User Manual: Computational Material Model of Polyurethane Bone Foam

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USER MANUAL: Computational Material Model of Polyurethane Bone Foam

General Information

A calibrated and validated material model of polyurethane (PU) bone foam was developed for use in finite element modeling simulations. The model incorporated transversely isotropic elasticity, isotropic crushable foam plasticity, and ductile damage initiation and evolution to replicate the foam's elastoplastic and failure behavior. Calibration was performed using simulations of shear, compression, bone screw pullout, and intervertebral body fusion device subsidence experiments. Validation results showed agreement when compared to experimental mean values. The findings of this study represent a first step toward establishing computational models to accelerate development of new medical devices.

Material Model Specifications for Proper Implementation

To ensure proper implementation of this material model, the chosen finite element analysis (FEA) software package should be capable of solving dynamic problems (explicit formulation), and capable of implementing transversely isotropic elasticity, ductile damage initiation, ductile damage evolution, a crushable foam plasticity model, and a crushable foam hardening model.

Once the appropriate FEA software package is chosen the parameters shared in Table 1 below can be imported to fully describe a computational material model of polyurethane bone foam with a density of 20 pounds per cubic foot (PCF).

Model Validation Results

The final material model as described by parameters listed in Table 1 was validated by simulating test standards described in ASTM F543 (bone screw pullout) and ASTM F2267 (intervertebral body fusion device subsidence) [Figures 1, 2, & 3]. These simulations used mock bone screw and intervertebral body fusion device designs.

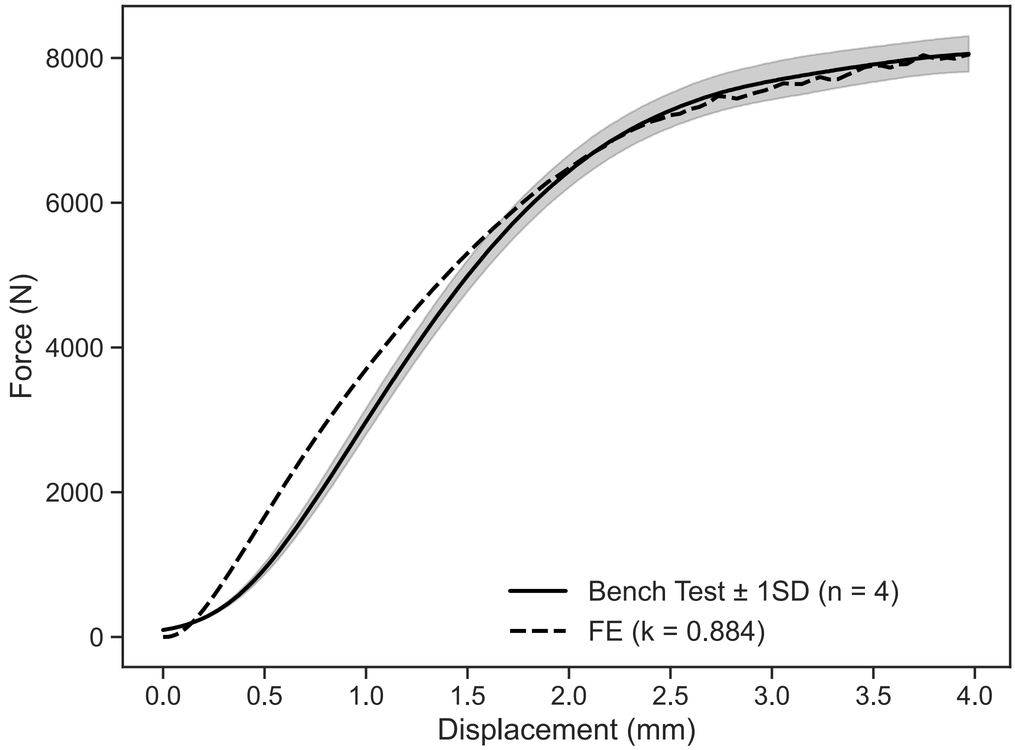

Figure 1 - Experimental force-displacement data and corresponding FE simulation results for 4-hole intervertebral body fusion device subsidence.

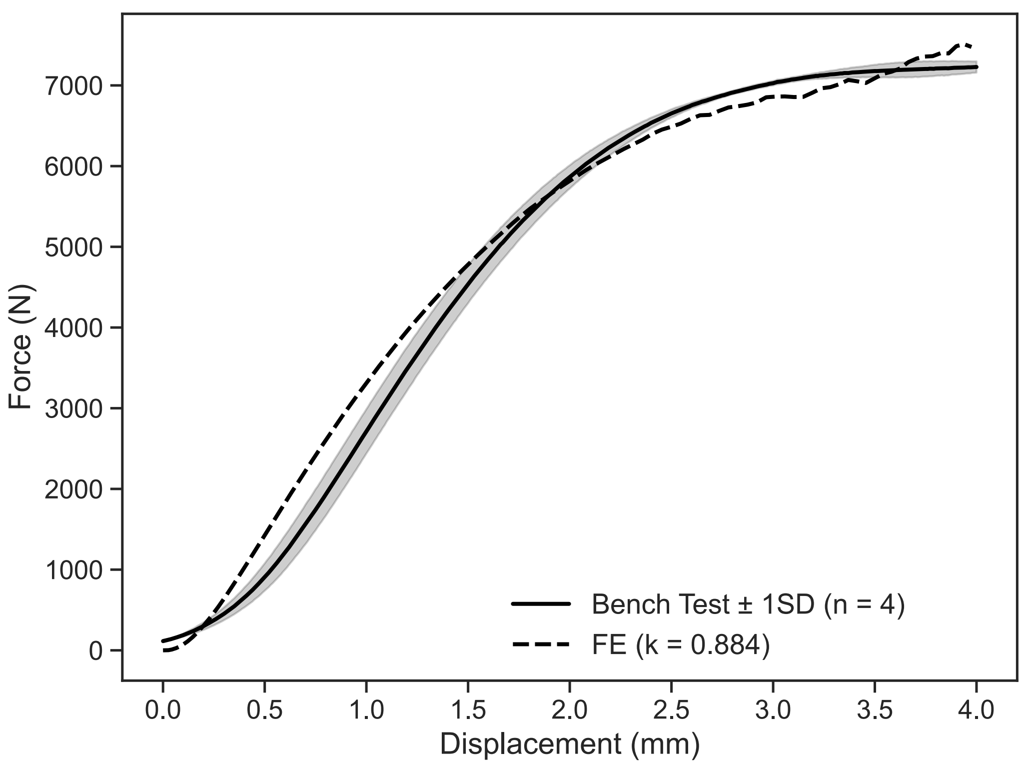

Figure 2 - Experimental force-displacement data and corresponding FE simulation results for solid intervertebral body fusion device subsidence.

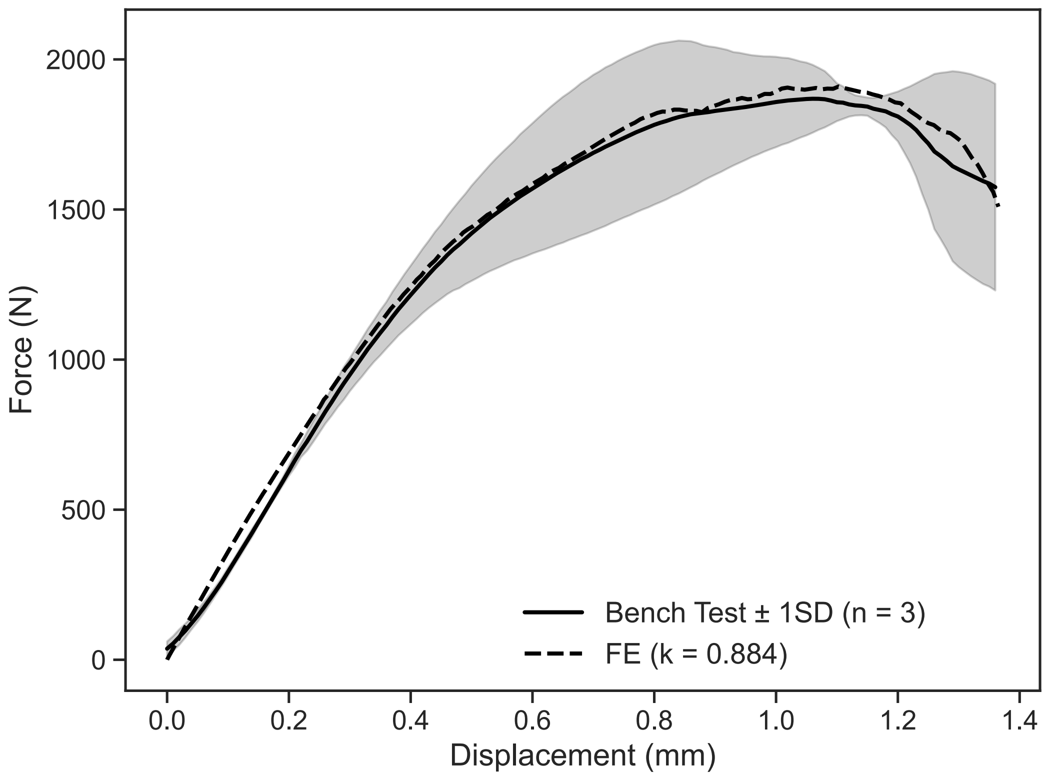

Figure 3 - Experimental force-displacement data and corresponding FE simulation results for bone screw pullout.

Table 1 - Material Properties for 20 PCF PU Foam (SKU: 1522-03, Sawbones, Inc.), including transversely isotropic elasticity, crushable foam plasticity, and ductile damage initiation and evolution.

Transversely Isotropic Elasticity	
$E_{\parallel}$ (MPa)	$E_{\perp}$(MPa)
176.53	159.58
ϑ	G (MPa)
0.34 [1]	39.56

Crushable Foam Plasticity	
k (3 cases)	ϑ_p
0.884/1.087/1.368	0.36 [2]

Crushable Foam Hardening	
Plastic Strain	Yield Stress (MPa)
0	5.64
0.001	5.97
0.002	6.27
0.004	6.53
0.006	6.77
0.008	6.97
0.010	7.14
0.012	7.30
0.014	7.44
0.017	7.55
0.019	7.66
0.022	7.75
0.024	7.83
0.027	7.90
0.030	7.96
0.033	8.01
0.036	8.06
0.039	8.10
0.042	8.14
0.045	8.17
0.048	8.20
0.051	8.22
0.054	8.24
0.058	8.26

Ductile Damage Initiation	
Equivalent Plastic Strain	Stress Triaxiality
1.9	-0.33
1.9	-0.01
0.2	0
0.03	0.33
0.15	0.5
0.5	0.9

Ductile Damage Evolution	
D	u(mm)
0	0
0.046	0.0005
0.096	0.0010
0.145	0.0015
0.192	0.0020
0.237	0.0025
0.282	0.0030
0.325	0.0035
0.367	0.0040
0.407	0.0045
0.447	0.0050
0.486	0.0055
0.523	0.0060
0.560	0.0065
0.596	0.0070
0.631	0.0075
0.665	0.0080
0.698	0.0085
0.730	0.0090
0.761	0.0095
0.792	0.0100
0.822	0.0105
0.852	0.0110
0.880	0.0115
0.908	0.0120
0.936	0.0125
0.963	0.0130
0.989	0.0135
0.994	0.0136
0.999	0.0137
1	0.0138

Notes: $E_{\parallel}$: Young's modulus parallel to the foam rise direction, $E_{\perp}$: Young's modulus perpendicular to the foam rise direction, ϑ: Poisson's ratio, G: Shear modulus, k: compression yield stress ratio, ϑ_p: plastic Poisson's ratio, D: damage parameter for element stiffness reduction, u: plastic displacement.

[1] H. Jin, W.-Y. Lu, S. Scheffel, T.D. Hinnerichs, M.K. Neilsen, Full-field characterization of mechanical behavior of polyurethane foams, International Journal of Solids and Structures 44(21) (2007) 6930-6944.

[2] N. Kelly, J.P. McGarry, Experimental and numerical characterisation of the elasto-plastic properties of bovine trabecular bone and a trabecular bone analogue, Journal of the mechanical behavior of biomedical materials 9 (2012) 184-197