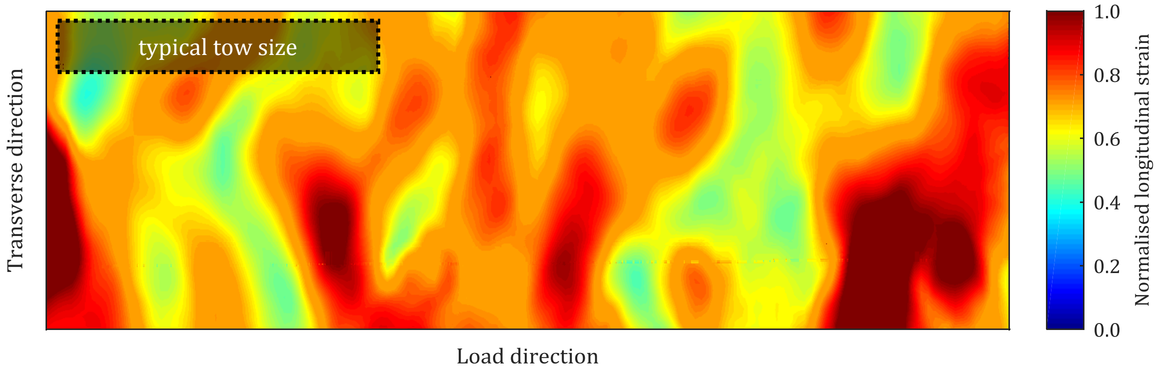
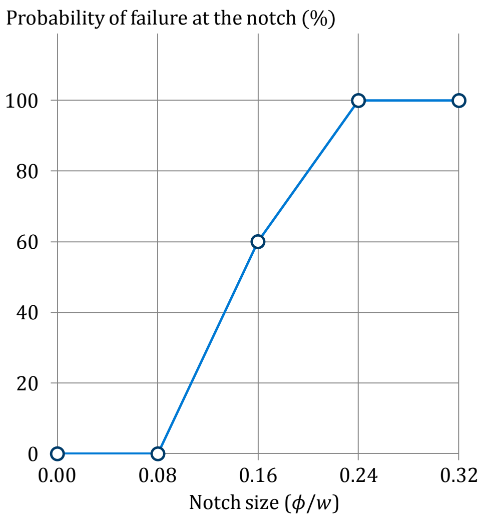



Figure 1: Longitudinal strain map of an unnotched specimen under uniform tension, obtained with DIC (strains normalised against the maximum strain in the map).

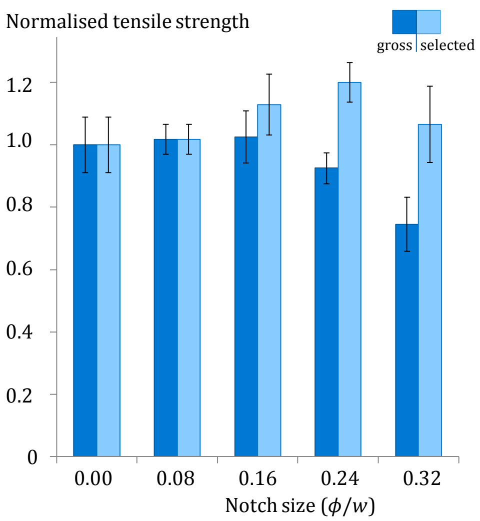
(a) Failure at the notched section.

(b) Failure at the unnotched section.

Figure 2: Typical failure locations observed in nominally-identical open-hole tensile specimens with $\phi/w = 0.32$.




a) Relationship between the probability of failure at the hole and the hole size.




b) Relationship between *gross* and *selected* tensile strengths and the hole size.

Figure 3: Results of the unnotched ($\phi/w = 0.00$) and open-hole ($\phi/w = \{0.08, 0.16, 0.24, 0.32\}$) tensile tests.

## 2. Experimental testing

A commercially-available TBDC material was characterised through unotched (ASTM D3039) and open-hole (ASTM D6484) tensile tests. All open-hole tests were performed using specimens with the same overall dimensions, but with a range of notch sizes (defined by $\phi/w \in [0.00, 0.32]$, where $\phi$ is the hole diameter and $w$ is the width of the specimens).

Figure 1 shows the strain map of an unnotched tensile specimen obtained with Digital Image Correlation (DIC). Given the unnotched geometry of the specimen, we can conclude that the heterogeneity of the strain fields (with a CoV of approximately 17%) is due to non-homogeneous elastic properties of the TBDC material.

We have observed that, for notched specimens with intermediate hole diameters, a fraction of the specimens failed at the notched section (as expected, see Figure 2a), while others fail away from the notch (see Figure 2b); the proportion of notch failures increased for larger hole diameters (Figure 3a). Figure 3b also shows that the *gross* tensile strength (calculated based on the gross/unnotched cross-section of the specimens) of the TBDC material is not affected by the presence of small holes; moreover, the *selected* strength (calculated based on the cross-section where failure actually occurred) actually increases for small holes, which demonstrates a level of notch insensitivity beyond the conventional limits of continuum solid mechanics.

## 3. FE simulation

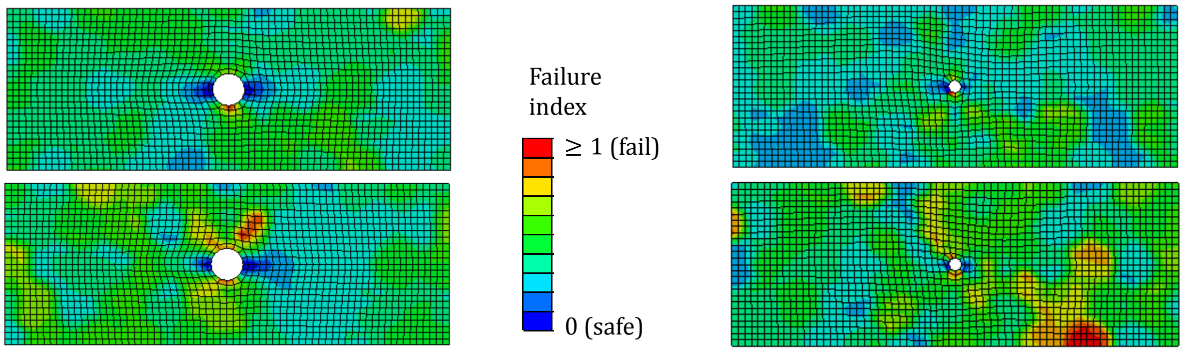
A Finite Element (FE) Monte-Carlo framework accounting for the variability in TBDC microstructures and local mechanical properties has been used to perform a Monte-Carlo statistical analysis of open-hole tensile specimens. The development of the framework will be detailed in another paper in the Conference [1] but, in a nutshell, it is based on the following features:

- The structure to be analysed is mapped with non-uniform stochastic fields of elastic constants and failure envelopes; the spatial distributions of these fields are generated based on the microstructure of the TDBC material, and assigned in a mesh-independent way;
- The analytical material models used to predict the elastic constants and failure envelopes of material points in the structure are based on stochastic equivalent laminates [2], and take into account the discontinuous nature of the tows through a stochastic shear-lag model [3];
- The framework is fully automated to run a Monte-Carlo analysis of FE models in Abaqus, and can cope with any shell-type structure, even with complex 3D geometries and/or assembled with other material types.

Figure 4 shows the failure index fields calculated by the framework for open-hole tensile specimens with two different hole sizes. Figure 4a consideres the largest hole size, and the maximum failure index in both realisations is located near the hole; Figure 4b considers the smallest hole size, and the maximum failure index in one of the realisations is located away from the hole. Qualitatively, these results agree with the experiments, as they suggest that specimens with small holes might fail away from the notch.

## 4. Conclusions

We have quantifyied the effect of heterogeneous microstructures and variable local mechanical properties on the performance of TBDCs, by performing tensile tests with a range of notch sizes. We have observed that, for intermediate notch sizes, a fraction of the specimens fails away from the notch, and that the apparent tensile strength of the material actually increases near small notches. These results are in contrast with those expected for most conventional continuous-fibre composites (which present relatively uniform materials properties), and provide evidence that it is vital to account for the variability in the microstructure in structural design of TBDC structures.




(a) Open-hole specimens with $\phi/w = 0.20$, showing maximum failure index near the notch.

(b) Open-hole specimens with $\phi/w = 0.08$, showing maximum failure index either at the notch (above) or away from the notch (below).

Figure 4: Failure index in open-hole tensile specimens, predicted by the FE virtual testing framework considering variability in the microstructure and heterogeneous local properties.

We have used our in-house developed FE Monte-Carlo framework for TBDCs to predict the failure index fields of virtual open-hole specimens; the analysis shown that the critical point of the specimen shift from (i) randomly located in the specimen for small hole sizes, to (ii) preferentially-located near the notch for large hole diameters. On-going work is focusing on developing an efficient non-local criterion to predict the ultimate failure load of unnotched and open-hole specimens, as well as their and fracture location; comparisons against experiments will be shown at the Conference. The application of our FE Monte-Carlo framework to a real-sized component of a Lamborghini car will be presented at the conference as well [4].

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## References

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