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Characterization of failure in human aortic tissue using digital image correlation

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1 Introduction

An aortic aneurysm is a localized dilation of the aorta in a weakened area [1, 2]. The increase of aneurysm size may result in rupture, which will be a life threatening emergency. The mechanism of failure in aneurysms is now relatively well understood. However, only limited research has provided quantitative values for the stresses that cause the failure of pathologic arterial tissue. The evaluation of the local failure stress remains an open problem. In this study we apply digital image correlation (DIC) to excised pieces of tissue that we test in a bulge inflation test. The tissue is taken from the ascending aorta in diseased patients requiring an excision for removing an aneurysm. All procedures are carried out in accordance with the guidelines of the Institutional Review Board of the University Hospital of Saint-Etienne, France.

2 Methods

2.1. Testing device

To identify the constitutive parameters and the stress at failure, an inflation test is performed as shown in Figure 1, providing a biaxial loading. The specimens considered here are taken from the ascending aorta of diseased patients having an aneurysm. Square flat specimens are cut from the cylindrical excised aorta to fit in the inflation test device. Then the specimen is separated into media (including intima) and adventitia layers. Each layer is tested separately. Pressure is applied to inflate the specimen up to failure.

2.2. Measurement technique

The in-plane and out-of-plane displacements of the inflated specimen are measured using the Aramis software (www.gom.com). The full-field measurement technique applied here with the

Aramis software is the stereo digital image correlation (S-DIC) [3]. It consists in observing the grey speckle pattern at the surface of the tested specimen by two cameras with incidence angles, allowing measurement of 3D coordinates of each subset during deformation. It is assumed that the deformation of the speckle pattern is the same as the deformation of the specimen throughout its whole thickness.

The deformation gradient is obtained from the undeformed and deformed coordinates of each data point according to the theory of finite deformation, assuming a plane stress state and constant thickness [4].

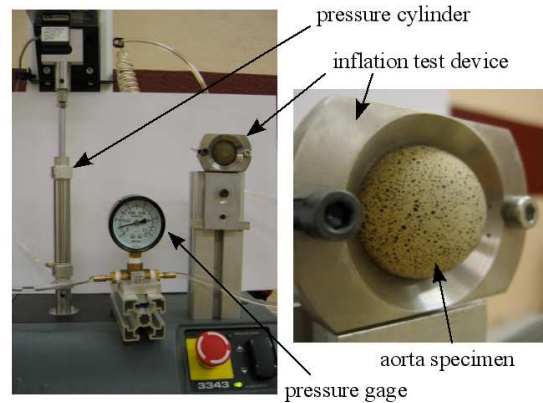


Figure 1 Views of the inflation test set-up

2.3. Identification approach

Then the Green-Lagrange strain tensor is derived from the deformation gradient. An anisotropic hyperelastic constitutive model proposed by Holzapfel [5] is adopted for the strain energy function as in equation 1.

$$W = \frac{c}{2}(\bar{I}_1 - 1) + \frac{k_1}{2k_2} \sum_{i=4,6} \left[e^{k_2(\bar{I}_i - 1)^2} - 1 \right] \quad (1)$$

where c and k_1 are stress-like material parameters, k_2 a dimensionless parameter, I_1 the first invariant of the right Cauchy-Green tensor, and I_4 and I_6 are the squares of the stretches in the direction of the two families of collagen fibres, depending on a mean orientation angle denoted α . The virtual fields method (VFM) [6] is used as an inverse procedure for the identification of the constitutive parameters. The Cauchy stress tensor is deduced from the strain energy function and the Green-Lagrange strain tensor. Then the difference between the internal and external virtual works is minimized for the identification [7]. Once the constitutive parameters are identified, the Cauchy stress components at failure can be calculated, in the circumferential direction of the artery, denoted σ_{xx}^R , and in the axial direction, denoted σ_{yy}^R . Eventually, the following stress value is deduced:

$$\sigma_{\alpha}^R = \sigma_{xx}^R \sin^2(\alpha) + \sigma_{yy}^R \cos^2(\alpha) \quad (2)$$

3 Results and Discussion

| sample | 1 (adventitia) | 2 (media) | 3 (media) | 4 (media) |
|---------------------------|-------------------|--------------|--------------|--------------|
| Patient sex and age | Male 81 | Male 81 | Male 69 | Male 68 |
| c (kPa) | 0 | 0 | 0 | 0 |
| k_1 (kPa) | 285 | 133 | 307 | 174 |
| k_2 | 6770 | 1963 | 9883 | 5118 |
| α | 58° | 40° | 24° | 37° |
| σ_{xx}^R (kPa) | 418 | 417 | 1152 | 556 |
| σ_{yy}^R (kPa) | 1143 | 339 | 216 | 327 |
| σ_{α}^R (kPa) | 625 | 371 | 368 | 410 |

Table 1. Material properties obtained on 4 samples.

Five samples were obtained from the University Hospital of Saint-Etienne, France. They have been tested with the methodology described previously. Due to different experimental reasons (leakage, poor speckle patterns), only 4 experiments could be analyzed completely. It is worth noting that the existence of thick, stiff and fragile intima layer in some aneurysms may cause intima delamination before rupture, preventing the identification of material properties. Those specimens have to be discarded in our procedure.

The currently available results are presented in Table 1.

4 Discussion and conclusion

Thanks to the novel methodology presented in this paper, the material properties of human aneurismal tissue are identified and the stress at failure is deduced. The obtained values represent important data for the community of vascular biomechanics. They confirm that the aneurism behavior is generally anisotropic. The anisotropy is characterized by parameter α . Stresses tend to be preferably larger in the circumferential direction for $\alpha < 45^\circ$ which is typical of a media layer, and preferably larger in the axial direction for $\alpha > 45^\circ$,

which is typical of an adventitia layer [5]. Parameter σ_{α}^R is found fairly stable for the media, with an average value of 383 kPa. The importance of this parameter, quantifying the stress in the direction normal to both families of collagen fibres, is confirmed by the observed modes of rupture (Figure 2), which are characterized by oblique tears.

A larger number of tests will now be carried out to confirm the preliminarily observed trends and analyze statistically the inter-individual variations of materials properties. This will also permit to evaluate the validity and effects of different assumptions made in this study, such as the constant thickness, plane stress etc... The methodology also relies on the assumption that the whole experimental procedure does not affect the mechanical properties of the tissue. This fundamental aspect will be investigated further in the near future.

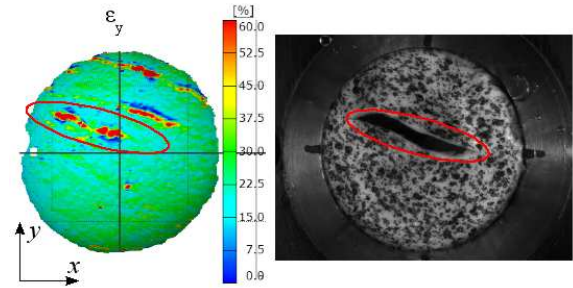


Figure 2. Example of a measured strain field and image of the specimen at rupture (sample 2)

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