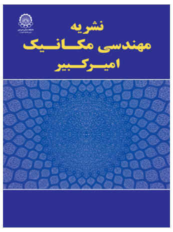

Amirkabir Journal of Mechanical Engineering

Amirkabir J. Mech. Eng., 53(8) (2021) 1083-1086
DOI: 10.22060/mej.2021.17632.6632

The Prediction of Femoral Fracture Location Using Extended Finite Element Method

R. Shahbad, F. Alavi*, M. Mirzaei

Department of Mechanical Engineering, Tarbiat Modares University, Tehran, Iran

ABSTRACT: The advances in the extended finite element method enable the prediction of crack initiation and propagation without prior knowledge about the crack pattern. In this regard, the purpose of this study was to investigate human femoral fracture location using voxel-based finite element simulation. The simulation was developed in terms of an anisotropic failure mechanism coupled to the extended finite element method to describe the femoral progressive fracture pattern in specimen-specific models. An anisotropic failure mechanism (4 damage criteria) was developed based on the combination of Hashin failure criteria and maximum principal stress criterion to capture femur fracture behavior dependency on femur anisotropy and heterogeneity. Three specimen-specific femur FE models were constructed based on CT-scan images under a particular loading condition. The load was applied to the head of the femur at an angle of -15 degrees relative to the sagittal and coronal planes. To demonstrate the potential of the current approach, a one-to-one comparison of predicted extended finite element method fracture pattern and experimental results were performed. An acceptable agreement was obtained between the predicted and observed fracture patterns suggesting that the proposed failure mechanism in the extended finite element method is capable to simulate femoral fracture type and progressive crack propagation. The presented results indicated that the crack on-set location and subsequent crack trajectories can be correctly captured using the proposed anisotropic failure mechanism in the extended finite element method.

Review History:

Received: Dec. 30, 2019
Revised: May. 13, 2020
Accepted: Aug. 31, 2020
Available Online: Jul. 19, 2021

Keywords:

Bone fracture
Finite element method
Anisotropic damage criteria
Fracture mechanics
Orthopedic biomechanics

1. INTRODUCTION.

The femur bone plays a significant role in bearing human weight and maintaining human balance during daily physical activities. Hence, femur fracture would lead to several disabilities and mortalities [1]. Several experimental studies have been conducted to assess the femur fracture risk and its pattern. The experimental methodologies' high cost raised a need for a non-invasive and low-cost method. Among the suggested methods, the Quantitative Computed Tomography (QCT)-based finite element method was a great tool helping researchers simulate bones complex geometries containing bone mechanical properties in detail. The good agreement between this computational method and experimental results makes it a reliable tool for assessing bone injuries [2-4].

Among the common Finite Element (FE) methods, the Extended Finite Element Method (XFEM) is the most efficient computational approach for handling complex discontinuities. Although the Cohesive Zone Method (CZM) needs a predefined fracture pattern, XFEM is able to anticipate crack initiation and growth along an arbitrary path without remeshing. The notable differences between XFEM and CZM have encouraged many researchers to implement XFEM in different fields of study during the last years. In biomechanics cases, several three-dimensional FE analyses based on XFEM have been conducted to investigate bone fracture behavior [5, 6].

Despite the bone heterogeneous and anisotropic material properties, most of the recent studies used simple isotropic failure criteria such as von mises or maximum principal stress to predict bone fracture behavior. [7, 8]. The incapacity of conventional failure criteria in considering the anisotropy behavior of cortical bone makes clear the need for implementing fracture criteria that take these aspects into account.

In this study, the simulation was developed in terms of an anisotropic failure mechanism coupled to the XFEM to describe the femoral progressive fracture pattern in specimen-specific models.

2. METHODOLOGY

Three human femur specimens were used in this study. The raw images of the femur specimens obtained from QCT scanning (DICOM format) were converted into binary format. A homemade MATLAB code implementing an image processing toolbox was used to separate bone hard tissues from the surrounding. A complimentary homemade MATLAB

---

*Corresponding author's email: fs.alavi@modares.ac.ir

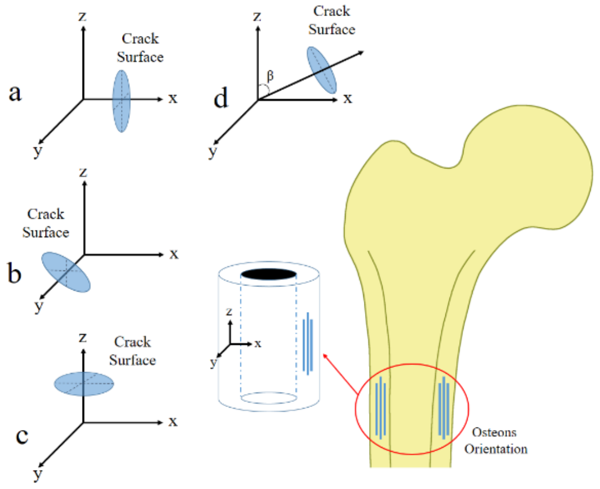

Fig. 1. Osteon orientations and crack path for each failure criterion

code was used to build the FE models by conversion of each voxel into an 8-noded brick element. Eventually, the code prepares an input file (node and element file) which is compatible with the format of the ABAQUS software.

A failure mechanism including 4 separate failure criteria was implemented. The number 1, 2, and 3 criteria were related to bone main directions in local *x*, *y*, and *z* directions respectively. A material orientation is assigned to femur cortical and to represent the osteon direction in local *z*. The remaining local *x* and local *y* represent the directions perpendicular to the osteon's directions in the femur bone. In order to establish a relationship between the bone failure properties and local *x*, *y*, and *z* directions, criteria number 1, 2, and 3 have been developed based on the Hashin damage theory which is usually used for fiber-reinforced composites [9]. The crack path may not fully follow the main directions and may grow in a path off the main bone directions. Hence the criterion number 4 is based on maximum principal stress to capture this likely failure behavior. The failure mechanism can be expressed as Eq. (1).

$$\begin{aligned}
&(FailureCriterion)_1 : \sqrt{\left(\frac{\sigma_{11}}{\sigma_{xx}}\right)^2 + \left(\frac{\sigma_{12}}{\sigma_{xy}}\right)^2 + \left(\frac{\sigma_{13}}{\sigma_{xz}}\right)^2} \\
&(FailureCriterion)_2 : \sqrt{\left(\frac{\sigma_{22}}{\sigma_{yy}}\right)^2 + \left(\frac{\sigma_{21}}{\sigma_{yx}}\right)^2 + \left(\frac{\sigma_{23}}{\sigma_{yz}}\right)^2} \\
&(FailureCriterion)_3 : \sqrt{\left(\frac{\sigma_{33}}{\sigma_{zz}}\right)^2 + \left(\frac{\sigma_{31}}{\sigma_{zx}}\right)^2 + \left(\frac{\sigma_{32}}{\sigma_{zy}}\right)^2} \\
&(FailureCriterion)_4 : \frac{\sigma_{\max ps}}{\sqrt{\sigma_{zz}^2 \cos^2\beta + \sigma_{xx}^2 \sin^2\beta}}
\end{aligned} \quad (1)$$

As shown in Fig. 1 for each failure damage criterion a separate crack propagation direction perpendicular to the failure criterion direction has been considered. Once each of the damage failure criteria reaches the value of 1, the crack will initiate for that criterion and tend to propagate in the associated direction.

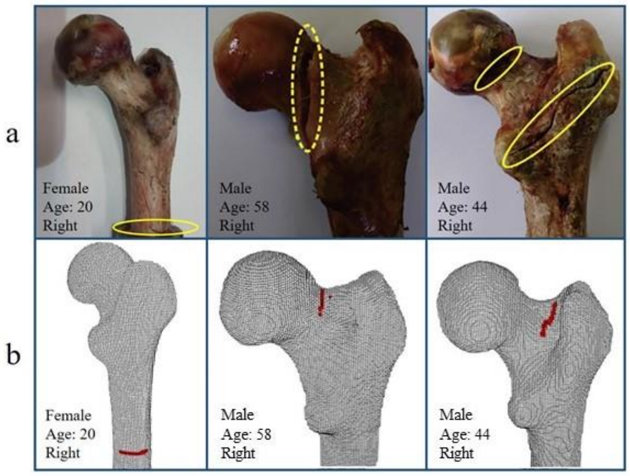

Fig. 2. comparison of the experimental and FE results (fracture pattern predictions) (a) experimental [9]. (b) XFEM

3. RESULTS AND DISCUSSION

Fig. 2 (a) depicts the fracture pattern of three femur specimens for (α=-15 and β=-15) loading orientation which was obtained experimentally by Mirzaei et al. [10]. Three different fracture patterns (basicervical, subcapital, and subtrochantric) occurred in three specimens in a particular loading condition. Fig. 2(b) shows the results of QCT-based femur fracture simulations in this study. In all three specimens, the fracture initiation location and subsequent path predicted by anisotropic damage criteria matched closely with experimental tests. The numerical models and experiments show good agreement in the fracture initiation location and path.

Our damage criteria were able to predict the crack initiation location and subsequent trajectory in good agreement with experimental results.

As observed in Fig. 2(b)., the complete fracture path was not simulated during XFEM analyses. XFEM analyses of QCT-based models confronted some convergence problems which prevented the crack propagate all the way through the bone. The convergence problems were in the result of some computational challenges due to complex bone 3D geometries and it was also reported in previous studies [21, 23]. Some numerical control parameters were modified to make the crack propagate further (e.g. decreasing the minimums step size and increasing the number of iteration), but it was still problematic.

4. CONCLUSIONS

In this study, three different forms of femoral fracture patterns were simulated using anisotropic failure mechanics in combination with XFEM. The predicted fracture patterns and transition in crack trajectory as a function of osteons' direction were in good agreement with experimental results. The approach used in this study was not only limited to the cortical bone fracture pattern but rather was able to predict fracture patterns in trabecular bone.

Various forms of femoral fracture were observed under particular loading conditions. Hence, it can be concluded that although the general fracture behavior of femurs can be specified by the loading orientation and boundary condition, the specific femoral fracture pattern is affected by microstructural characteristics, densitometric heterogeneity, and geometry. The implemented failure mechanism was able to capture these parameters' effects in fracture patterns.

REFERENCES

[1] O. Johnell, J. Kanis, An estimate of the worldwide prevalence and disability associated with osteoporotic fractures, Osteoporosis international, 17(12) (2006) 1726-1733.

[2] J.H. Keyak, Improved prediction of proximal femoral fracture load using nonlinear finite element models, Medical engineering & physics, 23(3) (2001) 165-173.

[3] M. Bessho, I. Ohnishi, J. Matsuyama, T. Matsumoto, K. Imai, K. Nakamura, Prediction of strength and strain of the proximal femur by a CT-based finite element method, Journal of biomechanics, 40(8) (2007) 1745-1753.

[4] J.E. Koivumäki, J. Thevenot, P. Pulkkinen, V. Kuhn, T.M. Link, F. Eckstein, T. Jämsä, Ct-based finite element models can be used to estimate experimentally measured failure loads in the proximal femur, Bone, 50(4) (2012) 824-829.

[5] A. Idkaidek, I. Jasiuk, Cortical bone fracture analysis using XFEM–case study, International journal for numerical methods in biomedical engineering, 33(4) (2017) e2809.

[6] M. Marco, E. Giner, R. Larraínzar-Garijo, J.R. Caeiro, M.H. Miguélez, Modelling of femur fracture using finite element procedures, Engineering Fracture Mechanics, 196 (2018) 157-167.

[7] A.A. Ali, L. Cristofolini, E. Schileo, H. Hu, F. Taddei, R.H. Kim, P.J. Rullkoetter, P.J. Laz, Specimen-specific modeling of hip fracture pattern and repair, Journal of Biomechanics, 47(2) (2014) 536-543.

[8] J.H. Keyak, S.A. Rossi, Prediction of femoral fracture load using finite element models: an examination of stress-and strain-based failure theories, Journal of biomechanics, 33(2) (2000) 209-214.

[9] Z. Hashin, Failure criteria for unidirectional fiber composites, (1980).

[10] M. Mirzaei, F. Alavi, F. Allaveisi, V. Naeini, P. Amiri, Linear and nonlinear analyses of femoral fractures: Computational/experimental study, Journal of biomechanics, 79 (2018) 155-163.

HOW TO CITE THIS ARTICLE

R. Shahbad, F. Alavi, M. Mirzaei, The Prediction of Femoral Fracture Location Using Extended Finite Element Method , Amirkabir J. Mech Eng., 53(8) (2021) 1083-1086.

DOI: 10.22060/mej.2021.17632.6632