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Mechanical characterisation of Dacron graft: Experiments and numerical simulation

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ABSTRACT

Experimental and numerical analyses focused on the mechanical characterisation of a woven Dacron vascular graft are presented. To that end, uniaxial tensile tests under different orientations have been performed to study the anisotropic behaviour of the material. These tests have been used to adjust the parameters of a hyperelastic anisotropic constitutive model which is applied to predict through numerical simulation the mechanical response of this material in the ring tensile test. The obtained results show that the model used is capable of representing adequately the nonlinear elastic region and, in particular, it captures the progressive increase of the rigidity and the anisotropy due to the stretching of the Dacron. The importance of this research lies in the possibility of predicting the graft's mechanical response under generalized loading such as those that occur under physiological conditions after surgical procedures.

1. Introduction

The aorta is the central artery of the cardiovascular system in charge of dampening the pulsating pressure coming from the left ventricle of the heart. Among the different diseases that can affect it, we find ascending aortic aneurysms which consist in focalized dilations of the arterial wall. For that reason, the pathological tissue must be replaced by a vascular prosthesis, generally artificial, the first implants being reported in 1958 by DeBakey and Cooley with Dacron grafts.

Repairing the damaged tissue involves replacement with a Dacron graft (De Paulis et al., 2008). Over the years, Dacron has been used as a substitute in the ascending aorta region because of its good post-operative performance and ease of insertion during the replacement surgery. The prostheses consist of a cylindrical structure made of orthogonally oriented polyethylene terephthalate (PET) fibres that have great resistance and rigidity, in addition to biocompatibility with the medium. Research has shown that differences between the mechanical properties of the graft and the native tissue generate adverse effects on the functioning of the cardiovascular cycle, altering the pressure wave due to the different distensibility in the anastomosis (Berger and Sauvage, 1981; AbuRahman and DeLuca, 1995; Zilla and Bezuidenhout, 2007) but, to date, the real stress state that is generated in the aortic arch is unknown.

In the literature, there is a limited number of papers related to the mechanical characterisation of Dacron. Hasegawa and Azuma (1979) and Lee and Wilson (1986) carried out *in-vitro* tensile and relaxation tests on *woven* and *knitted* Dacron grafts for circumferential and longitudinal specimens. Their results show differences depending on orientation, showing a clear anisotropic response according to the direction of the fibres, attributing it mainly to the fabric's configuration and the corrugation present in the prosthesis. More recent studies like that of Tremblay et al. (2009) indicate, from biaxial tests, that grafts of this kind have considerable differences, reaching 24 times greater rigidity than that of human aorta. Yet none of the work that has been done has proposed a realistic constitutive model considering the directions of the material's fibres and their nonlinear response. However, in papers like those by Vardoulis et al. (2011) and Hajjaji et al. (2012), on the basis of assumptions of isotropic linear elasticity, comparisons with respect to the geometric configuration and the influence on hemodynamics in numerical models have been respectively established considering a Dacron graft.

The objective of the present paper is to characterise and model the mechanical response of Dacron. The methodology of this study includes the following stages: (1) Realisation of uniaxial tensile tests under different orientations in order to assess the anisotropic effects due to the material composition, (2) proposal of a hyperelastic anisotropic constitutive model, (3) adjustment of the parameters of the constitutive model by numerical simulation of

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the uniaxial tensile tests, (4) realisation of ring tensile tests, (5) validation of the model by comparing the experimental and numerical values of the ring tensile test. The materials and methods considered are presented in Section 2, where Section 2.1 includes the experimental procedure and Section 2.2 summarises the proposed constitutive model that describes the material's anisotropic response. The experimental and numerical results are given in Section 3. Specifically, the adjustment of the model's parameters by means of the uniaxial tensile tests is detailed in Section 3.1. Moreover, Section 3.2 presents the measured and computed results for the ring tensile test. Finally, the experimental and numerical results are discussed in Section 4 where a satisfactory validation of the model with respect to the experimental data, as well as the complex tensional state generated by the stress to which it is subjected, is achieved in both tests.

2. Materials and methods

2.1. Experimental procedure

2.1.1. Material

The material used for all the tests was a Boston Scientific *Hemashield Platinum woven* Dacron prosthesis. It has a straight corrugated tubular configuration formed with fibres (PET) covered with a double layer impregnated with bovine collagen (matrix); see Fig. 1. The black longitudinal line observed at the bottom of the prosthesis serves to align the graft during the surgery.

Specimens for the uniaxial and ring tensile tests were obtained from it. Fig. 2 shows the configuration of the corrugation folds, which were obtained digitally using an optical microscope.

2.1.2. Uniaxial tensile test

The purpose of this test is to get the relation between the force and the stretching of the material subjected to a uniaxial load, which makes it possible to determine the mechanical properties and the rupture limits. The anisotropic degree of the material can also be determined by testing specimens in different orientations.

Since the material is composed of various filaments, the results will be considered until the first drop of the load registered in the test which represents an evident rupture of some of the threads that make up the prosthesis.

The tested specimens were cut mechanically with a die in two directions following the weave of the prosthesis, defining the circumferential (90°) and longitudinal (0°) directions with respect to its axis, and some specimens were also cut at 45° (bias direction). It should be noted that the corrugated structure was conserved during the extraction, allowing the evaluation of its influence on the mechanical response.

Fig. 3 shows the sizes of the test specimens obtained. The sizes of the test pieces at 45° were cut with a rectangular scalpel (16 × 6 mm) keeping the corrugated structure.

The tests were performed immersed in water conditioned at a temperature of 37 ± 1 °C in an acrylic cell. All the tests were performed at a constant loading cell speed of 0.03 mm/s to preclude viscous effects. Before each test, the specimens were subjected to loading–unloading conditioning cycles up to a force equal to 5% of the maximum load. The specimens were then tested to rupture, recording the displacement between the jaws and the axial force directly from the testing machine with precisions of ± 1 μm and ± 0.01 N, respectively. In this context the axial stretch is defined as $\lambda = l/l_0$ with l and l_0 being the instantaneous sample axial lengths.

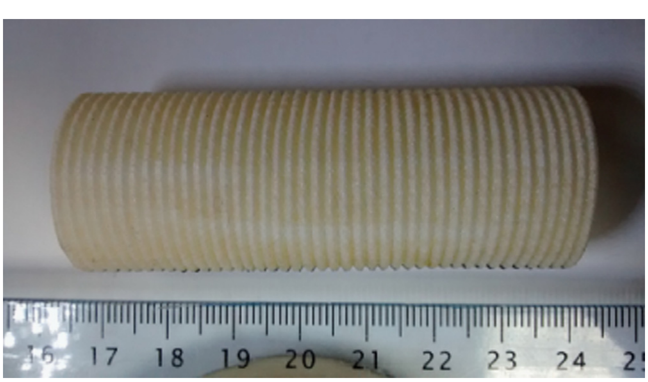

Fig. 1. General view of the analysed Dacron prosthesis.

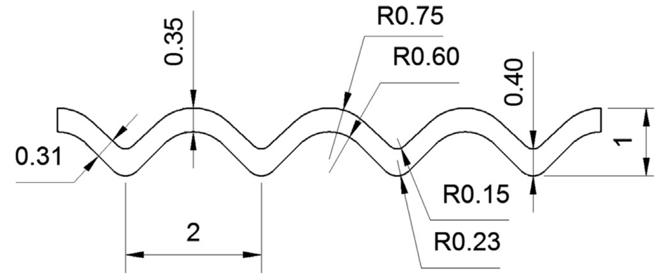

Fig. 2. Detail of the corrugation of the tested Dacron prosthesis (sizes in mm).

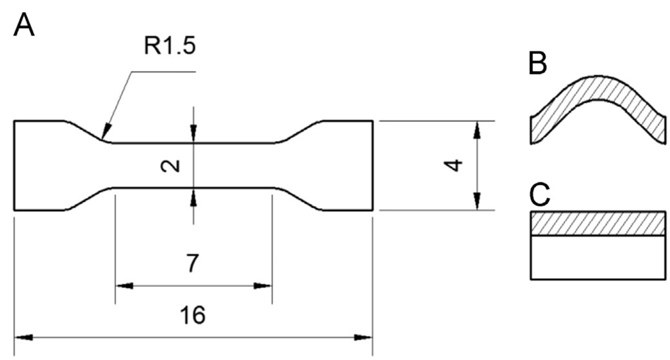

Fig. 3. Sample used in the tensile test. The sizes of the test specimens in mm are depicted in (A)–(C) that show the cross sections of the circumferential and longitudinal orientations.

Because of the low rigidity of the specimens at the beginning of the test, it is not apparent to determine the initial length of each sample with the axial load at the instant at which its rate changes significantly, particularly in the test specimens oriented in the longitudinal and bias directions. For this reason, a digital camera was set up configured at 10 images per second to record the displacement between two points separated by a known distance (defined as $l_0 = 4$ mm in this study). Therefore, the beginning of the test is set at the time at which the separation between the points and the reference length become equal.

2.1.3. Ring tensile test

As in the previous test, the ring tensile test allows the evaluation of the mechanical properties, specifically for the overall behaviour of the material. The test consists in applying tension through two pins inserted in a ring-shaped test specimen under the hypothesis that the initial bending is negligible and there is no friction between the specimen and the pins.

Several rings were cut with a scalpel following the direction of the circumferential fibres between the folds. Each specimen was approximately 4 mm thick, corresponding to two folds of the corrugated structure (see Fig. 2).

The temperature control system used in this test was the same as that of the uniaxial tensile test. Special jaws were used to tension the ring specimens. First, the jaws were set up in the testing machine by means of a ball joint attached to a 500 N loading cell. The initial distance between the jaw pins was adjusted to 17 mm. Then, the ring specimen was introduced between the pins and the assembly was finished with the filling of the test cell.

Before each test, three loading–unloading cycles to 5% of the maximum rupture load were carried out. Then the test was performed at a loading cell speed of 0.03 mm/s, recording continually the force and the displacement.

2.2. Constitutive modelling

The constitutive model analyzed in this work, which is an extension of that proposed by Planas et al. (2007), considers a deformable matrix reinforced by a dispersion of fibres. This model proposes a macroscopic approximation equivalent to the microscopic description of the reinforcing fibres, obtained by equating the mechanical deformation work of the fibres with the work of the effective continuum medium per unit volume in the reference configuration. Thus, the Second *Piola–Kirchhoff* stress tensor of the fibres $\boldsymbol{S}_{fibres}$ is

$$\boldsymbol{S}_{fibres} = \sum_{\Theta=1}^{m} \frac{f_f^{\Theta} s_f^{\Theta}}{\lambda_f^{\Theta}} (\boldsymbol{N}_{\Theta} \otimes \boldsymbol{N}_{\Theta}) \tag{1}$$

where f_f^{Θ} is the volume fraction of the different m families of the fibres Θ, so that

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