ARTIFACTUAL NONLINEARITY DUE TO WEAR GROOVES AND FRICTION IN FOUR-POINT BENDING EXPERIMENTS OF CORTICAL BONE

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Abstract—Experiments and analyses were performed to determine the cause of a nonlinear force-deflection response observed in four-point flexural fatigue of beams of cortical bone machined from the mid-diaphysis of the equine third metacarpus. Observable grooves which formed on the beam surface at supports and load noses were found to be the primary cause of the nonlinearity. An additional geometric nonlinearity at large deflections revealed by finite element modeling may be minimized by using the smallest diameter supports and load noses recommended in ASTM 790. However, frictional constraint of the beams at the load noses and supports can occur at low load levels and should be avoided by using roller-bearing supports and load noses, or some equivalent method.

INTRODUCTION

Fatigue injuries such as stress fractures in military recruits, athletes, and thoroughbred racehorses are a common occurrence. To understand the mechanisms which cause these injuries, bone is subjected to experimentation under conditions similar to those experienced in vivo. Because bone is a complex material subjected to multimodal loading states, a firm base of reliable experimental material properties data obtained under simplified loading modes such as tension, compression, bending, and torsion is needed. This facilitates the development of reliable predictive models of whole bone behavior.

In one such study of the flexural fatigue response of cortical bone taken from the equine third metacarpus (cannon bone), 24 beams (10 × 4 × 100 mm) were machined in conformity with ASTM 790 for flexural testing (Gibson et al., 1995). These bone beams were cyclically loaded in four-point bending to a maximum flexural strain of 10,000 microstrain (με) at 2 Hz while immersed in a physiologic saline solution at 37°C. The supports and load noses (ASTM D790) were 9.5 mm diameter stainless steel cylinders, with support and load nose spacings of 64 and 32 mm, respectively. A tangent (elastic) modulus was defined as the slope of the stress-strain curve in the linear region. A secant modulus was defined as the stress range divided by the strain range for one load cycle.

Early flexural fatigue tests produced unexpected results. While the tangent modulus tended to decrease with the number of cycles, as expected, the secant modulus began to increase near the end of the fatigue life, especially in specimens taken from the dorsal regions of the cannon bone (Gibson et al., 1995). The secant modulus increase was associated with the development of a nonlinear force-deflection curve. While nonlinear stiffening of cortical bone in bending had not been reported in the literature, a recent study indicated that previously reported nonlinear behavior of trabecular bone was an artifact caused by crushing and frictional effects at the loading platens. It was observed that grooves approximately 0.75 mm in depth formed on the surface of the beam under the supports and load noses (Fig. 1) of many specimens, including those that exhibited the increasing secant modulus, during the conduct of fatigue experiments (Gibson et al., 1995). A review of the literature revealed a note in ASTM D790-86 on flexural tests indicating that crushing of the material at the load noses and beam supports may produce an artificial "toe" in the force-deflection curve (ASTM, 1992). Therefore, the grooves were hypothesized to be the primary cause of the nonlinearity. Experiments and analyses were conducted to determine: (i) if crushing, rather than friction and wear, could produce grooves similar to those observed in the fatigue experiments; (ii) the effect of grooves on the force-deflection response; (iii) the effect of friction at the supports-to-beam interfaces on the force-deflection response.

METHODS AND MATERIALS

To evaluate whether crushing could produce the observed grooves, a Hertzian mathematical model of an elastic cylinder in contact with an elastic, semi-infinite medium in plane strain was used to test if direct contact would produce deformations as large as those observed (Johnson, 1985). The stainless steel cylinder support used in the experiments was modeled as 9.5 mm in diameter, with an elastic modulus of 105 GPa and a Poisson ratio of 0.305. The bone was considered to be isotropic with a modulus of 17 GPa and a Poisson ratio of 0.3. The contact load applied to the beam was 280 N, which corresponds to the maximum load at the supports and load noses during the flexural fatigue tests. No attempt was made to assess inelastic deformation of the bone material at the point of contact.

An experiment using two Plexiglas beams was conducted to determine if grooves at the supports and load noses would produce the nonlinear response that we observed in bone. Two 100 × 10 × 5 mm beams (approximately the same dimensions as the bone samples) were machined from a single piece of Plexiglas. The same four-point bending test fixtures as the bone experiment were used. Grooves with a radius of 4.75 mm and a depth of 0.3 mm were machined on one beam at the sites located below the supports and load noses; the other beam had no grooves. Both Plexiglas beams were tested for force-deflection response using an MTS 880.10 load frame with MTS TestStar 2 control electronics. Both beams were loaded monotonically to failure at a constant actuator displacement rate of 1 mm s⁻¹. Force was measured using a 2200 N load cell and the mid-span displacement was measured using...
an LVDT (model DC-E 125, Schaevitz Engineering). Stresses and strains were calculated from the force-deflection response using elementary beam theory.

Three two-dimensional, plane strain, finite element method (FEM) models were constructed in Patran® and solved using Abaqus®. Due to the symmetry of four-point bending, one half of the total beam was modeled. Each FEM model included second-order interfacial elements on the beam surface in the vicinity of the contact points and on the surface of the loading noses and supports, allowing for the possibility of frictional contact.

Each beam was modeled using 800 nine-node elements with an aspect ratio of 1:1. The supports and load noses were modeled as semi-circular with radius 4.5 mm, each containing 150 six-node triangle elements. The solution was obtained using an incremental, iterative technique due to the presence of nonlinearities, such as friction. Large deformation theory was used in the analysis. The beam was modeled as isotropic with an elastic modulus of 17 GPa and a Poisson ratio of 0.3. The supports were isotropic with an elastic modulus of 207 GPa and a Poisson ratio of 0.305. The beam was loaded incrementally by a ramp to approximately 10,000 N at the outer fiber of the beam, which was the strain level of the fatigue test. Three levels of kinetic friction ($\mu_k$) were used in each model: 0.00, 0.25, and 0.50, which bracket experimentally obtained wet and dry kinetic friction coefficients (Griffin et al., 1995).

Friction was modeled as a step-function, assuming the static friction coefficient was equal to the coefficient of kinetic friction. The first FEM model was a beam with no grooves; the second, a beam with grooves the shape of a circular segment of radius 4.5 mm and depth 0.25 mm located directly under the supports and load noses (circular groove); the third, a beam with grooves the shape of a circular segment of radius 5.4 mm and depth 0.25 mm located directly under the supports and load noses (oblong groove), similar to those observed on fatigued bone samples (Fig. 1).

RESULTS

The Hertzian model predicted highly localized compressive stresses of approximately 180 MPa and shear stresses of approximately 55 MPa at the contact site.

The grooved Plexiglas beam produced a nonlinear force-deflection curve similar to that observed in the bone (Fig. 2). To simplify comparison, and account for the variability of the elastic modulus, the force-deflection results for each data set were normalized by the force and displacement which would produce 10,000 N at the contact site.

The FEM analysis of the ungrooved beam under the frictionless loading predicted a small amount of nonlinearity in the force-deflection curve associated with large deflections [Fig. 3(a)]. As the friction coefficient increased, the amount of nonlinearity increased. The degree of nonlinearity depended on the geometry of the grooves and the value of the kinetic friction coefficient [Fig. 3(b) and (c)]. As the friction coefficient increased, the final displacement of the beam also became significantly less than that predicted by beam theory, which is manifest as an increasing secant modulus. The case of oblong grooves produced a response very similar to that seen in the actual test of the bone beam [compare Fig. 2(b) with Fig. 3(b)].

Examination of the stress state in the FEM model indicated that an additional axial tension is present between the load noses as evidenced by a shift in the neutral axis toward the compressive edge (Fig. 4). Essentially, the maximum value of the tensile stress is greater than the maximum compressive stress. Furthermore, there were no shear stresses between the inner supports.

DISCUSSION

Crushing does not appear to be the primary cause of the grooves observed in the fatigue experiments. The compressive stresses at the contact points were estimated to be 180 MPa. The longitudinal compressive yield strength of cortical bone tissue of the equine third metacarpus is 150-250 MPa (Len et al., 1994). The compressive yield in the transverse direction should be less than these reported values, and suggests that some crushing could occur. However, the model predicts lower stresses if the modulus input is lower. The Poisson ratio may be varied up to 0.5 (due to isotropic linear elasticity restrictions) and results in slightly higher stress predictions.

Strictly speaking, the Hertzian model is not valid due to the anisotropy of bone, which was modeled as isotropic. However, bone beams...
Fig. 3. FEM and beam theory force-deflection curves for various beam models: (a) no grooves; (b) oblong grooves; (c) circular grooves. Note the similarity of the force-deflection behavior of the beam with oblong grooves to that of actual bone shown in Fig. 2(b).

Fig. 4. The effect of grooves and friction in the mid-span flexural stress state of the beam as determined by the FEM. Notice the definite shift of the neutral axis of bending from the geometric center of the beam toward the compressive side of the beam predicted at small deflections.

cycled to failure at 10,000 με in flexure using roller bearing supports have produced no residual indentations on the beam surface, nor have they exhibited any nonlinear stiffening behavior (Gibson et al., 1995). Therefore, crushing does not seem to be the cause of the grooves or the nonlinearity. We postulate the primary cause of the grooves to be predominately wear.

The cause of the observed nonlinearity appears to be a combination of grooves and friction at the supports and load noses. The effect of grooves on the force-deflection behavior is clearly demonstrated in the Plexiglas beam experiment. The Plexiglas beams were cut from the same piece of material and loaded at the same rate, so the material behavior of the Plexiglas is common to both. Since the only difference is that one beam had grooves while the other did not, it is concluded that the cause of the nonlinearity in the force-deflection curves for the Plexiglas beams is the grooves.

The FEM models of the grooved beams demonstrate a stiffening nonlinear force-displacement response [Fig. 3(b) and (c)]. As friction at the supports-to-beam interfaces was increased, the predicted force-displacement nonlinearity increased considerably—even in the beam with no grooves [Fig. 3(a)]. Apparently friction serves to constrain the
beam at the supports and load noses. Since the material modeled in the FEM beams is strictly linear elastic, the observed nonlinearity must be caused by the test configuration.

The shift of the neutral axis toward the compressive edge of the beam can appear at low loads (Fig. 4). Because neutral axis shift appears even in the ungrooved FEM beam, the cause is apparently constraint of the beam at the supports and load noses by friction and/or grooves.

The FEM model of a beam with no grooves and no friction produced a small amount of nonlinearity [Fig. 3(a)], which is also observed experimentally in bone with roller-bearing supports and load noses [Fig. 2(b)]. This nonlinearity is a geometric effect, caused by the circular supports and load points combined with the large deflections in reaching 10,000 µ. By using the large diameter supports, the test configuration behaves as a nonlinear stiffening spring (Shigley and Mischke, 1989). The geometric nonlinear stiffening may be minimized by using the smallest diameter support and load nose recommended by ASTM 790, or conducting studies at small deflection levels.

It should be mentioned that while the Plexiglas beam demonstration of the nonlinear stiffening is not a powerful test, on its own, the result is strengthened by considering that the only cortical bone beams that have exhibited the nonlinear stiffening behavior had grooves and were loaded using fixed supports that can produce friction at the load noses and supports. Furthermore, the FEM results agree with the Plexiglas beam experiment and the observation that grooves produce a force-displacement curve exhibiting nonlinear stiffening in bone beams.

Thus, friction and grooves produce nonlinearity in the force-deflection curve as well as altering the expected stress state between the load noses. In a controlled test environment, all sources of linearity, or nonlinearity, need to be understood to avoid mistaking experimental artifact for material behavior. We conclude that application of the flexural mode of testing to bone requires minimization of nonlinear stiffening behavior associated with friction and wear groove formation by the use of roller-bearing supports and load noses, or some equivalent method.

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REFERENCES


