Journal of the Mechanical Behavior of Biomedical Materials 81 (2018) 72–82

Contents lists available at ScienceDirect

Journal of the Mechanical Behavior of Biomedical Materials

journal homepage: www.elsevier.com/locate/jmbbm

Simulating damage onset and evolution in fully bio-resorbable composite under three-point bending

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ARTICLE INFO

Keywords:
Continuum damage mechanics
Flexural strength
Finite element analysis
Bio-resorbable composite

ABSTRACT

This paper presents a strain-based damage model to predict the stress-strain relationship and investigate the damage onset and evolution of the fibre and matrix of a fully bio-resorbable phosphate glass fibre reinforced composite under three-point bending. The flexural properties of the composite are crucial, particularly when it is employed as implant for long bone fracture. In the model, the 3D case of the strain and stress was used and the response of the undamaged material was assumed to be linearly elastic. The onset of damage was indicated by two damage variables for the fibre and matrix, respectively. The damage evolution law was based on the damage variable and the facture energy of the fibre and matrix, individually. A finite element (FE) model was created to implement the constitutive model and conduct numerical tests. An auto-adaptive algorithm is integrated in the FE model to improve the convergence. The FE model was capable of predicting the flexural modulus with around 3% relative error, and the flexural strength within 2% relative error in comparison with the experimental data. The numerical indices showed that the top surface of the sample was the most vulnerable under three-point bending. It was also found that the damage initiated in the fibre, was the primary driver for composite failure under three-point bending.

1. Introduction

Traditionally, load-bearing metal implants have been used in surgical procedures for bone fixation purposes. However, these implants are commonly associated with the 'stress shielding' effect, which weakens the surrounding bone and increases the risk of re-fracture after the device has been removed (Engh et al., 1987; Huiskes et al., 1992; Nagels et al., 2003; Parsons et al., 2009). Bio-resorbable implants provide an opportunity to match the properties of bone whilst transferring load to the healing bone more appropriately, along with being easily formed and their degradation products should be tolerated by the human body. There are reports of the application of fully bio-resorbable polymers as bone fracture fixation devices such as plates, screws, pins, and rods (Parsons et al., 2009; Casteleyn et al., 1992; van Manen et al., 2008). However, un-reinforced polymer implants have insufficient stiffness, particularly for load-bearing applications (Törmälä et al., 1998; Hoffmann et al., 2001). The ideal replacement for traditional metallic bone fixation devices should have excellent biocompatibility, be fully bio-resorbable and have sufficient mechanical properties to support the bone during the early healing stages, before gradually degrading over time (Parsons et al., 2009; van Manen et al., 2008; Chen et al., 2016; Felfel et al., 2013). A composite comprising polylactide (PLA) matrix reinforced with phosphate glass fibre (PGF) has been regarded as a desirable reinforcement because of the mechanical properties it has achieved and it is fully bio-resorbable, releasing calcium and phosphate ions which are ideal for bone repair applications (Bitar et al., 2004; Parsons et al., 2004). Considerable effort has been put into investigating the mechanical properties of these materials (Parsons et al., 2009; Chen et al., 2016; Felfel et al., 2011; Liu et al., 2013; Sharmin et al., 2016), particularly the flexural strength (Mannocci et al., 2001; Steeves and Fleck, 2004; Harper et al., 2012), however damage initiation and accumulation in the fibre and matrix under three-point bending has not been investigated before. Therefore, the current paper seeks to develop an effective approach to assess the damage accumulation and resulting reduction in flexural performance of this bio-resorbable glass fibre reinforced polymer composite. Knowledges about the damage onset and evolution of the fibre and matrix extracted from this study are beneficial to the manufacturing of this type of composites, e.g. the selection of the fibre and matrix materials, the improving of manufacturing method, and possible optimization of fibre/matrix configuration. Subsequently, the results of this study are useful for pushing the research of employing bio-resorbable composites

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https://doi.org/10.1016/j.jmbbm.2018.02.022
Received 11 December 2017; Received in revised form 10 February 2018; Accepted 17 February 2018
Available online 21 February 2018

as bone fixation device material forward, which, ultimately, is beneficial to patients in the need of using bone fixation devices.

Damage initiation and evolution in the composite can be described using continuum damage mechanics (CDM), as long as the problem size is assumed to be sufficiently larger than the defect/microcrack size, to facilitate homogenisation (Mishnaevsky and Brøndsted, 2009). Typically, a progressive damage model (PDM) consists of three steps: stress analysis, material properties degradation and failure analysis (Tserpes et al., 2002; Lu et al., 2016, 2015). The crucial part of a PDM is to appropriately define the damage initiation criterion and evolution law. For unidirectional fibre reinforced composites, early work by Hill (1948) was adopted by Tsai (1965) to simulate the damage initiation in fibre reinforced composites. Hill's model was only intended for anisotropic ductile metals, and the yield stress in tension and compression were considered to be the same, which is unrealistic for the bio-resorbable composites whose compressive and tensile strength are different. Hoffman (1967) later proposed a phenomenological fracture condition for orthotropic brittle materials which was capable of simulating the different properties of fibre reinforced composites in both the longitudinal and transverse directions. Hoffman developed Hill's model to consider different tensile and compressive yield stresses. However, both models lacked the capability of simulating the onset and evolution of damage. Matzenmiller et al. (1995) proposed a damage model based on Hashin (1981) criterion involving five damage variables to simulate the elastic-brittle nature of the fibre reinforced composites. The tensile and compressive damage was modelled for both fibre and matrix, respectively. The 3D-Hashin and Tsai-Wu failure criteria were adopted to describe the damage initiation of yarns (Xu and Xu, 2008), in which the damage evolution of composites was strongly dependent on the reduction coefficients, which were controlled by the local stress and strain. Zhou et al. (2013) and Fang et al. (2011) proposed a modified 3D-Hashin failure criterion to model the damage initiation and evolution, and the reduction coefficients introduced by Murakami's theory (Murakami, 1983) was adopted which were controlled by the equivalent stresses and equivalent strains. For these Hashin and Tasi-Wu based criterion, at least six different damage mechanisms were included, leading to a large number of equations which resulted in high computational cost. Linde et al. (2004) developed a 2D criterion for progressive damage of fibre metal laminates, which was based on a strain-based continuum damage mechanics. Unlike Matzenmiller's model, Linde's model integrated the tensile and compressive damage as two damage variables for the fibre and matrix, respectively, but required the tensile and compressive strength of the fibre and matrix as input parameters. Lu et al. (2013) extended the 2D failure criterion to 3D and adopted it to model the tensile properties of 3D braided composites. In both Linde's model and the modified model by Lu et al., the shear strain in the fibre direction was not part of the damage formulation. In the work of Wang et al. (2015), a modified 3D model based on Linde's model was proposed to simulate the damage onset and failure for braided composites, in which the shear strain was taken into account and a better prediction was obtained (the relative error between the numerical and experimental results was reduced from 7.74% to 3.18% for the tensile strength and from 1.02% to 0.41% for the tensile modulus, see (Lu et al., 2013; Wang et al., 2015)).

In this paper, the modified Linde's model in (Wang et al., 2015) has been adopted to simulate the three-point bending of a bio-resorbable composite. The model is three dimensional and takes into account shear strain in the fibre direction. The bio-resorbable composite modelled in this paper is a unidirectional continuous glass fibre reinforced polymer, which exhibits transversely isotropic properties. The constitutive model has been implemented in an FE environment, and an auto-adaptive algorithm has been integrated to improve convergence. The FE model is capable of capturing the onset and evolution of damage in the fibre and matrix under three-point bending. The numerical modelling in this paper is conducted by using the commercial FE software ABAQUS 6.13.

2. Experiment description

Three-point bending experiments were conducted on a Bose ElectroForce® Series II 3320 testing machine, following the British Standard (EN ISO 14125:1998 + A1) to determine the flexural properties. The dimensions of the samples were manufactured as 40 mm × 15 mm × 2 mm. During sample testing, the specimens were placed on two round supports with radius of 2 mm at a span of 32 mm. The load was applied vertically at the centre line of the specimen by a round cross-head loading member with a radius of 5 mm. The temperature throughout the test was kept at room temperature (∼ 22 °C) to exclude the thermal influence. Displacement/deflection loads were measured via the testing machine, for which the stress and strain were calculated according to the equations below:

$$\sigma_f = \frac{3FL}{2bh^2} \tag{1}$$

$$\varepsilon_f = \frac{6sh}{L^2} \tag{2}$$

where σ_f is the flexural stress, F is the applied load, ε_f is the flexural strain, s is the measured vertical displacement, L, b and h are the span, width, and thickness of the specimen, respectively.

3. Determination of the material constants

The continuous long fibre-reinforced composite exhibits transverse isotropy (Castellano et al., 2014; Mortazavian and Fatemi, 2015). Once the material properties of the fibre and matrix are known, the elastic material properties of the composite can be readily obtained by creating a simple homogenised representative volume element (RVE) (Barbero, 2013). The strength properties of the composite can be approximated by using the Rule of Mixture (ROM) in the longitudinal and transverse directions:

$$X_1 = V_f X_f + (1 - V_f) X_m \tag{3}$$

$$X_2 = \left(\frac{V_f}{X_f} + \frac{1 - V_f}{X_m}\right)^{-1} \tag{4}$$

In the above formulae, X represents the material properties of the composite, e.g. tensile strength or compressive strength, and the subscript 1 represents the longitudinal direction while 2 represents the transverse direction. Subscripts f and m refer to the fibre and matrix respectively; V_f is the fibre volume fraction (FVF). It should be noted that the resulting composite strength estimates assume that the fibre and matrix are perfectly bonded. More information on determining the material properties can be found in (Gao et al., 2017).

4. Damage initiation and evolution

4.1. Constitutive model

The strain-based continuum damage model proposed by Linde et al. (2004) is capable of capturing the damage initiation of fibre reinforced composite as well as fibre-metal laminates (Lu et al., 2013; Lapczyk and Hurtado, 2007; Sadighi et al., 2012). However, it does not consider the contribution of the shear strain in the fibre direction to the damage initiation criterion. For the composite considered in this paper, the shearing effect in the fibre direction cannot be ignored since the continuous long fibre receives significant shear stress in the fibre direction under three-point bending, which is one of the dominant load cases when the implant is in-service in the body. Therefore, a modified model was adopted to assess the damage initiation and evolution of the composite in three-point bending (Wang et al., 2015), which is presented in this section. For the fibre, the damage initiates when the following criterion is met: