Springer

KSME

Journal of Mechanical Science and Technology 25 (9) (2011) 2211~2215

www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-011-0602-x

Dynamic deformation behavior of bovine femur using SHPB †

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(Manuscript Received March 6, 2011; Revised April 25, 2011; Accepted May 26, 2011)

Abstract

This paper investigates the dynamic deformation behavior of bovine femur using a modified split Hopkinson pressure bar (SHPB) with a pulse shaper technique. The shape of the incident and reflected pulses modulated by the pulse shaper were measured and compared to each other to find a suitable thickness. The experiments were carried out under varying strain rates with a selected thickness for the pulse shaper. The effect of pulse shaper thickness on the rising time, stress-strain relationship, strain rates, and front and back-end stresses during the dynamic deformation period was investigated. Experimentally-obtained data were used to find a bilinear relationship between the failure stresses and the strain rates of bovine femur specimens in both longitudinal and radial directions. The failure strains, however, linearly decreased with increasing strain rates.

Keywords: Dynamic deformation; Split Hopkinson pressure bar (SHPB); Pulse shaper; Bovine femur; Failure stress; Failure strain; Strain rate

1. Introduction

Recently, many mechanical and materials researchers have been interested in the mechanical deformation behaviors of bone-materials by adopting varying constitutive models. However, they have not sufficiently emphasized that the dynamic mechanical properties are different from static values [1-3]. The split Hopkinson bar (SHPB) technique has been widely used to determine the mechanical properties of varying engineering materials, such as steels, aluminum alloys, copper alloys, and rubber materials deformed under high strain rate and different boundary conditions [4-7].

In this paper, a modified SHPB experimental setup with the pulse shaper technique utilized on metal specimens is used to measure the dynamic deformation behaviors of bovine femur specimens taken along the longitudinal and radial direction under varying strain rate conditions [8]. Some specific outcomes showing the effects of pulse shaper thickness on the rising time of the impact wave and dynamic equilibrium state in the bovine femur specimen during a short dynamic deformation period of about 60 μs are presented in detail. Furthermore, the relationship between failure stress and failure strain vs. strain rates of the bovine femur are investigated and empirical equations are formulated by using the obtained experimental data.

† This paper was recommended for publication in revised form by Associate Editor Mohammad Abdul Aziz Irfan

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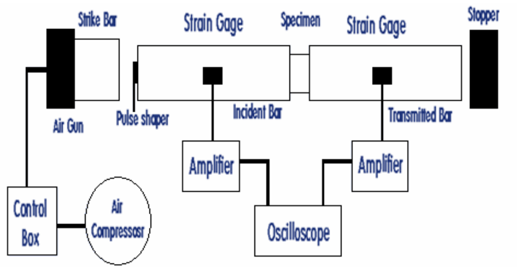


Fig. 1. Schematic of a modified split Hopkinson pressure bar setup with a pulse shaper.

2. Basic theory of SHPB technique

Fig. 1 shows the major components of the conventional SHPB experimental set-up.

A compressed air gun is used to accelerate the striker bar in Fig. 1 to impact the incident bar. The incident elastic compressive wave travels along the bar until it meets the specimen set between the incident and the transmitted bars. Part of the incident elastic wave is reflected from the bar-specimen interface because of the material impedance mismatch while part of the incident elastic compressive wave transmits through the specimen into the transmitted bar.

Fig. 2 shows a uni-axially loaded cylindrical specimen inserted between incident and transmitted bars. Note that F_1 and F_2 are equilibrated during a short dynamic deformation period of the order of 60 μs as shown in Fig. 8. Using equations of motion and the theory of elasticity, the dynamic strain and stress can be obtained by the strain gages attached on the bars as shown in Fig. 1 as follows:

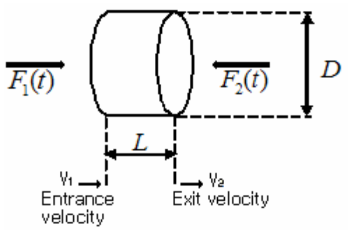


Fig. 2. A cylindrical specimen under uni-axial stress state.

$$\frac{d\varepsilon(t)}{dt} = -\frac{2C_0}{L}\varepsilon_R(t)$$

$$\varepsilon(t) = -\frac{2C_0}{L}\int \varepsilon_R(t)dt$$

$$\sigma_{AVG}(t) = \frac{EA_0}{2A}[\varepsilon_I(t)+\varepsilon_R(t)+\varepsilon_T(t)]$$

$$\sigma_S = E\frac{A_0}{A}(\varepsilon_T(t))$$

where L is the initial length of the specimen, C_0 ($C_0 = \sqrt{E/\rho}$, ρ is the mass density of pressure bar) is wave propagation velocity, A and A_0 are the cross-sectional areas of the pressure bar and the specimen, respectively, and E is the Young's modulus of the material of the pressure bars [6].

3. Experimental

3.1 Basic apparatus

The basic compressive SHPB apparatus used in this study consists of a striker bar, two pressure bars, an impact-loading facility, and the measuring instruments. A simplified schematic of the SHPB is shown in Fig. 1. The incident bar, transmitted bar and strike bar are made of Inconel 718, a hard steel alloy having Young's modulus of 211 GPa and is 16 mm in diameter. Each pressure bar is 1600 mm in length and the striker bar is 200 mm in length. A compressive air device is used to launch the strike bar to impact the incident bar. A Lecroy Wavepro 940 oscilloscope, Instruments Divison 2311 signal conditioning amplifier, a photo sensor, and a Graphic mini logger GL220 are used to measure the dynamic strain output, and the velocity of the striker bar.

3.2 Specimen

In this study, cylindrical specimens (taken from a raw material with dimensions of 60 mm x 35 mm x 20 mm) having a length of 4 mm and a diameter of 10 mm, as shown in Fig. 3, are used. The two orientations of the used specimens are shown in Fig. 4 [9].

The specimen dimensions are chosen to minimize the longitudinal and the radial inertia effects by noting that under L/D= $\sqrt{3}\,\nu/2$ (where L is length, D is diameter, and ν (=0.185 [10]) is the Poisson's ratio of the specimen) conditions, the inertia effects could be minimized even under non-uniform rate conditions [11].

Table 1. Material properties and impedances of bar and bovine femur.

	Inconel 718	Bovine femur
Density (kg/m^3)	8190	2010
Elastic modulus (GPa)	211	20 [12]
Wave speed (m/s)	5076	3154
Impedance (kg/mm^{2}s)	41.57	6.33

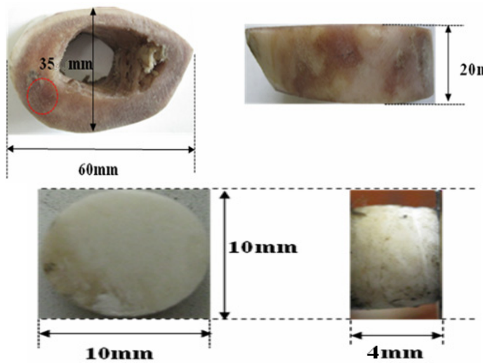


Fig. 3. Raw material and specimen geometries.

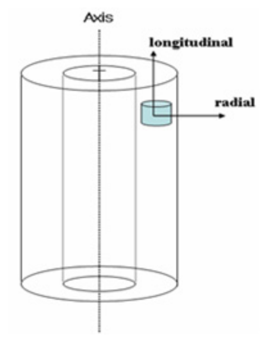


Fig. 4. Two orientations of specimens in longitudinal and radial directions.

Table 1 shows the material properties and impedance of bar and specimen materials.

3.3 Pulse shaper

The experimental evidence obtained during the last decade at the first author's laboratory recommended that pure copper may be used as a proper pulse shaper material. The proper geometry of the pulse shaper has been selected after carrying out multiple experiments with different thicknesses of pulse shaper material. Fig. 5 shows the typical compressive waves obtained without pulse shaper and with a 0.3 mm thick pulse shaper, respectively.

It is noted that the pulse wave is well modulated by the pulse shaper, and the rising time of the wave, defined as shown in Fig. 6 and obtained by using the pulse shaper, is longer than the one obtained without a pulse shaper.

Fig. 7 shows a variation of the rising time of the wave in the incident bar according to varying thickness of pulse shapers. The rising time R_t may be related to the thickness of the pulse

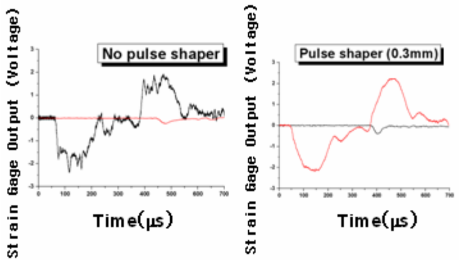


Fig. 5. Typical waves obtained without pulse shaper and with 3mm thick pulse shaper, respectively.

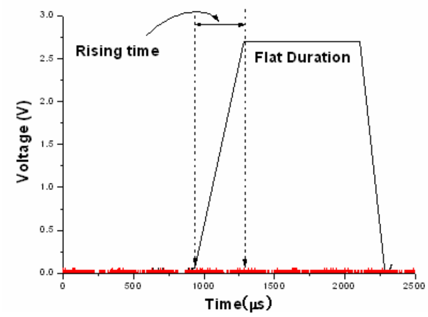


Fig. 6. A definition of rising time of a typical stress wave [16].

shaper by an empirical equation, e.g., $R_t = (0.77\text{-}t)/0.17$, where t is the thickness of the pulse shaper material, copper.

It was noted that the longer rising time promotes a better dynamic equilibrium in the specimen inserted between the two bars in the SHPB experiment [13, 14].

The proper thickness of the pulse shaper in this study was chosen as 0.3 mm, which results in a better dynamic stress equilibrium state as shown in Fig. 8. Fig. 8 clearly shows that the front end and back end stresses of the specimen are equilibrated in a better shape under the experiment carried out by using a 0.3 mm thick pulse shaper than other thicknesses.

Fig. 9 shows that the effect of thickness of a pulse shaper on the distribution of strain rate with respect to the true strain of a specimen is highly pronounced. Furthermore, it is confirmed in this study that more uniformly deformed specimens can be obtained under a varying strain rate loading condition by selecting a proper pulse shaper, as was discovered by the previous publications [15, 16].

4. Results and discussion

In this study, a modified SHPB experimental set-up with a pulse shaping technique described in the experimental section was successfully used to obtain the dynamic deformation behavior of bovine femur specimens oriented in two directions, i.e. longitudinal and radial as shown in Fig. 4.

The stress and strain curves experimentally obtained for the longitudinal and radial directions under varying strain rates are shown in Fig. 10(a) and (b), respectively.

Two results that overlapped for both longitudinal and radial

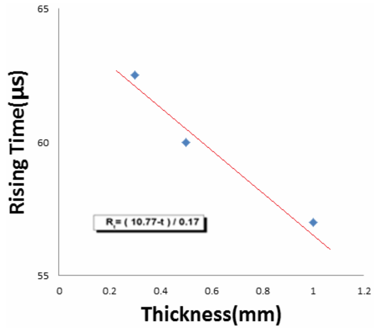


Fig. 7. Variation of rising time according to thicknesses of pulse shapers.

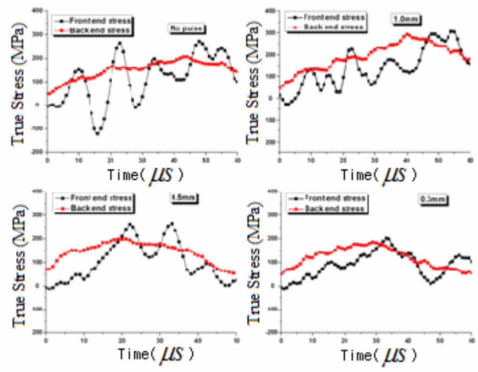


Fig. 8. Comparison of the dynamic equilibrium state in terms of the front end and the back end stresses, respectively: (a) No pulse shaper; (b) 1.0mm thick; (c) 0.5mm thick; (d) 0.3mm thick.

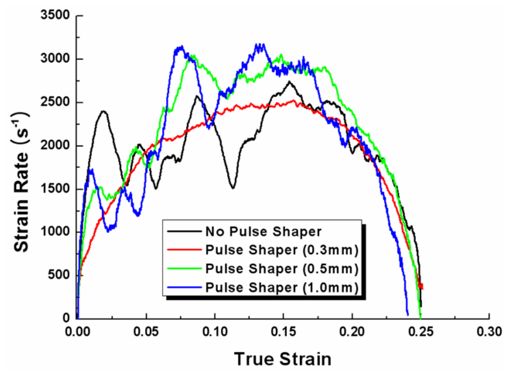
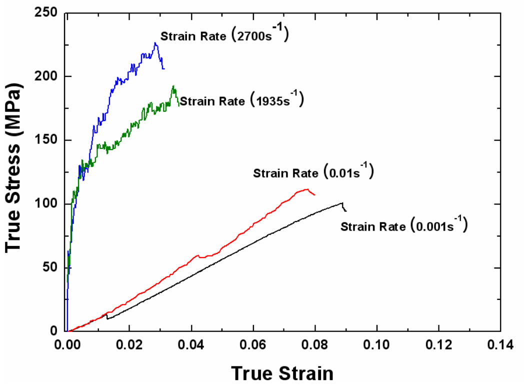
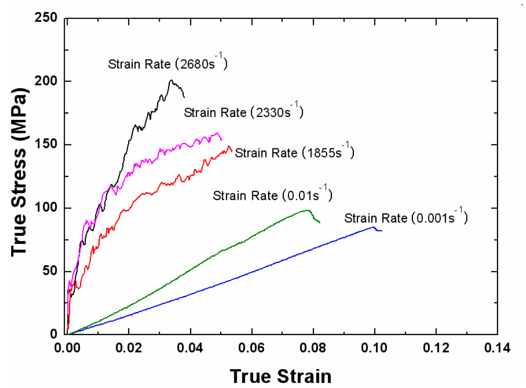


Fig. 9. Effect of the thickness of a pulse shaper on the distribution of strain rate with respect to the true strain.

directions under varying strain rates are shown in Fig. 11. Fig. 11 shows that longitudinally-oriented specimens had approximately 20% higher strength than the radially-oriented specimens under dynamic strain rates of the order of 2000/s. However, less than 10% increase in strength is noted in longitudinally-oriented specimens compared to the strength in radially-oriented specimens under the static strain rates of the order of 0.001/s indicating the effect of strain rate on the dynamically loaded bovine femur. Higher the strain rates result in greater increases of anisotropic behavior in the bovine fe-



(a)



(b)

Fig. 10. Stress-strain curves of bovine femur under the varying strain-rates: (a) in longitudinal direction; (b) in radial direction.

mur. This phenomenon is speculated to occur by the influence of the intrinsic anisotropic of the bovine femur and further details need to be investigated [9, 17, 18].

The general dynamic deformation behavior obtained in this study is, however, found to be similar to those obtained by other researchers [19].

A high dependence of the magnitudes of failure stresses on the strain rates is also noted. Furthermore, the general trend of a relationship between the failure stresses and the strain rates for specimens oriented in both longitudinal and radial directions are noted as similar to those obtained by Ferreira et al. [16]. This is plotted in Fig. 12. There also exists a bilinear relationship between failure stresses and strain rates on a semi-log scale chart that is similar to those obtained in varying metal cases obtained by many researchers around the world [20]. Fig. 13 shows, however, a linear relationship on a semi-log scale chart between the failure strains, ε_f and strain rates $\dot{\varepsilon}$. An empirical expression, $\varepsilon_f = 0.07 - 0.08\log\dot{\varepsilon}$, is obtained in this study.

5. Conclusions

In this experimental study, a modified SHPB experiment with pulse shaping technique was carried out for investigating

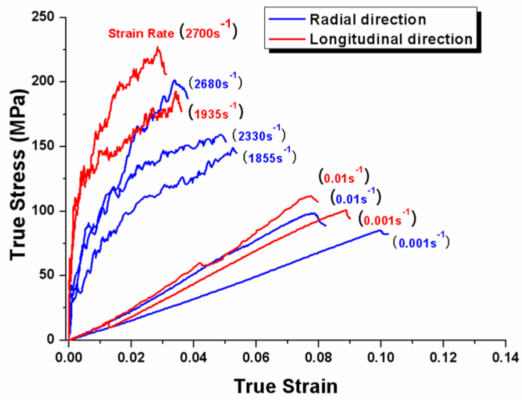


Fig. 11. Dynamic stress and strain curves of bovine femur specimens oriented in longitudinal and radial directions under varying strain rates.

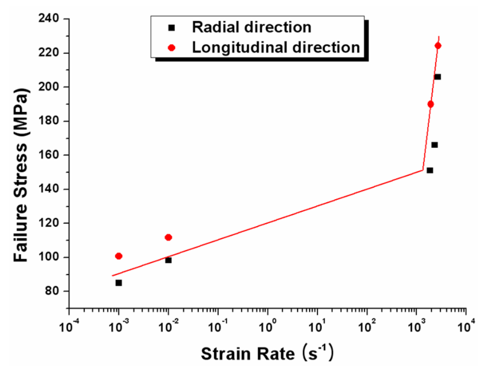


Fig. 12. Relationship between failure stresses of bovine femur specimens in longitudinal and radial directions and strain rates.

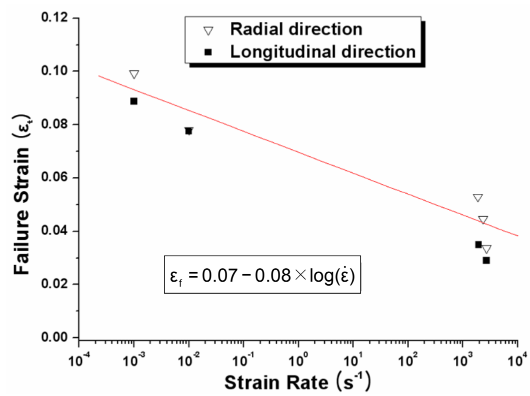


Fig. 13. Relationship between failure strains of bovine femur specimens in longitudinal and radial directions and strain rates.

the dynamic deformation behavior of bovine femur specimens. The following experimental results are obtained:

(1) Pulse shaping technique was successfully used to obtain dynamic stress equilibrium condition, and a relationship between the rising time (R_t) and thickness (t) of the pulse shaper was empirically formulated to be R_t=(10.77-t)/0.17.

(2) It is found that the strength of the bovine femur specimen is moderately dependent on the orientation of the speci-

mens. About 20% and 10% higher strength in longitudinally-oriented specimens than in radially-oriented specimens under dynamic strain rates of the order of 2000/s and the static strain rates of the order of the 0.001/s, respectively, are noted in this study.

(3) It is also found that the effect of strain rates on the deformation behavior of the bovine femur is very high.

(4) A bilinear relationship on a semi-log chart between failure stress and strain rates similar to those for varying metals is noted.

(5) A linear relationship on a semi-log scale chart between the failure strains and strain rates is obtained. The empirical expression $\varepsilon_f = 0.07 - 0.008 \log \dot{\varepsilon}$ is formulated in this study.

Acknowledgment

This work was supported by the Inha University Research Grant.

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