CROSS-MODAL EFFECT OF DAMAGE ON CORTICAL BONE STRENGTH

[1] Won Joo, [1]Dwigth T. Davy
[1]Case Western Reserve University, email: dtd@cwru.edu

INTRODUCTION

Bone is a complex biological material which continually undergoes damage accumulation and repair in-vivo [1]. The effects of damage are often studied in terms of the mechanical property degradation in the loading mode (e.g. tension, torsion, etc.) in which damage was accumulated [2]. However, in-vivo loading is more complex, and it is important to understand how damage accumulated in one loading mode affects mechanical properties in other loading mode. Our previous studies demonstrated complex cross-modal effects of damage on viscoelastic properties [3]. The purpose of this study was to determine how monotonic strength in each of three loading modes (tension, compression or torsion) is affected by damage mode and magnitude.

METHODS

Cortical bone samples were machined from the mid-diaphyses of 18 human femurs (7 females and 11 males, 38-55 years old age). The final machined samples had a reduced diameter section (4 mm diameter x 18mm long) with the axis along the nominal bone axis. During all machining and testing, specimens were kept wet and testing was performed at 37°C. Samples were randomly assigned to experimental and control groups. For control groups, 10 undamaged specimens were tested under strain control in each loading mode (Tension (T), Compression (C), Rotation (R)). Loading rates of ±1 %/s or 8 degree/s were used. The results from control group were used as undamaged measures and the yield strain of each loading mode used to prescribe the damage cycle magnitudes shown in Figure 1.

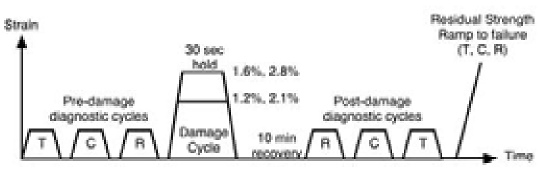

Figure 1. The protocol for strength degradation test.

Before and after the damage cycle, diagnostic cycles in three modes were performed to measure the change of viscoelastic properties by damage (Data shown in [3]). Damage was induced in one of three loading modes (T, C, or R) during damage cycle with two different magnitudes for each mode, which for tension were 1.2% and 1.6% (150% and 200% tension yield), compression were 1.2% and 1.6% (120% and 160% compression yield) and torsion were 2.1% and 2.8% (150% and 200% rotation yield). Following the damage cycle, 10 minutes recovery time was allowed at zero-stress (zero-torque) hold condition. After the recovery period, each specimen was monotonically loaded to failure in one of the three modes. Six specimens were tested for each test group. For the torsional tests, the following equation [4] was used to calculate shear stress.

$$\gamma = \theta \frac{a}{l}, \qquad \tau = \frac{1}{2\pi r^3}\left[\theta \frac{dT}{d\theta} + 3T\right]$$

Changes in properties due to damage were compared using 1-way ANOVA (with Tukey's pairwise comparisons) and paired t-tests ($p<0.05$).

Table 1: Measured parameters from monotonic failure test after damage. All values are normalized to mean values of control group (mean±SD).

Damage mode	failure mode	Damage strain	Yield strain, ε_y	Yield stress, σ_y	Failure stress, σ_f
Tension damage	T	1.2%	0.82±0.03	0.62±0.05	0.91±0.05
		1.6%	0.78±0.03	0.60±0.05	0.80±0.08
	C	1.2%	0.85±0.04	0.66±0.04	0.92±0.05
		1.6%	0.79±0.04	0.62±0.05	0.77±0.05
	R	1.2%	0.97±0.03	0.93±0.06	1.03±0.08
		1.6%	0.90±0.04	0.80±0.03	0.84±0.11
Compression damage	T	-1.2%	0.95±0.02	0.79±0.05	0.81±0.09
		-1.6%	0.69±0.06	0.45±0.07	0.79±0.10
	C	-1.2%	0.87±0.06	0.68±0.07	0.88±0.05
		-1.6%	0.65±0.03	0.44±0.04	0.68±0.14
	R	-1.2%	0.97±0.06	0.89±0.13	0.97±0.14
		-1.6%	0.94±0.05	0.92±0.10	0.98±0.09
Rotation damage	T	2.1%	0.99±0.01	0.87±0.01	0.93±0.07
		2.8%	0.96±0.06	0.82±0.07	0.83±0.04
	C	2.1%	1.05±0.06	0.90±0.03	0.94±0.04
		2.8%	1.00±0.07	0.89±0.07	0.97±0.13
	R	2.1%	0.88±0.03	0.79±0.04	0.97±0.06
		2.8%	0.80±0.04	0.65±0.06	0.87±0.08

RESULTS AND DISCUSSION

There were significant and mode dependent inter-modal damage effects on monotonic strength of human cortical bone. Axial (compressive and tensile) damage reduced tensile and compressive yield strain and stress (Table 1). Higher damage strains tended to produce greater property degradation, although not all differences were significant. Compression damage of -1.6% strain induced more degradation than tensile damage of 1.6% strain on tension and compression strengths. Axial damage modes affected torsion properties far less than axial properties. Conversely, shear (torsion) damage induced small degradations in tension and compression compared to shear strength degradation. The failure stresses showed significant decreases but smaller magnitudes of degradation than yield stress and strain (Table 1).

The un-coupling between axial and rotation damage modes is consistent with our earlier observations on viscoelastic properties [3]. They also are consistent with the qualitative differences in damage morphologies that have been observed [2,5]. Work in histological measurements of damage is ongoing to further explore the relationship between the observed cross-modal mechanical property changes due to damage and the morphological nature of the damage in each mode.

REFERENCES

1. Burr DB, Turner CH, et al. J. Biomech. 31:337, 1998
2. Jepsen KJ, Davy DT, J. Biomech. 30:891, 1997
3. Joo W, Jepsen KJ, Davy DT, Trans. ORS 29, 2004
4. Nadai A. Theory of flow and fracture of solids, pp. 347-352. McGraw-Hill, New York. 1950
5. Carter DR, Hayes WC, Clin. Orthop. Rel. Res., 127, 265-274, 1997

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