Links between microstructural properties of cancellous bone and its mechanical response to different strain rates.

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1 Introduction

Automobile accidents and sporting injuries may lead to osseous fractures. To reduce the number of road accidents and their societal costs, governments have partnered with car manufacturers to develop an overall road safety. To achieve this, researchers are working on improving the design of automotive structures. However, researchers must first quantify the risk of injury incurred during an impact. Indeed, in France osteoporosis is responsible of approximately 150 000 fractures per year. A better understanding of this fracture mechanism will aid in the design of protective features that will guard against fracture under these loading conditions.

Bone is generally divided into two micro-structural types: cortical and cancellous bone. Cortical bone is a compact bone, denser than cancellous bone and accounts for 80 % of the skeletal mass in the human body. Cancellous bone, also called trabecular or spongy bone has a porous structure that protects the bone marrow, acts as a core material to support the shape of thin layers of cortical bone and assist in transferring joint forces to the thick load bearing cortical bone layers.

Several studies have been able to make great progress on characterizing and modeling the behavior of cortical bone. Regarding the cancellous bone, much remains to be done and studies are mainly focused on quasi-static loadings cases **[1]**. In order to analyze and understand the mechanism of cancellous bone for speed ranges above the quasi-static regime, experimental work using SHPB have been. However, no modeling, including the different parameters of cancellous bone, have yet been developed to analyze and understand the mechanism of rupture of the cancellous bone.

This issue raises a keen interest in the scientific community, and this comes through in the work presented here. Indeed, the aim of this study is to characterize the mechanical properties of cancellous bovine bone for compression loading under different strain rates and identifying links with the microstructural description.

2 Methods

2.1 Microstructure Properties

Microstructural characterization is performed on 25 cylindrical specimens of distal parts of bovine femoral bones (diameter: 41mm, length: 15mm). The peripherical quantitative tomodensitometry technique (pQCT) was used to identify the microstructure properties of each frozen cylinder. Several architectural parameters of cancellous bone were computed with Image J software: BV/TV (Bone Volume/ Total Volume), Tb. Th (mean thickness of trabeculae), BS (Bone Surface), Conn.D (Connectivity Density or number of trabeculae per unit volume), DA (Degree of Anisotropy), SMI (Structure Model Index) and FD (Fractal Dimension).

2.2 Experimental Technique & Mechanical Properties

The samples were divided in three groups and three different tests were performed: quasi static tests (QS, ca 0.001 s^{-1}), dynamic tests (D, ca 1000 s^{-1}) and confined dynamic tests (CD, ca 1500 s^{-1}). Mechanical parameters identified are: E (Apparent Young's modulus), ε_{Max} (maximum strain), σ_{Max} (yield stress) and σ_p (Plateau stress).

2.3 Statistical Analysis

Kruskal-Wallis statistical test assessed that the samples are from the same distribution. Then, the Mann–Whitney statistical test was performed to identify the influence of the boundary conditions. Finally, Spearman statistical test was used to highlight correlations between mechanical and microstructural properties.

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3 Results and Discussion

3.1 Influence of the architectural properties on quasi-static loading mechanical properties.

ε_{Max} is found to have significant correlations with Conn. D & DA. σ_{Max} correlates with BV/TV, Tb.Th & BS and σ_p with BV/TV, BS, Conn.D. Similar results were found in litteratury. No correlation was found in regards with E. Follet **[1]** and Mittra et al. **[2]** found E to be correlated with Tb.Th and BV/TV. This difference could be explained by the fact that they were working with other species. For Syahrom **[4],** who were testing on bovine bone too, shows that E correlates well with BV/TV. The lack of similar correlation in the present study could be explained because Syahrom cleaned the bone marrow from the specimens.

The table 1 presents Spearman's test results and a highlighting of correlations between mechanical properties (dynamic and quasi-static loadings) and architectural parameters.

	BV/TV	Tb.Th	BS	Conn.D	DA	SMI	FD
E	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
ε_{Max}	*NS*	*NS*	*NS*	*	*	*NS*	*NS*
σ_{Max}	*	*	*	*NS*	*NS*	*NS*	*NS*
σ_P	*	*NS*	****	*	*NS*	*NS*	*NS*

Table 1 : a) Quasi-Static loading correlations

	BV/TV	Tb.Th	BS	Conn.D	DA	SMI	FD
E	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
ε_{Max}	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
σ_{Max}	*	*NS*	**	*NS*	*NS*	*NS*	****
σ_P	**	*	**	*NS*	*	*	*

Table 1: b) Dynamic loading correlations NS: Not Significant, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, **** $p < 0.0001$

3.2 Influence of the architectural properties on dynamic loading mechanical properties

σ_{Max} is having a significant correlation with BV/TV, BS, FD and σ_p with BV/TV, BS, DA, SMI and FD. Dynamic correlations were found to be relevant in comparison with Halgrin work **[5]**.

3.2 Influence of the architectural properties on confined dynamic loading mechanical properties

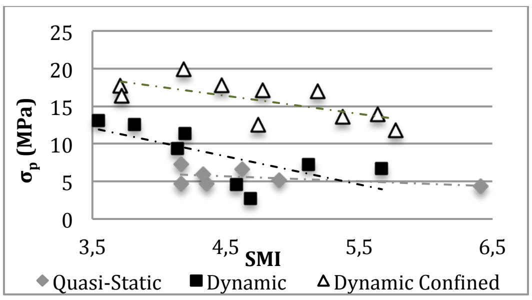

Figure 1: Correlation for the plateau stress

No correlation is significant for E or σ_{Max}. As for dynamic loading, correlations for confined dynamic loading are established: σ_p correlates with BV/TV, BS, and SMI (Figure 1). However for confined dynamic loading, ε_{Max} is found correlated with FD.

The differences between dynamic loading and confined dynamic testing, especially for DA correlation, could be explained by the bone marrow influence and the limit conditions of the confinement.

4 Conclusions

Results prove that architectural parameters such as BV/TV, BS, Tb.Th and DA can predict bone stiffness and strength, at different strain rate, through imaging, as they shown significant correlation with mechanical response parameters. Moreover, the additional correlation of SMI and FD regarding dynamic loading and Conn.D regarding quasi-static loading could improve the prediction.

Finally, this study permitted to underlines in what extent the marrow will influence the global behaviour of cancellous bone.

An analytical model of the rupture mechanism via imaging acquisition method could then be developed based on the previous investigation results. Parameters identified as "main" parameters *i.e* having a significant influence on mechanical behaviour will be inputs for the running mode.

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