



Experimental Characterization and FE Simulations of Ribs under Impact Loads

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► To cite this version:

Aravind Rajan Ayagara, André Langlet, Ridha Hambli. Experimental Characterization and FE Simulations of Ribs under Impact Loads. 8th World Congress of Biomechanics, Jul 2018, Dublin, Ireland. hal-02137590

HAL Id: hal-02137590

<https://hal.science/hal-02137590>

Submitted on 23 May 2019

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Introduction

Several authors have been studying the behaviour of ribs subjected to impact loads both in medical and biomechanical domains. The advances in numerical techniques and their advantages over expensive and painstaking experiments have led to the development of finite element human models. Despite their extensive use, these models have respective constraints. Knowing the realistic behaviour aids in the comprehension of the relation between injury criteria and fracture of ribs and indeed the severity of injury.

Objectives

1. To develop an experimental methodology in order to accurately characterize the bone fracture induced by impacts to chest
2. To develop a three-dimensional finite element model of bone to simulate bone fracture and to predict its occurrence under specific dynamic environments

Material and Methods

- Modified Split Hopkinson Pressure Bar for three-point bending tests using nylon bars [1]. Experimental data classified as (i) Short duration tests $t_{frac} \leq 0.8E - 3 s$ (ii) Medium duration tests $0.8E - 3 s \leq t_{frac} \leq 1.0E - 3 s$ and (iii) Long duration tests $t_{frac} \geq 1.2E - 3 s$

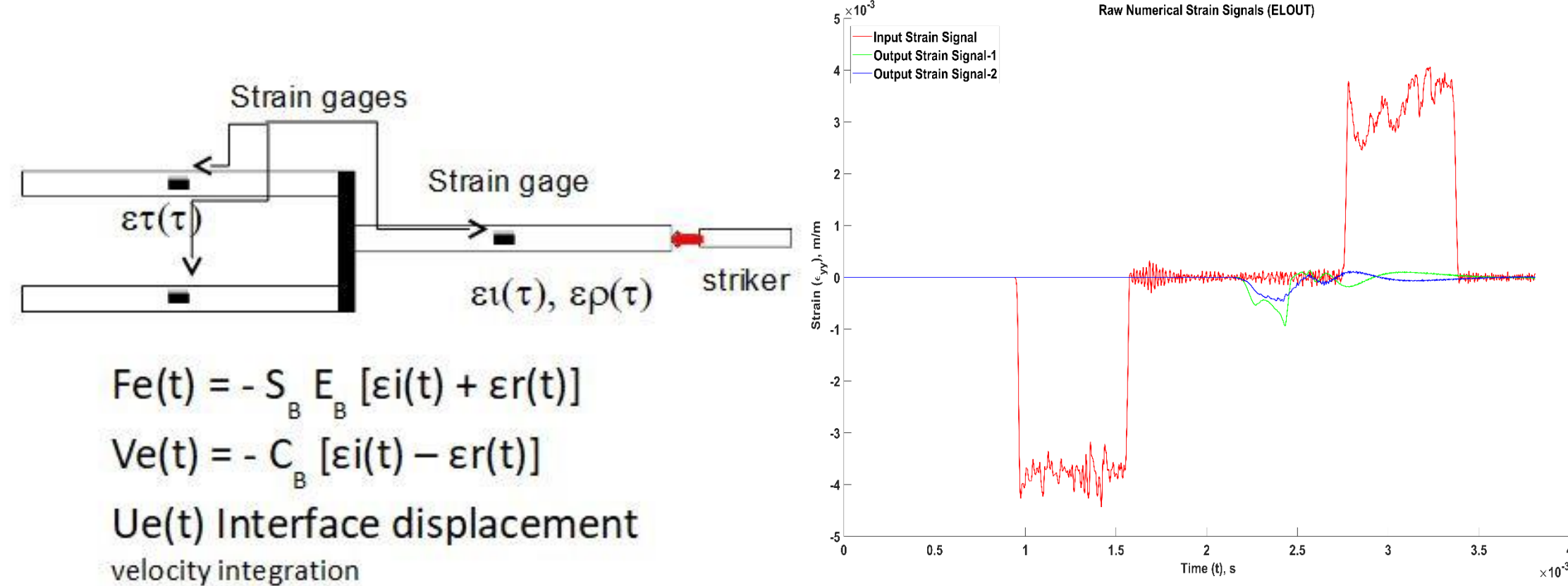
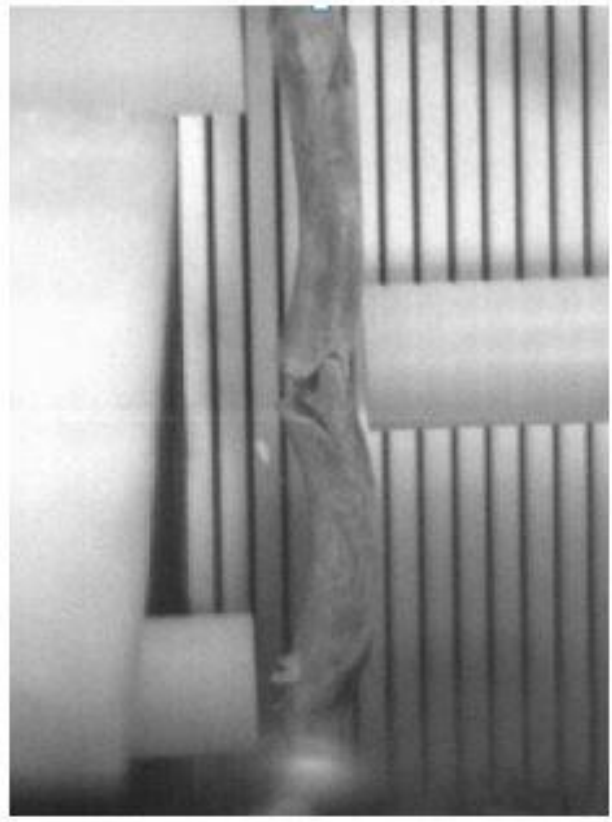


Figure-1 : Three point bending setup of SHPB

- Numerical rib sample was generated from DICOM images of HR-pQCT scans. The apparent density ρ_{app} was interpolated through a linear relation with CT_{bone} (Eq.1) as in [2].
$$\rho_{app} = 1.2907 CT_{bone} \quad (1)$$
- Mechanical properties were assigned through power law regression with ρ_{app} as independent variable. Respective equations were used with respect to porosity P_o

Property	Cortical bone	Trabecular bone
Apparent Density ρ_{app}	1690.090 kg. m ⁻³	222.611 kg. m ⁻³
Young's Modulus E	10.46 GPa	0.378 GPa
Tensile Yield σ_{yT}	75.36 MPa	2.096 MPa

Table-1 : Mechanical properties of porcine rib constituents

Constitutive Law

- Both cortical and trabecular bone were assigned a modified elastic-plastic law to consider the effects of strain rate $\dot{\epsilon}$ to have an elasto-viscoplastic behaviour through Cowper-Symmonds model (Eq.2).

$$\sigma_{y_d} = \sigma_{y_0} \left[1 + \left(\frac{\dot{\epsilon}}{C} \right)^{\frac{1}{P}} \right] \quad (2)$$

- Where:
 σ_{y_d} is dynamic yield stress
 σ_{y_0} is initial yield stress
 $C = 2.5$ and $P = 7.0$ are Cowper-Symmonds parameters [3]

Damage Law

- An incremental, stress state dependent damage law was coupled externally to the constitutive law. It also considers damage accumulation (Eq.3) and instabilities (Eq.4) due to damage and also the effects of strain rate $\dot{\epsilon}$ on fracture strain ϵ_f .

$$\Delta D = \frac{n}{\epsilon_f(\eta)} D^{(1-1/n)} \Delta \epsilon_p \quad (3)$$

$$\sigma = \tilde{\sigma} \left[1 - \left(\frac{D - D_{crit}}{1 - D_{crit}} \right)^m \right] \quad (4)$$

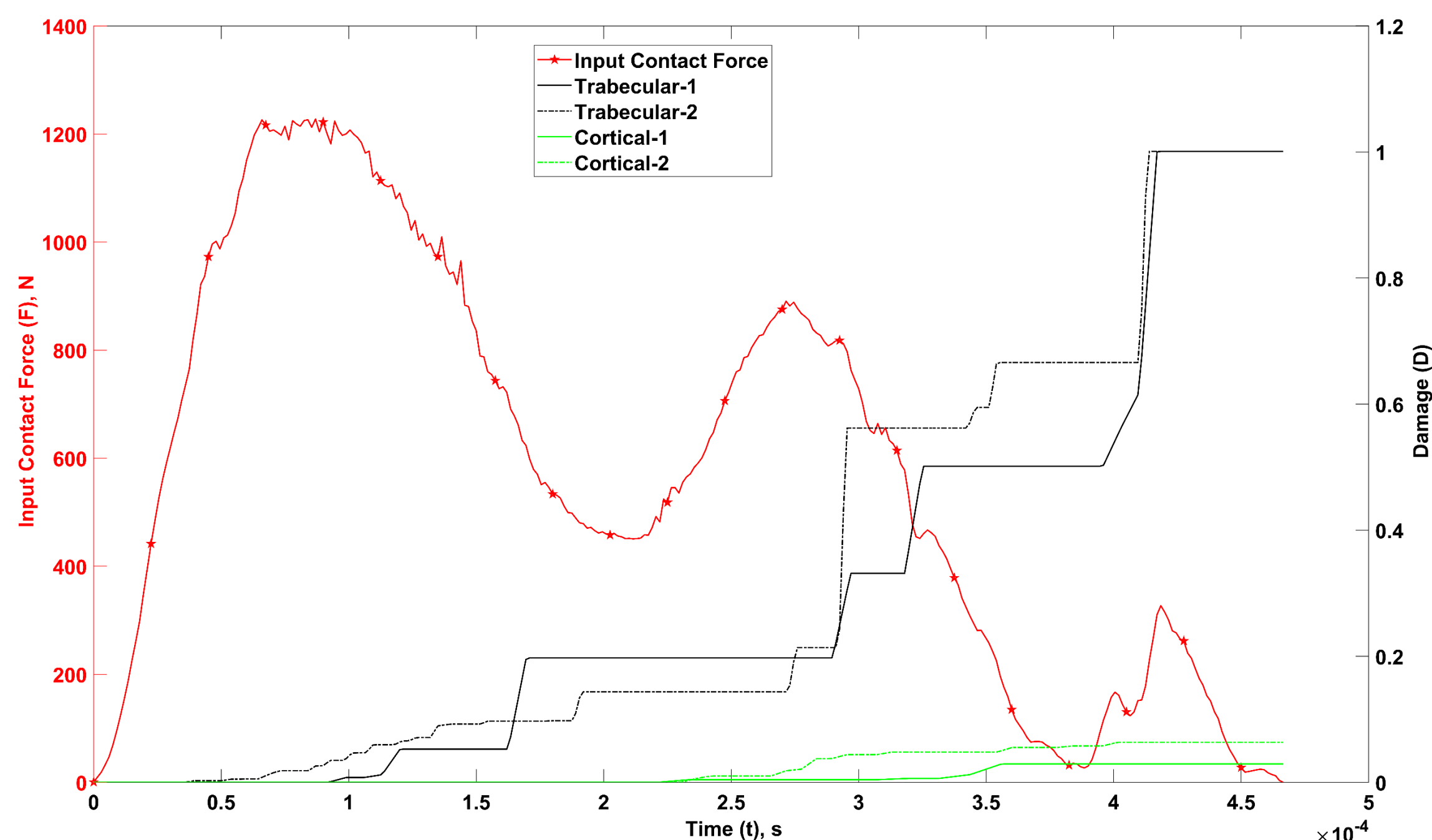


Figure-2 : Damage Evolution with respect to Force

Results

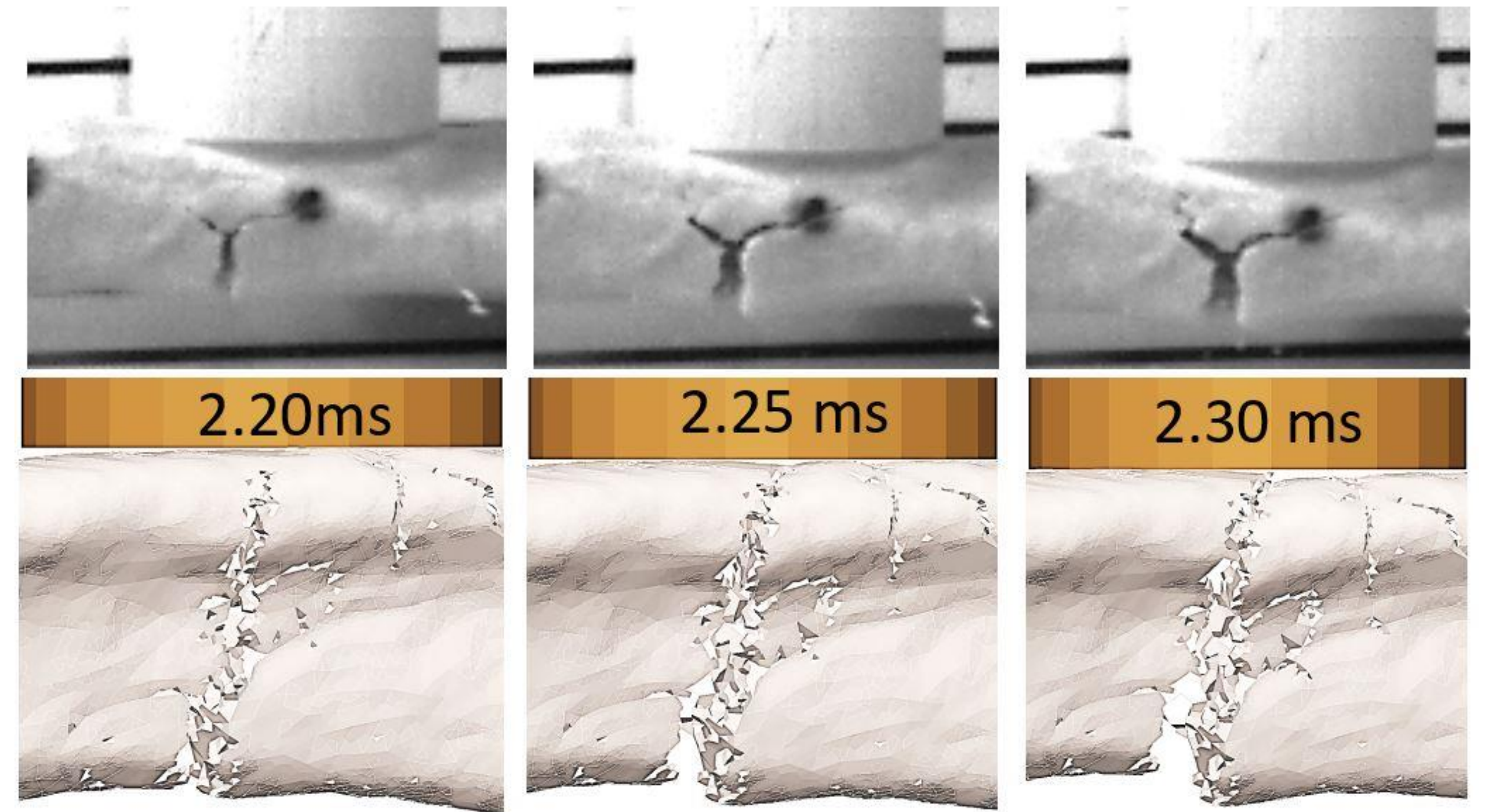


Figure-3 : Fracture Pattern

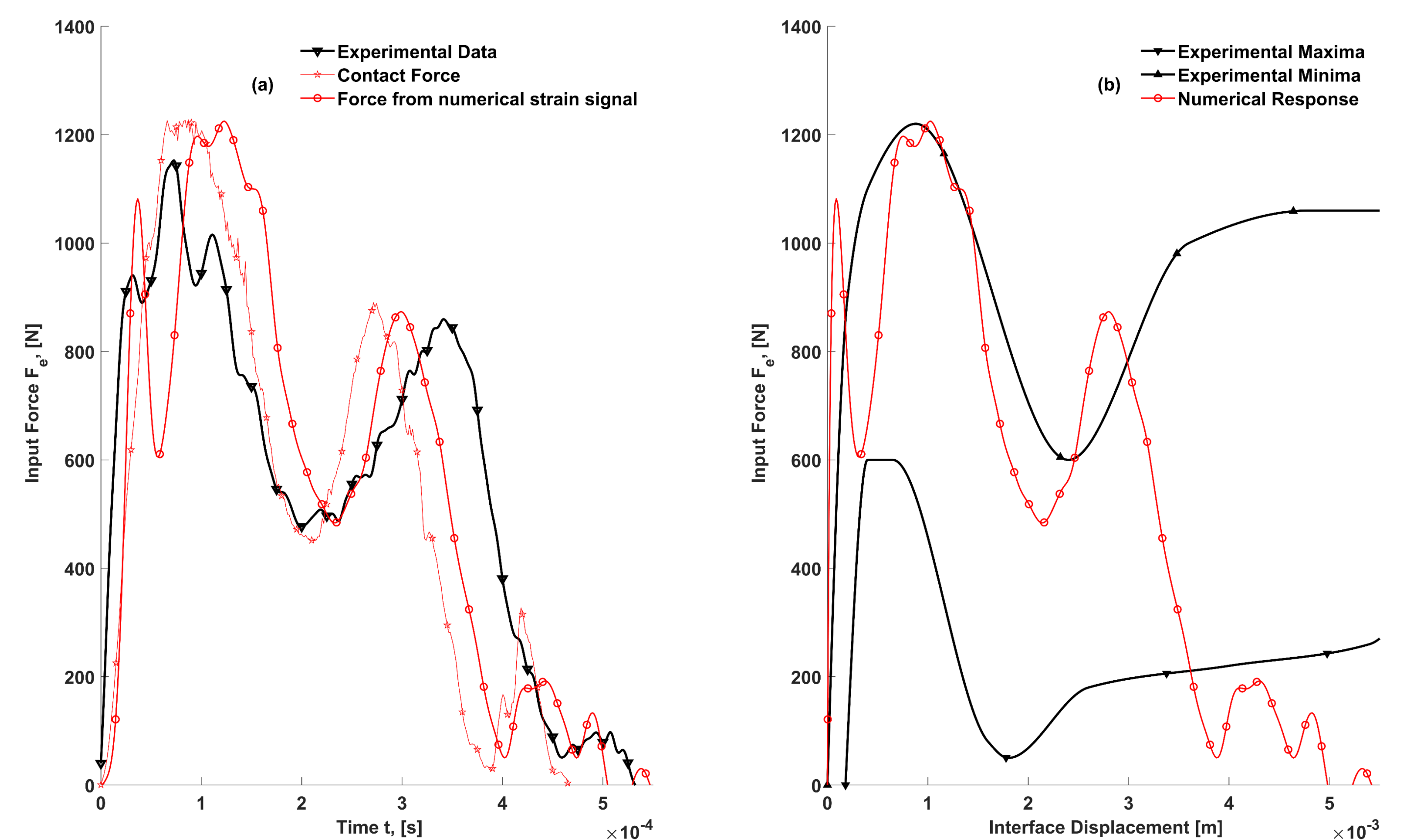


Figure-4 : Comparison of numerical and experimental response

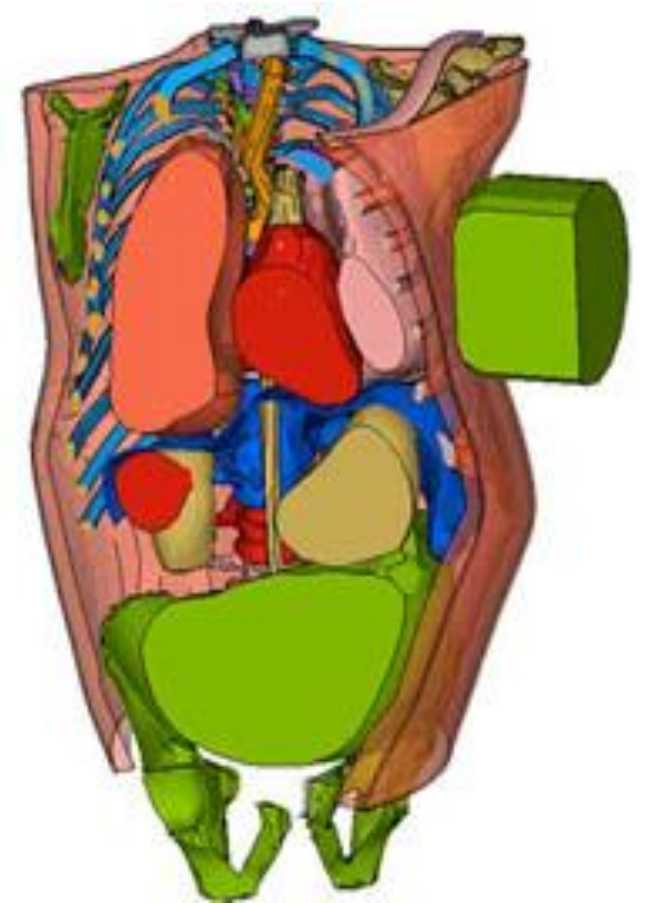
Conclusions

- Apparent density ρ_{app} as an independent variable for dependence of mechanical properties is sufficient for coherent results, given that it is correctly correlated to grey scale intensity CT_{bone} .
- Elasto-viscoplastic constitutive law for trabecular bone produced promising results at a preliminary stage.
- Despite the possibility to generate numerical sample with different parts, dynamic fracture propagation in porcine ribs consisting only one cortical and one trabecular bone material was successfully simulated.
- Optimization of damage and constitutive laws parameters through experimental characterization of human ribs will permit us to extent fracture prediction in human numerical models

Forthcoming Research

Implementation of current damage coupled constitutive law to generalized human thorax model and FE thorax model HUBYx of Radioss courtesy of Altair Hyperworks, to study and quantify the response of human thorax under different impact cases such as Automotive accidents and Ballistic impacts (Non-lethal projectiles).

This aids us in the comprehension of injury criteria and to predict the severity of the injury.



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