



**HAL**  
open science

## Crack propagation experiment on long human bone

Y Godio-Raboutet, Théophile Kurtz, Claude Boulay, J.-L Tailhan

► **To cite this version:**

Y Godio-Raboutet, Théophile Kurtz, Claude Boulay, J.-L Tailhan. Crack propagation experiment on long human bone. 46e Congrès de la Société de Biomécanique, Oct 2021, Saint-Etienne, France. <hal-05349627>

**HAL Id: hal-05349627**

**<https://hal.science/hal-05349627v1>**

Submitted on 5 Nov 2025

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

# Crack propagation experiment on long human bone

Y. Godio-Raboutet<sup>a</sup>, T. Kurtz<sup>a\*</sup>, C. Boulay<sup>c</sup> and J.-L. Tailhan<sup>b\*</sup>

<sup>a</sup>Aix-Marseille Université, Université Gustave Eiffel, LBA, Marseille, France; <sup>b</sup>Université Gustave Eiffel, MAST-EMGCU, Marne la Vallée, France; <sup>c</sup>CME, France

**Keywords:** experiment; cortical bone; crack propagation; fracture mechanisms; natural geometry

## 1. Introduction

Mechanical testing on complex media such as bone for crack propagation is a field of investigation in which numerous studies have been published (Giner et al. 2017; Granke et al. 2016; Zioupos and Currey 1998). Tests are often performed on small samples with controlled geometry. It ensures reasonable control of boundary conditions, but the main counterpart remains with the small dimensions of the samples, requiring dedicated devices (Choi et al. 1990; Zioupos and Currey 1998). An experimental procedure has been developed to carry out a crack propagation test on long human bones. This choice is justified by a mean of comprehension of macrocracks propagation in human cortical bone, taking into account their specific geometry. The scale of the experiment has to remain consistent with the one of future modelling as this work is part of a project focusing on developing a probabilistic model to predict bone cracking. The experiment is a three-point bending test performed on a notched shaft segment of bone taken in the mid-diaphysis of a human femur. The test is controlled by the notch opening displacement (NOD). Only the cortical part of the bone is considered here.

The paper presents the experimental cracking test for macrocrack propagation in long human femoral bones, describing equipment and methods. Some typical results are given. Then, comments and conclusions are drawn.

## 2. Methods

### 2.1 Preparation and preservation

Femurs, cut in the mid-diaphysis to get 180 mm long specimens, are retrieved from human cadavers preserved in zinc chloride. Tissues are cleaned by hand without chemicals, and trabecular bone is removed. Then, a notch is machined using a 200  $\mu\text{m}$ -thick saw to initiate and localise the macrocrack by stress concentration. Specimens are stored at  $-18^{\circ}\text{C}$  and put at  $4^{\circ}\text{C}$  the day before testing. Note that each hollow bone is also scanned with a medical scanner before testing. Thus, sample geometry can be

reconstructed in further work and used for numerical simulations.

### 2.2 Experimental setup

The three-point bending test (155 mm span with load applied in the middle of the bone) is performed on an MTS Landmark 370.10 hydraulic press equipped with a 15 kN sensor for force measurement. The experiment focuses on pure mode I cracking and aims to analyse the macrocrack's behaviour initiated by the notch under loading. A non-contacting Displacement Measuring System KAMAN KD-2300 (range 0 to 2 mm) bridges the notch and measures the crack opening.

Steel prismatic supports are glued to the specimen on each side to diffuse stresses at the contact points. One of those supports is designed to sliding in the bone axis with a polished surface and a grease layer to minimize friction. Sensor brackets are glued to the specimen in the axis of the steel supports, thanks to a 3D-printed device. They are designed in aluminium to suppress electromagnetic interferences. Once glued, the specimen is placed on the press, and the sensor is mounted on the brackets.

### 2.3 Experimental procedure

The experimental procedure mainly consists of about ten unloading/reloading cycles controlled by NOD (thanks to the Kaman sensor) and performed every 200  $\mu\text{m}$  of NOD up to 2 mm at a rate of 36  $\mu\text{m}/\text{min}$ . The unloading part of the cycles is controlled by force down to 15 N in 5 minutes. After the last unloading, the force goes back to 0 N. A camera is placed in front of the press rear face to take pictures before unloading and at the same NOD level while reloading. It aims to give a qualitative view of crack propagation.

## 3. Results and discussion

Fig. 1 gives two examples of force versus NOD global responses of two bone segments taken from the same human subject (92 years old woman) and with two different notch lengths.

In the pre-peak part, the curves show nonlinearities, a sign of the Fracture Process Zone (FPZ) formation by nucleation of microcracks (Vashishth et al. 1997). At the curves' peaks, the macrocrack localises due to the

microcracks' coalescence in the FPZ. The post-peak corresponds to the propagation of the macrocrack and its associated FPZ. The result is a structural softening behaviour.

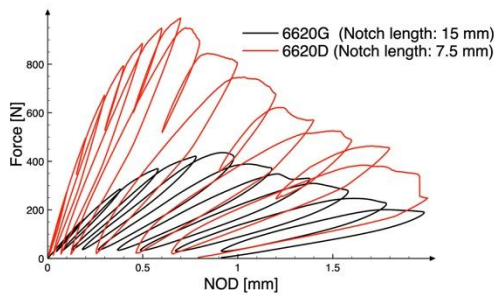


Figure 1 Force versus NOD curves

The analysis of the unloading/reloading cycles provides information on the cracking process. Their global slope reveals the structural effects of cracking processes on bones. The states of residual openings illustrate the irreversibility of the phenomena. The shape of the cycles shows a significant hysteresis consequence of dissipative phenomena.

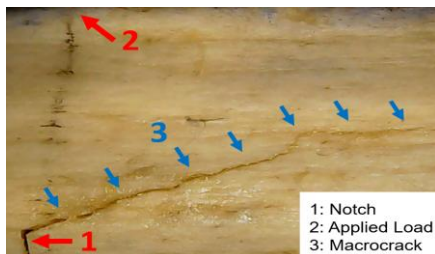


Figure 2 Macrocrack at the final state

The results clearly show that cracking is the prominent phenomenon involved in the failure of the specimens. The pre-peak nonlinearity is immediately accompanied by structural damage, characteristic of the presence of microcracking. Plasticity may occur in the material. However, it should remain at a sub-microscopic scale and confined at the crack tip. During the unloading/reloading cycles, friction phenomena between the crack lips, maybe amplified by the release of some internal stresses (linked to the bone remodelling undergone during the subject's life (Yamada and Tadano 2010), can explain the presence of hysteresis and the main part of the residual NOD.

Figure 2 shows an example of a crack profile at the end of a test. All performed tests (different subjects and different initial notch lengths) lead to the same conclusion: even if the longitudinal osteonal structure tends to deviate transversal cracks, one can presume that the effect of the material anisotropy (the longitudinal toughness is largely lower than the transversal one) may play a role in the final crack

orientation. However, this aspect must still be confirmed with further experiments.

## 4. Conclusions

The three-point bending test presented allows studying the crack propagation in a notched segment of femoral bones. The experiments give valuable information on processes and mechanisms during the macrocrack propagation. Current results (5 femurs from 3 female subjects) and future ones will constitute a robust database necessary to develop our future probabilistic cracking model. Complementary microscopic analyses will also provide additional information on the material microstructure and its effect on the macrocrack path. The statistical link between the characterisation of bone heterogeneity and mechanical properties will be a crucial point for the model.

## Acknowledgements

The authors acknowledge L. Thollon, P. Rossi and P.-J. Arnoux for their precious help and support on this work.

## References

- Choi K, Kuhn JL, Ciarelli MJ, Goldstein SA. 1990. The elastic moduli of human subchondral, trabecular, and cortical bone tissue and the size-dependency of cortical bone modulus. *Journal of Biomechanics*. 23(11):1103–1113.
- Giner E, Belda R, Arango C, Vercher-Martínez A, Tarancón JE, Fuenmayor FJ. 2017. Calculation of the critical energy release rate  $G_c$  of the cement line in cortical bone combining experimental tests and finite element models. *Engineering Fracture Mechanics*. 184:168–182.
- Granke M, Makowski AJ, Uppuganti S, Nyman JS. 2016. Prevalent role of porosity and osteonal area over mineralization heterogeneity in the fracture toughness of human cortical bone. *Journal of Biomechanics*. 49(13):2748–2755.
- Vashishth, D., Behiri, J.C., Bonfield, W., 1997. Crack growth resistance in cortical bone: Concept of microcrack toughening. *Journal of Biomechanics* 30, 763–769.
- Yamada, S., Tadano, S., 2010. Residual Stress Around the Cortical Surface in Bovine Femoral Diaphysis. *Journal of Biomechanical Engineering* 132, 044503.
- Ziopoulos P, Currey JD. 1998. Changes in the Stiffness, Strength, and Toughness of Human Cortical Bone With Age. *Bone*. 22(1):57–66