Implementation of a Strain Rate Dependent Human Bone Model

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Summary:

Strain rate dependency of mechanical properties of cortical bone has been well demonstrated in literature studies. Nevertheless, the majority of these studies have been done on nonhuman bone and at lower magnitudes of strain rates. The need for a mathematical model which can describe the mechanical behavior of bone at lower strain rates as well as higher ones is essential. A human finite element model THUMS (Total Human Model for Safety) [1], developed by Toyota R&D Labs and the Wayne State University, USA has been applied for this study. This work proposes an isotropic elastic-plastic material model of cortical bone where rate effects have also been considered.

Keywords:

Strain rate dependency, cortical bone, THUMS

1 Introduction

Bones, rigid organs that constitute a major part of the endoskeleton of the human body are composed of a cellular component and an extra-cellular matrix. The cellular component is made of osteoblasts, bone-forming cells, osteoclasts, bone-destroying cells, and osteocytes, bone-maintaining cells which are inactive osteoblasts trapped in the extracellular matrix. The matrix, which is responsible for the mechanical strength of the bone tissue, is formed by an organic and a mineral phase. The organic phase is mainly composed of collagen fibres and the mineral phase of hydroxyapatite crystals.

Bone is generally classified into two types, cortical bone also known as compact bone, and trabecular bone or cancellous bone. The classification is based on the porosity and the unit microstructure. Cortical bone is one of the two types of osseous tissue that form bones. Cortical bone forms the cortex or the outer shell of most bones. It is much denser than cancellous bone [2]. Cancellous bone is the later type of the osseous tissue. It has a higher surface area but is less dense, softer and less stiff in comparison to the cortical bone.

A numerous number of studies have been performed on understanding and analysing the mechanical properties of bone and the mechanism of its fractures [3-7]. Determination of the mechanical properties of bones is done on the same methods used in other structural materials. The mechanical behaviour of bone is affected by its mechanical properties, its geometry, the loading direction and mode and loading rate. James McElhaney was one of the premiers who performed an experimental study on dynamic response of bone in 1966 [3]. He took human bone specimens from the femur of a 24-year old white male, embalmed the sample with a mixture of formalin, phenol, alcohol and glycerin and carried out uniaxial compression tests at rates ranging from 0.001 to 1500 s^{-1}.

Recently, Hansen and Zioupos [4] did an extensive study on the strain rate effect on mechanical properties of human cortical bone. In the mentioned study femoral cortical bones of a 51 year old donor (male) was tested longitudinally at strain rates between 0.14-29.1 s^{-1} in compression and 0.08-17 s^{-1} in tension.

The present paper describes a strain-rate dependent material model which stems from the experimental data.

2 FE Model of THUMS

The THUMS (Total Human Model for Safety) has been developed by Toyota Central Research and Development Labs, Japan in collaboration with Wayne state university [8]. THUMS represents a 50% American male with a body size of 175 cm and 77 kg weight. The whole structure of the THUMS model is shown in Figure 1. The model contains about one hundred eight thousand nodes and one hundred forty five thousand elements that include 67,800 solid elements, 74,000 shell elements and 3,200 beam elements.

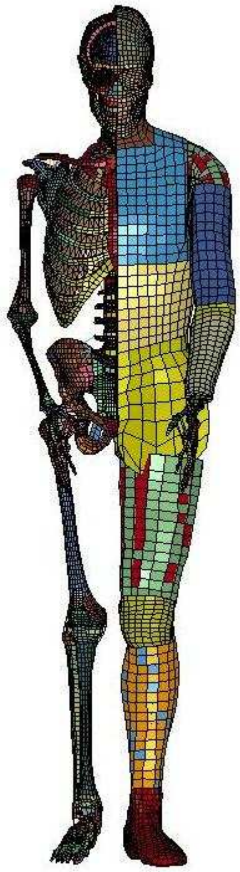

Figure1. Pedestrian AM-50 THUMS model

3 Validation of the FE model of Tibia

The lower extremity in THUMS consists of,

1. Foot Bone
2. Tibia
3. Fibula
4. Patella
5. Femur
6. Ligaments
7. Muscles, Tendons
8. Skin, Soft Tissue

The FE model of Tibia from THUMS model is extracted for further investigations on material modelling. Prior to the modelling, the Tibia is validated against the quasi-static three-point bending experimental results reported by Yamada [9]. The test setup for the simulation is shown in Figure 2.

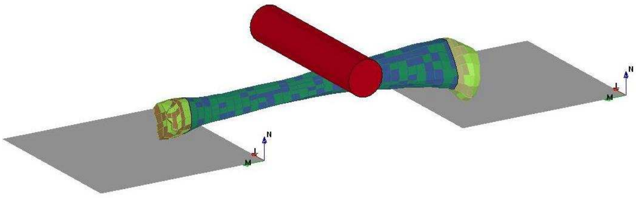

Figure 2. Three-point bending test of Tibia

Figure 3 shows the comparison between the simulation results and experimental ones verified by Yamada. The simulation results are clearly in good agreement with the test results for force-deflection curves.

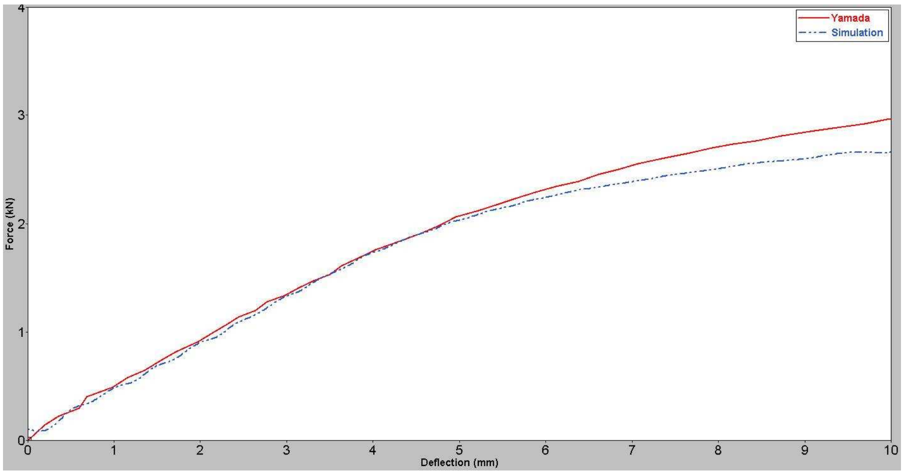

Figure 3. Comparison of load-deflection response of bone in quasi-static 3-point bending between experiment and simulation

4 Material Modelling

There exists several ways to implement the strain rate effects of material models in LS-DYNA. In this work a table input of stress strain curves for different strain rates from experimental results is given to the model.

An isotropic elastic-plastic material where unique yield stress versus plastic strain curve is defined for compression and tension is chosen. For each strain rate value a load curve is defined that gives the stress versus effective plastic strain for the rate. Table 1 presents the material properties of the cortical bone of femur according to the published experimental results [4].

Table 1. Material properties of the human femur bone at various strain rates obtained from experimental results reported by Hansen, Zioupos [4]

Specimen Human Femur bone strain rate s^{-1}	Ultimate Tensile Stress (MPa)	Tensile Failure Strain (%)	Ultimate Compressive Stress (MPa)	Compressive Failure Strain (%)
0.13	137	1.5	177	1.8
1.33	127	2.4	207	2.2
5.88	78	0.93	209	3.1
18.51	43	0.7	193	5.3
27.23	na	na	210	1.07

5 Results

Strain rate dependency is an important feature of the mechanical behaviour of cortical bone which should be considered in modelling. The behaviour of the bone model depending on strain-rate material implementaion can be seen in Figure 4. There is an obvious difference in fracture occurrence of both models.

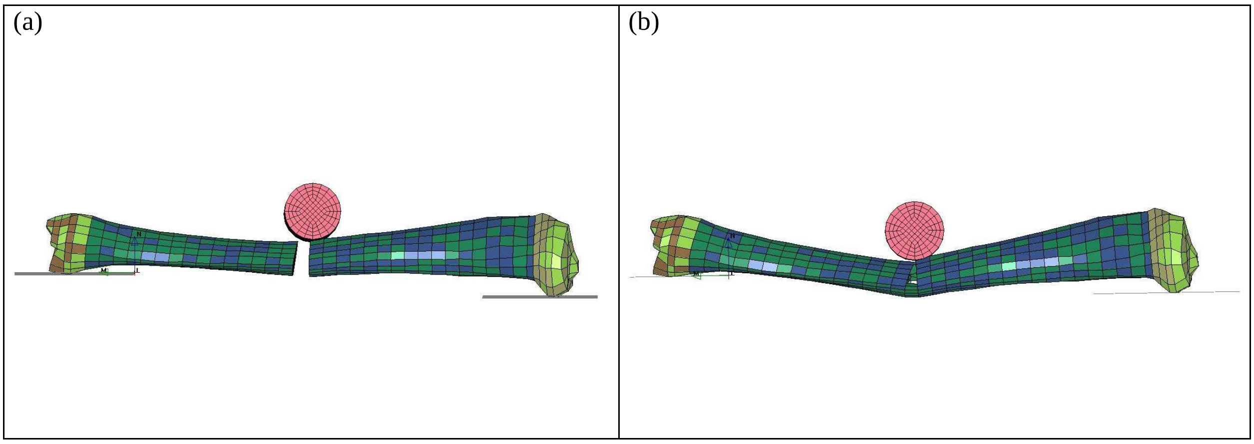

Figure 4. (a) without strain-rate effects, (b) with strain-rate effects

6 Conclusion

Biomechanical behaviour of the bone varies with the rate at which the bone is loaded. Bone is stiffer and sustains higher loads to failure when loads are applied at higher rates. It also stores more energy before failure at higher loading rates. In order to consider this important effect , in this work an FE model of THUMS-Tibia is extracted and a material model based on published experimental results is developed.

The effect of the strain rate dependent material model on the results is found to be considerable, therefore applying such a model would lead us to the results which are closer to the real-case.

In the future a comparison between a viscoleastic material model of the bone with the presented elastic-plastic material needs to be investigated.

7 ACKNOWLEDGEMENTS

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