

Ultimate Tensile Strength of Dentin: Evidence for a Damage Mechanics Approach to Dentin Failure*

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Abstract: Dentin structure and properties are known to vary with orientation and location. The present study explored the variation in the ultimate tensile strength (UTS) of dentin with location in the tooth. Hourglass specimens were prepared from dentin located in the center, under cusps, and in the cervical regions of human molar teeth. These were tested in tension at various distances from the pulp. Median tensile strengths ranged from 44.4 MPa in the inner dentin near the pulp, to 97.8 MPa near the dentino–enamel junction (DEJ). This increase in the median UTS with distance from the pulp to the DEJ was statistically significant ($P < .001$). Of particular importance was the observation that the UTS measurements followed a Weibull probability distribution, with a Weibull modulus of about 4.5. The Weibull behavior of the UTS data strongly suggests that the large variances in fracture strength data result from a distribution of preexisting defects in the dentin. These findings justify a damage-mechanics approach to studies of dentin failure. © 2002 Wiley Periodicals, Inc. *J Biomed Mater Res (Appl Biomater)* 63: 342–345, 2002

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INTRODUCTION

Dentin is a structurally anisotropic biological composite, and exhibits regional differences in mineral concentration, tubule density and diameter, and collagen orientation.^{1,2} The influence of these regional variations on biomechanical function are of importance to dentin bonding, as well as for understanding pathological conditions of teeth, such as caries, cervical erosion/abfraction, and tooth fracture.

Microtensile testing was originally developed to measure the ultimate tensile strength (UTS) and modulus of elasticity of dentin.³ The technique was later applied to testing UTS and elastic modulus of the demineralized dentin matrix, in an effort to estimate the relative contribution of collagen to the mechanical properties of dentin.⁴ Other techniques have also been used to study the mechanical properties of dentin. Smith and Cooper used a punch method and reported shear strengths

that ranged from 39 MPa near the pulp to 131 MPa near the dentino–enamel junction (DEJ).⁵ Gwinnett, using relatively large samples made from third molars, reported the shear strength of dentin in lap-shear to be 36.2 MPa; the exact location within the tooth was not mentioned.⁶ Watanabe, Marshall, and Marshall also with lap-shear, reported the strength of dentin at the center area to be 78.0 MPa and that at the location of the cuspal area to be 91.8 MPa; dentin under the cusps had significantly higher shear strengths than did the central dentin.⁷ The tensile strength has been reported to vary with orientation: A 20% variation in UTS has been observed, depending on whether the tubules were aligned perpendicular or parallel to the force axis.⁸

The large standard deviations common to all measurements of dentin strength suggest that the tensile strengths depend upon the distribution of flaws, or defects, in the specimen. A flaw is similar to the weakest link in a chain: Variations in the flaw size lead to variations in the failure strength. Specimens with large flaws will fail at lower stresses than specimens containing smaller flaws. If the flaw sizes were randomly distributed, the tensile strength data would be expected to follow a Weibull probability distribution, where the probability P_f that a specimen fails by stress level σ is given by the expression:

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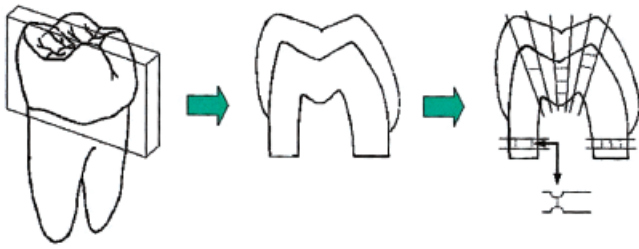


Figure 1. A diagram of the major steps in the preparation of the specimens.

$$P_f = 1 - \exp\left(-\left(\frac{\sigma}{\sigma_0}\right)^m\right), \quad (1)$$

In Eq. (1), σ_0 is the scale parameter, and m is the dimensionless Weibull modulus.

The aim of the present study was to evaluate the influence of the distance from the pulp on the UTS of dentin at various locations. In particular, this study undertook to establish the validity of a Weibull approach to modeling tensile strengths, and to determine the Weibull modulus of dentin. Such information is critical to a damage-mechanics approach to dentin failure, and for developing improved procedures in preventive and restorative dentistry.

MATERIALS AND METHODS

Twenty-five noncarious human maxillary third molars were used for this study. After extraction, the teeth were stored in deionized water for 1–4 weeks at 4 °C. The major steps in specimen preparation are diagrammed in Figure 1. A slow-speed diamond saw (Buehler, Lake Bluff, IL) was used to cut 1-mm-thick planar sections from the center area of the tooth in the bucco-lingual direction. Several specimens, representing the cervical, cuspal, and occlusal areas of the tooth, were then cut from each planar section. Finished specimens were prepared by grinding a narrowed fillet in the desired location, resulting in an hourglass shape. All specimens were kept in deionized water until testing for up to 48 h.

The specimens were mounted in a microtensile testing apparatus, and attached to the grips with cyanoacrylate adhesive. Testing was in tension in an Instron mechanical testing machine with the use of a crosshead speed of 1 mm/min. The device was a modification of the apparatus designed by Ciucchi as described by Pashley et al.;⁹ the modification consisted of making a narrower testing gap and attaching a small clamp on one grip. This made it possible to test specimens of smaller dimension, as the handle portion of some specimens was less than 0.5 mm in length. The total length of each specimen was the distance from the pulp to the outer surface of the tooth. Although the orientation of dentinal tubules was not examined microscopically prior to testing, the plane of testing was close to perpendicular to a line from the pulp to the outer surface of the tooth, which should

have resulted in a fracture-plane orientation nearly perpendicular to the dentinal tubules.

Immediately after failure, the load/displacement records and fracture surfaces were examined. A test was considered valid if the load/displacement record showed an appreciable linear range and if the fracture was entirely contained in the constricted region. Tests that failed either of these criteria were not included in the analyses.

STATISTICAL METHODS

As indicated above, a tooth could yield dentin specimens at multiple sites, varying by depth (inner, middle, outer) and location (cervical, occlusal, cuspal). Overall, 116 UTS measurements were made on 25 teeth. At each of the eight dentin sites, the UTS measurements were averaged within tooth. Thus the mean UTS values were independent within a site, but they were correlated across sites (each tooth was represented at three of the eight dentin sites, on average). The replicates were examined by site for outliers and were the two extreme outliers from subsequent analyses.

Weibull distributions were fit to the data at each site (SAS proc reliability) to obtain maximum-likelihood point estimates (MLE) and 95% confidence intervals for the Weibull moduli (shape parameters) and for the median UTS.¹⁵ The medians, defined at the 50th percentiles of the distributions, provide useful measures of the average UTS per site. Additionally, the median is similar to the Weibull scale parameter, which is defined at the 63.2th percentile. The equality of the Weibull moduli was tested across sites via the likelihood ratio test, comparing the model based on distinct scale parameters and modulus values at each site with the model based on distinct scale parameters and a common modulus value. In turn, the equality of the Weibull scale parameters was tested across the eight sites via the likelihood ratio test comparing the latter model with the model based on a common scale parameter and a common modulus for all sites. Similarly, likelihood ratio tests were used to compare the Weibull scale parameters across the three depths and across the three locations, assuming a common modulus for all sites. These statistical tests assume that specimens at different locations are from distinct teeth, but this was not always the case. Thus borderline *P* values (i.e., those near .05) should be interpreted with caution.

Finally, the Weibull moduli also were obtained via least-squares estimates (LSE), by regressing $\ln[\ln(1/(1-P_f))]$ on $\ln[\text{UTS}]$ (see Figure 2). For this analysis the mean UTS values were ranked in ascending order and the failure probability was estimated as $P_f = i/(N+1)$, where i was the rank order and N was the total number of teeth measured at each dentin site. It was found that the ML estimates were consistently higher than the LS estimates (by 0.75–2.5). Because a ML estimate of the Weibull modulus is unique, but a LS estimate depends on how the failure probability is estimated,¹⁴ the ML estimates were used for the tabulated data.

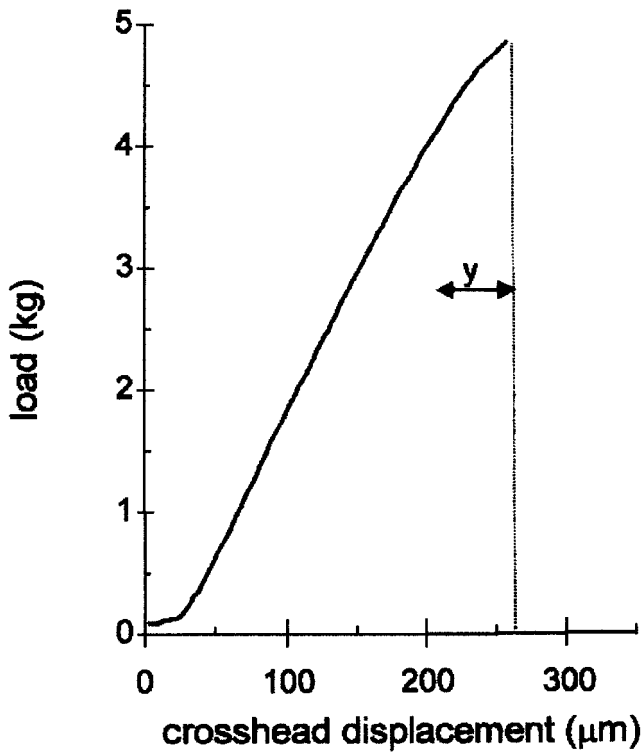


Figure 2. A representative load/displacement curve for a dentin specimen undergoing uniaxial tensile loading. Following an initial tow-in during grip alignment, the stress/strain behavior was linear until just prior to failure. The small deviations from linearity near failure were consistent with damage development preceding brittle failure.

RESULTS

A typical load/displacement record is graphed in Figure 3. The dentin response was linear up to approximately 80% of the ultimate tensile strength. A small deviation from linearity, or yielding, was noticeable just prior to failure. This behavior is consistent with brittle failure; damage accumulation and growth can account for the nonlinear behavior.

The results of the UTS measurements are presented in Table I. The median UTS varied significantly across the eight locations ($P < .001$), ranging from 44.4 MPa near the pulp in the occlusal area of the tooth to 97.8 MPa near the DEJ under the cusp. The UTS of the inner dentin was statistically significantly lower than in dentin farther away from the pulp ($P < 0.001$). There was no consistent trend toward greater or lesser tensile strength across the cervical, occlusal, and cuspal locations. However, variation in UTS by location was greatest at inner depths ($P = 0.005$) and least at outer depths ($P = 0.31$). Across the eight study sites, the Weibull moduli were not statistically significantly different ($P = 0.86$) from an overall estimate of 4.53 (95% CI, 3.74–5.45). However, Weibull moduli at the middle depth tended to be higher than those at inner and outer depths. The greatest difference was between the mid-cervical and outer-cervical locations.

DISCUSSION

The results of this study indicate that the UTS is lower in the inner dentin near the pulp, in agreement with earlier mea-

surements of shear strength.⁷ Because of the smaller size of the microtensile specimens, however, the present study allowed differences to be observed with finer spatial resolution within the tooth. The samples tested near the pulp were prepared such that the tested region was as close as 0.26 mm from the pulp in some of the samples. Such samples had been too difficult to test in the shear mode; the closest distance to the pulp in that mode was about 1 mm.

Dentin is not a uniform material; its mechanical properties and composition are known to vary from outer to inner dentin.¹⁰ The hardness and modulus of the intertubular dentin matrix is known to be lower in the inner dentin than in the outer dentin.¹¹ Therefore, it is likely that the tensile strength of dentin might also vary with proximity to the pulp. A critical strain to failure criterion is known to explain fracture in bone, a mineralized tissue of similar composition to dentin.¹² According to this criterion, sometimes called the St. Venant’s criterion, tissue is assumed to fail when a critical strain is reached. Therefore, if this failure model is applicable to dentin it would be expected that tensile failure should occur at lower stresses in the inner dentin because the lower modulus allows the critical strain to be reached at lower stress. Other mechanisms might also be responsible for the lower tensile strengths, however, such as the possibilities that the fracture toughness is lower near the pulp or that the flaw distribution is altered from that in outer dentin. Further study is needed to elucidate these mechanisms.

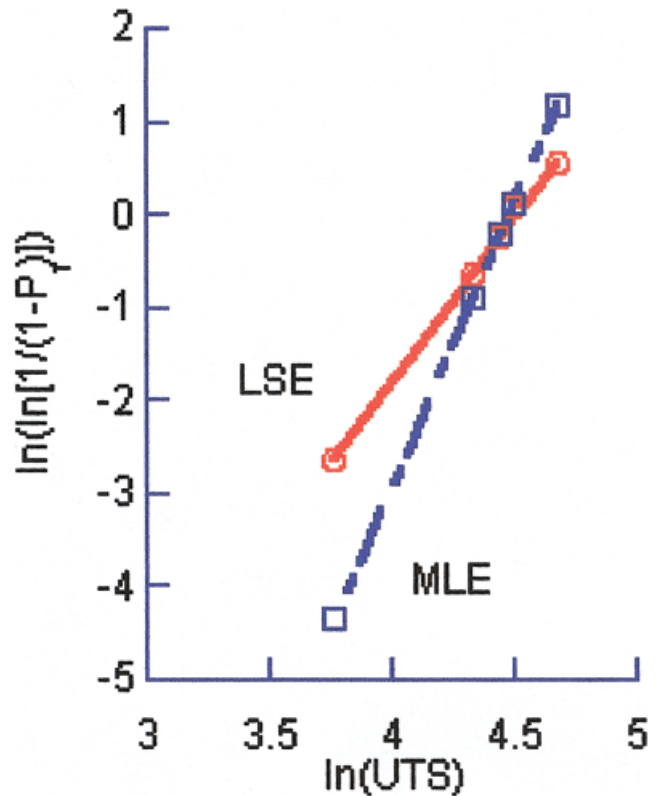


Figure 3. A Weibull probability graph of the UTS data in midcervical dentin showing the Weibull modulus (the slope) estimated via the maximum-likelihood method (MLE = 6.0) and via least-squares regression (LSE = 3.4).

TABLE I. Ultimate Tensile Strength: Medians (in units of MPa^a) and Weibull Moduli for the Different Dentin Locations.

Location, N ^a	Median UTS ^a (95% CI ^a)	Weibull Modulus (95% CI)
Inner-cervical, N = 10	63.74 (52.78–76.98)	3.89 (2.37–6.39)
Middle-cervical, N = 9	83.61 (73.63–94.94)	6.00 (3.54–10.16)
Outer-cervical, N = 8	85.60 (70.64–103.73)	3.15 (2.71–3.60)
Inner-occlusal, N = 7	44.45 (34.27–57.65)	3.35 (1.74–6.46)
Middle-occlusal, N = 10	61.74 (54.31–70.19)	5.73 (3.41–9.63)
Outer-occlusal, N = 8	86.58 (71.64–104.63)	4.20 (2.23–7.93)
Inner-cuspal, N = 0	—	—
Middle-cuspal, N = 11	62.86 (54.69–72.24)	4.99 (3.09–8.04)
Outer-cuspal, N = 11	97.78 (83.58–114.40)	4.47 (2.81–7.10)
All, N = 74		4.53 (3.74–5.45)

^a Abbreviations: MPa = mega-Pascals; N = number of teeth analyzed; UTS = ultimate tensile strength; CI = confidence interval.

The 95% CIs can be compared across locations as indicators of statistical significance, but this does not account for correlations among the teeth or for the effect of multiple comparisons.

Of significant interest was the confirmation that the UTS data followed a Weibull probability distribution: The large variance in reported data in the literature reflects the low values of the Weibull moduli obtained in this study. Because of the small number of teeth available in the present study, it is hoped that this finding will be confirmed by other groups. Additionally, it was found that the Weibull modulus did not vary by depth or location in dentin; the common value was estimated to be 4.5 (95% CI, 3.7–5.4). This is lower than the Weibull modulus found in most engineering ceramics ($m < 5$), and is more typical of the behavior of brittle foams.¹³ Because of the low Weibull moduli, the UTS of dentin should exhibit a pronounced specimen-size effect, which could explain the large variations in reported mean strengths in other studies. The observation definitely underlines the necessity to state the specimen size precisely when reporting strength measurements.

The traditional method of evaluating dentin strength has relied on measurements of ultimate compressive, tensile, or shear strengths. Very few studies have undertaken a fracture mechanics approach, where properties such as fracture toughness are measured. The present findings, however, question the meaning of strength measurements in dentin; instead, the observation that a preexisting population of flaws controls fractures is a strong motivator for using fracture- or damage-mechanics approaches to model dentin failure. It is conceivable that inherent flaws, or flaws introduced during cavity preparation, will have a significant impact on the ability to produce durable bonds to dentin. Therefore, research should be focused on identifying these flaws, and on determining the distribution of these flaws in normal and altered dentin. Though some Weibull moduli seemed to be lower in inner compared to outer dentin, the trend was not consistent and the differences were not statistically significant. However, the median UTS was significantly lower in inner than in outer dentin. It is premature to attribute these differences to inherent, regional variations in the flaw population. It will first be necessary to characterize the nature of the dentin flaws that are responsible for fracture.

In summary, the ultimate tensile strength was significantly lower in inner dentin than in outer dentin. In addition, tensile strengths followed a Weibull probability distribution, imply-

ing that flaws dominate tensile failure in dentin. The latter result justifies a fracture- or damage-mechanics approach to modeling dentin failure.

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