Journal of Materials Science & Technology 32 (2016) 597–604

Contents lists available at ScienceDirect

Journal of Materials Science & Technology

journal homepage: www.jmst.org

Effects of Process-Induced Voids on the Properties of Fibre Reinforced Composites

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ARTICLE INFO

Article history:
Received 2 September 2015
Received in revised form
9 November 2015
Accepted 16 November 2015
Available online 15 April 2016

Key words:
Polymer-matrix composites (PMCs)
Voids
Strength
Modulus
Tensile
Interlaminar shear strength (ILSS)
Finite element analysis (FEA)

It is well known that voids have detrimental effects on the performance of composites. This study aims to provide a practical method for predicting the effects of process induced voids on the properties of composites. Representative volume elements (RVE) for carbon fibre/epoxy composites of various fibre volume fractions and void contents are created, and the moduli and strengths are derived by finite element analysis (FEA). Regression models are fitted to the FEA data for predicting composite properties including tensile, compressive and shear. The strengths of composite laminates including tensile strength and interlaminar shear strength (ILSS) are calculated with the aid of the developed models. The model predictions are compared with various experimental data and good agreement is found. The outcome from this study provides a useful optimisation and robust design tool for realising affordable composite products when process induced voids are taken into account.

1. Introduction

Fibre-reinforced composite materials are widely used in many structural components in aircraft, automotive, marine, and other industries[1] because of their low density, high strength, high stiffness to weight ratio, excellent durability, and design flexibility. However, the high complexity and cost of the manufacturing process have been limiting the use of composite materials. One common problem associated with the complicated nature of material and processing is process induced defects, *e.g.* dry spots and voids, resin-rich surfaces/zones, fibre distortions. These defects can cause large variation in the product dimensions and mechanical performance, and even product scrap.

Conventional composite void characterisation techniques, *e.g.* Archimedes test, matrix burn-off, matrix digestion and microscopy, provide results of limited accuracy and/or reliability due to inherent testing errors. Recent techniques include X-ray computed tomography and micro-computed tomography (micro-CT)[2].

It is well known that voids have detrimental effects on the properties of composites. For the purpose of minimising voids, much research[3–6] has been done for process optimisation. Despite this effort, it is impossible to eliminate voids in the composites processing. Thus, it is very important to understand the effects of voids on the material properties.

Various results have been found on the effects of voids in the literature. In general, it is found that the matrix-dominated properties, *e.g.* interlaminar shear strength (ILSS)[7–9], flexural and compressive properties[10–12], fatigue[13,14] and fracture toughness[12] are affected by voids while the fibre-dominated properties are not affected by voids.

For tensile properties, Zhang et al.[15] found slight decrease in the tensile strength of the woven-fabric carbon/epoxy prepregs (T300/914) laminates when the void content increased from 0.33% to 1.50%. Similar results were found by Guo et al.[16] for T700/TDE85 carbon fibre reinforced epoxy composites.

Liu et al.[11] found that ILSS, flexural strength and flexural modulus were most sensitive to void content; tensile strength showed a slow decrease with increasing void content; and tensile modulus was insensitive to void. Hagstrand et al.[10] studied the effect of porosity on the flexural behaviour of unidirectional glass fibre reinforced polypropylene beams, and found that voids had a negative effect on the flexural modulus and strength, which both decreased by about 1.5% for each 1% of voids.

Many studies have been carried out on the effects of voids on ILSS. Hancox[17] found that voids had a serious degrading effect on shear modulus and strength, reducing properties to 30% of their void

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http://dx.doi.org/10.1016/j.jmst.2016.04.011
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Nomenclatures

E_{11}	longitudinal modulus of composite
E_{22}	transverse modulus of composite
E_{fL}	longitudinal modulus of fibre
E_{fT}	transverse modulus of fibre
E_{m}	modulus of matrix
E_{me}	effective modulus of matrix with voids
G_{12}	longitudinal-transverse (in-plane) shear modulus of composite
G_{23}	transverse-transverse shear modulus of composite
G_{f}	shear modulus of fibre
G_{me}	effective shear modulus of matrix with voids
K_{23}	transverse-transverse bulk modulus of composite
K_{f}	bulk modulus of fibre
K_{fTT}	transverse-transverse bulk modulus of fibre
K_{me}	effective bulk modulus of matrix with voids
K_{mTTe}	effective transverse bulk modulus of matrix with voids
S_{Lt}	longitudinal tensile strength of composite
S_{Tt}	transverse tensile strength of composite
V_{f}	fibre volume fraction
V_{v}	void content with respect to matrix
V_{vc}	critical void content
V_{vn}	void content with respect to composite (net void content)
$\varepsilon_{\mathrm{fu}}$	strain at failure of fibre
$\varepsilon_{\mathrm{mu}}$	strain at failure of matrix
ε_{u}	effective strain at failure of composite
ν_{12}	longitudinal-transverse Poisson's ratio of composite
ν_{23}	transverse-transverse Poisson's ratio of composite
ν_{me}	effective Poisson's ratio of matrix with voids

free value at 5 vol% voids. Costa et al.[18] studied the ILSS of T300 carbon fibre fabric reinforced epoxy composites with intentionally high porosity levels from 1.4% to 5.6% produced using the technique proposed by de Almeida et al.[8]. The stacking sequence was $[0/90]_{14}$, resulting in a nominal thickness of 4.1 mm. The volume fibre content was between 64% and 72%. The same technique was used to make T300 carbon fibre fabric reinforced epoxy bismaleimide (BMI) of the same stacking sequence with intentionally high porosity levels from 1.1% to 3.4%[18]. The fibre volume fraction was between 64% and 70%. For both materials, the ILSS was measured by the short-beam method described in ASTM D2344 and the adequacy of a fracture criterion to represent the experimental data for both materials was assessed. Jeong[9] studied the effects of voids on the ILSS for both unidirectional and woven graphite/epoxy composites. Guo et al.[16] studied the effects of voids on the shear and flexural strengths of T700/TDE85 carbon fibre reinforced epoxy composites. The nominal fibre volume fraction was 60% and the stacking sequence was $[0/90]_{3S}$. Bureau and Denault[13] studied the ILSS of continuous glass fibre/polypropylene (CGF/PP) composites. It is shown from these studies that ILSS significantly decreases due to the presence of voids.

More recently, Scott et al.[19] used a multi-scale computed tomography (CT) technique to determine the material structure and damage mechanisms in hydrostatically loaded composite circumferential structures. Their study revealed matrix cracking in the longitudinally wound plies and fibre breaks in the circumferentially wound plies. The matrix cracking within the longitudinally wound plies interacted directly with intralaminar voids, while less distinct correlation of voids with fibre breaks in the circumferential was found.

Since composite laminates have the ability to withstand high stresses acting over small regions, the strength of a laminate with high void content over a small area is unaffected by the existence of such defect. It is also shown that a critical volume fraction exists below which the strength is unaffected by voids[20]. De Almeida and Neto[8] presented a criterion to estimate the effect of void content on the strength of composites using Mar–Lin equation[21] and found the critical volume was about 3%. Jeong[9] studied the effect of voids on ILSS and determined the critical volume to be 1%. Guo et al.[16] showed that this critical volume was about 1% for ILSS, flexural and tensile strengths. Costa et al.[18] found that the ILSS of carbon/epoxy laminates and carbon/BMI laminates with void content above 0.9% decreased.

In addition to void content, Huang and Talreja[22] showed the effects of void geometry on the elastic properties of unidirectional fibre reinforced composites and concluded that voids had much larger influence on reducing the out-of-plane properties than the in-plane ones. The in-plane properties were found to be most sensitive to the width–height aspect ratio.

It is seen that various experimental results exist for the effects of voids on the moduli and strengths of composites. Voids remain a significant topic in the development of composites, especially in the nano-scale. Recent studies by Yu et al.[23,24] suggest a 3% decrease in the effective moduli of composites containing multiple nanoheterogeneities. This study aims at providing a model to take into account the effects of voids in the design stage. For this purpose, finite element models based on representative volume elements (RVE) with randomly distributed voids were developed. The resulting finite element analysis (FEA) data were used to fit a simple regression model. Using the regression model, the strengths of composite laminates with voids can be predicted conveniently. The model is validated against various experimental data.

2. Finite Element Analysis

FEA has been used in some studies to investigate the effects of process-induced voids[22]. In this study, an RVE-based FEA approach was employed with the aid of a commercial software package, ANSYS Mechanical APDL. For simplicity, 2D analyses were employed based on the assumption of plane strain conditions. Since fibre reinforced composites are highly orthotropic, FEA models were developed for transverse and longitudinal properties, respectively.

2.1. *Transverse properties*

For computing transverse properties, RVEs of 50 μm × 50 μm with three different fibre volume fractions: 33.73%, 42.92%, and 51.11%, were created, as shown in Fig. 1.

For each fibre volume fraction, RVEs of five different void contents are created. The voids are introduced to the matrix randomly. Only intra-tow voids are considered and their sizes are limited by the inter-fibre distances. The actual void content is determined by the area of RVE. As an example, the maximum void content is 17.64% for $V_{\mathrm{f}} = 42.92\%$, as shown in Fig. 2.

In this study, the void content, V_{v}, is defined to be with respect to the matrix only. The void content with respect to the composite is defined as the net void content, V_{vn}, which is related to V_{v} by

$$V_{\mathrm{vn}} = (1 - V_{\mathrm{f}})V_{\mathrm{v}} \tag{1}$$

PLANE183 element is used with the option of plane strain. As shown in Fig. 3, the horizontal and vertical displacements are constrained for the left and bottom edges, respectively. Periodical boundary conditions are applied to the right and top edges. A unit tensile stress ($p_0 = 1$ MPa) was applied at the right edge.