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Effects of fibre–fibre interaction on stress uptake in discontinuous fibre reinforced composites

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ABSTRACT

The response of discontinuous fibre composites to mechanical loading is regulated to a large extent by the cooperative action of the fibres but the underlying effects of fibre–fibre interaction remain unclear. Here, finite element analysis of a simple 3D representative volume element of an aligned discontinuous fibre composite reveals that the interaction of fibres—described by the fibre–fibre lateral separation distance and axial overlap length—influences the fibre stress uptake during elastic stress transfer. In particular, fibre–fibre lateral separation influences the magnitude of the stress; interestingly axial overlap produces a stepwise stress discontinuity in the fibre.

1. Introduction

It is well-known that materials reinforced by high-modulus fibres can result in enhanced mechanical properties [1]. The fibres may be in continuous or discontinuous (e.g. chopped strands, short filaments or whiskers) forms [1]. This paper is concerned with discontinuous fibres reinforcing composites. Discontinuous fibre composites can be found in many engineering applications ranging from aerospace, automotive to marine because they can be shaped easily by injection or compression moulding [1]. Over the years, the mechanics of stress transfer between the matrix and fibres has been the subject of intense research as the efficiency of stress transfer is key to enhancing the mechanical properties of the composite [1,2]. Essentially, stress transfer mechanisms are responsible for regulating the stress uptake in the fibres when a discontinuous fibre composite goes through different stages of the loading process before it finally breaks apart [1,3]. These stages address how the elastic stress uptake occurs during initial loading (small strain regime) [4–6], how the plastic stress uptake occurs as the matrix material yields [5,7] and, finally, how the fibres succumb to pullout [5,8] or rupture [5].

In order to predict the effective properties of the composite material, mathematical models have been developed and solved numerically using discrete element methods, such as finite element (FE) and boundary element methods [9–13]. Typically, these models feature a 3D construct of a representative volume element (RVE) of the composite comprising a predetermined number of discontinuous fibres embedded in the matrix material [9–14]. The fibres may be dispersed randomly (i.e. randomly oriented and spaced out) and, henceforth, non-uniformly distributed in the matrix [9–13] or form a regular arrangement with axial alignment [14], e.g. the square-diagonal model shown in Fig. 1C. Predictions from these models have revealed how the composite elastic modulus—an important mechanical parameter of the material [15]—is affected by the composition of the fibre and matrix [10,14], fibre slenderness (more formally known as aspect ratio, q) [9,14], fibre orientation [10–13] and elastic modulus of the fibre (E_f) relative to that of the matrix (E_m) [13]. Furthermore, the sensitivity of the composite stiffness to these parameters is consistent with results derived from experiments [3]. Altogether these findings have led to important insights concerning (1) the effectiveness of discontinuous fibres as the primary load-carrying components, and (2) the role of the fibre structure and mechanical properties of the respective fibre and matrix, in the presence of fibre–fibre interaction. However the conclusions of these findings are not based on any detailed analysis of the underlying stress transfer mechanisms that direct the stress uptake in these fibres. Additionally, for accurate prediction of the mechanical properties of the composite, it is

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Abbreviations

b	auxiliary parameter of the Cox model
E_c	composite stiffness
E_f	fibre modulus
E_m	matrix modulus
F	force acting on the cylindrical cross-section of the Cox model
L_f	fibre half-length
L_m	length of the composite (Cox's model)
P_f	fibre packing factor
q	fibre aspect ratio
r_o	radius of the fibre
RVE	representative volume element
ν_m	Poisson's ratio of the matrix material
V_f	fibre volume fraction
V_m	matrix volume fraction
Z	normalized axial distance, in the direction of the z-axis of the cylindrical polar coordinates system
α, β	symbols for representing the fibres in the unit cell
ε_0	applied strain
λ	length of the axial overlap between the fibres
ρ	lateral centre-to-centre separation between the fibres
ρ_{eff}	effective distance between the centre fibre and the adjacent fibre (Cox's model)
σ_c	composite normal stress
σ_z	axial tensile stress in the fibre

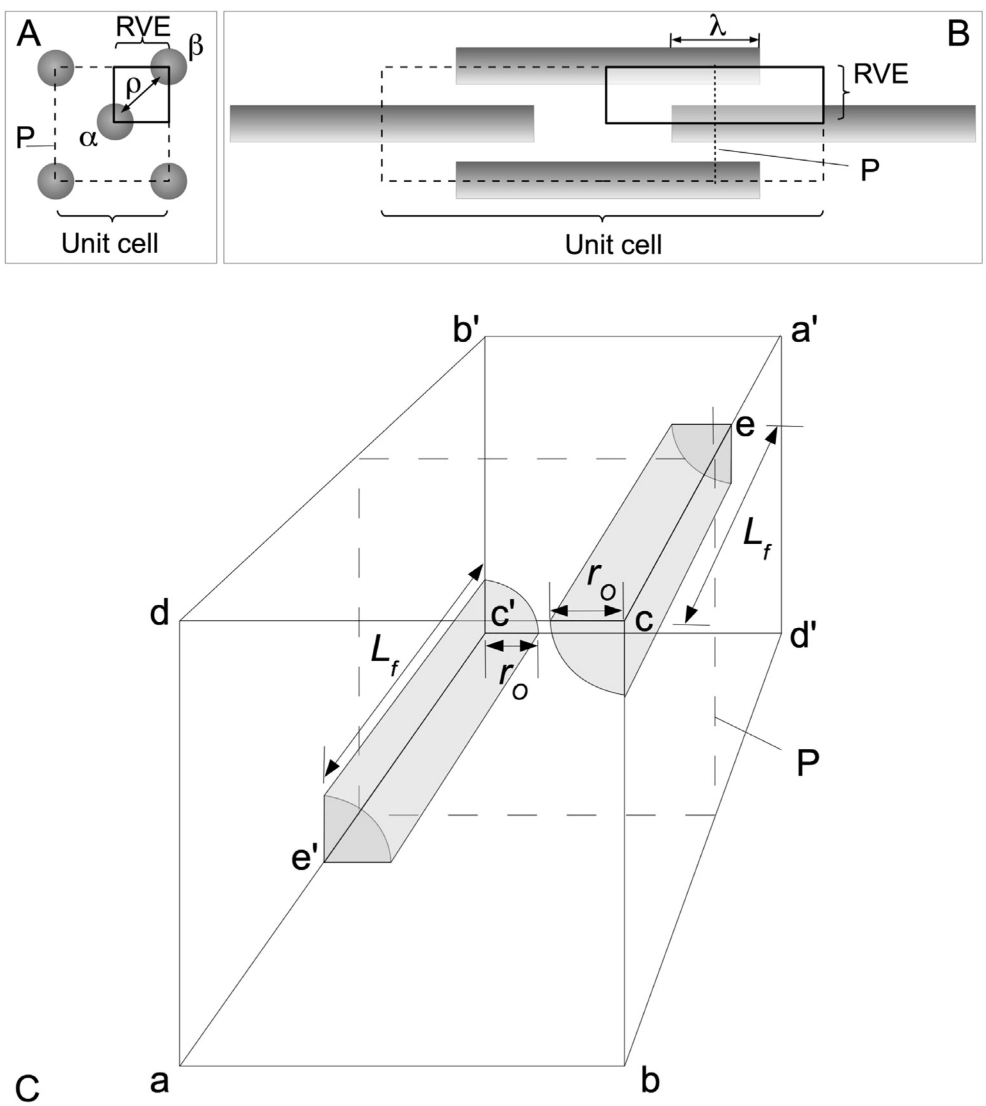

Fig. 1. Model of short (uniform cylindrical) fibres reinforcing composites showing the square-diagonally packed fibres in the (A) cross-sectional (plane, P) and (B) longitudinal views of the unit cell, and (C) representative volume element (RVE) containing fibre fractions taken from two fibres. Since the two fibre fractions are located at the diagonal corners of the RVE, this fibre arrangement is known as the square-diagonal packing distribution.