Acta Biomaterialia 55 (2017) 349–359

Contents lists available at ScienceDirect

Acta Biomaterialia

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

Full length article

Crack driving force in twisted plywood structures

F.D. Fischer [a], O. Kolednik [b], J. Predan [c], H. Razi [d], P. Fratzl [d,*]

[a] Institute of Mechanics, Montanuniversität Leoben, Leoben, Austria
[b] Erich Schmid Institute of Materials Science, Austrian Academy of Sciences, Leoben, Austria
[c] Faculty of Mechanical Engineering, University of Maribor, Maribor, Slovenia
[d] Max Planck Institute of Colloids and Interfaces, Department of Biomaterials, Research Campus Golm, 14424 Potsdam, Germany

ARTICLE INFO

Article history:
Received 29 November 2016
Received in revised form 6 April 2017
Accepted 6 April 2017
Available online 8 April 2017

Keywords:
Fiber composite
Lamellar bone
Stiffness matrix
Configurational forces
Fracture toughness

ABSTRACT

Twisted plywood architectures can be observed in many biological materials with high fracture toughness, such as in arthropod cuticles or in lamellar bone. Main purpose of this paper is to analyze the influence of the progressive rotation of the fiber direction on the spatial variation of the crack driving force and, thus, on the fracture toughness of plywood-like structures. The theory of fiber composites is used to describe the stiffness matrix of a twisted plywood structure in a specimen-fixed coordinate system. The driving force acting on a crack propagating orthogonally to the fiber-rotation plane is studied by methods of computational mechanics, coupled with the concept of configurational forces. The analysis unfolds a spatial variation of the crack driving force with minima that are beneficial for the fracture toughness of the material. It is shown that the estimation of the crack driving force can be simplified by replacing the complicated anisotropic twisted plywood structure by an isotropic material with appropriate periodic variations of Young's modulus, which can be constructed based either on the local stiffness or local strain energy density variations. As practical example, the concepts are discussed for a specimen with a stiffness anisotropy similar to lamellar bone.

Statement of Significance

Twisted plywood-like structures exist in many natural fiber composites, such as bone or insect carapaces, and are known to be very fracture resistant. The crack driving force in such materials is analyzed quantitatively for the first time, using the concept of configurational forces. This tool, well established in the mechanics of materials, is introduced to the modeling of biological material systems with inhomogeneous and anisotropic material behavior. Based on this analysis, it is shown that the system can be approximated by an appropriately chosen inhomogeneous but isotropic material for the calculation of the crack driving force. The spatial variation of the crack driving force and, especially, its local minima are essential to describe the fracture properties of twisted plywood structures.

1. Introduction

Twisted or rotated plywood structures [1,2], also referred to as the Bouligand patterns, are observed in arthropod cuticle [1,3], stomatopod dactyl [4], as well as in the lamellar bone of vertebrates [5–11]. These materials yield a remarkably higher fracture toughness than their constituents alone [12–15]. Plywood structure is based on a spiralling arrangement of fibers as sketched in Fig. 1. In essence, the structure consists of layers of parallel fibers (x_1–x_3-planes in Fig. 1) where the fiber direction, as defined by the fiber angle θ with respect to the x_1-axis, varies from one layer to the next. In the simplest case, the fiber orientation changes continuously along the x_2-direction leading to a simple spiral arrangement, where the angle increases linearly with x_2. In the case of lamellar bone, the spiralling may be interrupted by interlayers of more disordered fiber arrangement [10] or, in some cases, the angle has been reported to vary in a more complicated than linear way with x_2 [6,9]. Nevertheless, a spiral arrangement is a reasonable first approximation that we are using here in this theoretical treatment.

Plywood structures can be considered as multilayers where the (homogenized) properties of each individual layer are characterized by its fiber orientation. Hence, crack propagation may be

* Corresponding author.
E-mail address: fratzl@mpikg.mpg.de (P. Fratzl).

http://dx.doi.org/10.1016/j.actbio.2017.04.007

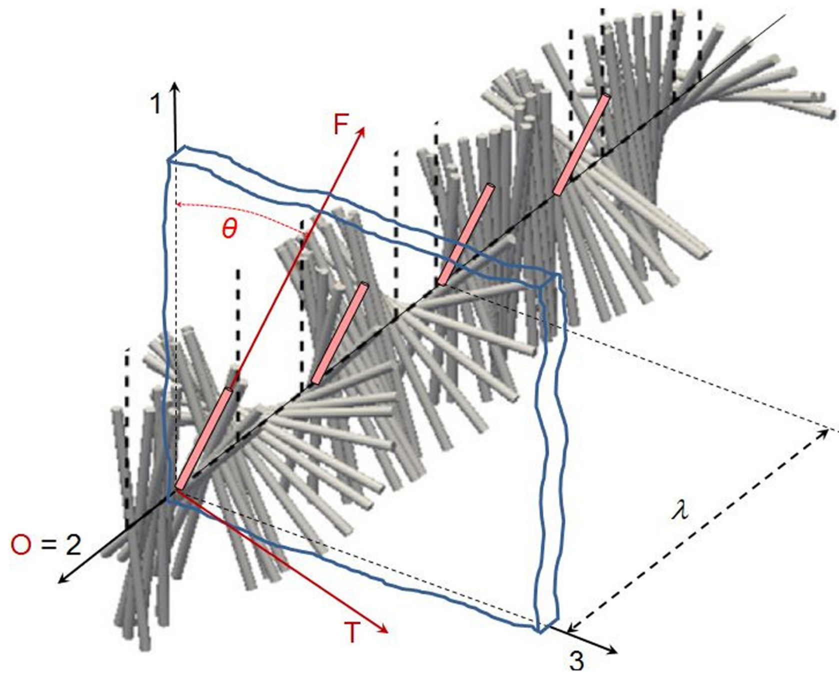

Fig. 1. Schematic representation of a twisted plywood structure, based on Fig. 6 in [9]. In each $x_1 - x_3$-plane the fibers are aligned and have a specific fiber angle θ with respect to the x_1-axis. The fiber angle changes in each subsequent layer so that the fiber orientation varies in a spiral manner. The wavelength λ is defined as the x_2-distance within which the fiber angle θ changes by 360°. The crack drawn in Fig. 2 extends perpendicular to the layers in negative x_2-direction; this is the direction where crack growth requires the highest energy.

influenced at two levels, by the homogenized layer properties and by the fiber direction within the layers. Considering crack bridging and energy dissipation in the process zone ahead of the crack tip, it has been shown that toughness amplification can be achieved by decreasing the layer thickness [16]. In plywood structures, such as in lamellar bone, crack extension in the direction perpendicular to the collagen fibril layers, i.e. in x_2-direction in Fig. 1, requires up to two orders of magnitude more energy than in the direction parallel to a layer with constant fibril orientation [13]. Crack propagation has also been shown to be significantly hindered in the stomatopod dactyl club in the direction perpendicular to its chitin fiber layers [4].

Plywood structures have been investigated in modeling approaches proving that the mechanical properties of these structures are influenced by their stacking density at the mesoscale level, i.e. finer stacking density leads to larger deformability and hardness [17]. Other groups have looked into the response of plywood structures to high impact loads, e.g. the stomatopod dactyl club, showing that the dominant failure mechanism close to the impact zone is fiber compression, leading to buckling of the fibers, while it is matrix cracking further away from the impact zone [18]. In addition, analytical attempts have been made to describe the role of plywood structures in enhancing the toughness of the exoskeleton cuticle [19]. However, a theoretical understanding of the toughening mechanisms in plywood structures is still missing.

Such an understanding would be desired for two main reasons:

On the one hand, bone fragility is an unresolved medical dilemma [20,21]. Neither is it fully known what leads to the increasing brittleness of bone with age, nor is it clear why a certain arrangement of the brittle mineral particles and soft collagen fibers in lamellar bone leads to such superior mechanical properties, compared to that of the woven bone. Many toughening mechanisms, intrinsic or extrinsic [14], operate in bone and, in particular, interfaces such as cement lines play an important role [22,23]. Nevertheless, the plywood arrangement in lamellar bone is contributing very significantly [24] and needs better understanding.

On the other hand, there exists a strong motivation to design bioinspired tough materials for engineering applications, e.g. in civil or aerospace engineering, or for synthetic materials that replace human skeleton parts. Insight into new design concepts has been gained from investigations of natural tough materials, e.g. [25,26]. The classical example is the brick-and-mortar structure of nacre, which is orders of magnitude tougher than its main constituent, calcium carbonate [14]. This has led to the design of bioinspired tough materials, such as the nacre-like hybrid ceramic material by Munch and co-workers, which is 300 times tougher than its constituent materials, aluminum oxide and PMMA [27]. Another innovative design concept has been derived from investigations of skeletons or spicules of glass sponges [28,29], which consist of cylindrical bio-glass layers with thin, soft protein layers in between [30,31]. It has been demonstrated that the layered structure with spatially varying Young's modulus, in combination with a clever architectural arrangement of the layers, explains the high toughness and damage tolerance of the material [29,32]. This effect is interesting also for the twisted plywood structure, since the variation of the fiber orientation in x_2-direction certainly influences the layer stiffness in various directions, see Fig. 1.

We have shown previously that in materials with periodically varying properties, crack propagation is hindered efficiently due to a decrease in crack driving force in regions with low Young's modulus, e.g. the soft protein interlayers in the glass [28,32,33]. Lower crack driving force means that a higher applied load is required to achieve crack propagation, i.e. the fracture toughness increases. This positive effect of spatially varying material properties on fracture toughness has been denominated as "material inhomogeneity effect" [34–36]. It should be mentioned that a beneficial material inhomogeneity effect leading to an increase in fracture toughness also occurs, if in elastic-plastic materials the Young's modulus is constant, but the yield stress shows a periodic variation [35,37–39].

All these theoretical studies have assumed materials with Young's moduli (or yield stresses) that vary periodically, but are