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Short communication

Geometrically controlled tensile response of braided sutures

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ABSTRACT

Sutures are the materials used for wound closure that are caused by surgery or trauma. The main pre-requisite to the success of the suture is to obtain ultimate level of tensile properties with defined geometrical constraints. In this communication, the model for tensile properties of braided sutures has been proposed by elucidating the most important geometrical and material parameters. The model has accounted for the kinematical changes occurring in the braid and constituent strand geometries under defined level of strain. A comparison has been made between the theoretical and experimental results of stress–strain characteristics of braided sutures.

1. Introduction

Sutures are the materials used for closing the wounds by providing necessary assistance in ligating the blood vessels. The selection of sutures for a desired wound closure depends upon the material properties (size, type of material, design, behaviour) and characteristics of wounds (size, shape, amount of edema, etc.) [1]. Accordingly, the sutures have been classified as absorbable and non-absorbable materials based on the fact that the former undergo degradation and are being absorbed in the tissues [2]. However, the latter maintains their tensile properties without being affected by the biological activities of body tissues. In general, non-absorbable sutures are made up of synthetic or natural fibres/filaments in the form of monofilament, multi-filament, twisted or braided materials [3]. In the past, braided sutures have exhibited excellent tensile properties under in vitro and in vivo conditions [4]. Therefore, it becomes imperative to understand the geometrical and constituent material characteristics that control the tensile properties of braided sutures.

Braided sutures are narrow rope-like materials formed by three or more interlacing helical strands of filaments or yarns. The tensile characteristics of braided sutures can be studied by investigating the synergistic deformation of classical textile structures, i.e. twisted yarns and square woven fabrics [5]. Although braiding is a traditional textile process, the published work pertaining to the tensile response of braided structures is quite sparse and not complete. Therefore, in this communication, an attempt has been made to elucidate the most important geometrical and constituent material parameters for predicting the tensile properties of braided sutures consisting of monofilament strands. A comparison has also been made between the theoretical and experimental results of stress–strain characteristics of braided sutures.

2. Theoretical analysis

Braided sutures are narrow tubular structures consisting of filament strands moving in a helically undulated path. A diamond trellis of filament strands is being formed when tubular braided structures are slit along the braid axis, as shown in Fig. 1. It should be noted that there are two diamond trellises being formed in a typical regular braided suture (2/2 repeat), which are normally produced on circular braiding machine [6]. Here, braid angle (ξ) is a key geometrical parameter that influences the mechanical characteristics of braided sutures. Braid angle is defined as the angle formed between the braid and constituent strand axes. It is also the main parameter that distinguishes between woven and braided structures. Therefore, a typical braid consisting of circular monofilaments being sectioned in the direction of the braid axis, the shape of the strands is manifested as elliptical in cross-section, as illustrated in Fig. 1c. Moreover, the relationship between various geometrical parameters can easily be formulated by extending the classical work of Brunnschweiler [7]. Here, the undulating strand length repeat unit can be divided into two segments, i.e. straight and elliptical arc, as shown in Fig. 1c. Hence, the total length of the strand in the undulation repeat along the direction of strand axis in a typical regular braided suture (l) is given by,

$$l = p + l_s + l_t \tag{1}$$

where p is the distance between two consecutive strands in the direction of strand axis, and l_s and l_t are the lengths of straight and arc segments in an undulating strand repeat unit, respectively.

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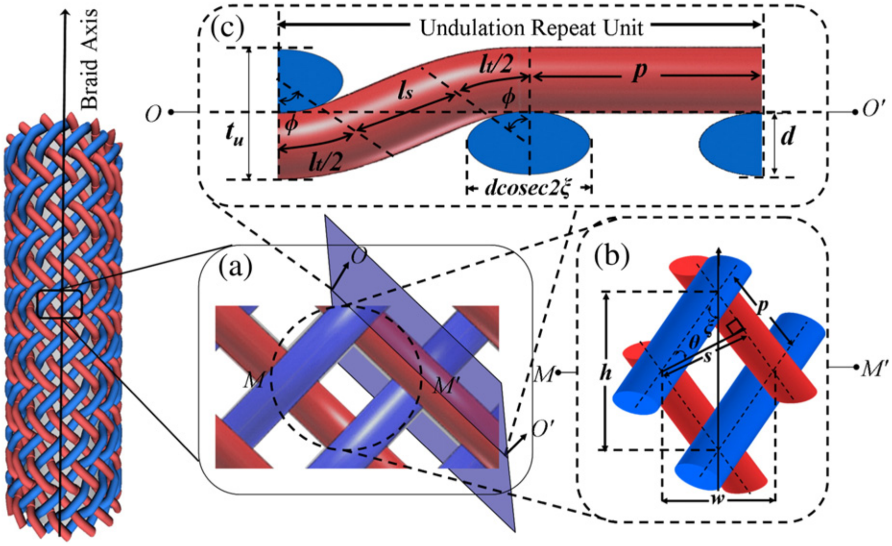

Fig. 1. Cartoon depicting regular braided suture in which magnified image of (a) unit cell, (b) diamond trellis and (c) cross-sectional view of undulation repeat unit is illustrated.

According to Brunnschweiler [7], the expressions of lengths of straight and arc segments are given below.

$$l_s = \sqrt{(s^2-3d^2)(\sin^2\phi + \operatorname{cosec}^2 2\xi \cos^2\phi)} \text{ and } \quad (2)$$
$$o \qquad l_t = 2d \cos ec2\xi E(\phi, m)$$

and

$$\phi = \tan^{-1}\left(\frac{s}{d}\right) - \cos^{-1}\left(\frac{2d}{\sqrt{s^2+d^2}}\right) \quad (3)$$

ξ is the braid angle, d is the strand diameter, ϕ is the crimp angle, $E(\phi, m)$ is an incomplete elliptical integral of second class, s is the projection of strand length normal to the direction of crossing strands (see Fig. 1b).

Introducing, the crimp of the undulated strand (c) which is defined as the excess of strand length between two successive cross-overpositions over the projected length. Mathematically,

$$c = \frac{l_s + l_t}{p} - 1 \text{ or } l_s + l_t = p(1+c) \quad (4)$$

In general, the braided sutures are porous materials and hence, the fibre volume fraction needs to be accounted whilst predicting their tensile properties. Fibre volume fraction is defined as the proportion of volume occupied by the strand of fibres to the total volume of the braid. Mathematically, the fibre volume fraction of the unit cell (v_f) in a typical regular braid (as shown in Fig. 1), is given by:

$$v_f = \frac{4kA}{(2w)t_u h} \quad (5)$$

where A is the cross-sectional area of the strand in the direction of the strand axis, h is the height of the unit cell, w is the width of the half unit cell or a single diamond trellis, t_u is the thickness of the unit cell (~$2d$) and k is the projection of total strand length in the undulation repeat normal to the direction of crossing strands.

Here,

$$k = s + s(1+c) \quad (6)$$

From Fig. 1,

$$A = \frac{\pi d^2}{4}\operatorname{cosec}2\xi,\ h = \frac{w}{\tan\xi},\ s = p\sin 2\xi,\ \theta = \pi/2 - 2\xi,\ p = \frac{w}{2\sin\xi}. \quad (7)$$

According to Potluri et al. [8], the width of a single diamond trellis (w) can be expressed as,

$$w = \frac{2\pi D}{N}. \quad (8)$$

where D is the braid diameter and N is the total number of constituent strands.

Combining Eqs. (5)–(8),

$$v_f = \frac{(2+c)Nd}{16D\cos\xi} \quad (9)$$

As mentioned earlier, the tensile mechanics of braided sutures can be investigated by synergistic deformation of classical textile structures, i.e. twisted strands and square woven fabrics. Neglecting the transverse forces between the constituent strands, the braid stress (σ_b) can be computed analogous to the calculation of stresses using well-known "fibre obliquity" effect, normally employed in yarn mechanics [9]. Therefore,

$$\sigma_b = v_f \sigma_f \cos^2\xi \quad (10)$$

where σ_f is the strand stress.

Combining Eqs. (9) and (10) would yield the following expression,

$$\sigma_b = \frac{(2+c)Nd\sigma_f\cos\xi}{16D} \quad (11)$$

In general, it is also well-known that the following constitutive model holds for strand in tension.

$$\sigma_f = f(\varepsilon_f) \quad (12)$$

where σ_f and ε_f are the strand stress and strain, respectively.

Under uniaxial tensile loading conditions, the braided sutures exhibit geometric transition, i.e. occurrence of strand reorientation and the diamond trellis formed by the strand tends to "scissor" with the increase