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To cite this version :

Marianne PROT, Dominique SALETTI, Stéphane PATTOFATTO, Valérie BOUSSON, Sébastien LAPORTE - Correlations between cancellous bone architecture and its dynamic behaviour - In: 4th International Conference on Impact Loading of Lightweight Structures, South Africa, 2014-01-12 - ICILLS - 2014

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Correlations between cancellous bone architecture and its dynamic behaviour

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Abstract

Previous studies showed that *in vivo* evaluation of the fracture risk of cancellous bone can be assessed by identifying the relationships between its microarchitecture description extracted from clinical imaging and its mechanical properties. The mechanical properties under dynamic loadings (with and without confinement) were obtained and compared to quasi-static ones. The architectural parameters of each specimen were extracted from pQCT images and split into four groups: geometry, topology, connectivity and anisotropy. Results show that architectural parameters are strong determinants of mechanical behaviour for the different applied boundary conditions.

Keywords: Cancellous bone, Dynamic behavior, Confined test, Microstructural Parameters

1. Introduction

Automotive accidents and osteoporosis disease may lead to bone fractures. According to the WHO [1], 2010 marks the transition between two important decades: the decade for bone and ligament and the decade for road safety. In 2004, the WHO reported that in the Americas and Europe, osteoporosis was responsible for about 3 million fractures per year, 1.3 million deaths and 20 to 50 million injuries. Researchers must quantify the risk of injury on living tissues during an impact. Eventually, researchers will work on vulnerable people such as old people or osteoporotic ones driving.

A better understanding of the bone fracture mechanisms could help to improve the design of the safety systems. If the strength of bone mainly depends on the cortical bone, the rupture of the cancellous bone, hosting the bone marrow, could lead to vascular problems or local irreversible damage. The study of the mechanical behavior of the cancellous bone is mostly focused on quasi-static compressive tests [2], for different boundary conditions or with or without bone marrow [3]. Recent experimental works have shown a strain-rate dependency of the cancellous bone mechanical behavior [4] and the influence of the bone marrow for high strain rate loading [5]. Even if studies have demonstrated the link between cancellous bone microarchitecture parameters, bone mineral density and mechanical parameters [6], cancellous bone fracture via architecture characterization has not been fully assessed, especially under high strain rate loading.

The aim of the present study is to identify the correlations between cancellous bone architecture and its dynamic behavior for different boundary conditions.

2. Materials and methods

2.1 Samples

Thirty-two distal segments of bovine femoral bones were used for this study (72 hours post mortem) and frozen at -20°C. A diamond slitting wheel was used to isolate two cylinders of cancellous bone from each frozen bone in the sagittal plane (diameter 41 mm and thickness 14 mm). Specimens were then preserved in vacuum-sealed plastic bags; they were slowly thawed for 12 hours at 5°C and exposed to room temperature (approximately 24°C) prior to mechanical testing.

2.2 Experimental technique and mechanical properties

Samples were divided into three tests series. In the first group, eight specimens were loaded using a quasi-static compression testing Instron machine with a constant nominal strain rate of 0.001 s^{-1} . For the remaining groups, twenty-four specimens underwent dynamic loading using a Nylon Split Hopkinson Pressure Bar system (SHPB). Two different boundary conditions were applied for these dynamic tests: compression tests without confinement for 12 specimens (D, Strain-Rate ca. 1000 s^{-1}) and confined dynamic tests for the 12 remaining specimens (CD, Strain-Rate ca. 1500 s^{-1}). The confined tests were used to limit the radial expansion of the bony structure and the expulsion of bone marrow. Mechanical properties were identified (Figure 1) by an automatic process. The apparent Young Modulus E_{app} was identified by fitting the slope of the second third of the linear part of each curve using a least square method. The ultimate parameters were identified at the maximum stress before trabeculae densification while yield parameters enhance the end of the elastic behavior. The plateau stress was identified where the impact energy is absorbed *i.e.* in a region of the stress-strain curve at nearly constant stress.

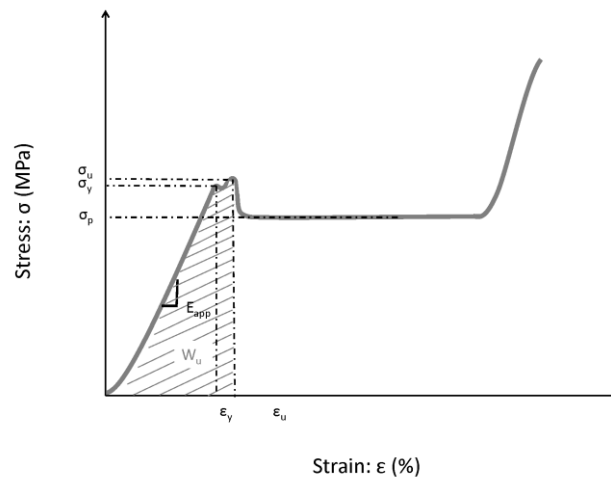


Figure 1: Identification of mechanical parameters

2.3 Microstructure properties

A peripheral quantitative computed tomography technique (pQCT) was used to identify the microstructure properties of each specimen. Eighteen architectural parameters of cancellous bones were selected and computed with BoneJ from the DICOM files. Parameters were divided into four groups: architectural descriptors of geometry and morphology, topology, connectivity and anisotropy. Parameters, units and groups are presented in Table 1.

2.4 Data analysis

The Kruskal-Wallis test was used to assess if there is a difference between the 3 groups of specimens. Mann-Whitney statistical test was performed on mechanical parameters in order to evaluate the influence of strain rate and boundary conditions. Spearman statistical test was used to highlight correlations and inter-correlations between architectural and mechanical parameters. A p-value of 0.05 was chosen as the upper threshold of significance.

3. Results & Discussion

3.1 Mechanical response under high strain rate

Mean values and standard deviations of mechanical parameters are given in Table 1. Data published [7], for bovine cancellous bone solicited to these strain rates set the same magnitude of individual variation.

Apparent Young's modulus values were lower under high strain rates than under quasi-static loadings. To explain this unexpected effect, investigations were performed on about potential errors (elastic wheel point due to local non planarity area of bar / specimen interface, temperature, difference of testing between machine used for high strain rate and low strain rate loading, difficulty to determine Young's modulus with SHPB measurements), but any explanation can be proposed for this result.

Table 1: Mean values and Standard Deviation (italic) of mechanical parameters. D: Dynamic, CD: Confined Dynamic, QS: Quasi-Static.

	D		CD		QS	
E_{app} (MPa)	135	(22)	329	(57)	510	(190)
ϵ_y (%)	7.68	(1.13)	5.74	(1.07)	4.78	(3.82)
ϵ_u (%)	8.84	(1.26)	6.88	(1.57)	4.84	(3.82)
σ_y (MPa)	10.93	(2.64)	18.56	(1.09)	12.62	(2.63)
σ_u (MPa)	11.84	(3.43)	20.57	(1.32)	12.64	(2.63)
σ_p (MPa)	8.46	(3.80)	13.78	(2.64)	5.55	(1.39)
W_u (J)	8.2	(2.9)	13.00	(2.9)	5.9	(3.6)

Since the p-value of the Mann Whitney test is always less than the threshold of 0.05 (maximum p-value of 0.006 for comparison between the quasi-static group and the dynamic one and maximum p-value of 0.006 for comparison between the dynamic group and the confined dynamic one), one of the two samples of different strain rate loadings/boundary conditions shows a significant difference.

3.2 Microstructure properties

Mean values and standard deviations of microstructure parameters are given in Table 2. Architectural values have been found relevant to the literature [8].

Table 2: Description, mean values and standard deviation (italic) of architectural parameters.

Family	Parameter	Description	Unit	Mean Value	(SD)
Geometry & Morphology	BS	Bone Surface	mm ²	6849	(4940)
	BV	Bone Volume	mm ³	3168	(912)
	BV/TV	Bone Volume/ Total Volume	%	0.20	(0,07)
	BV/TV _{min}	Extremal values of Bone Volume/Total Volume		0.15	(0,07)
	BV/TV _{Max}			0.38	(0,11)
	Tb.Th	Mean thickness of trabeculae	mm	0.30	(0,04)
	Tb.Th _{min}	Extremal values of Mean thickness of trabeculae		0.24	(0,04)
	Tb.Th _{Max}			0.34	(0,06)
	Tb.Sp	Trabecular Separation	mm	0.31	(0,09)
	Tb.Sp _{min}	Extremal values of Trabecular Separation		0.15	(0,06)
Tb.Sp _{Max}			0.38	(0,13)	
	Conn.D	Connectivity Density or number of trabeculae per unit volume	/mm ³	2.39	(0,67)
Topology	FD	Fractal Dimension		2.72	(0,02)
	SMI	Structure Model Index		4.38	(0,93)
Connectivity	N.Nd	Number of Junctions	/mm ³	3.03	(0,63)
	N.Jnv	Number of Junction Voxel, i.e. number of voxels labelled as being in a junction with more than 2 neighbors	/mm ³	11.20	(3,73)
	N.Slv	Number of Slab Voxel, i.e. number of voxels labelled as being in a junction with 2 neighbors	/mm ³	13.59	(2,32)
	N.Tp	Number of Triple Point, i.e. Number of Junctions with 3 branches	/mm ³	1.77	(0,31)
	N.Qp	Number of Quadruple Point, i.e. Number of Junctions 4 branches	/mm ³	0.69	(0,15)
Anisotropy	DA	Degree of Anisotropy		0.31	(0,06)
	MIL ₁	Mean Intercept Length : Principal Direction	mm	0.56	(0,13)
	MIL ₂	Mean Intercept Length 2	mm	0.51	(0,14)
	MIL ₃	Mean Intercept Length 3	mm	0.39	(0,13)

Since the p-value of Kruskal-Wallis test is always higher (minimum value: 0.44) than the significance level $\alpha=0.05$, the null hypothesis, samples coming from the same population, cannot be rejected (minimum risk of rejecting the null hypothesis is 41.5 % for bone surface study).

3.3 Relationships between mechanical properties and microstructural parameters

Some results regarding the correlation between connectivity and anisotropy parameters and mechanical parameters are reported in Table 3.

No correlation was identified with regards to E_{app} under quasi-static loading. The absence of correlation with DA was also found in the literature [8]. Similar correlations were observed between E_{app} for unconfined and confined dynamic loading and MIL₁, MIL₂, MIL₃. Correlations were also observed at different strain rates between the Plateau Strain and the Number of Slab Voxel.

Table 3: Spearman's tests results* for significant correlation i.e. $p < 0.05$ & *: $p < 0.0001$**

D: Dynamic, CD: Confined Dynamic, QS: Quasi-Static.

		Nd.Nd	N.Nd	N.Jn _v	N.Sl _v	N.Tp	N.Qp	DA	MIL ₁	MIL ₂	MIL ₃
E_{app}	QS										
	D		*		*	*	*		*	*	*
	CD	*			*				*	*	*
σ_p	QS	***	*		***	*	*		***	***	***
	D	*			***			*	***	***	***
	CD		*	*	***	*	*		***	***	***

4. Conclusions

This study examined in what extent the relationship between architectural parameters from clinical-CT and mechanical response parameters at low strain rate (0.001 s^{-1}) can be extrapolated for high strain rate loading (1000 s^{-1}). The compression experiments were performed using two different boundary conditions (confined and non-confined). This work presents a new approach to cancellous bone mechanical prediction under dynamic loading via architectural parameters description: the relative usefulness of architectural parameters has been highlighted with regard to the prediction of mechanical parameters. Our data suggest that a model based on the imaging acquisition method (i.e. architectural description) can be built for the prediction of daily risks or rupture mechanism in the case of a known magnitude trauma such as a car accident.

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