ABSTRACT

Studies of bone have determined multiple toughening mechanisms slowing the propagation of a crack. These toughening mechanisms contribute to the fracture toughness of bone in life, making their activities of clinical interest. The primary standard methods for measuring bone fracture toughness use either a single-notched compact type specimen (CT) or single-notched bending specimens in four-point bending (SN4PB) or three-point bending (SN3PB). There is currently no method for calculating fracture initiation toughness using a double-notched bending specimen tested in four-point bending (DN4PB). Such specimens are useful for simultaneously studying fracture toughness and pre- and post-failure damage. We developed a mechanistic method to determine accurate fracture toughness measurements using double-notched specimens. After applying three correction factors post-hoc analysis reveals that a thousand sample sets would be needed to detect a statistical difference between the mean values of toughness measured using the new DN4PB method and the well-validated SN3PB method. In a double notch specimen, total failure occurs primarily at one notch leaving the other in a less damaged state. Thus, the new double notch method permits using a single specimen to measure toughness and examine post-failure and pre-failure damage to the bone matrix.

BACKGROUND

The standard methods to determine fracture toughness use either compact type or three-point bending beam specimens with a single notch that acts as an inherent flaw in the bone specimen. While effective for determining fracture toughness, the single-notch beam and compact type specimens are typically loaded to complete failure, making it difficult to examine the damage that causes fracture initiation. As a result, these specimen types are used to determine fracture toughness and to study post-failure damage. In contrast a double-notched beam in four-point bending can be used to study post- and pre-failure damage [1]. The two notches provide two nominally identical sites for failure. In a perfectly homogeneous material failure would occur at both notches simultaneously because both notches experience the same stress. However bone is a highly heterogeneous material preventing both sites from being identical. As a result, only one notch fails during testing leaving the other notch in a preserved state that can be studied for events just preceding fracture.

METHODS

48 rectangular cortical bone beams (~2 x 2 x 22 mm) were cut, using an Exakt cutting system (Exakt Technologies, Oklahoma City, OK), from the diaphysis of the third metacarpal (cannon) bone of three female, Thoroughbred racehorse (2, 4, and 6 years old) cadavers. Both the left and right legs were used from each horse. The bones were kept frozen post-failure damage. In contrast a double-notched beam in four-point bending can be used to study pre- and post-failure damage [1]. The two notches provide two nominally identical sites for failure. In a perfectly homogeneous material failure would occur at both notches simultaneously because both notches experience the same stress. However bone is a highly heterogeneous material preventing both sites from being identical. As a result, only one notch fails during testing leaving the other notch in a preserved state that can be studied for events just preceding fracture.

To simulate a pre-existing flaw in the bone beams, either one or two notches were cut in each using a 150 µm thick diamond-coated dental cutting disk (22-mm diameter SummaDisk, Shofu Dental Corporation, San Marcos, CA) mounted to a proLIGHT 1000 CNC milling machine (Light Machines Corp., Manchester, NH). Due to vibrations during cutting the actual notch width was consistently around 240 µm with a notch root radius of 120 µm.

Of the 48 beams used for fracture testing, 24 were tested using the single-notched three-point bending geometry (SN3PB) while the remaining 24 were tested using the double-notched four-point bending geometry (DN4PB). All of the notch depths were cut to an a/W (ratio of notch depth to beam width) equal to 0.3. Beams were cut such that the long axis of the beam was parallel to the long axis of the bone. Notches were placed on the endosteal side of the beams so that all cracks propagated in the transverse plane from an endosteal to periosteal direction. A dial indicator (The L.S. Starrett Co., Athol, MA) was used to make three measurements (accurate to within 0.001 in) for depth of each notch, which were averaged. The beam width, height, and length were measured using digital caliper (accurate to within 0.01 mm) (Mitutoyo Corp., Aurora, IL).

Upon completing the mechanical tests and calculating the fracture toughness for both geometries the indications were that the calculated fracture initiation toughness values from the two bending test geometries were different. The mode I fracture toughness for the DN4PB geometry calculated using the SN3PB equations for toughness was significantly smaller than that calculated using the SN3PB geometry. Hence, a modification of the standard method of calculating fracture toughness was needed for DN4PB. This led to the development of a series of mechanistic correction factors to bring the calculations for the two geometries into agreement. The three mechanistic correction factors: 1) Finite element estimation of the notch strains in DN3PB and DN4PB notch roots to ensure correspondence of tensile strain, 2) Correction of failure force estimate using the secant method for a systematic error caused by stiffness difference between SN and DN specimens, 3) Correction for the reduction in strength caused by presence of two notches in the specimen (A specimen will break at the weakest notch, making a low failure force more likely in a double compared to a single notch specimen.)

RESULTS

FE model of the (a) SN3PB beam and (b) DN4PB beam. Both images show the stress field in the x-direction, which lies along the length of the beam. For the same displacement of the loading head, the maximum strain at the notch root for the DN4PB specimen was 1.076 times that in the SN3PB specimen.

Analysis of the three systematic differences between DN4PB and SN3PB specimens (the latter two analyses too large to include in this abstract) results in an overall nondimensional correction factor for Ke of 1.191 = 1.076*1.064*1.04, where the factors are in the order above.

When all three of the correction factors were used the mean fracture toughness for DN4PB transformed from 4.15 ± 0.46 MPa*m^1/2, without any correction factors, to 4.95 ± 0.55 MPa*m^1/2. The difference in the mean fracture toughness between the two geometries was reduced from 17.21% to 1.43%. The effect of geometry (three- vs. four-point bending) on fracture toughness was eliminated by the correction. (Repeated measures ANOVA: n=46, p=0.552, horse as repeated measure and geometry treated as a fixed effect. Post hoc power analysis showed >1000 samples would be needed to show a significant effect.)

CONCLUSION

After applying the mechanistic correction factors the mean fracture toughness of DN4PB was not different from values calculated using the standard SN3PB beam specimen. The new method permits calculating bone fracture initiation toughness and examining pre- and post-yield damage using the same specimen.

REFERENCES


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