



US DEPARTMENT OF DEFENSE

# BLAST INJURY RESEARCH PROGRAM COORDINATING OFFICE

## Blast Exposure Analysis

### Development of Deformation and Failure Criteria for Human Femoral Bone under Ballistic Loading Rates

An accurate understanding of fracture in human bone, under complex loading scenarios, is critical to predicting fracture risk. Cortical bone, or dense, compact bone, is subject to complex loading due to the inherent multi-axial loading conditions, which are also influenced by the anisotropy of the microstructure. When determining critical fracture parameters, bone is traditionally idealized as isotropic. This work presents a method to examine rate-dependent mode mixity associated with cortical bone crack initiation. Four-point bend experiments have been conducted on cortical femoral bone samples from three human donors at quasi-static (slow), intermediate, and dynamic loading rates. Digital image correlation was used to obtain full-field displacement maps, at the crack tip, during the experiments. An over-deterministic least squares method was used to evaluate Mode I (opening) and Mode II (shear) stress intensity factors (SIF) for fracture initiation at slow (10.2 MegaPascals-meter<sup>1/2</sup> per second), intermediate (15 MegaPascals-meter<sup>1/2</sup> per second), and high (4.54 MegaPascals-meter<sup>1/2</sup> per second) SIF rates. Results show that under dynamic loading, the critical SIF in Mode I, assuming material anisotropy, is approximately 50 percent lower than fracture toughness assuming isotropy.<sup>1,2</sup> Additionally, critical Mode I and II SIFs had the lowest values at the highest rate of loading examined, decreasing to one third of the values shown under quasistatic loading. Crack growth in the low and intermediate SIF rates appears to be Mode II dominant, and shows a transition to completely mixed-mode at the high rate of loading. This suggests that the conventional assumption of isotropy is a conservative estimate, at low and intermediate rates, but overestimates fracture strength at dynamic rates. These fracture thresholds and mechanistic understandings can be used to develop fracture initiation criteria from defects and micro-cracks in bones of the lower extremities. Fracture initiation criteria can be implemented in large scale computer codes to predict bone fracture when the Service Member is exposed to military-relevant, high rate, blast and ballistic loading. These studies will promote development of novel lower extremity protection concepts to mitigate fracture injuries from blast and impact loading.

1 Shannahan, L., Weerasooriya, T., Gunnarsson, A., Sanborn, B., & Lamberson, L. (2015). Rate-dependent fracture modes in human femoral cortical bone. *International Journal of Fracture*, 194(2), 81–92. <https://doi.org/10.1007/s10704-015-0035-0>

2 Sanborn, B., Gunnarsson, C. A., Foster, M., & Weerasooriya, T. (2016). Quantitative Visualization of Human Cortical Bone Mechanical Response: Studies on the Anisotropic Compressive Response and Fracture Behavior as a Function of Loading Rate. *Experimental Mechanics*, 56(1), 81–95. <https://doi.org/10.1007/s11340-015-0060-y>

