Extracting the orthotropic stiffness components of bone using DIC and the Virtual Fields Method

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Introduction

Hip fracture is the most common serious injury in older people in the UK and is associated with a total cost to health and social services of over £1 billion per year [1]. Many researchers are working on the development of Finite Element (FE) models to assess bone strength, surgical treatments' outcomes and fracture risk in individuals. Despite the fact that bone is a complex material with heterogeneous and anisotropic mechanical properties, most of the existing models rely on extensometer measurements and a series of assumptions which cannot fully describe bone's mechanical behavior [2]. Recent advances in image-based displacement measurements, such as digital image correlation (DIC), have led to new methods of testing materials which allow for the use of heterogeneous stress states.

The aim of this work is to provide a new method which will allow for the identification of all orthotropic stiffness components of cortical bone in a single test. Digital image correlation (DIC) and inverse identification (Virtual Fields Method, VFM) are used. The current work consists of a computational approach where several experimental configurations are designed and analyzed using image deformation simulations. Synthetic image deformation is used to estimate identification errors.

Experimental Design

Testing of cortical bone provides unique constraints on the specimen geometry because it is not possible to cut the sample at an angle to the long axis of the bone. Different experimental configurations which satisfy these geometric constraints were simulated and analyzed. Each configuration was first tested with FE modelling and then with synthetic image deformation simulations. The configurations were compared in terms of their total error. Thirty copies of random noise were analysed with the systematic error (Err_{sys}) taken as the difference between the mean identified stiffness and the reference stiffness from the FE model. The random error (Err_{rand}) was taken as the standard deviation of the identified stiffness over the thirty copies of noise. Finally, the total error was taken as $Err_{tot} = |Err_{sys}| + 2Err_{rand}$.

The configuration with the minimum total error was a deep notch sample loaded at an angle, as shown in Fig. 1. The strain fields which were obtained from the image deformation are also shown in Fig. 1 [3]. A summary of the selected DIC parameters is presented in Table 1. The calculated total error for all stiffness parameters as well as for their summation is shown in the box plot in Fig. 2. As seen in the figure, the off-axis loading activated the shear stress significantly, leading to a minimum total error of the Q_{66} parameter. The Q_{22} parameter was the most difficult parameter to identify, since the stress in the x_2 direction was less activated. It should be noted that both the systematic and the total error for each of the Q parameters was less than 1%. The total error of the summation of the errors of the four parameters was 1.8%.

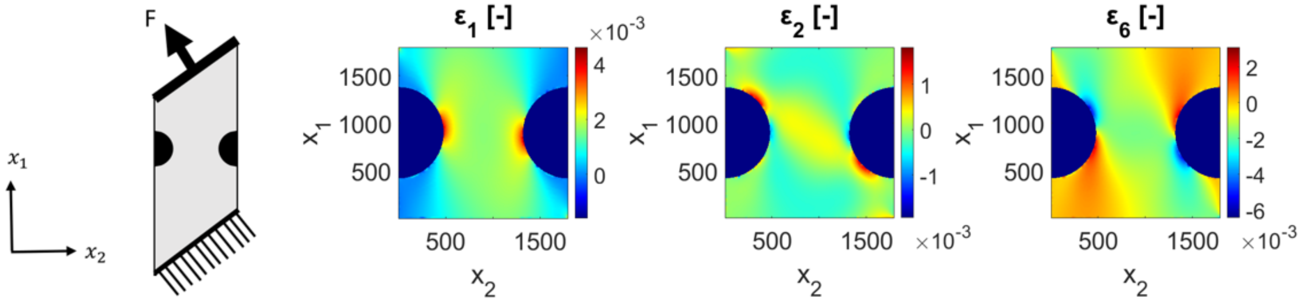

Figure 1 Experimental configuration and strain fields.

Table 1 Summary of DIC parameters for image deformation

Technique Used	2D Digital Image Correlation	**Correlation Criterion**	Zero-Normalized Sum of Squared Differences (ZNSSD)
Camera resolution	16bit, 3600×3600 pixels	**Prefiltering**	Gaussian (Kernel size = 5)
Pixel to mm conversion	0.00418	**Strain**	
Average speckle size	5.6 pixels	**Strain Window**	41 data points
Subset Size	31 pixels	**Virtual Strain Gauge (VSG)**	110 pixels
Step Size	2 pixels	**Strain Interpolation Function**	Bilinear Quadrilateral (Q4)
Shape Function	Quadratic	**Strain Tensor**	Hencky
Interpolation Function	Bicubic Spline Interpolation	**Virtual Mesh Size**	6×6

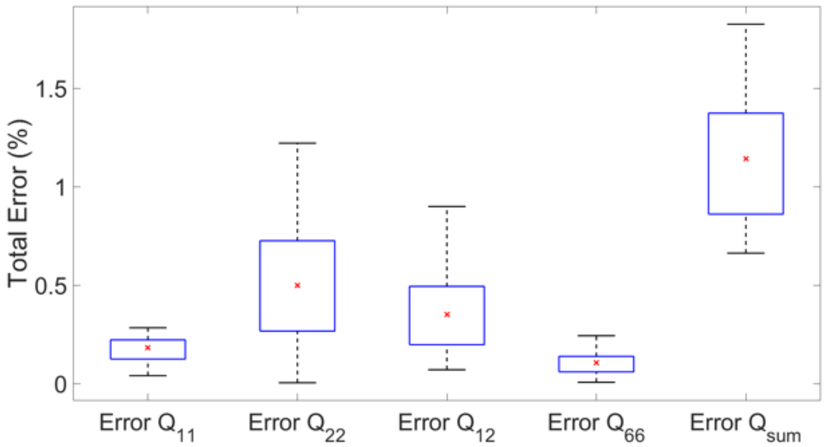

Figure 2 Total error (%) for a deep notch sample loaded at an angle. The mean value of each error is shown with a red 'x'. The edges of the box are the 25th and 75th percentiles. The minimum and maximum recorded values are shown with dashed lines.

Conclusion and Future Work

This work develops a new test configuration for the identification of the four orthotropic stiffness components of bone in a single test. First, the strain fields are obtained with image deformation techniques and then they are used as an input for the VFM in order to extract the material orthotropic parameters. An experimental design is also performed in order to find the optimal test for the identification of bone, in terms of systematic, random and total error. It is shown that a deep notch sample loaded at an angle can activate all stiffness components, leading to a minimum total error. In the future, the described configuration is going to be tested experimentally and the orthotropic stiffness parameters of bone will be identified.

References

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