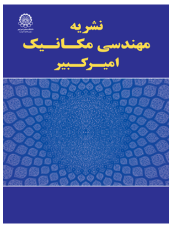

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Numerical Investigation of Elastoplastic and Damage Behavior of Cortical Bone by Applying a New Damage Model

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ABSTRACT: Due to the need for orthopedic surgery, the mechanical behavior of the cortical bone in cyclic loading and physiological strain rate has been investigated. The emphasis is on developing a structural law that can establish the behavior during loading, unloading and reloading observed in experiments. These models will be formulated by combining rheological elements and energy principles. First, two one-dimensional models independent of the strain rate are formulated, one with one damage variable and the other with two different damage variables in tension and compression, are examined, and using laboratory data, the coefficients of each model are obtained. By comparing the simulation results and laboratory data, the necessary modifications have been made to the models. Finally, by combining the Bresler-Pister anisotropic yield criterion and the one-dimensional model independent of the rate associated with the two damage variables, the corresponding three-dimensional model was obtained. This three-dimensional model was implemented in the form of an explicit finite element method and the result showed acceptable compatibility with the simulation results of the one-dimensional model and experimental data. This three-dimensional model will be suitable for simulating complex geometries. The coefficient of determination for one-dimensional models RI , $RI\pm$, RI , and $RI\pm$ has been modified and the three-dimensional model has obtained values of 0.882174, 0.965665, 0.995508, 0.996279, and 0.984866, respectively.

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1- Introduction

The mechanical behavior of bone varies according to the mechanical load it is exposed to, and the effect of its response depends largely on how the load is applied. Garcia has calculated the structural laws of elastic-plastic-damage, which are rate-independent and physiologically strain-dependent, and has used tensile testing to load, load, and reload during the structural process [1]. In another study, Garcia et al. [2] proposed a three-dimensional structural law describing the mechanical behavior of elastoplastic- damage, independent of strain rate, with respect to the analysis of the implant-bone system. Garcia et al. [3] Continued their research with a one-dimensional structural law independent of the strain rate for the cortical bone to simulate the accumulation of damage during tensile or compressive loading.

2- Methodology

The Rheological arrangement of all one-dimensional models consists of a series of connections of a main elastic spring with a damage element, the damage element itself consisting of a parallel connection of a vulnerable sub-spring with a plastic barrier. The sub-elastic spring in models RI and $RI\pm$ suffers from rate-independent damage, Fig. 1.

2- 1- Model RI

The elastic modulus of healthy cortical bone is positive ($E_0 > 0$). Three damage-dependent functions, plastic hardening function $S^p(D) \geq 0$ and damage hardening functions $S_+^D(D) > 0$ and $S_-^D(D) > 0$ are used [1]:

$$S^p(D) = \chi^p(1 - \exp(-lD)) \tag{1}$$

$$S_\pm^D(D) = S_{0\pm}^D\left(1 + \chi^D(1 - \exp(-kD))\right) \tag{2}$$

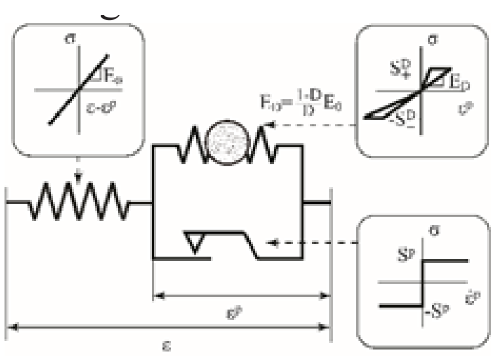

Fig. 1. Arrangement of one-dimensional rheological elements

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Table 1. Coefficients of models RI and $RI\pm$

Coefficients	Unit	RI	$RI\pm$
E_0	MPa	25000	25000
S^D_{0+}	MPa	4	2
S^D_{0-}	MPa	9.6	3.8
χ^P	MPa	52.9	79.9
χ^D	-	19.8	65
k	-	15.3	15
l	-	6.1	21.9

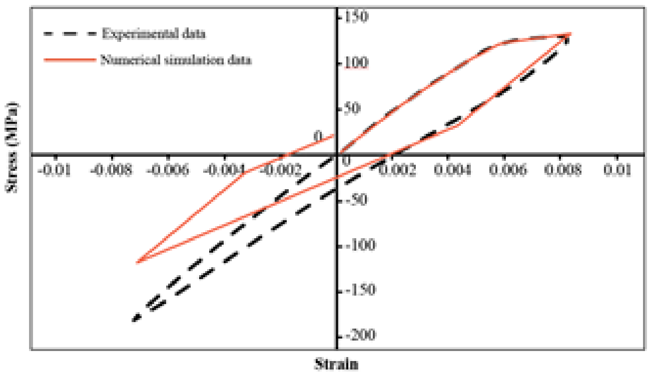

Fig. 2. Stress-strain curve of Model RI

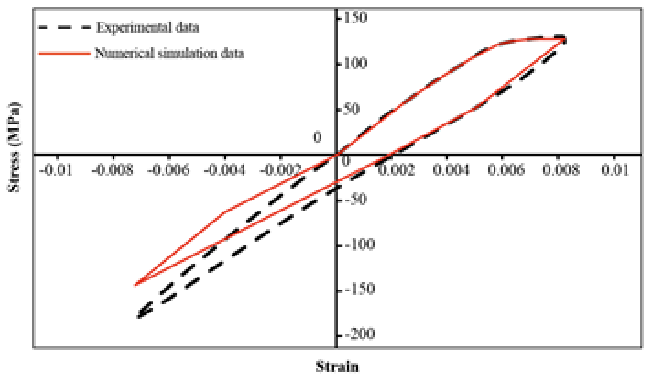

Fig. 3. Stress-strain curve of Model $RI\pm$

$X^P \geq 0$ and $l > 0$ Plastic hardening coefficients S^D_{0+} and $S^D_{0-} > 0$ are the initial stress threshold stresses in tension and pressure, respectively.X^D and $k > 0$ are the hardness coefficients of the damage.

2- 2- Model $RI\pm$

In this model, two damage variables are used and the damage situation is described by two variables, tensile damage D_+ and compressive damage D_- [1]:

$$S^P_+(D_-) = \chi^P\left(1 - \exp(-lD_-)\right) \tag{3}$$

$$S^P_-(D_+) = \chi^P\left(1 - \exp(-lD_+)\right) \tag{4}$$

$$S^D_\pm(D_+, D_-) = S^D_{0\pm}\left(1 + \chi^D\left(1 - \exp(-k(D_+ + D_-))\right)\right) \tag{5}$$

3- Determining the Coefficients of One-Dimensional Models and Numerical Simulations

The coefficients of each model are calculated according to the experimental data of cortical bone [2] which includes the values of stress and strain in a tensile-compressive cycle with a strain rate of $\dot{\varepsilon} = 3.4\times10^{-3}\text{sec}^{-1}$, Table 1.

The results of numerical simulation of one-dimensional models RI and $RI\pm$ in comparison with experimental data are plotted in Figs. 2 and 3, respectively, and the coefficient of determination for the one-dimensional model RI and RI ± are 0.882174 and 0.965665, respectively. Consider the effect of velocity on the plastic element and on the damage element.

The model $RI\pm$ is more accurate in predicting experimental results. Simulations of two models will be performed on the control strain load cycle. As shown in Fig. 4, the plastic part of the reloading pattern in the stress-strain cycle curve of the Model $RI\pm$ is along the coordinate origin, but the Model RI lacks this feature specific to bone tissue. The reason for this difference is the number of damage variables and the dependence of the plastic hardness on the damage variables.

Table 2. Modifier coefficients of one-dimensional models

Coefficients	Unit	RI	$RI\pm$
S^D_{0-}	MPa	8.9	3.6
w_-	-	0.3	0.5

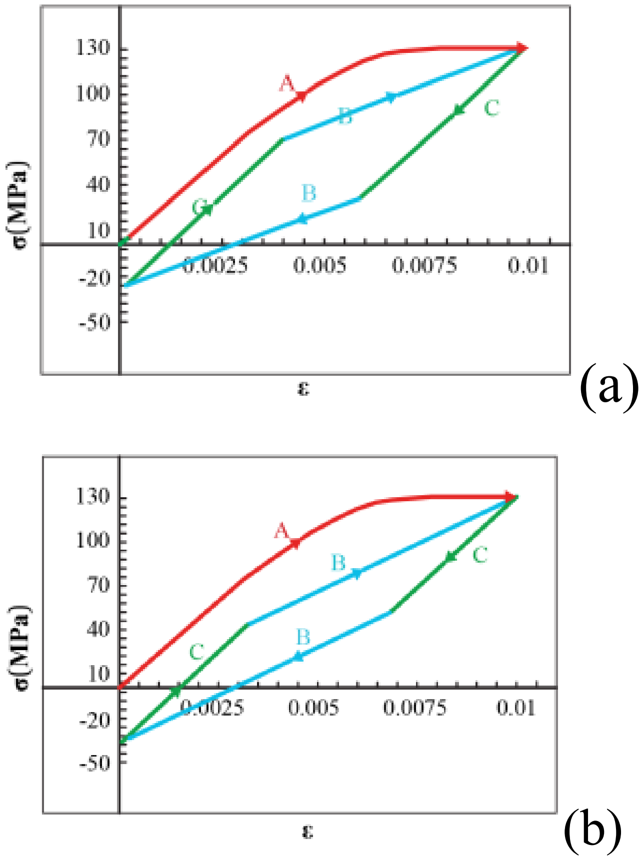

Fig. 4. Stress-strain cyclic curve of the model $RI\pm$ (b) and model RI (a) with three modes of deformation: elastic mode (C), damage mode (A), and plastic mode (B).

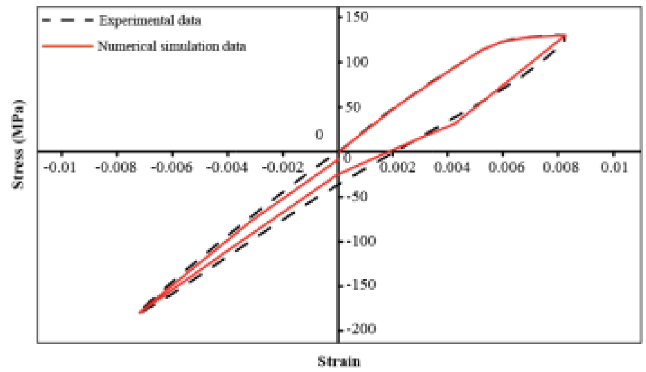

Fig. 5. Modified stress-strain curve of Model RI compared to the experiment

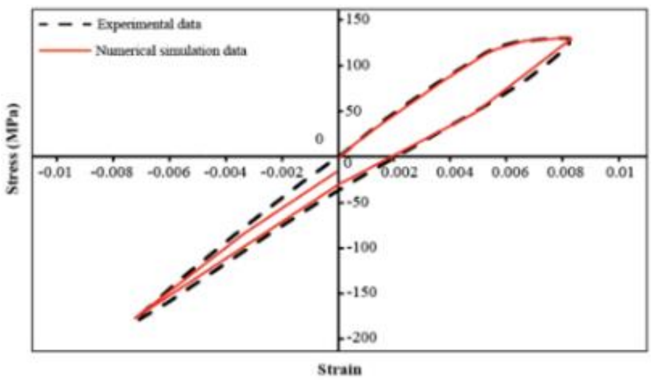

Fig. 6. Modified stress-strain curve of Model $RI\pm$ compared to the experiment

3- 1- Modification of one-dimensional models

The one-dimensional models of the previous section have a relatively good ability to predict experimental data, but not in the compression section. In the compressive part, the slope of the model curve is not compatible with the slope of the test curve. This is because, in the proposed models, the recovery of the Young modulus in the transition from tension to compression is not considered. This effect can be considered by using a correction factor (w) in the definition of Young's modulus of the damaged material, Table 2. The results of numerical simulation of modified models RI and $RI\pm$ in comparison with experimental data are shown in Figs. 5 and 6. The coefficient of determination for the modified RI and $RI\pm$ one-dimensional models is 0.995508 and 0.996279 and the reason is to consider the effect of velocity on the plastic element and the damage element.

4- Results and Discussion

4- 1- Make three dimensions

For application, the one-dimensional damage model independent of rate $RI\pm$ will be generalized to three-dimensional. The Bresler-Pister yield criterion is used for the application use of the model. This criterion is used to express a yield function that has different tensile and compressive strengths under multi-axis loading4]] The numerical algorithm code of the 3D model $RI\pm$ is implemented in the form of VUMAT subroutine related to ABAQUS software. Loading is in the form of displacement control. The bone sample is simulated as an axial symmetric model, Fig. 7. Comparing the two simulations of the Model $RI\pm$, it can be seen that the formulation of the 3D model is correct, Fig. 7.

Slight differences between the two curves can be related to two causes, one due to the effect of the Poisson ratio on the three-dimensionality and the effect of normal stress on the axial direction of lateral strains, and another due to numerical calculation errors in plastic yield and damage threshold functions. These two reasons make the three-dimensional model $RI\pm$, unlike the one-dimensional model $RI\pm$, not pass through the origin of the coordinates in the last stage of the cyclic loading, and at a strain equal to zero, the stress is not equal to zero. The coefficient of determination for the three-dimensional model compared to the one-dimensional model is 0.984866 and the reasons for its difference are the effect of Poisson's ratio, isotropic elasticity in the three-dimensional model, and also the scalar damage variable.

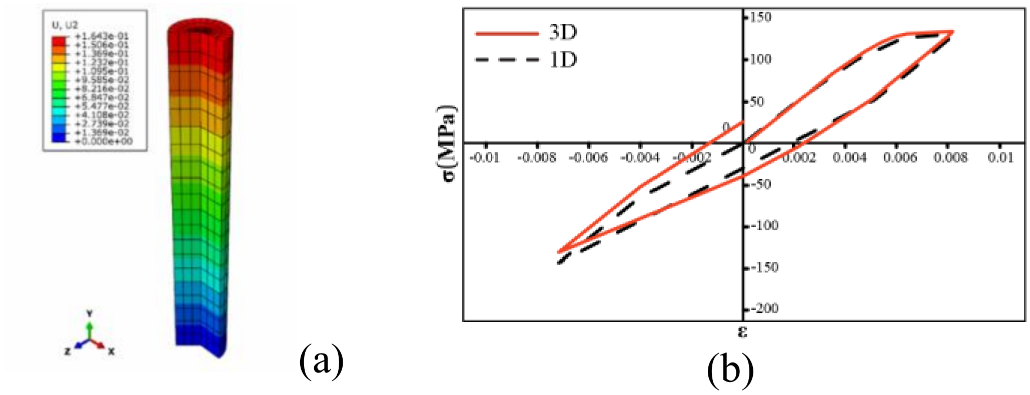

Fig. 7. (a) Axial displacement contour for 3D model RI ±, (b) Comparison of simulation results of three-dimensional model RI ± with one-dimensional model RI ±.

5- Conclusion

Two rate-independent one-dimensional models with a combination of rheological elements have been investigated. The coefficients for each model are calculated by matching the laboratory data. In one-dimensional models, a correction factor for the modulus is considered. This coefficient creates the phenomenon of recovery of the material hardening in the transition from the tensile state to the compression resulting from the closure of the microcracks in the stress-strain curve. By combining the Bresler-Pister yield criterion and the rate-independent one-dimensional model, a corresponding three-dimensional model was obtained. This three-dimensional model is implemented in the form of an explicit finite element method and the result is acceptable with the simulation results of the one-dimensional model and experimental data. This three-dimensional model will be suitable for simulating complex geometries.

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