6th European Conference on Computational Mechanics (ECCM 6)
7th European Conference on Computational Fluid Dynamics (ECFD 7)
11 – 15 June 2018, Glasgow, UK

EFFECT OF MICRO-SCALE UNCERTAINTIES ON THE ELASTIC PROPERTIES OF FIBRE-MATRIX COMPOSITES

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Key words: Composites, Uncertainty, Sensitivity analysis, Homogenisation, Elastic properties.

Abstract. This study evaluates the effect and sensitivity of micro-scale geometric and material property uncertainties on the numerically determined effective elastic properties of unidirectional fibre reinforced matrix composite materials. Due to the multi-scale build-up nature of composites many uncertainties occur, mainly material properties and geometric uncertainties. These uncertainties present a challenge in estimating composite material properties. Research has been conducted to understand their effect. However, there are limited studies investigating the effect of geometric random fibre stacking uncertainty. Hence, this study examines the effect of geometric along with seven material property uncertainties on a composite's effective elastic properties using a developed periodic RVE homogenisation tool. A factorial design method is used to investigate the sensitivity of all possible uncertainty combinations. It is concluded that fibre stacking uncertainty is an influential uncertainty that needs to be represented along with constituent material properties uncertainties in a multi-scale analysis approach. Additionally, concept of a polynomial-based surrogate model is developed to approximate homogenised effective elastic properties under the effect of uncertainties without the need to run numerical homogenisation.

1 INTRODUCTION

Composites are increasingly used in many industries for the improved stiffness-weight ratio compared with alloys. However, the heterogeneous nature and the manufacturing process of composites opens the door to many material and geometrical uncertainties to occur within all scales [1, 2]. As a result, composites are often designed with high factors of safety to ensure reliability compared with alloys used for the same purpose [3, 4]. To avoid imposing such high factors of safety, it is important to quantify the effect of these uncertainties at their occurrence scale. Additionally, clarifying the effect of each uncertainty will contribute in promoting effective uncertainties for reliability analysis instead of adding complexity by unnecessarily representing uncertainties that are not influential.

Micro-scale is the smallest scale of Fibre Reinforced Polymer composites (FRP), where the contribution of constituent materials occurs. This scale is usually presented by a

Representative Volume Element (RVE) [5]. The RVE is used to estimate the effective elastic properties of the composite [1, 5-7]. As a result, much research has been carried out to account for the effect of uncertainties at this scale. For instance, a study investigated the uncertainty of constituent materials properties and their probabilistic propagation from micro-scale to upper scales [8]. In addition to material uncertainty, other studies examined the effect of some geometrical uncertainties in failure related behaviour using larger RVEs. For example, a numerical study by Brockenbrough et al. [9] looked into the deformation behaviour of edge-stacked square fibres, square diagonal-stacking of square fibres, and triangle-stacking of hexagonal fibres. Based on observed effects, the study concluded that reliable methods need to be developed that account for the distribution of fibres to ensure reproducibility of composite properties. Another study by Nikopour [10] addressed modelling of matrix/voids ratio uncertainty by systematic matrix absence between fibres and its effect on elastic properties. A study by Huang [11] focused on the effect of random and systematic fibre placement within an RVE on elastic properties, where it was concluded that all arrangements have a similar effect. It is important to note that many studies used a large RVE that is computationally expensive to analyse specifically if many samples needed for a reliability analysis

It is clear that several uncertainties were investigated. However, the joint effect of these uncertainties together in a small RVE that can be used for efficient analysis was not fully examined. Additionally, clear understanding of the effect of fibre stacking randomness is not available. Hence, this study will cover the effect of individual and joint geometrical and material property uncertainties on the estimation of composite's effective elastic properties.

Two categories of uncertainties are modelled within small RVEs: Material properties (five of fibre, and two matrix properties), and fibre geometrical stacking uncertainty. The elastic properties are calculated with the commonly used unified periodic RVE homogenisation method [7]. The joint effect of several sources of uncertainty creates many combinations, each having its own effect on the elastic properties. To understand which uncertainty(ies) and combination(s) are influential, a factorial design sensitivity method is used as it can deal with combinations and normalises their effects to highlight the most influential uncertainties and combinations [12].

This study is conducted by: 1) selecting bounds of the uncertainties, 2) modelling all possible RVEs, 3) using RVE homogenisation method to estimate the effect of uncertainties on elastic properties, 4) conduct a sensitivity analysis to identify most influential uncertainty(ies) and/or combination(s). See Fig. 1.

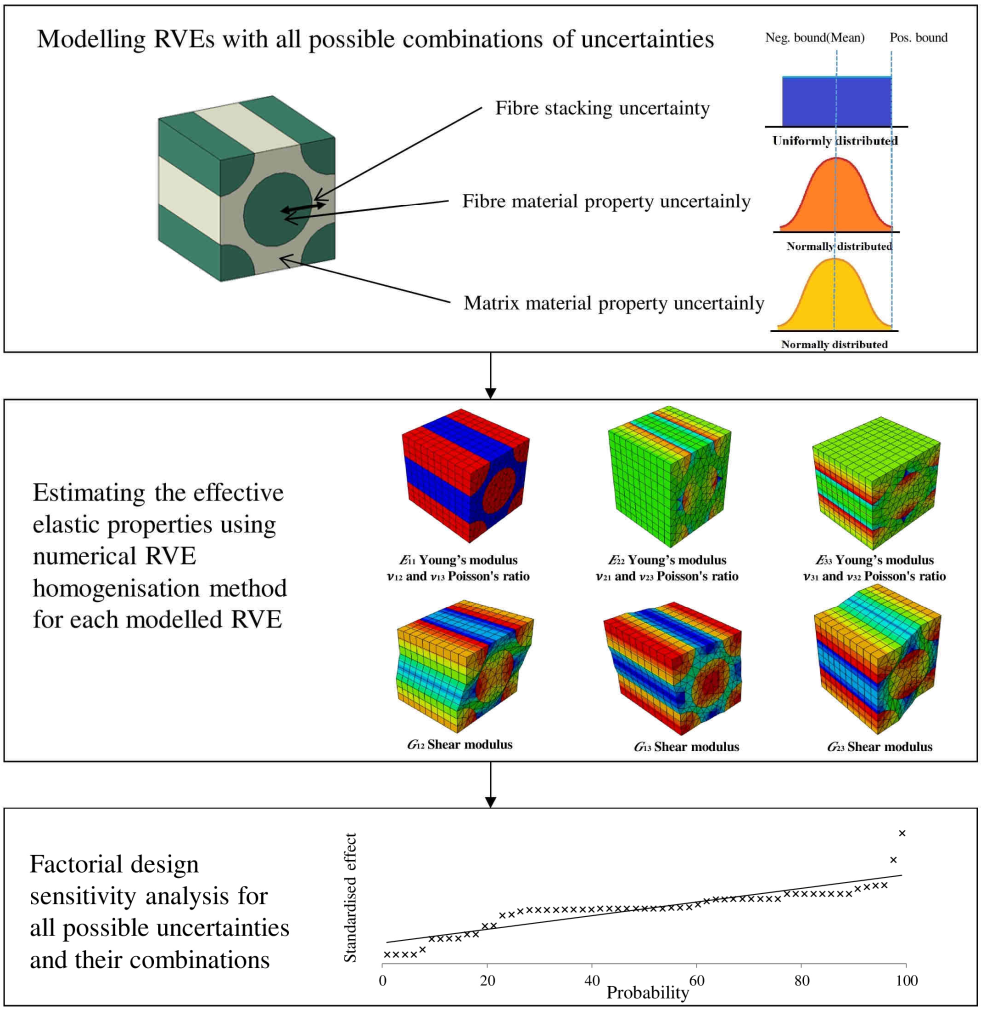


Figure 1: Uncertainties effect and sensitivity analysis framework.

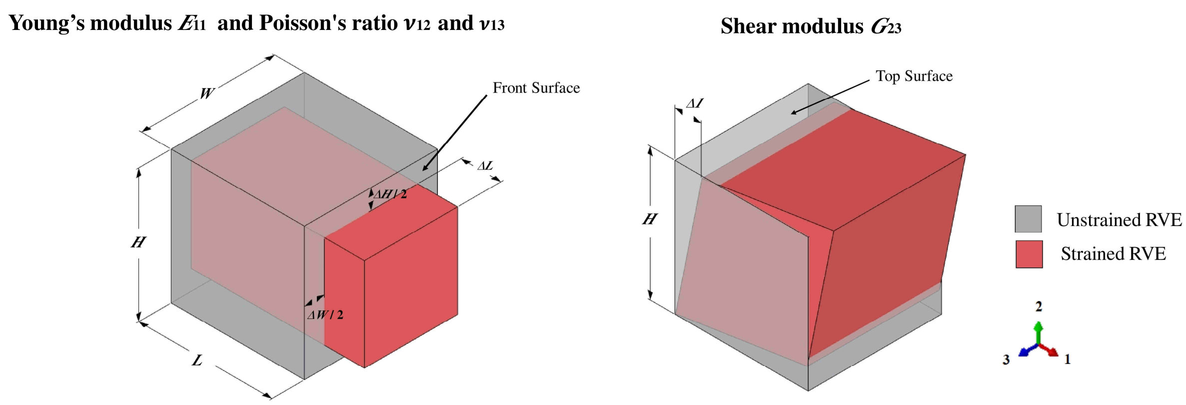
2 HOMOGENISATION

Engineering with composites is a more challenging process than metals because their properties are inherited from constituent materials with uncertainties. In addition to other uncertainties related to its heterogeneous build-up nature [1]. Thus, many researchers tried to address these design issues by homogenising the properties between scales [13] through employing composite's periodic microstructure [14]. Some of the main developed theoretical homogenisation methods are Chamis' micromechanical model equations [15], and Mori-Tanaka asymptotic mean-field homogenisation approach [16]. On the other hand, Finite Element Method (FEM) is used as a homogenisation tool by means of an RVE [5]. This tool is considered more accurate and becoming the standard approach and widely recommended to estimate the effective elastic properties of composites [14, 17].

In this study, none of the theoretical homogenisation methods are used as they are incapable of representing the effect of micro-scale geometrical uncertainties. Additionally, smaller error is expected using FE RVE homogenisation [18]. Therefore, the optimum method is FE RVE homogenisation.

The theory of RVE homogenisation is imposing uniform sets of strains to calculate the effective elastic properties of an RVE. Applied strain on the RVE is opposed by internal resistance, building reaction forces at the strained boundary surfaces. Summing principle reaction forces and dividing by the area of that surface equals the stress value that corresponds to the applied strain. Using stress values, Young's modulus for that specific direction are found by dividing it by the known applied strain. In addition, Poisson's ratios (for two transverse directions) are estimated by calculating the transverse strain and dividing it by the applied axial strain. On the other hand, Shear moduli are similarly estimated by dividing the shear stress value by corresponding shear strain (see Fig. 2).

The RVE is assumed to be an element of a periodic material, hence, it is important to simulate the periodicity of the strained RVE with the surroundings. Prior homogenisation studies accomplished periodicity by imposing boundary conditions that ensure RVE's plane boundary surfaces remain plane under applied strain [9, 19]. This is valid for a transversely isotropic RVE under longitudinal and transverse strains. However, that is not the case for orthotropic representation and shear modulus estimation because it will over-constrain the RVE, resulting in an overestimating the composite elastic properties. Thus, it is necessary to apply node-to-node periodic conditions, at which deformed boundary surfaces can distort and no longer remain plane [6, 20]. Accomplishing these periodicity conditions requires linking nodal degrees of freedom (DoF) in commercial FE software, based on concepts of unified periodic RVE homogenisation [7]. There is no built-in tool in commercial FE software, therefore, an Abaqus CAE FE analysis software [21] plugin is developed by the authors' that automates the process of computing effective elastic properties of a fully-customised RVE. The tool calculates orthotropic elastic properties by applying the necessary constraint equations and imposing appropriate boundary strain sets to satisfy the unified periodicity conditions, based on the concept of periodic RVE homogenisation. Using this tool, the elastic properties of each RVE are efficiently calculated in this study.



$$E = \frac{stress}{axial\ strain}, \quad E_{11} = \frac{\dfrac{\sum front\ surface\ reaction\ forces}{front\ surface\ area\ (H * W)}}{\dfrac{\Delta L}{L}}$$

$$\nu = \frac{-transvers\ strain}{axial\ strain}, \quad \nu_{12} = \frac{\dfrac{\Delta H}{H}}{\dfrac{\Delta L}{L}}, \nu_{13} = \frac{\dfrac{\Delta W}{W}}{\dfrac{\Delta L}{L}}$$

$$G = \frac{shear\ stress}{2 * \text{tensor of shear strain}}$$

$$G_{12} = \frac{\dfrac{\sum top\ surface\ normal\ reaction\ forces}{top\ surface\ area\ (L * W)}}{2 * \dfrac{\Delta 1}{H}}$$

Figure 2: RVE's Young's moduli, Poisson's ratios and Shear moduli calculations.

3 SENSITIVITY

In order to efficiently represent composite uncertainties in a multi-scale framework, it is necessary to identify the most influential uncertainties and their combinations at the micro-scale instead of adding complexity to the system by representing ineffective uncertainties. In this study, a total of eight uncertainties are examined. The selected method to estimate the sensitivity of these uncertainties is the 2^k factorial design approach (2, k are a factorial method and the number of factors respectively). This method was also used by to evaluate the effect of both material and geometrical uncertainty in woven composite fabric at meso-scale [1].

2^k factorial design approach requires a positive (upper) and negative (lower) bounds to represent each input [12]. For this study, the eight uncertainties make 247 possible RVE combinations (except deterministic run and individual uncertainties). Elastic properties from each model are normalised and presented on normal probability plots, where the most influential uncertainty(ies)/combination(s) are those furthest from the theoretical normal distribution line.

4 UNCERTAINTIES

Composite materials are associated with local and global uncertainties similarly to other engineering systems. Therefore, the design of composite structures involves a number of uncertainties related to, e.g. loading conditions, material properties, and geometrical characteristics [18]. For the purpose of this study, load uncertainties are not relevant as it relates to environmental conditions, application, change of use, etc. However, the focus is on material uncertainty mainly related to inherited defects and variations in the constituent material properties [2, 18, 22]. Additionally, geometrical uncertainties that occur due to the heterogeneous nature and randomness in the build-up of the composite's scales, and possible manufacturing defects [2]. One of the most foreseen geometrical uncertainties is the randomness of fibre stacking within the matrix [9, 23-25]. In order to investigate the effect of these uncertainties a micromechanical model of Graphite-Epoxy composite (AS4 - 3501-6) is used [6], represented by RVEs of a fixed 0.6 fibre-volume ratio composed of a full fibre at the centre, and four quarter fibres at each corner (see Fig. 3). The properties of the transversely isotropic fibre, and the isotropic matrix are considered as uncertainties. For the purpose of sensitivity analysis, the deterministic (mean) values are assumed as negative bounds, and an increase of 5% to that value represents positive bounds $\{F1, F2, F3, F4, F5, M1, M2\}$ as illustrated in Table 1. On the other hand, fibre stacking uncertainty is represented by shifting the central fibre by 0.08 fraction of the RVE's edge length along 3-direction as shown in Fig. 3. Again, the deterministic location of the fibre at the centre of the RVE is the negative bound, whereas the shifted configuration represents the positive bound.

Table 1: Material properties and uncertainty bounds for fibre and matrix.

	Fibre (Graphite AS4)					Matrix (Epoxy 3501-6)	
Properties	E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	v_{12}	v_{23}	E (GPa)	v (GPa)
Uncertainty Label	$F1$	$F2$	$F3$	$F4$	$F5$	$M1$	$M2$
Mean (negative)	235	14	28	0.2	0.25	4.8	0.34
Uncertainty (positive)	246.75	14.7	29.4	0.21	0.2625	5.04	0.357

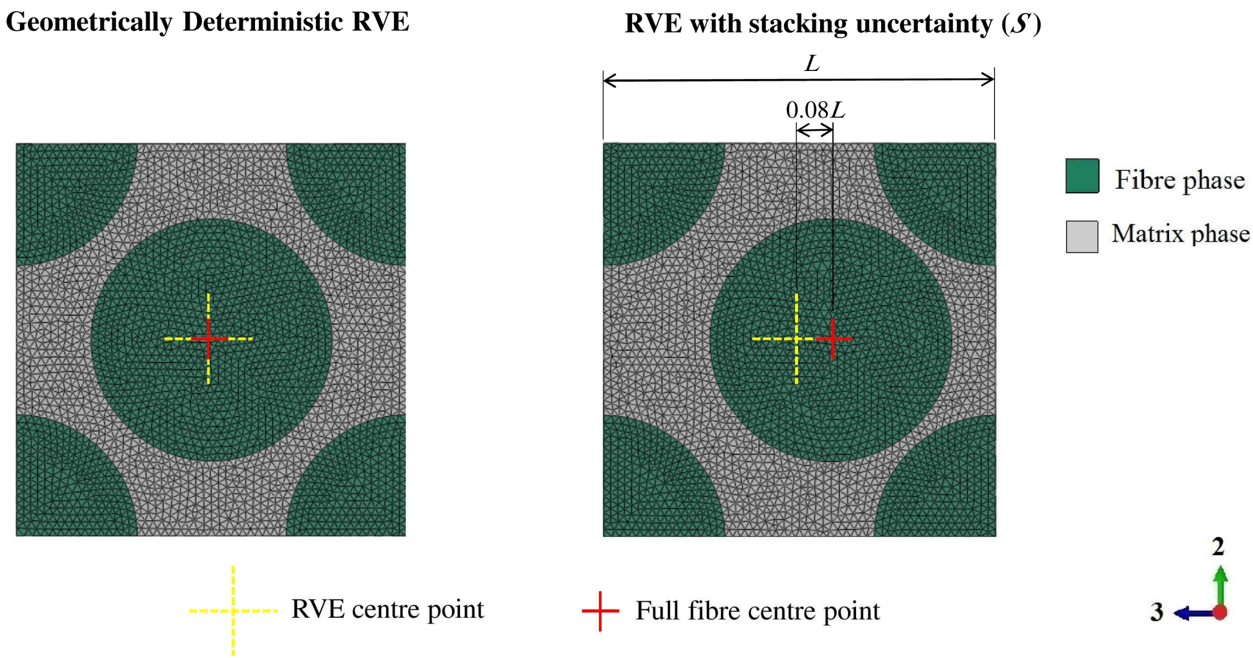


Figure 3: Illustration of fibre stacking uncertainty.

4 RESULTS AND DISCUSSIONS

4.1 Effect of uncertainties on elastic properties

Table 2 shows the effect of uncertainties on homogenised effective elastic properties, presented in terms of change percentages to the deterministic RVE properties (all uncertainties at their negative bounds). This effect is explained in terms of Young's moduli, Poisson's ratios, and shear moduli as follows.

Table 2: Individual uncertainties effect on the effective elastic properties.

	Material uncertainties							Geometrical uncertainty
	Fibre uncertainties					Matrix uncertainties		Fibre stacking
Elastic properties	E_1 *F1*	E_2 *F2*	G_{12} *F3*	v_{12} *F4*	v_{23} *F5*	E *M1*	v *M2*	S
E_{11}	4.9%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%
E_{22}	0.0%	2.0%	0.0%	0.0%	0.0%	2.9%	0.8%	1.7%
E_{33}	0.0%	2.0%	0.0%	0.0%	0.0%	2.9%	0.8%	1.0%
G_{12}	0.0%	0.0%	1.0%	0.0%	0.0%	3.9%	-1.0%	11.9%
G_{13}	0.0%	0.0%	1.0%	0.0%	0.0%	3.9%	-1.0%	-1.3%
G_{23}	0.0%	2.8%	0.0%	0.0%	-0.6%	2.1%	0.0%	-1.2%
v_{12}	0.0%	-0.1%	0.0%	2.5%	0.0%	0.1%	2.9%	-0.8%
v_{13}	0.0%	-0.1%	0.0%	2.5%	0.0%	0.1%	2.9%	0.7%
v_{21}	-4.7%	1.9%	0.0%	2.5%	0.0%	2.9%	3.7%	0.8%
v_{23}	0.0%	0.8%	0.0%	0.0%	1.3%	-0.8%	5.3%	-1.3%
v_{31}	-4.7%	1.9%	0.0%	2.5%	0.0%	2.9%	3.7%	1.7%
v_{32}	0.0%	0.8%	0.0%	0.0%	1.3%	-0.8%	5.3%	-2.4%

4.1.1. Effect on Young’s moduli and Poisson's ratios

The increase in longitudinal fibre material stiffness ($F1$) has a direct effect on the RVE’s E_{11} elastic property, as expected. Whereas, minimal effect is caused by matrix stiffness increase for the same homogenised property, as it is more dependent on the stiffer fibre in the longitudinal direction (1-direction). On the other hand, matrix uncertainty has a greater influence on transvers stiffness moduli, as it is the critical media for applied strains in these directions (2 and 3-direction). Noticeable effect is caused by stacking uncertainty as a result of disturbing matrix distribution within the RVE.

The above can also be understood by examining the difference between E_{11} and E_{22} or E_{33} fibre/matrix stain energy ratio for effected RVEs, where it clearly shows that fibre has the higher stain energy in E_{11}, and the opposite in E_{22} or E_{33}, see Fig. 4(a). On the other hand, shifting fibre location decreases fibre/matrix stain energy ratio indicating that the matrix phase is experiencing higher stain energy, resulting in higher stiffness. See Fig. 4(b).

The effect on Poisson's ratios is firmly related to fibre and matrix Poisson's ratio uncertainties ($F4$, $F5$, $M2$). In addition to moderate effects caused by fibre stacking uncertainty (S) and Young’s moduli of both fibre and matrix.

4.1.2. Effect on Shear moduli

The most influential factor for shear modulus G_{12} is fibre stacking uncertainty (S). The shift of the central fibre position creates a denser fibre region which is significantly stiffer than the deterministic RVE configuration and mainly effects stress in 1 and 2-directions. On the other hand, matrix stiffness uncertainty ($M1$) considerably influenced all shear moduli as this region of the RVE prone to deform more than fibres’ under shear stresses.

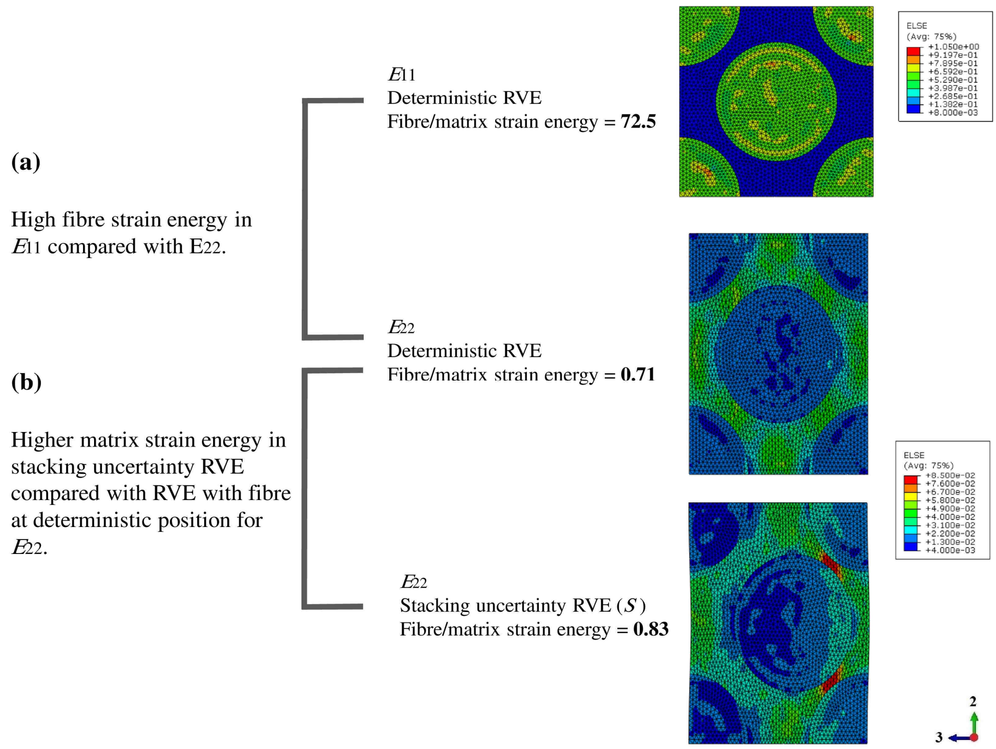


Figure 4: Fiber/matrix strain energy ratio for three homogenisation cases.

4.2 Sensitivity of uncertainties

Homogenised elastic properties for all possible RVE combinations are used to in the 2^k sensitivity analysis summarised in Appendix 1(a-c). The effective uncertainties for each homogenised properties lay off the theoretical normal distribution line. For all homogenised properties the effective uncertainties are individuals rather than combinations, arranged based on their effect percentage as shown in Table 2. This indicates that none of the combinations are effective, or that there is no significant extra effect caused by combining more than two uncertainties and the overall effect is simply the addition of individual uncertainties. Further investigation of the behaviour of both material and geometrical uncertainties identified that they have independent effects on the composites homogenised stiffness properties. As a result, the total effect is the sum of individual effects from all uncertainties as expressed in Eq. 1:

$$E_i = \bar{E}_i + \sum_{j=1}^{N} f_i(x_j) \tag{1}$$

Where E_i is one of the approximated elastic properties, $\bar{E}_i$ is the deterministic property value estimated through RVE homogenisation, N the number of uncertain parameters, x_j, and $f_i(x_j)$ is a polynomial that links the value of uncertain parameter j with the change in elastic property i (relative to deterministic value). To validate this, Table 3 shows excellent agreement between stiffness properties estimated by summing the effect of these uncertainties plus the established RVE that is analysed with deterministic properties, against homogenised stiffness properties computed using FE analysis of an RVE that explicitly models the same uncertainties together. Similar results are obtained while examining other uncertainty combinations. The maximum error observed using this approach is 0.51%, which is mainly caused by numerical analysis error due to the changing discretization in the FE analysis when a fibre is shifted.

The created polynomial-based surrogate models can obtain the dependant homogenised effective elastic properties at any independent uncertainty value immediately without the need to generate and run computationally expensive numerical models. This can be very useful to improve the efficiency of reliability-based analysis and design methods for composite materials.

Table 3: Verification of uncertainties independent effect on the homogenised elastic properties.

		Accumulative homogenised property									$\sum(F1, F2, .., M2) - 7 * Det.$	FE RVE homogenisation	Error %
Elastic property	**Unit**	***F1***	***F2***	***F3***	***F4***	***F5***	***M1***	***M2***	***S***	**Det.**			
E_{11}	GPa	149.90	142.85	142.85	142.85	142.85	142.95	142.86	142.85	142.85	150.00	150.00	0.00%
E_{22}		8.77	8.95	8.77	8.77	8.77	9.02	8.84	8.92	8.77	9.42	9.43	0.19%
E_{33}		8.77	8.95	8.77	8.77	8.77	9.02	8.84	8.86	8.77	9.35	9.38	0.32%
G_{12}	GPa	6.08	6.08	6.14	6.08	6.08	6.32	6.02	6.81	6.08	7.05	7.08	0.51%
G_{13}		6.08	6.08	6.14	6.08	6.08	6.32	6.02	6.00	6.08	6.24	6.24	0.02%
G_{23}		3.56	3.66	3.56	3.56	3.54	3.64	3.56	3.52	3.56	3.67	3.67	0.07%
v_{12}	ratio	0.2523	0.2523	0.2520	0.2523	0.2585	0.2522	0.2526	0.2596	0.2523	0.2658	0.2634	0.08%
v_{13}		0.2523	0.2523	0.2520	0.2523	0.2586	0.2522	0.2526	0.2596	0.2523	0.2658	0.2676	0.04%
v_{21}		0.0155	0.0148	0.0158	0.0155	0.0159	0.0155	0.0159	0.0161	0.0155	0.0164	0.0166	0.08%
v_{23}		0.4072	0.4074	0.4103	0.4072	0.4070	0.4123	0.4039	0.4286	0.4072	0.4336	0.4281	0.09%
v_{31}		0.0155	0.0148	0.0158	0.0155	0.0159	0.0155	0.0159	0.0161	0.0155	0.0165	0.0167	0.14%
v_{32}		0.4072	0.4073	0.4103	0.4072	0.4070	0.4123	0.4039	0.4286	0.4072	0.4336	0.4238	0.01%

12 CONCLUSIONS

This study investigated the influence of material and geometrical uncertainties on fibre reinforced composite effective elastic properties. The aim of the study is to find which uncertainties and their combinations have a significant influence on effective elastic properties, in order to promote investigating their propagating effect through scales. Conversely, uncertainties with minimal effect can be neglected to reduce analysis complexity. Thus, effect and sensitivities of eight uncertainties on effective elastic properties are estimated using a periodic RVE homogenisation method and a factorial design method.

It is concluded that material properties uncertainties have higher effect on corresponding homogenised elastic property. In general, fibre uncertainties showed higher effect on longitudinal properties and limited effect on shear moduli. Whereas, matrix uncertainties resulted in wider effect on all properties except longitudinal Young's modulus. Similarly, fibre stacking uncertainty showed noticeable effect on most uncertainties, yet significant effect on G_{12} shear modulus, which is more than double the highest effect observed by material uncertainties. On the other hand, the sensitivity study prompted the same effective uncertainties based on their effect magnitude individually rather than combinations. This indicates that all eight uncertainties have independent effect on the homogenised RVE properties. This behaviour lead to constructing polynomial-based surrogate models capable of estimating effective elastic properties for any combined material and geometrical uncertainties based on those derived from FE-based homogenisation rather than theoretical homogenisation methods. This polynomial-based surrogate model can be used efficiently to account for and propagate the effect of stacking geometrical uncertainty when estimating the effective elastic properties and generalising it to higher scales in future reliability studies.

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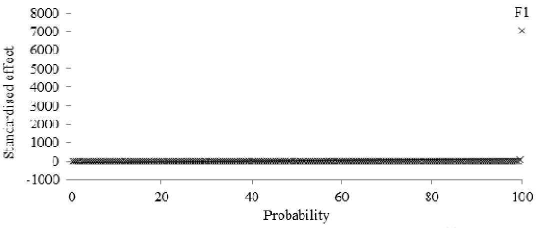
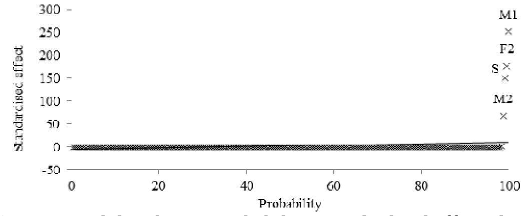
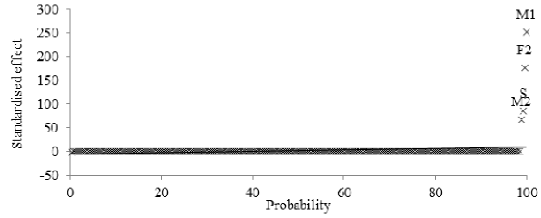
Appendix 1: Normal probability plots of the 2^k factorial design for all uncertainties and combinations.



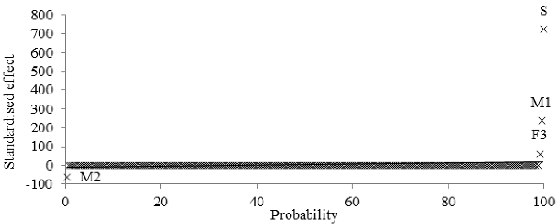
(a) E_{11} normal distribution probability- standardised effect plot.



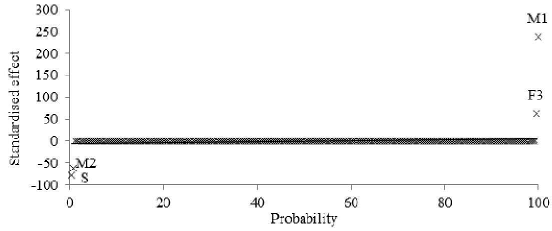
(b) E_{22} normal distribution probability- standardised effect plot.



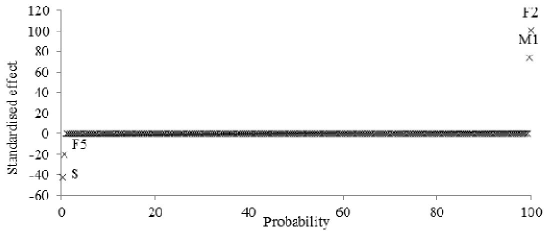
(c) E_{33} normal distribution probability- standardised effect plot



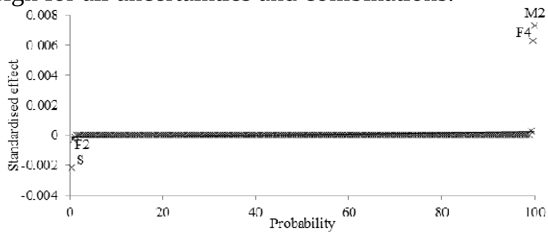
(d) G_{12} normal distribution probability- standardised effect plot.



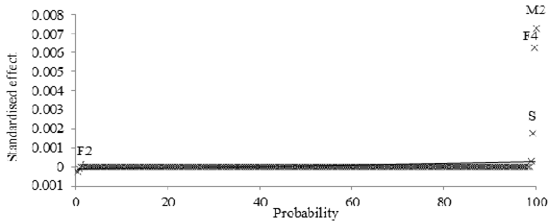
(e) G_{13} normal distribution probability- standardised effect plot.



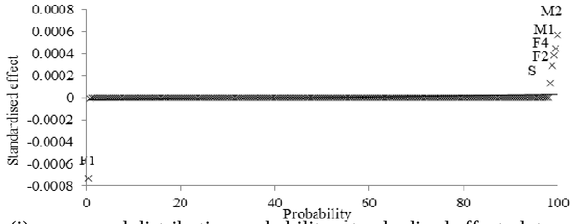
(f) G_{23} normal distribution probability- standardised effect plot.



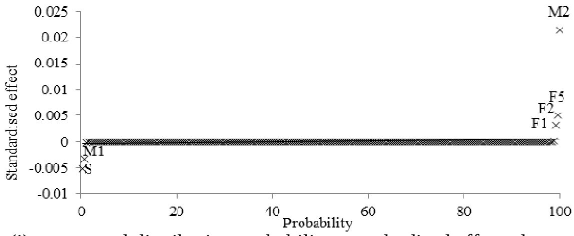
(g) ν_{12} normal distribution probability- standardised effect plot.



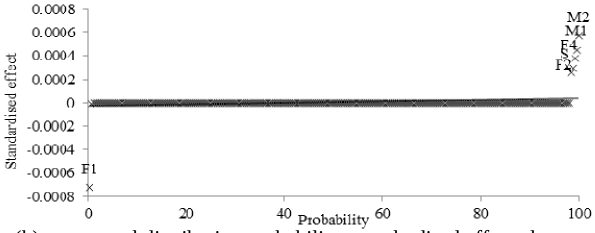
(h) ν_{13} normal distribution probability- standardised effect plot.



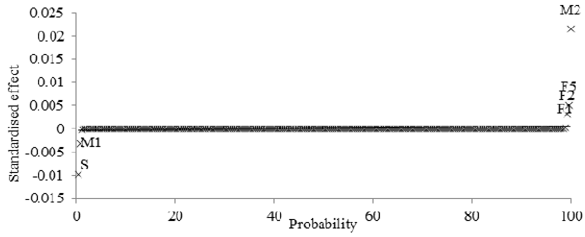
(i) ν_{21} normal distribution probability- standardised effect plot.



(j) ν_{23} normal distribution probability- standardised effect plot.



(k) ν_{31} normal distribution probability- standardised effect plot.



(l) ν_{32} normal distribution probability- standardised effect plot.