Composites Science and Technology 72 (2012) 1012–1019

Contents lists available at SciVerse ScienceDirect

Composites Science and Technology

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

Bio-inspired tapered fibers for composites with superior toughness

Heide Humburg, Deju Zhu, Samia Beznia, Francois Barthelat *

Department of Mechanical Engineering, 817 Sherbrooke Street West, McGill University, QC, Canada H3A 2K6

ARTICLE INFO

Article history:
Received 15 November 2011
Received in revised form 6 February 2012
Accepted 13 March 2012
Available online 21 March 2012

Keywords:
A. Short-fiber composites
B. Fracture toughness
C. Fiber bridging
C. Modelling
Biomimetics

ABSTRACT

The toughness of fiber-reinforced composites largely relies on crack bridging. More specifically, intact fibers left behind the tip of a propagating crack are progressively pulled out of the matrix, dissipating energy which translates into toughness. While short fibers are traditionally straight, recent work has showed that they can be shaped to increase the pullout strength, but not necessarily the energy to pullout. In this work we have modeled, fabricated and tested short fibers with tapered ends inspired from a high-performance natural material: nacre from mollusc shells. The main idea was to duplicate a key mechanism where a slight waviness of the inclusion can generate strain hardening and energy dissipation when the inclusion is pulled out. We have incorporated a similar feature to short fibers, in the form of tapered ends with well defined opening angles. We performed pullout tests on tapered steel fibers in epoxy matrices, which showed that the pullout of tapered fiber dissipates up to 27 times more energy than straight fibers. The experimental results also indicated the existence of an optimum taper angle to maximize work of pullout while preventing the brittle fracture of the matrix. An analytical model was developed to capture the pullout mechanism and the interaction between fiber and matrix. The analytical model can guide the design of tapered fibers by providing predictions on the influence of different parameters.

1. Introduction

Stiffness, toughness and strength are highly desirable properties for structural materials. In short-fiber reinforced composites (SFRCs), these properties are largely controlled by the interfaces between the fibers and the matrix. These interfaces must be strong enough to transfer stresses between the matrix and the fibers to promote high modulus and strength, yet weak enough to allow for fiber debonding and fiber pullout, which are critical for toughness [1,2]. The toughness of well-designed short-fiber composites is mainly produced by fiber pullout. In the ideal scenario, when the material endures extreme stresses a crack may propagate in the matrix and will intersect some fibers which remain intact behind the crack front, exerting a closure force on the crack. As the crack faces spread apart these fibers debond from the matrix, and energy is dissipated through frictional sliding of the fiber on the matrix [3]. The amount of frictional force is a function of the friction coefficient and of the normal force at the matrix–fiber interface, which is provided by residual compression in the matrix from the curing and cooling process. Successful toughening is therefore conditional on these mechanisms, which will only occur with proper design of the material (alignment and density of the fibers, aspect ratio of the fibers, interfacial strength, and residual stresses) [4,5]. Ultimately the improvement in toughness is controlled by the energy dissipated in the pullout process, which is typically measured from a single fiber pullout test [6,7].

Careful design of the fiber–matrix interface is therefore critical and it can be achieved, for example, by fiber sizing or chemical functionalization [8,9]. Another approach to tailoring the pullout response of individual fibers is fiber shaping. Residual compressive stresses in the matrix impose a normal pressure on the interface, which generate frictional forces that are partially controlled by the surface roughness of the fibers [10]. Another approach is to alter the macroscopic shape of the fiber by introducing enlarged ends [1,11,12], flat and ripple ends [13,14] which effectively anchor the fibers in the matrix and enhance their overall mechanical performance. Fracture mechanics applied to composite materials demonstrates that the energy to pullout of individual fibers has a direct impact on the overall toughness of a composite made of such fiber. This principle has been demonstrated experimentally in the past, including for shaped fibers. For example, Zhu et al. [15] studied polyethylene fiber/polyester matrix systems and found that composites with shaped fibers were 9 times stronger and 17 times tougher than composites with straight fibers. Likewise, Bagwell and Wetherhold [16] conducted four-point bending tests on an end-shaped copper fiber/epoxy matrix composites and found an improvement in fracture toughness of 49% compared to straight fiber composites. These two studies demonstrated how shaped fibers, by altering the transfer of load between fiber and matrix,

---

* Corresponding author.
E-mail address: francois.barthelat@mcgill.ca (F. Barthelat).

0266-3538/$ - see front matter
http://dx.doi.org/10.1016/j.compscitech.2012.03.013

can significantly improve the overall strength and toughness of composites. The most interesting feature is the observed pullout-hardening, which is defined as the slope of the load–displacement curve after debonding. The steeper the slope the more the fiber resists pullout at a crack plane and therefore exhibits crack-bridging and crack-closure forces that reduce the stress intensity factor at the crack tip [17]. The displacement over which the hardening occurs is also of great importance, as it determines the pullout-distance that the fiber can travel without complete pullout leading to failure of the material. However, a too large end-shape can have deteriorative effects, since the fiber ends have a tendency to initiate matrix cracks [15]. If properly designed, intact tapered fibers can transfer sufficient load after first cracking to allow the composite to undergo multiple cracking and spread debonding and pullout over larger volumes [18]. This would allow a significant amount of deformation before a crack localizes and the composite fails. In these systems the geometry of the fiber was significantly altered, which firmly anchored the fiber to the matrix and increased the pullout force. However, the locking between fiber and matrix is so strong that sliding and energy dissipation was limited. Interestingly, a similar design problem was solved in nature in mollusk shells, a five million year old natural composite material. In particular, nacre (mother of pearl) is made of microscopic mineral tablets which provide stiffness and hardness. Under tensile stress the tablets can slide and pullout from one another, dissipating a tremendous amount of energy which translates into toughness: Nacre is 3000 times tougher than the mineral it is made of [19]. An important requirement for this behavior is hardening. As tablets slide a mechanism must make it slide further so that tablet sliding spreads over large volumes. The structural feature which generates strain hardening in nacre was recently identified as dovetail-like features at the ends of tablets (Fig. 1a) [20]. This feature generates progressive locking as the tablets are pulled out (Fig. 1b), which generates hardening, makes pullout stable and generates toughness at the macroscale [20].

The waviness of the tablets – a very simple geometrical feature – is therefore a key mechanism for the high toughness of nacre, leading to stable crack propagation and crack-arresting capabilities. This type of insights into the performance of natural materials can inspire similar designs in engineering materials, through a process called biomimetics [21]. For example, in recent work the waviness of the tablets has been successfully implemented into macro-composites which duplicated the remarkable behavior of nacre in tension [22,23]. In this work we applied the concepts of dovetail, progressive locking, hardening and energy dissipation to short fibers.

2. Tapered fiber geometry: overview and impact on toughness

Incorporating short fibers with tapered ends into a ductile matrix is expected to alter the deformation and fracture mechanisms significantly (Fig. 2). In the presence of a macroscale crack the tapered fibers bridging the crack will pull out of crack faces and "plow" through the ductile matrix, adding viscoplastic energy dissipation to frictional dissipation. In terms of force response the taper is expected to greatly increase the force and energy to pullout, which will result in enhanced toughness at the macroscale. In addition, the pullout force will rise progressively to its maximum value as the pullout distance increases, generating deformation hardening. As a result, fibers will start debonding in other sites in the neighborhood ahead of the main crack, generating secondary cracks. In the optimum case, we anticipate that the locking of the fiber can be strong enough to develop a "process zone" ahead of the main crack, consisting of micro-cracks that are stabilized by the tapered fibers. While such material is not available yet in engineering form, a natural material like nacre demonstrates that this mechanism is feasible.

3. Pullout experiments

As a first step to developing the material described above, we performed pullout tests on short stainless steel fibers with different tapered angles. Millimeter size stainless steel shaft and hollow truncated cones with five different opening angles (0°, 2°, 5°, 10° and 20°) were machined. The ends of the shafts and the inner cavity of the cones were threaded so the cones were mounted at the ends of the shafts to form the required tapered fibers. This two-step fabrication process was found to be the most efficient and accurate approach to machine small fibers with high aspect ratio, with dimensions showed in Fig. 3a. The fibers were cleaned with acetone prior to embedding in the matrix.

The matrix was prepared from a two component room-temperature cure epoxy (Miapoxy 100/95, MIA Chemicals Inc., Avon, Ohio, USA) mixed in a weight ratio 100:24 and stirred thoroughly until the resin appeared clear and transparent. The mixture was subjected to vacuum at room temperature for 10 min for degassing, and was immediately poured into cylindrical molds with a diameter of 26 mm. The fiber was then partially embedded in the matrix over a length of about 8 mm, and positioned with a custom-made holder to ensure that the axis of the fiber was aligned with the axis of the cylindrical matrix. The system was cured at 24 °C ± 2 °C for 24 h, followed by applying a post cure at 65 °C ± 2 °C for 6 h to achieve full cure. The resulting samples consisted of an epoxy cylinder with a partially embedded fiber emerging perpendicularly to the top surface. The embedded length was measured on each sample and was found to be 8.3 mm ± 0.2 mm. The sample was then extracted from the mold and mounted in a universal testing machine (MTS Insight, 5 kN load cell, MTS Systems Corp., USA). The epoxy cylinder was held with a custom-made aluminum fixture, while the lower end of the fiber was mounted in a coupling nut and in the jaws of the loading machine (Fig. 3b). The upper crosshead was moved at a constant speed of 1 mm/min, while pullout

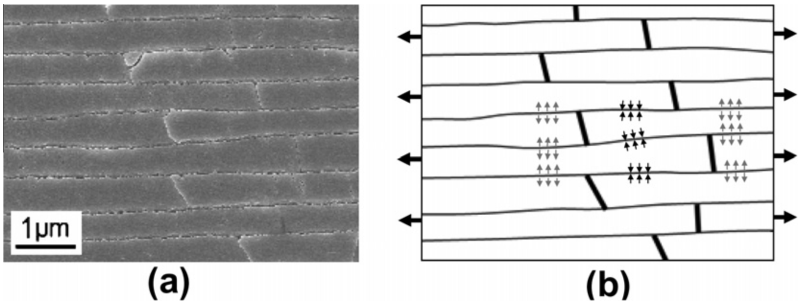

Fig. 1. (a) SEM-picture of nacre revealing the waviness of the aragonite tablets. Under tensile load (b) this geometry creates compressive stresses that prevent further sliding of the platelets and delay crack-localization.