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Statistical correlation between elastic properties of plain-weave composite and its influence on structure reliability

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ABSTRACT

Statistical correlation between in-plane elastic properties of plain-weave composite (E-glass fabric/epoxy and carbon fabric/epoxy) is studied by probabilistic finite element method. The in-plane elastic properties including Young's moduli, shear moduli and Poisson's ratios are derived from finite element model on a composite unit-cell subjected periodic boundary constraint. It is shown that significant statistical correlation exists between the in-plane elastic properties and it depends on the variations of both the constituent properties and the unit-cell geometry. Two numerical examples are present on the reliability evaluation of unidirectional and multi-layer laminated plates bearing multi-axial in-plane loads, and this is conducted at two scenarios: considering and neglecting the statistical correlation. Monte-carlo (MC) method is employed to conduct the reliability calculation and Gibbs sampling is used for drawing samples where there is statistical correlation between random variables. For the multi-layer laminated plates, it is observed that neglecting the statistical correlation would result an 15–20% overestimation on the laminate failure probability, which indicates the importance of consideration of the statistical correlation in the process of reliability evaluation or reliability based design of plain-weave composite structures.

1. Introduction

Fibre reinforced composites are extensively used in aircraft structures, marine structures and wind turbine blades due to their superior mechanical stiffness/strength as well as low density. However, a disadvantage of fibre reinforced composite in comparison to metals is its large uncertainty on mechanical properties. By a recent summary in [1], the uncertainty of elastic properties of CFRP and GFRP is around 5%–10%, while the uncertainty of the strength of CFRP and GFRP may reach 15%–20%. The large uncertainty may be introduced by uncertainty of the mechanical properties of constituent materials and also random variation of microstructures. Due to the large uncertainty on mechanical properties, appropriate probabilistic methods which provide accurate structure reliability index or failure probability would be required in composite structure design process, and research in this area has aroused much attention in recent years [2].

In most of current publications on reliability evaluation of composite structures, ply (or lamina) mechanical properties are considered as main random variables, but they are mostly assumed to be independent with each other (eg. E_1 and G_{12} are assumed to be statistically independent with each other) [3–7]. A practical reason for ignorance of the statistical correlation between mechanical properties is related to relative test standards to obtain these mechanical properties. It is known that in ASTM or ISO standards different mechanical properties of FRP composites (such as E_1 and G_{12}) are suggested to be achieved from different test configurations and also different shaped samples. However, if the statistical correlation between two mechanical properties were to be achieved experimentally, values of the two mechanical properties from the same sample are required. Therefore, data on statistical correlation between different mechanical properties of composite is currently very limited. Recently, Shaw et al. [8] firstly demonstrated that there is significant statistical correlation between all in-plane mechanical properties of unidirectional FRP (including E_1, E_2, G_{12}, ν_{12}, X_t, Y_t, S). The statistical correlation was derived from numerical calculation by a combination of Monte-carlo (MC) simulation and micromechanical model. Zhang et al. [9] further demonstrated that the statistical correlation between elastic properties could lay a large influence on failure probability of FRP structures under a certain loading configuration. Still, current study on the statistical correlation between mechanical properties of FRP is limited in laminate constituted by unidirectional fibres, and the main cause of the statistical correlation between mechanical properties is that their stochastic variation all

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depend on certain constituent material properties.

For weave composite where the reinforcement is fibre fabric instead of unidirectional fibres, not only constituent material properties but also microstructure geometry determines ply mechanical properties. Komeili et al. [10] has studied the effect of different meso-level uncertainty factors on the mechanical response of a glass fibre woven fabric, and it is shown that cell geometrical factors gives significant influence on uni-axial and bi-axial loading response. Fang et al. [36] and Kang et al. [37] use Yushanov and Bogdanovich's stochastic theory [38,39] to investigate the effect of yarn distortion on mechanical properties of 3D braid and woven composites. By variable metric calculation model, Wang et al. [11,12] have shown significant effects of variations in yarn path and cross-section shape parameters on elastic properties of plain-weave composites. Vanaerschot et al. [13] utilize Markov Chain algorithm to simulate tow position of woven composite and stochastic variation of its mechanical properties are derived. Mori-Tanaka homogenization method and Monte Carlo method have also been respectively used to evaluate homogenized macroscopic laminate stiffness tensor mean value [32–35]. However, to the authors' knowledge, the statistical correlation between mechanical properties of woven composite is an issue that has rarely been paid attention to, and whether it affects the structure reliability or not is unclear.

The objective of the present study is to provide an insight on the statistical correlation between in-plane elastic properties of plain-weave composite and its influence on structure reliability. Probabilistic finite element analysis is employed to derive linear correlation coefficients between in-plane elastic properties of plain-weave glass and carbon fibre reinforced composite. FE model on a unit cell of plain-weave composite is constructed to derived in-plane elastic properties, including Young's modulus in the yarn direction, major Poisson's ratio and shear modulus. Linear correlation coefficients between the in-plane elastic properties are derived, and their sensitivity is analyzed. Two numerical examples are discussed about the difference of structure reliability by considering or neglecting the statistical correlation. It is shown that significant statistical correlation may exist between the in-plane elastic properties and it would lays a notable influence on structure reliability.

2. Microscale statistics of plain-weave composite

2.1. Statistics of geometry of unit cell

In this study, the geometrical configuration of a unit cell of the weave fabric is characterized by yarn space (S), yarn width (w) and yarn thickness (h), as has been suggested and discussed in [10,14,15]. The geometrical configuration of the micro-structure and unit-cell is shown in Fig. 1. The sample materials studied in this work are fifteen layered E-glass fabric/epoxy and fourteen layered carbon fabric/epoxy composite, and each ply contains a plain-weave fabric. Images of composite microstructure are achieved by micro-CT method. E-glass fabric/epoxy sample with a size of 6.58 mm × 3.76 mm × 17.40 mm and carbon fabric/epoxy sample with a size of 6.51 mm × 3.23 mm × 17.40 mm are scanned in NIKON XTH225 ST and Sanying nanoVoxel-2000, respectively, and cross section images are extracted using image analysis software VG Studio MAX 2.2. A typical image on the microstructure of the E-glass fabric/Epoxy is shown in Fig. 2, where S, w and h are determined as sketched. 33 slices of the E-glass fabric/Epoxy specimen and 20 slices of the Carbon fabric/Epoxy specimen in warp direction with respective 0.123 mm and 0.209 mm intervals are chosen to measure statistics of the geometrical parameters, as listed in Table 1. After labeling yarn cross-sections slice by slice, quantification of geometrical parameters is implemented by fitting the labeled yarn cross-sections using software Fiji [31]. Then the statistical properties of geometrical parameters are obtained by Reference Period Method [30], the main progress of which is that (1) translating each periodic yarn segment to the reference period one by one, (2) averaging all slice data of each geometrical parameter to acquire the mean value and (3) subtracting the mean value from each slice data to acquire the standard deviations of geometrical parameters.

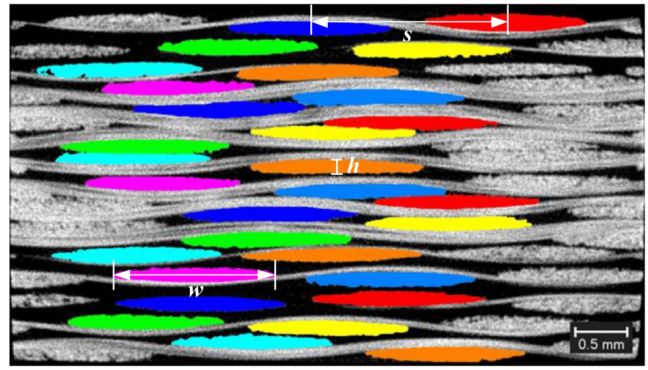

Fig. 2. A micro-graph of the cross section of plain-weave composite derived from the micro-CT measurement [12].

2.2. Statistics of constituent properties

The statistics of mechanical properties of E-glass fibre, T300 carbon fibre and epoxy are shown in Table 2. It is important to notice that E-glass fibre tends to be mechanically isotropic while carbon fibre is mechanically transverse isotropic [16]. Experimental measurement results on the statistics of fibre mechanical properties are generally rarely reported, and their coefficient of variation (standard deviation/mean value) listed in Table 2 is assumed to be 5% if a reference is not given. The randomness of fibre or epoxy elastic properties are assumed to follow a normal distribution. In this study, woven fabric with the same weft yarn and warp yarn is considered, but woven fabric with different weft yarn and warp yarn can also be accounted by the methodology

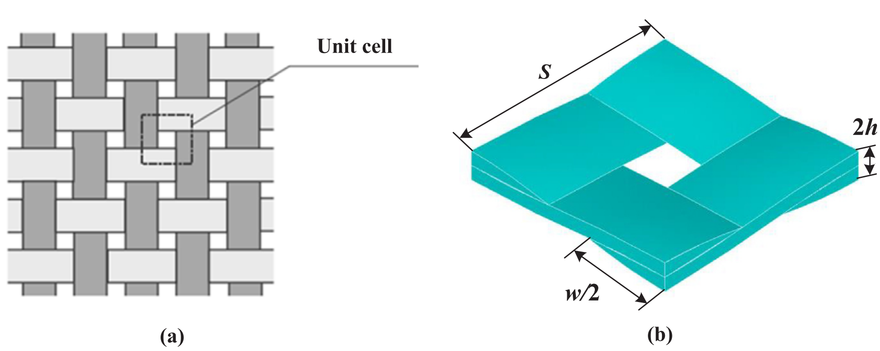

Fig. 1. Geometrical description of the unit cell of plain-weave composite. (a) boundary of unit cell; (b) geometrical shape of unit cell [14].