NON-LINEAR ELASTIC TESTING AND FINITE ELEMENT MODELLING OF RIGID POLYURETHANE FOAM

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Introduction

Rigid polyurethane (PU) foam is an industry standard bone surrogate as it mimics the mechanical behaviour of cancellous bone. Medical implant industries commonly use PU foam for implant evaluation which includes physical testing and virtual modelling or Finite Element Analysis (FEA); therefore, it is of interest to understand the mechanical behaviour of PU foam to accurately analyse the interaction between implants and PU foam [1]. PU foam exhibits non-linear elastic and viscoelastic characteristics, which are assessed based on applied strain rates. A quasi-static strain rate is a slow rate of strain that allows the assessment of PU foam in approximately static conditions; this is required for observing the non-linear elastic response. A high strain rate would result in a response that combines non-linear elastic and viscoelastic traits. Compression testing is the most common type of test for analysing of the mechanical behaviour of PU foam [2].

The goal of this study was to verify the stress-strain response of FEA models against mechanical tests for 20 pounds per cubic foot (PCF) PU foam under quasi-static compression loading.

Methods

The study incorporated both quasi-static compression testing on 20 PCF PU foam samples (SKU 1522-03, Sawbones, Pacific Research Laboratories Inc, WA, USA) and FEA replicating the experiment. The tests (Figure 1) were performed in accordance with ASTM D1621 [3]. The height and diameter of the cylindrical samples were 4 mm and 8 mm, respectively. The specimen aspect ratio met standard specifications; however, the dimensions were reduced to meet load capacity of the test apparatus (Bionix Servohydraulic Test System). The test protocol was a displacement ramp of 0.08 mm/s (quasi-static strain rate of 0.025 s^{-1}) until the sample was compressed to 20% of the initial height. The analyses were executed with the implicit (static) and explicit (dynamic) FEA solvers (ABAQUS 2017, Simulia, Providence, RI). The models were consistent with the test setup (Figure 1); PU foam was modelled as a solid cylinder, and compression plates were rigid with a coefficient of friction was 0.01. Nominal test stress-strain relations were imported into ABAQUS for material property calibration using hyperelastic Ogden model (N=3) and Hyperfoam (N=3).

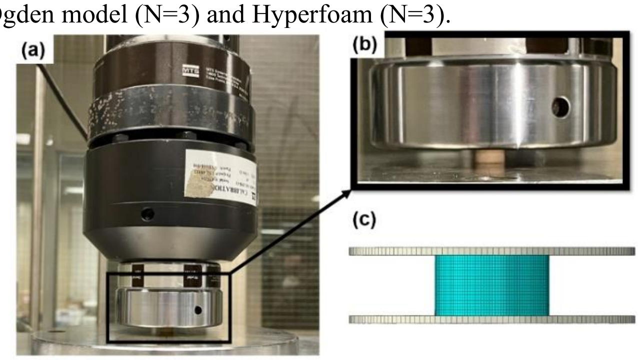

Figure 1: PU foam compression test setup and FEA model. (a) Test Setup (b) Close-up view (c) FEA model and compression plates; the bottom plate was constrained in vertical direction; displacement (Static FEA) or velocity (Dynamic FEA) was applied on the top plate

Results and Discussion

The stress-strain relationship for the nominal test, material model fit (Ogden N=3), and FEA results were plotted (Figure 2).

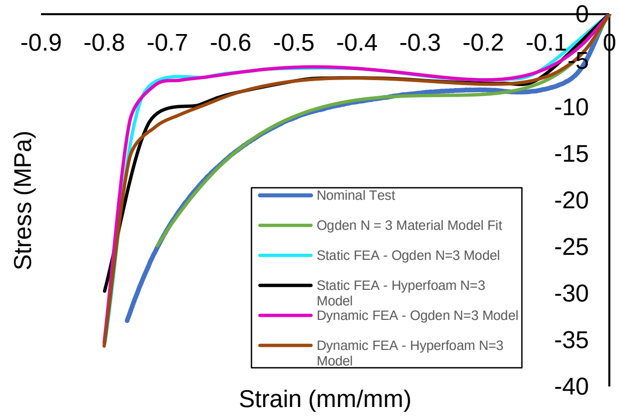

Figure 2: PU foam (20 PCF) stress-strain relations for Nominal Test, Ogden N = 3 Model, and FEA Static/Dynamic/Ogden/Hyperfoam

The ABAQUS Ogden material model fit the test well in the plateau and densification phases. The linear-elastic phase of the nominal test was stiffer (larger stress/strain ratio) than the Ogden model. As a result, the static and dynamic FEA stress-strain relations with Ogden material models followed a similar trend with lower stiffness. All FEA results showed an extended plateau phase where strain continued to increase as stress remained constant. The maximum stress predicted by all FEAs were similar to the test stress and in the range of 30 MPa and 35 MPa. The maximum strain predicted from FEA and test were 0.8 and 0.76 mm/mm, respectively. The test provided some verification of the FEA non-linear elastic response of PU foam. The differences in the plateau and the linear-elastic phases can be attributed to the material models. The Ogden model was developed for rubbers which exhibit different mechanical behaviour than rigid PU foams. To improve the results, a custom material model can be implemented with subroutine UMAT in ABAQUS.

Significance

PU foam is an industry standard in orthopaedics; therefore, modelling the mechanical behaviour in an accurate and efficient manner is of importance. The hyperelastic Ogden and Hyperfoam material models provide simple and efficient methods in modelling the non-linear elastic response in FEA. The models also provide close approximations of stress-strain relations, but still require refining to obtain better accuracy.

Acknowledgments

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References

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