STRAIN RATE DEPENDENT MECHANICAL PROPERTIES OF BOVINE BONE IN AXIAL COMPRESSION

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ABSTRACT

Strain rate dependent bone fracture thresholds are investigated to improve the understanding of dynamic lower extremity injury criteria for threats at different rates of compressive impact. Cortical bone specimens were extracted from eleven bovine femur bones and compressed at constant strain rates (10^{-4} s^{-1}, 10^{-3} s^{-1}, 10^{-2} s^{-1} and 3×10^{2} s^{-1}). The experimental bone response is fitted with a viscoelastic constitutive model with non-linear strain rate dependence. Probability of failure is estimated (from the ultimate compressive specimen stress) with a Weibull cumulative distribution function and discussed with respect to strain rate.

Keywords: Bones; Constitutive model; Viscoelasticity; Injury probability

THE LOWER EXTREMITY INJURY CRITERION (IC) for anti-vehicular (AV) landmine resistant vehicles is based on an axial force threshold of 5400 N, measured in the lower tibia load cell of a Hybrid III crash test dummy during ballistic impact (AEP-55, 2006). The IC stems from tests on Post Mortem Human Surrogates (PMHS) (Yoganandan et al., 1996) and represents a 10% risk of ankle/foot fracture (AIS 2+) for dynamic impact to the plantar foot surface. The PMHS experiments were designed to simulate lower extremity trauma sustained during frontal vehicular impact. The specific loading conditions of frontal vehicle impact are likely to differ from those due to the dynamic deformation of a vehicle structure that compresses the lower extremity during an AV blast. A more detailed understanding of lower extremity and bio-material response is necessary to estimate human predisposition to injury due to AV blast. The strain rate dependent properties of cortical bone are particularly important, given that it is the main structural element of the lower extremity and the IC pertains to bone fracture.

Bone fracture is strain rate sensitive in that it occurs at a higher stress and lower strain with increased loading rate. McElhaney (1966) observed a critical velocity at compressive strain rates around 10^{-1} s^{-1}, where m aterial properties change rapidly over a small range of strain rates for bovine and human femoral bone. The exact strain rate histories were not reported, but the quoted values coincide with the strain rates observed in car crashes and those that are assumed to occur in the limbs of occupants during AV blasts. Further investigation is warranted as these observations stem from specimens from a single right femur from both a 24-year old male and a 3-year-old steer. The dynamic properties of cortical bone have been investigated using the Split Hopkinson Pressure Bar (SHPB); however the strain rate was not constant throughout the testing period (Katsamanis and Raftopoulos, 1990 and Lewis and Goldsmith, 1974). Adharapurapu et al. (2006) achieved a constant dynamic strain rate of 10^{3} s^{-1} in compression using sacrificial high work hardening alloy pulse shapers.

The first objective of this work is to discuss the experimental technique used to extract the constant strain rate dynamic properties of cortical bone. Secondly, to develop a constitutive relation that is capable of simulating both quasi-static and dynamic compressive bone response. Finally, to obtain the metrics of fracture risk which supplement the formulation of lower extremity IC.

EXPERIMENTS

METHODS: The present study is limited to bovine bone with ethical approval to perform experiments on animal material in vitro. Five cylindrical specimens (diameter 5.99 ± 0.07 mm, length 5.95 ± 0.12 mm) were turned from the mid-diaphysis of eleven bovine femurs. These bones were chosen for their ready availability, thick cortical cortex and relatively uniform alignment of the material direction to the bone axis along the mid-diaphysis. The specimens were placed in containers with water and frozen until 32 hours before testing, when they were defrosted and allowed to rehydrate (Adharapurapu et al., 2006).

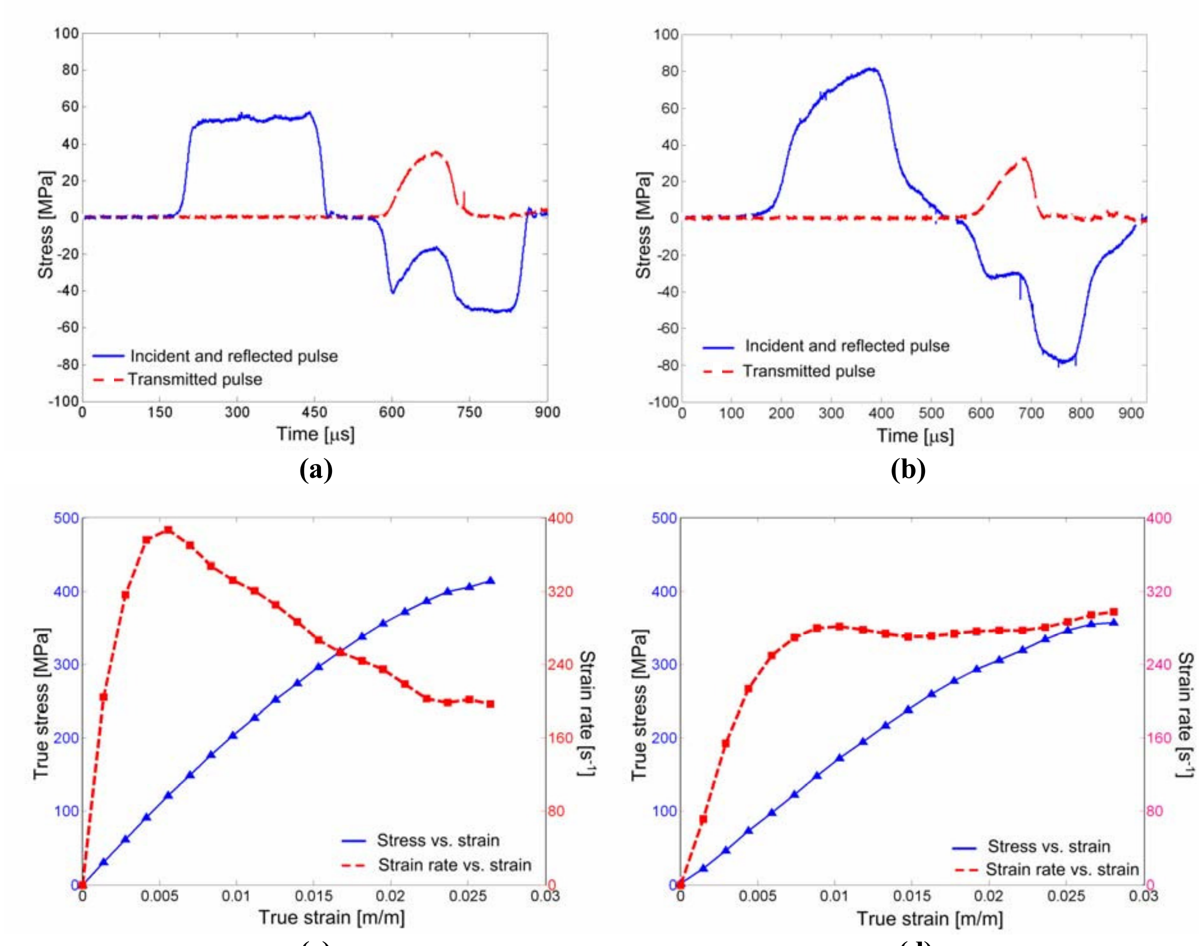


Fig. 1 - Incident, reflected and transmitted pulses from a conventional SHPB test with a (a) uniform area striker and (b) conical striker. Stress and strain rate vs. strain data with a (c) uniform area striker and (d) conical striker

Quasi-static compression tests were conducted on a Zwick screw driven machine with displacement control. The specimens were compressed at constant strain rates (between 10^{-4} s^{-1} and 10^{-2} s^{-1}), producing force-time and deformation-time histories. Dynamic tests were performed on a SHPB. The bars were steel, 2 m length, 20 mm diameter, with density of 7938 kgm^{-3} and a wave propagation speed of 5143 ms^{-1}. The use of a conventional uniform area striker (diameter 12 mm, length 650 mm) resulted in a varying strain rate, which implies that the measured bone properties are smeared across a range of strain rates (raw data shown in Figs. 1(a) and 1(c)).

A conical striker (length of 550mm and end diameters 19mm and 10mm) was used to shape the input pulse and achieve a nominally constant strain rate of 3×10^2 s^{-1} (Figs. 1(b) and 1(d)). The advantages of reusable conical strikers over sacrificial pulse shapers include test repeatability as well as improved control of the pulse shape as shown by Kumar et al. (2004).

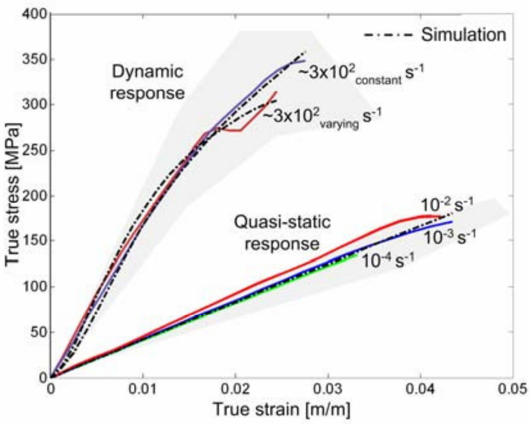
RESULTS: Experiments confirm that bovine bone fractures at a higher stress with increasing strain rate and bone density. There is a nominal 2.25% difference between the ranges of specimen wet density (2081 kgm^{-3} to 2194 kgm^{-3}) and dry density (2029 kgm^{-3} to 2145 kgm^{-3}). The stress-strain response (Fig. 2(a)) remains roughly consistent at all the quasi-static strain rates tested (σ_{ut}= 174.5 ± 26.7 MPa, ε_{ut}= 0.045 ± 0.006 m/m), but varies significantly at the dynamic strain rate (σ_{ut}= 376.1 ± 29.7, MPa, ε_{ut}= 0.024 ± 0.003 m/m), where the material response is more brittle. Non-uniform dynamic strain rates result in irregular stress-strain curves; however the stress-strain responses comprise the same corridor as the constant strain rate responses. It remains to determine the constant strain rate compressive properties of bovine bone at 10^{-1} s^{-1} to 10^1 s^{-1}.

CONSTITUTIVE MODEL AND FAILURE PROBABILITY

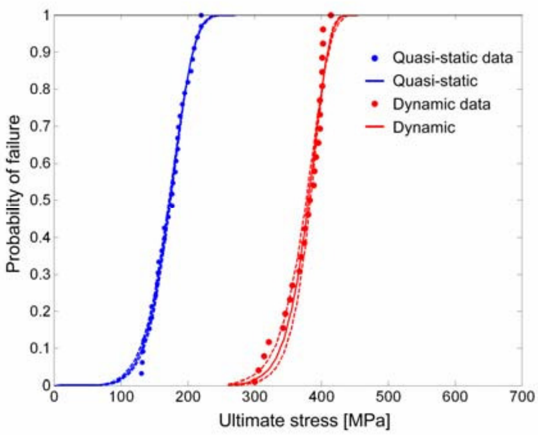
Shim et al. (2005) implemented a viscoelastic constitutive relation (Eq.1), which accurately models the strain rate dependent response of cancellous bone from the human cervical spine. The model comprises Maxwell and Voigt elements in parallel. The contribution of the Voigt damper is assumed to be non-linear. The model reported by Shim is herein implemented with the exception that the non-linearity of the viscous term is assumed to be a general power law with the form, $\eta_1 \dot{\varepsilon}^P$ whereas Shim et al. (2005) specified that $P = 0.5$.

$$\sigma(t) = k_1\varepsilon(t) + \eta_1\dot{\varepsilon}(t)^P + \int_0^t k_2\dot{\varepsilon}(\tau)e^{-\frac{k_2}{\eta_2}(t-\tau)}d\tau \qquad (1)$$

Twenty data points are extracted at equal intervals of strain from the stress, strain and strain rate histories of compression experiments (indicated by the marker positions in Figs. 1(c) and 1(d)). An inverse problem is solved to identify the five parameters of the viscoelastic model, k_1, η_1, k_2, η_2 and P (Table 1). In its current form the model simulates the average of the quasi-static and dynamic response corridors. Note that the greatest simulation error is expected for bone specimens that fail at a comparatively higher strain and lower stress in dynamic compression. Future work includes the expansion of the viscous term to accommodate a greater variety of strain rates.



(a) Stress strain corridors



(b) Failure probability curves

Fig. 2 - Experimental data and simulation models at quasi-static and dynamic strain rates

Pithioux et al. (2004) investigated the tensile ultimate stress of bovine cortical bone and expressed the probability with a Weibull cumulative distribution function (Eq.2).

$$P_R(\sigma_{ut}) = 1 - e^{-\left(\frac{\sigma_{ut}}{a}\right)^b} \tag{2}$$

The ultimate stresses of the quasi-static (33 samples) and dynamic compression experiments (22 samples) were used to generate curves of the probability of bone fracture (Fig. 2(b) and Table1). The ultimate stress corresponding to a 10% probability of dynamic bone failure is 3 times larger than the corresponding static stress for a similar risk. All bone specimens tested in quasi-static compression failed at a lower stress than any tested occurrence of dynamic failure.

Table 1. Identified material parameters

Viscoelastic model					Weibull curve			
k_1 [GPa]	η_1 [MPas^{-1}]	k_2 [GPa]	η_2 [MPas^{-1}]	P	a_{static}	b_{static}	a_{dynamic}	b_{dynamic}
4.01	0.98×10^{-6}	16.51	2.60	0.83	183.93	6.74	389.63	16.25

CONCLUSIONS

Bone specimens tested in quasi-static compression failed at a lower stress and higher strain than those tested dynamically. A conical striker with an appropriate diameter ratio enables measurement of constant strain rate dynamic bone response. The 1-D compression of bovine bone results in a viscoelastic response that depends non-linearly on strain rate. Prospective investigations include the constant strain rate properties and constitutive model of cortical bone at strain rates between (10^{-1} s^{-1} to 10^{1} s^{-1}).

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