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The behavior of cancellous bone from quasi-static to dynamic strain rates with emphasis on the intermediate regime

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ABSTRACT

Previous studies, conducted using quasi-static and dynamic compression tests, have shown that the mechanical strength of cancellous bone is strain rate dependent. However, these studies have not included the intermediate strain rate (ISR) regime (1/s to 100/s), which is important since it is representative of the loading rates at which non-fatal injuries typically occur. In this study, 127 bovine bone specimens were compressed in 3 regimes spanning 8 distinct strain rates, from 0.001/s to 600/s, using three different devices: a conventional quasi-static testing machine, a wedge-bar (WB) apparatus and a conventional split Hopkinson pressure bar (SHPB) implemented with a cone-in-tube (CiT) striker and a tandem momentum trap. Due to the large sample size, a new robust automated algorithm was developed with which the material properties, such as the apparent Young's modulus and the yield and ultimate values of stress and strain, were identified for each individual specimen. A statistical summary of the data is presented. Finally, this study demonstrates that results obtained at intermediate strain rates are essential for a fuller understanding of cancellous bone behavior by providing new data describing the transition between the quasi-static and dynamic regimes.

1. Introduction

An improved understanding of cancellous bone fracture, along with detailed knowledge of cortical bone behavior, is necessary to advance human musculoskeletal modelling. Bone is composed of an inner core structure of cancellous bone, which hosts the bone marrow while supporting the shape of and transferring forces to the load bearing outer shell of dense cortical bone. For this reason the mechanical behavior of cancellous bone needs to be well understood and modelled. Several cancellous bone modelling approaches have been investigated, such as lattice homogenization (Goda et al., 2014), function based modelling (Pasko et al., 2011), random media (Padilla et al., 2003), finite element analysis (Hambli, 2013) and skeleton based models (Van Lenthe et al., 2006). Human bone is subjected to dynamic loadings on a daily basis with intensities that range from falls of elderly individuals (low level) to vehicle accidents (high level). Whichever model is used, its fidelity suffers from a lack of representative data. Literature studies have primarily focused on quasi-static compression loadings (up to 0.1/s, equivalent to a brisk run (Burr and Allen, 2013)), while more recently some researchers have developed dynamic compression tests (10^2–10^3/s (Shim et al., 2005; Pilcher et al., 2010; Johnson, 2010)). While some authors have reported studies on the mechanical response of cancellous bone at intermediate strain rates (from 1/s (Halgrin, 2009) to 10/s (Carter and Hayes, 1977; Linde et al., 1991)), there is a general lack of data for this range, which is mainly due to experimental difficulties experienced with traditional devices used in experimental mechanics, i.e. deformation velocities are too low for split Hopkinson bar set-ups using conventional strikers while the initial accelerations are too high for standard hydraulic testing machines with a cut-off frequency response in the order of 1 kHz. While some studies have reported trabeculae behavior to be unaffected by the strain rate (Szabó et al., 2011), the general consensus is that cancellous bone behavior is strain rate dependent (Guedes et al., 2006), and can vary with anatomic location, among other factors (Morgan and Keaveny, 2001; Hulme et al., 2007). Therefore, this rate dependence should be investigated at strain rates that are representative of typical accidents, such as falling (Burr and Allen,

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2013) or vehicle collisions (Hiermaier, 2007), in order to improve model predictions and contribute to the development of enhanced protection solutions. However, natural variations between specimens from different sources make comparisons difficult and there appear to be no published studies in which specimens from a common source were tested at strain rates from quasi-static, through the intermediate and up to the dynamic regime. Hence, the aim of the present study is to develop a robust method to characterize a large randomized set of cancellous bone specimens under compression loading in 3 different regimes equivalent at 8 distinct strain rates from 0.001/s to 600/s.

2. Materials and methods

2.1. Samples

In total, 127 cylindrical cancellous bone specimens (length: 7.5 mm; diameter: 10.5 mm) were extracted from 6 different femoral bones of 4 years old cattle. A slow cutting speed was used in order to avoid thermal degradation of the specimen and mechanical damage to the peripheral trabeculae. The anatomical positions and orientations were recorded during sampling (i.e., femoral head/great trochanter; sagittal, transversal, and frontal). The non-defatted bovine specimens were stored frozen in a saline solution (Linde and Sørensen, 1993) and thawed for 24 h at +5 °C before being brought up to room temperature prior to testing (Mitton et al., 1997). These tests were conducted within the animal welfare regulations and guidelines of South Africa.

2.2. Experimental technique

Compression experiments at various strain rates ($\dot{\varepsilon}$) were conducted using three different devices: A standard universal testing machine for low strain rate and two custom-made devices to compress cancellous bone material at elevated strain rates.

2.2.1. Universal testing machine

A Zwick 1484 universal testing machine was used for quasi-static compression ($10^{-3}/\text{s} < \dot{\varepsilon} < 10^{-1}/\text{s}$) of cancellous bone specimens up to the first collapses of trabeculae. Specimens were preloaded in order to minimize potential parallelism defects.

2.2.2. Wedge bar apparatus

A wedge bar (WB) apparatus (Cloete et al., 2014), illustrated in Fig. 1, was adapted to test cancellous bone.

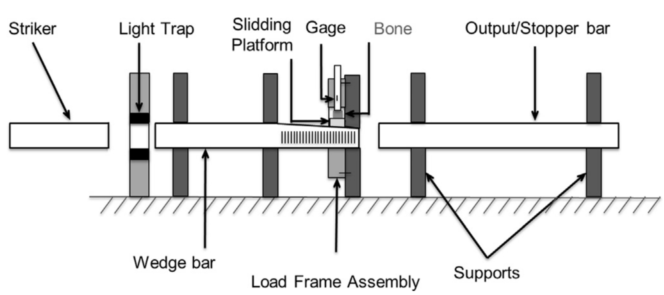

Fig. 1. Wedge bar apparatus system.

The wedge-bar layout consists of a load frame assembly and three 20 mm diameter steel bars: the striker, wedge bar and stopper bar, which are nominally identical except for a shallow wedge machined into the wedge bar. The wedge bar can move through the load frame assembly, which consists of a load frame, backing plate, load cell and sliding anvil, which has a lower surface machined to match the wedge. The length of wedge bars and ratios used vary from 1500 mm and 500 mm for 1/s to 500 mm and 200 mm for 10/s, but in all cases the maximum anvil displacement is only 1 mm, which is sufficient to fracture the specimen. Further details of the wedge-bar technique are given by Cloete et al. (2014).

During testing, the striker is fired from a gas gun and comes to rest through co-linear elastic impact upon the wedge-bar, which rapidly attains the desired test velocity. The wedge-bar motion, which is captured using a reflective object sensor, causes the sliding anvil to compress a small cylindrical specimen against the load cell, which captures the load history. The specimen deformation is inferred from the wedge bar motion, which is arrested through impact with the carefully positioned stopper bar to enable specimen recovery at a well-defined final strain (between 5% and 10%, i.e., after the elastic range but before densification of the broken trabeculae).

The wedge-bar is suited to the ISR regime. The compact load frame assembly, with no fluid components, rapidly attains equilibrium. The shallow wedge angle generates large forces with a large speed reduction, which ensures a near constant deformation rate because the wedge-bar kinetic energy is far greater than required to deform the specimen.

2.2.3. Modified Split Hopkinson Pressure Bar

In this study, a standard Split Hopkinson Pressure Bar (SHPB) apparatus was implemented with a cone-in-tube (CiT) striker and a tandem momentum trap, as shown in Fig. 2.

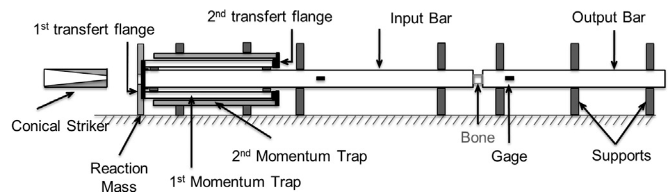

Fig. 2. SHPB set-up implemented with a CiT striker and a tandem momentum trap.

In a conventional SHPB test, a uniform striker, typically launched using a gas gun, impacts upon the input bar, causing a compressive stress wave to propagate along the bar and deform the specimen. Since the specimen has a lower strength and impedance than the two bars, it deforms while supporting only a portion of the load, which is transmitted into the output bar, while the remaining portion reflects back into the input bar as tensile stress wave. By capturing and analysing the three stress waves using the principles of elastic wave propagation, the strength of the specimen can be determined under dynamic loading conditions.

The use of the CiT striker allows for the constant strain rate compression of a bone specimen to a point just after the ultimate stress, after which the tandem momentum trap allows for whole specimen recovery without any subsequent reloading.

The CiT striker produces a trapezoidal stress wave with a steeply rising central slope that is tailored to compensate for the anticipated increase in the specimen response during a test and thus ensures a near constant strain rate compression. This, in turn, allows the impact velocity to be reduced, resulting in a strain rate in the upper IRS regime.

The tandem momentum trap consists of two nested co-axial aluminum tubes that are impedance matched to the input bar and placed in mutual contact using transfer flanges, as shown in Fig. 2. The function of the outer tube is to ensure that the inner tube remains in contact with the input bar by capturing the stress waves transferred through the inner tube during the striker impact. In this way, the inner tube is correctly positioned to capture the reflected pulse in the input bar after the specimen has been deformed and thus prevent further loading of the specimen.

For this study, a 20 mm diameter by 3.3 m long aluminum input bar was used with a 20 mm diameter by 2 m long magnesium output bar to increase the intensity of the output signal. The CiT striker and the momentum trap tubes were also made from aluminum of a similar grade to that of the input bar. Further details of the CiT striker and tandem momentum trap techniques are given by Cloete et al. (2014) and Prot and Cloete (2016), respectively.

2.3. Specimen distribution

Specimens were divided into three strain rate regimes: quasi-static (QS), intermediate (ISR) and dynamic (*D*), spanning 8 different strain rates (Table 1). Each specimen was carefully inspected before being incorporated into one of the sets. The specimens with observed architectural abnormalities, such as a machining error or the presence of cartilage, were removed from the study. Furthermore, if the recorded test signal had too much noise effects, the specimen was also discarded from the study. Specimens with similar anatomical locations and orientations were evenly divided between the specimen sets.

Table 1
Specimen repartition.

Regime	Quasi-static			Intermediate			Dynamic	
Strain rate	0.001/s	0.01/s	0.1/s	1/s	10/s	100/s	400/s	600/s
Apparatus	Zwick	Zwick	Zwick	Wedge	Wedge	SHPB	SHPB	SHPB
Number of specimens	10	9	24	22	14	18	20	10
		43			54			30