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Multi-scale FEA-based reliability analysis framework for FRP composites

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Abstract

Alloy materials have been used for centuries. However, the recent thriving industrial advances required a superior alternative that provides improved stiffness/weight properties, namely Fibre Reinforced Polymer (FRP) composites. The multi-scale build-up nature and the complex manufacturing process of the composites introduce many material uncertainties. As a result, their use is still conservative and limited to advanced products in aerospace, transportation and wind energy. Hence, understanding composites uncertainties is an active research and development topic. In this study, we aim to expand the scope of uncertainties to have a better understanding of the materials' performance compared with what is currently considered. This will contribute towards optimal use of the available resources and designing components with higher confidence. The proposed inclusive representation is achieved by developing surrogate techniques that enable probabilistic estimation of the materials' properties using larger samples of the representative volume element (RVE). The outcomes of the developed framework are verified to provide less conservative designs.

[Keywords]: Composites; Uncertainty; RVE Homogenisation; Stiffness; Surrogates; Reliability.

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INTRODUCTION

Composites provide improved stiffness/weight properties compared with conventional materials such as alloys. However, their heterogeneous nature and manufacturing process introduces many uncertainties. As a result, the use of composite materials is still limited to advanced products in aerospace, transportation and wind energy (Yancey, 2016), and when in use, they are designed conservatively with high safety factors.

To avoid imposing such high factors of safety, it is important to account for system uncertainties by propagating their effect between the component's scales. Thus, a clear understanding of the overall composite properties under all uncertainties can be obtained. Clarifying this could lead to safer designs and more efficient use of composites. This can be achieved using a probabilistic design approach.

A probabilistic design approach for composites is more beneficial compared with the conservative safety factor approach (Zhu, 1993). However, the use of analytical-based reliability analysis tools are not suitable to capture the various types of composite uncertainties due to restricting assumptions. i.e. the rule of mixture by Chamis (1983) assumes that both matrix and fibres are linearly elastic and fibres are spaced periodically in square-packed or hexagonal packed arrays, which is not an accurate representation of the randomly packed fibres within the matrix. The alternative is the use of numerical tools such as finite element analysis (FEA). However, FEA is computationally expensive, making it unfeasible to use in a probabilistic framework.

The goal of this study is to develop an efficient FEA-based reliability analysis framework that accounts for the effect of many uncertainties on the probability of failure using Monte Carlo simulation (MCS). In order to achieve this, two procedures are developed: a novel large representative volume element (LRVE) concept that allows representing multi-scale uncertainties in a more inclusive manner compared with other techniques (see Figure 1), and a set of multi-scale surrogate models derived from a limited number of reliable FEA datapoints that provide significant reduction of processing time while maintaining high accuracy (Omairey et al., 2018, Omairey et al., 2019).

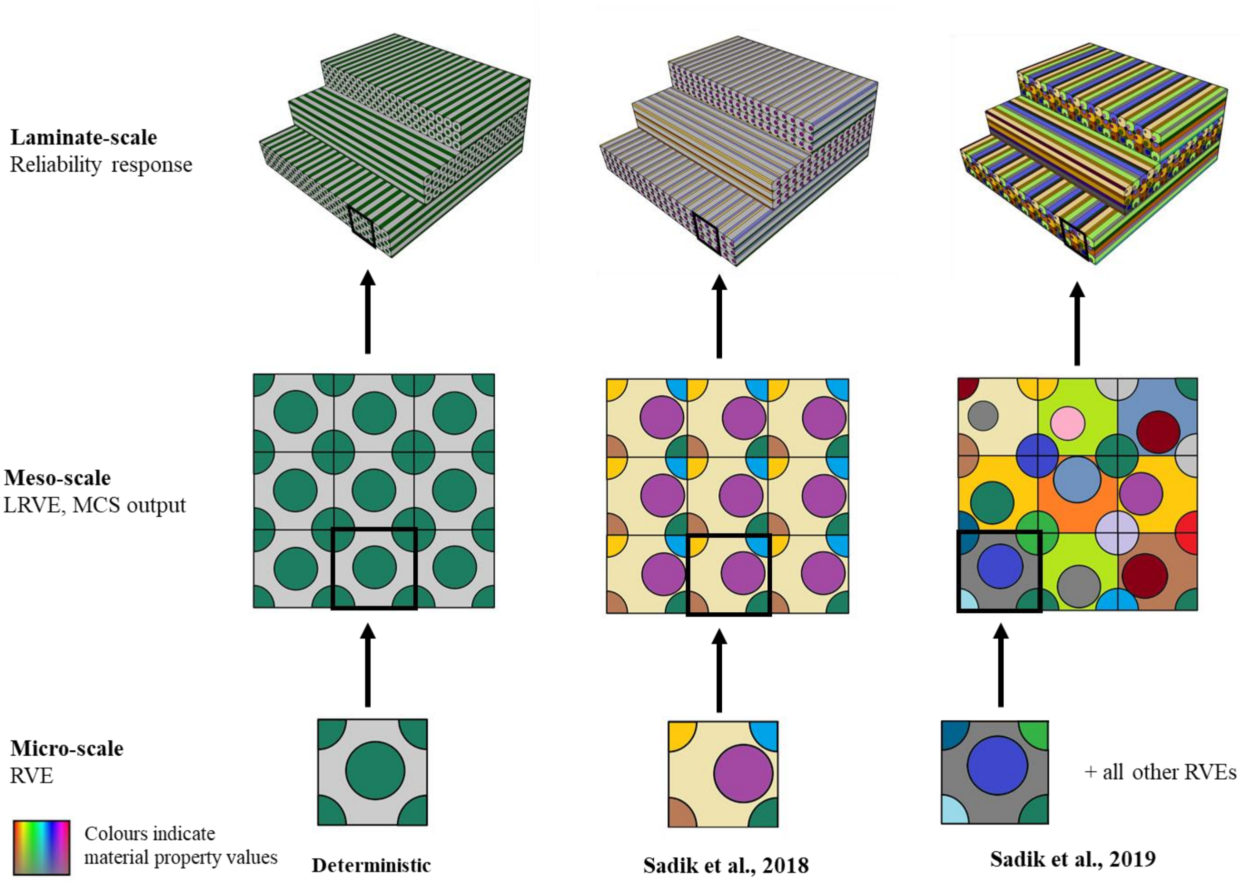

Figure 1. The developed formworks compared with the deterministic approach.

Methodology

Most MCS reliability studies use a single micro-scale RVE (contains 1 – 2 fibres) as an output of each cycle to represent the next meso-scale. A direct generalisation of these micro-scale outputs to meso-scale misrepresents the latter, and eventually the estimated reliability performance.

However, the developed LRVE is constructed using correlated neighbouring micro-scale RVEs to produce a more realistic representation of the underlying uncertainties compared to the use of a single RVE (see Figure 1). The micro-scale RVE correlation criteria include: shared corner fibre properties, categorising fibre locations into fixed and non-fixed, and applying a blur filter to smooth out matrix properties. The process of implementing these criteria is shown in

Figure 2.

The use of surrogate models within the framework is required as analysing thousands of LRVEs for reliability using FE is unfeasible. Therefore, sets of specific deterministic data points are analysed using EasyPBC tool for FEA periodic RVE homogenisation (Omairey et al., 2018b). These data points are used to create polynomial-based surrogate models; within the developed framework, these models take the random uncertainties of each MSC cycle as an input to estimate the stiffness properties of the desired RVE and LRVE. Finally, the estimated properties are assigned to laminate scale plies, at which the responses of the laminate are assessed using the desired limit state functions (LSFs) to find the probability of failure. The algorithm of this process is illustrated in

Figure 2.

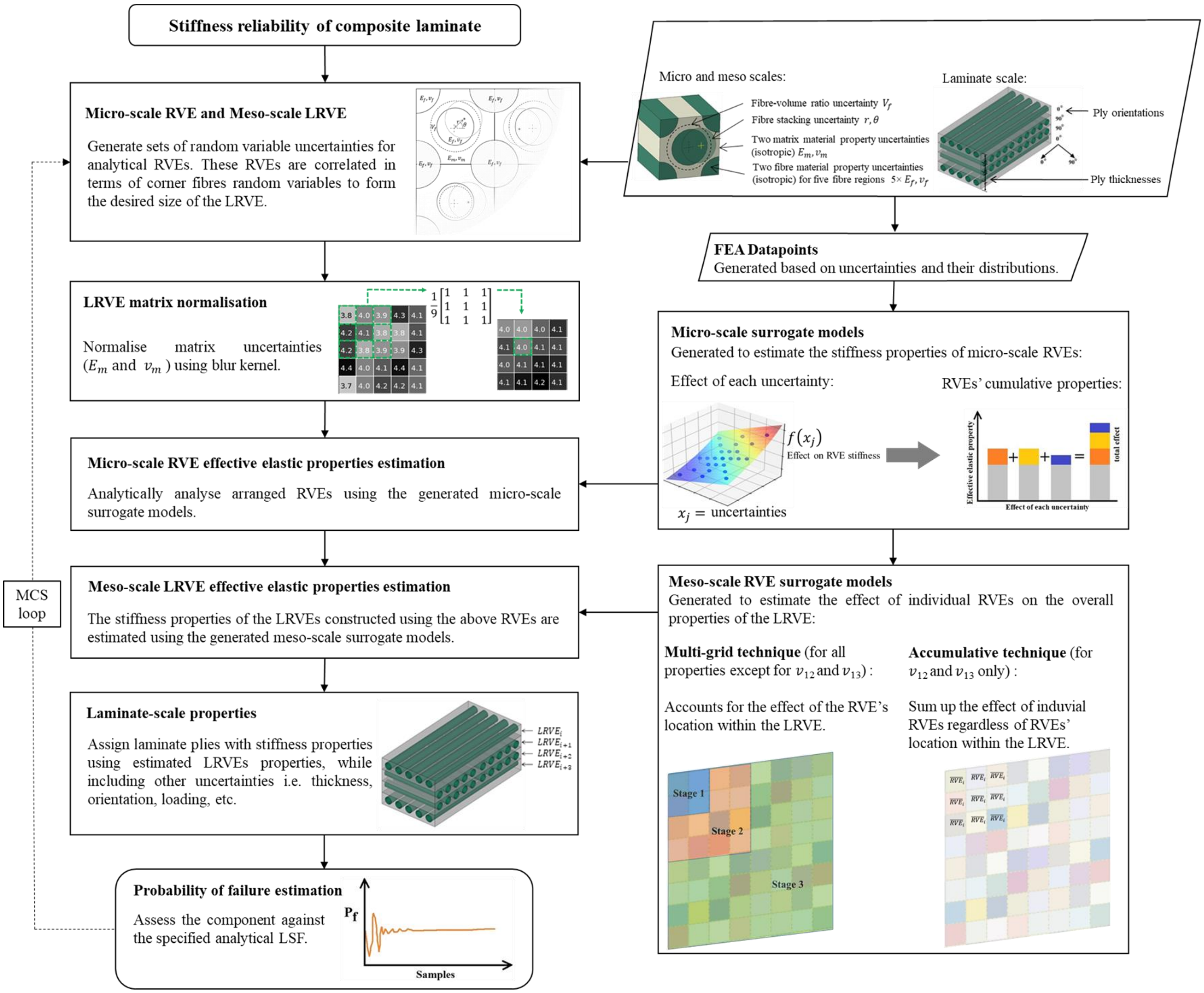

Figure 2. Framework flowchart for evaluating laminate probabilistic stiffness performance.

Results and discussion

Employing the developed framework, four meso-scale configurations are used to compute the stiffness reliability of the selected composite laminate examples, which are: 1×1 (single RVE), 2×2, 4×4, and 8×8 LRVEs. Stiffness reliability results for the different sizes of LRVEs (and RVE) indicate that the probability of failure reduces as the size of the LRVE increases and that all sizes of LRVEs compute a lower probability of failure value, compared with using a single RVE (i.e. no meso-scale transition). This result can be explained because increasing the size of the representative unit leads to less variability of homogenised properties at the lamina-scale, thus reducing the chances of assigning extremely low stiffness values to the whole lamina that causes failure. Detailed applications and results are presented in a recent study by the author's (Omairey et al., 2019).

Conclusions

Composites probabilistic design approach is widely used, yet it is mostly limited to analytical theories that are incapable of representing many uncertainties; such uncertainties require the use of the computationally expensive FEA to fully understand their effect, thus, making probabilistic design approach impracticable. On the other hand, the developed framework uses a small number of FEAs to create accurate surrogate models capable of representing many uncertainties in a multi-scale configuration while significantly reducing their overall processing time. With these capabilities, this tool will contribute towards a more inclusive understanding of composites performance and optimising their use to produce efficient structures with greater efficiency and reliability.

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