A BENCHMARKING EXERCISE FOR THREE LONGITUDINAL STRENGTH MODELS FOR UNIDIRECTIONAL FIBRE-REINFORCED COMPOSITES

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ABSTRACT

The longitudinal strength of unidirectional fibre-reinforced composites is one of the most basic strength properties of fibre-reinforced composites. Many different models have been developed, but a systematic and unbiased comparison between those models is not available in the literature. This paper therefore presents a benchmarking exercise that compares three state-of-the-art models: a hierarchical scaling law, a direct numerical simulation method and a multiscale finite element simulation method. The results reveal significant discrepancies between the predictions of the models, which can be explained by the inherent assumptions of each of the models. Experimental results were compared against blind predictions by all three models. This comparison revealed that the basic mechanisms are understood and captured, but that more experimental and modelling work is required to advance our understanding to a higher level.

1 INTRODUCTION

The longitudinal strength of unidirectional fibre-reinforced composites is a basic, but vital property needed in the design of parts and structures. This property is controlled by fibre breaks and the stress concentrations around them, which eventually lead to the development of clusters of fibre breaks. These clusters further increase the stress concentrations, which eventually leads to a critical cluster that propagates unstably and causes final failure.

Reliably predicting this entire process is a challenging task that many researchers have attempted to undertake [1]. It is challenging to reliably compare the different fibre break models as they are often based on a different set of assumptions and use different modelling tools. Some models use many assumptions, but are fast and can simulate large composite structures. Other models use less assumptions, but are slower and limited to smaller composite specimens. Assessing such differences is not always possible based on the available literature, which further hampers the evaluation of the effect of the various assumptions.

A benchmarking exercise was therefore set up to compare three fibre break models: a hierarchical scaling law [2, 3], a direct numerical simulation [4-6], and a multiscale FE² simulation [7-9]. The comparison was based on blind predictions for two cases: (I) a hypothetical composite without any
experimental data, and (II) a T800/M21 composite for which the strength was experimentally determined and the fibre break development was measured using synchrotron computed tomography. The goals of the exercise were to:

- Compare model predictions with detailed experimental data
- Establish benefits and drawbacks of the models
- Identify gaps in the literature and propose future improvements

2 ORGANISATION

The document describing the scope and objectives of the benchmarking exercise was set up jointly by all participants and finalised in June 2014. This document was then used to invite ten research teams from all over the world to join the benchmarking exercise. Five of these teams agreed to participate and four of them actually submitted their results. The experimental results were disclosed to all participants only after all modelling predictions were submitted. The results were then collated and circulated to all participants, after which the participants met to discuss the results.

3 RESULTS

3.1 Case I: Hypothetical composite

The first case was a hypothetical composite with isotropic fibre and matrix properties. All the relevant input parameters are summarised in Table 1.

<table>
<thead>
<tr>
<th>Fibre parameters</th>
<th>Diameter</th>
<th>12 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Young’s modulus</td>
<td>100 GPa</td>
</tr>
<tr>
<td></td>
<td>Poisson’s ratio</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>Weibull modulus</td>
<td>8.0</td>
</tr>
<tr>
<td></td>
<td>Weibull scale parameter</td>
<td>3000 MPa</td>
</tr>
<tr>
<td></td>
<td>Reference gauge length</td>
<td>1.0 mm</td>
</tr>
<tr>
<td>Matrix-related parameters</td>
<td>Young’s modulus</td>
<td>10 GPa</td>
</tr>
<tr>
<td></td>
<td>Composite interlaminar shear strength</td>
<td>50 MPa</td>
</tr>
<tr>
<td></td>
<td>Poisson’s ratio</td>
<td>0.3</td>
</tr>
<tr>
<td>Composite-related parameters</td>
<td>Fibre volume fraction</td>
<td>50%</td>
</tr>
<tr>
<td></td>
<td>Gauge length</td>
<td>1.0 mm</td>
</tr>
<tr>
<td></td>
<td>Number of fibres in cross-section</td>
<td>2000</td>
</tr>
</tbody>
</table>

Table 1: Input parameters of the hypothetical composite for case I.

Figure 1 reveals the strength predictions for case I. Using the correct matrix behaviour was found to be vital for correct predictions, as the predictions for an elastic and plastic matrix differ significantly. The direct numerical simulation with a plastic matrix still predicts a higher strength than the other models. In this particular case, the composite is hypothetical, implying that comparisons with experimental data are impossible.
3.1 Case II: T800/M21 composite

The second case was a T800/M21 composite. All the relevant model inputs are summarised in Table 2. The experimental data was obtained using synchrotron computed tomography, and the methodology was exactly the same as described in earlier works [4].

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fibre-related parameters</strong></td>
<td></td>
</tr>
<tr>
<td>Diameter</td>
<td>5 µm</td>
</tr>
<tr>
<td>Longitudinal Young(\alpha) modulus</td>
<td>294 GPa</td>
</tr>
<tr>
<td>Longitudinal Poisson(\alpha) ratio</td>
<td>0.2</td>
</tr>
<tr>
<td>Transverse Young(\alpha) modulus</td>
<td>19 GPa</td>
</tr>
<tr>
<td>Longitudinal shear modulus</td>
<td>27 GPa</td>
</tr>
<tr>
<td>Transverse shear modulus</td>
<td>7 GPa</td>
</tr>
<tr>
<td>Weibull modulus</td>
<td>4.8</td>
</tr>
<tr>
<td>Weibull scale parameter</td>
<td>3900 MPa</td>
</tr>
<tr>
<td>Reference gauge length</td>
<td>100 mm</td>
</tr>
</tbody>
</table>

| **Matrix-related parameters**   |             |
| Young\(\alpha\) modulus        | 3.5 GPa     |
| Composite interlaminar shear strength | 96 MPa |
| Poisson\(\alpha\) ratio        | 0.3         |

| **Composite-related parameters** |          |
| Fibre volume fraction           | 55%       |
| Gauge length                    | 1.54 mm    |
| Number of fibres in cross-section | 5500    |

Table 2: Parameters of the T800/M21 composite for case II (data obtained from technical datasheets and references [10, 11]).

Figure 2 reveals similar trends to Figure 1: the direct numerical simulations predict the highest strength. The predictions of the hierarchical scaling law are very close to the experimental strength, whereas the multiscale \(\text{FE}^2\) simulation underpredicts the strength.
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![Graph showing comparison of tensile strength](image)

**Figure 2**: Comparison of the longitudinal tensile strength predicted by the three models for the T800/M21. The dashed line indicates the experimental data.

**DISCUSSION**

The hierarchical scaling law and the multiscale FE² simulation consistently predict a lower strength than the direct numerical simulations. This is likely due to the intrinsic model assumptions:

- The hierarchical scaling law assumes a stress concentration factor of 2 on the nearest neighbour, whereas the other two models use lower stress concentration factors, but spread over more fibres.
- The multiscale FE² model has several assumptions that are conservative by design. For example, it assumes a debond length such that the stress concentrations are spread over the entire length of the representative volume element, which is 4 mm long. Additionally, it assumes that all fibre breaks in a cluster are co-planar, as that is the worst-case scenario.

![Graph showing fibre break density](image)

**Figure 3**: Comparison of the fibre break density predicted by the three models for the T800/M21. The dashed line indicates the experimental data.
More detailed comparisons were performed based on the fibre break density and cluster development, but these are not shown here. Overall, the exercise revealed the benefits and drawbacks of the three modelling approaches:

- The hierarchical scaling law provided good agreement with the experimental data and has a very low computational cost (running in less than one second). It was also the only model that considered the increase in ineffective length with cluster growth.
- The direct numerical simulation method uses fewer assumptions than the other models and has greater versatility. In contrast with the other two models, it can predict all possible cluster sizes and allows for clusters which are not co-planar.
- The multiscale FE$^2$ model is the only one in the exercise that can predict the response under non-uniform stress fields and multidirectional laminates. It is also the only one that considers the viscoelasticity of the matrix.

The benchmarking exercise also allowed the participants to establish routes for future improvements. These are:

- More comprehensive and reliable experimental data. This would be desirable because
  - The current data was coming from a single sample, rather than from multiple samples.
  - The tests were interrupted for 2 minutes at every load level, which can cause additional fibre breaks to develop. Performing continuous scans will avoid potential artefacts introduced by this hold-at-load.
- More accurate input parameters:
  - The fibre strength distribution is notoriously difficult to measure [12].
  - The matrix properties are size-dependent [13].
  - Access to neat resins for commercial prepregs is limited, and the properties of the matrix system for case II had to be derived from technical data sheets.
- More reliable and comprehensive data close to final failure:
  - Experiments cannot capture final failure, as it occurs too fast. Due to technological advances, however, it is now possible to get closer to final failure.
  - The three models assume failure driven by strength of materials, although damage localisation could also be derived by fracture mechanics.

5 CONCLUSIONS

This paper presented an international benchmarking exercise that compared three state-of-the-art longitudinal strength models of unidirectional composites. The main conclusions are:

- Significant discrepancies were found between the three different models, and these were attributed to the inherent assumptions of the model.
- The specific benefits and drawbacks of each of the modelling approaches were identified.
- Although models can be successful in predicting strength, they fail to correctly predict the accumulation of fibre breaks.

These conclusions suggest that we need to:

- Improve our understanding of the fundamental micromechanisms governing longitudinal tensile failure of unidirectional composites.
- Develop more reliable experimental methodologies to measure the required input data, such as fibre and matrix properties.
- Experimentally collect more data regarding the evolutions of fibre breaks and cluster development with loading.
- Continue performing blind comparisons between the models.

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