Strain-adaptive bone remodelling simulations using the proposed open-source framework

Problem definition:

To benchmark the proposed open-source framework for bone remodelling studies, a strain-adaptive bone remodelling model proposed by Weinans et al. (1992) was analysed. For this, a classical 2D plate model (see Fig 1) representing the cross-section of bone tissue was simulated and the results obtained were compared with those reported in Weinans et al. (1992). The square plate of size 100 x 100 mm was meshed with 40x40 quadrilateral elements in open-source finite element software FEniCS. For this problem, the boundary conditions are as shown in Fig 1.

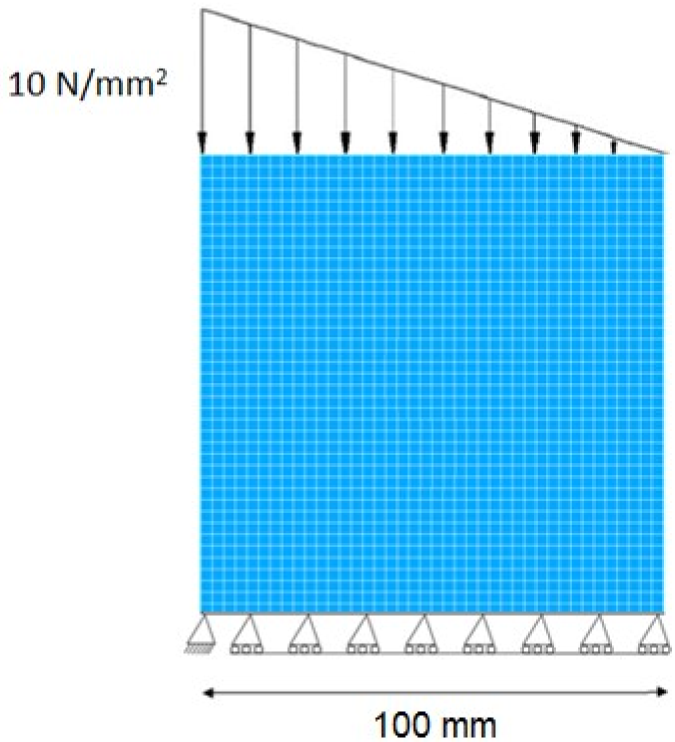

Fig 1: FEM model with boundary conditions relating to bone remodelling (adapted from Weinans et al. 1992)

In this model, the plate was assumed to be fixed on its lower horizontal boundary with the left-most node completely clamped, whereas the rest of the nodes on this boundary have only their vertical displacement constrained. The plate is being acted upon by a linearly increasing compressive load on its top boundary with a maximum magnitude of 10 N/mm^2 (see Fig 1). Here, the plane stress condition was assumed and simulations were performed under the small displacement theory (Weinans et al. 1992).

Flowchart of the implemented algorithm

The main features of the strain-adaptive model are briefly summarized below. This model uses the apparent density as the characterization of the internal morphology of bone. The rate of change of the bone density at a particular location can be described as:

$$\frac{d\rho}{dt} = B(S - k), \qquad 0 \leq \rho \leq \rho_{cb} \tag{1}$$

where B is a constant, S is the mechanical stimulus, k is a constant, and ρ_{cb} is the maximal density of cortical bone. In the above Eq. 1, the mechanical stimulus S represents the strain energy per unit of bone mass given by U/ρ, where U is the strain energy density (SED) and ρ is the apparent bone density. In this model, the relation between Young's modulus E and the apparent density ρ was taken as follows:

$$E = c\rho^{\gamma} \tag{2}$$

where c and γ are the constants and ρ is the apparent bone density. More details of this model can be found in Weinans et al. (1992). A schematic illustration of the implemented bone remodelling algorithm is presented in Fig 2.

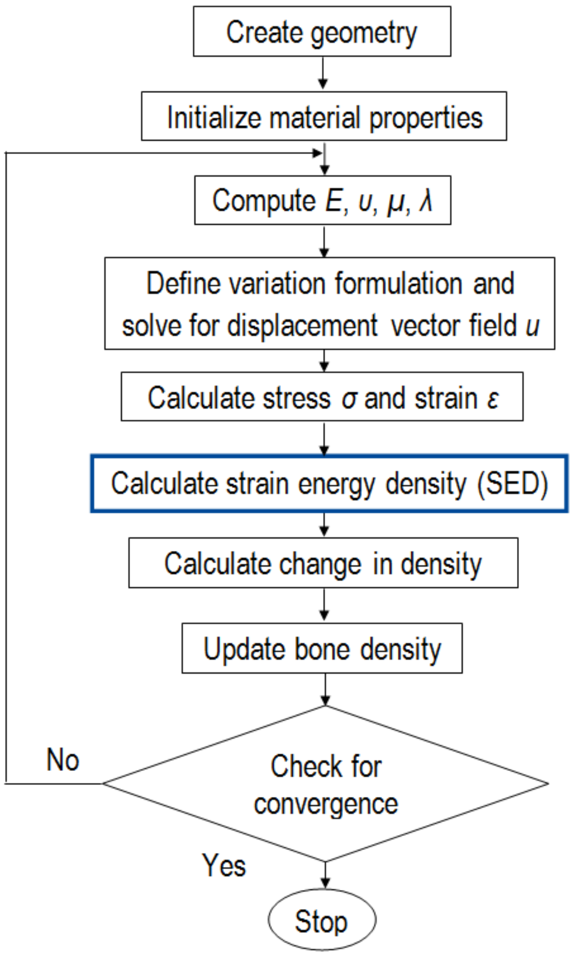

Fig 2: Schematic representation of the implemented bone remodelling algorithm

Here, the bone mass density variation over time depends on the mechanical stimuli that exist at each spatial point of the bone. To calculate the evolution of apparent bone density, an element-based approach was implemented, where the density was assumed to be element-wise constant.

Proposed open-source framework

Figure 3 represents a flow diagram of the main simulation steps executed using the proposed open-source software framework and more details can be found in Bansod et al. (2019).

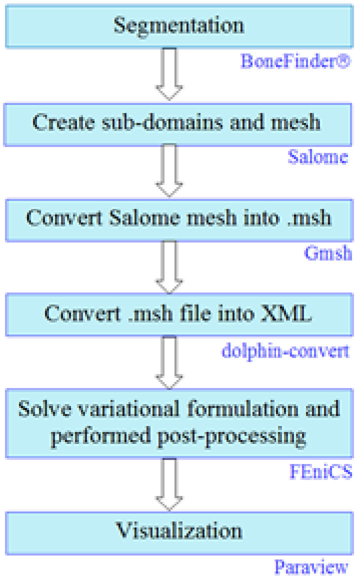

Fig. 3 Open-source software framework used for simulations (Bansod et al. 2019)

The Python scripts and other files created for this study are available for open access on the GitHub repository (https://github.com/YDBansod/Bone_Remodelling)

Comparing obtained simulation results with those from the literature

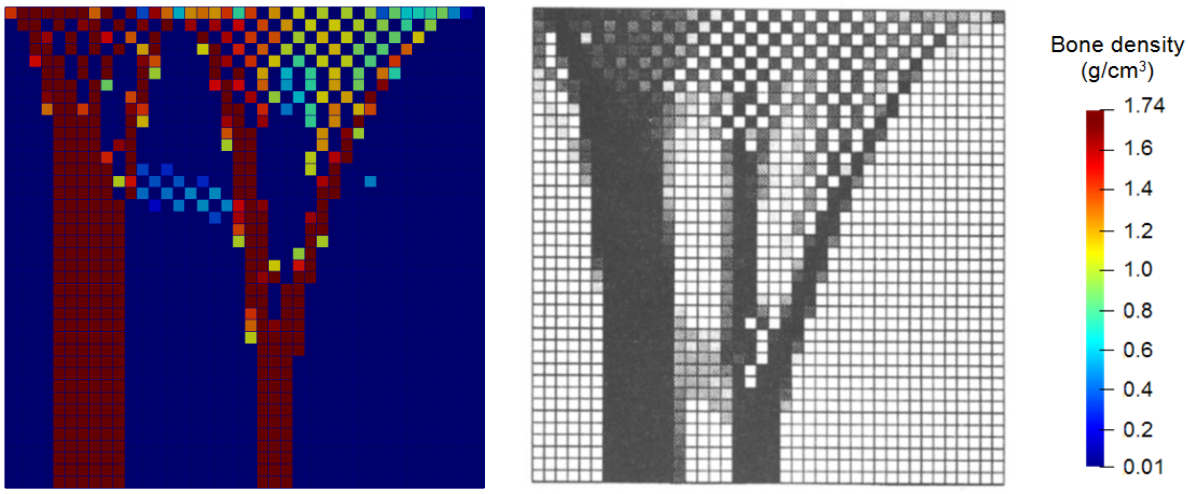

Fig. 4: Density distribution obtained using the open-source framework (left) and the corresponding results from Weinans et al. (1992) (right) (please see Fig 12d on pg-1434)

Starting from a homogeneous density distribution, the bone density predicted by the model is shown in Fig 4 and this result is in line with that obtained by Weinans et al. (1992). This can serve as preliminary evidence demonstrating that the strain-adaptive bone remodelling simulations can be performed precisely using the proposed open-source framework shown in Fig 3.

References

Weinans H, Huiskes R, and Grootenboer H (1992) The behavior of adaptive bone-remodeling simulation models. J Biomech 25:1425-1441. http://dx.doi.org/10.1016/0021-9290(92)90056-7

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