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RESEARCH ARTICLE

Effect of Window Geometry on Strength of Shaft Part of Femur Bone

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Abstract
Femur bone is known as the largest and longest bone in human body. It bears most of the body weight during activities such as standing, walking, and running. This study investigates impact of the geometry of the window perforated in the shaft part of this bone on its strength. Four window geometries, including square, circle, trapezoid and triangle were employed in order to assess yield stress under tension, compressive 3-point bending, 4-point bending and torsional loadings. 5 mm interval CT scan images were employed for modeling the femur bone. Analyses were performed in ANSYS finite element code. Trapezoidal window showed much better resistance in 3-point bending and axial loadings compared to other window geometries, while it showed the weaker performance in torsional and 4-point bending loads. However, the femur bone is very unlikely to be loaded in 4-point bending. Moreover, in torsion, the femur bone with trapezoidal window was only 12% weaker than the femur bone with circular window (in axial loading, the femur bone with trapezoidal window had 33.6% higher strength than the bone with circular window). Therefore, summing up all the results of this study, it is suggested to use trapezoidal as the most appropriate window type for orthopedic surgeries.

Keywords
Femur bone, Biomechanics, Opening, ANSYS, Elastic properties, Finite Element

1 Introduction

Bones are brittle, porous living tissues which form body framework or skeleton. From macro point of view, bones are categorized according to their shape; each category has a certain functionality based on its shape. Bones are also divided into two groups of cortical and cancellous. Bone injuries may appear in form of diseases (e.g. osteoporosis and tumor) or fracture (under repetitive loadings). These injuries may also appear because of perforations or cuttings created for installing implants. Due to internal (e.g. energy absorption capacity, elasticity modulus, fatigue strength and bone density) and external factors (e.g. duration and orientation of the exerted force, and pace of loading), biomechanical analysis of bone injuries is a very important issue.

Based on their shape, bones are categorized into four categories of long (femur and arm), flat (parietal), short (wrist) and irregular (vertebra) bones. Long bones are best for bearing compressive and bending loads. Short bones are suitable for compressive loads; and flat bones usually protect inner body parts. A long bone has a median hollow axis and two round broad ends [1]. In average, the femur bone is 48 cm long and 2.34 cm thick and can bear up to 30 times an adult's weight. It can be generally divided into three main sections: the proximal section (femoral neck and femoral head), the axial section and the distal section [2]. As the biggest and the longest bone in human body, the femur bone has been the subject of a large number of biomechanical studies.

Structural functionalities of the femur bone require bearing mechanical loads via changes in its size, shape, and mass [3]. According to the type of daily loadings, architecture of different parts of the femur bone would change [4]. Anthropologists who work in biology fields are very familiar with properties and ductility of bones in compatibility to mechanical loads or other environmental conditions. This behavior is called plasticity. In 1892, Julius Wolff, German anatomist, was the first to discuss plasticity of bones [5]. He formulated a mechanical rule which describes a direct relation between mechanical usage and structure of the bones; it seems that shape of the bones are generally associated with local mechanical situation [6].

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Bones tend to change their geometry in order to be more compatible with mechanical condition of their environment [7]. Considering the proximal section of the femur bone as an example, shape of the femoral neck is elliptical near its connection to the axial section, because it is usually under bending loadings. On the other hand, shape of the femoral head is circular near femoral head since this location is usually under compressive loadings [8, 9].

Measurements can determine inherent physical properties of bones under different loadings, e.g. tension, compression, shear and bending loadings. The stress-strain relationship (Fig. 1) can be determined via physical analysis of the bone. Physical properties of bones can be determined through measuring the slope of stress-strain curve in the elastic region (also called Young's modulus) and strain/stress values at yield and failure situations. After the yield stress point, the stress-strain curve becomes nonlinear and reaches permanent plastic deformation. The area beneath the stress-strain curve represents the work per volume required for destruction of the material.

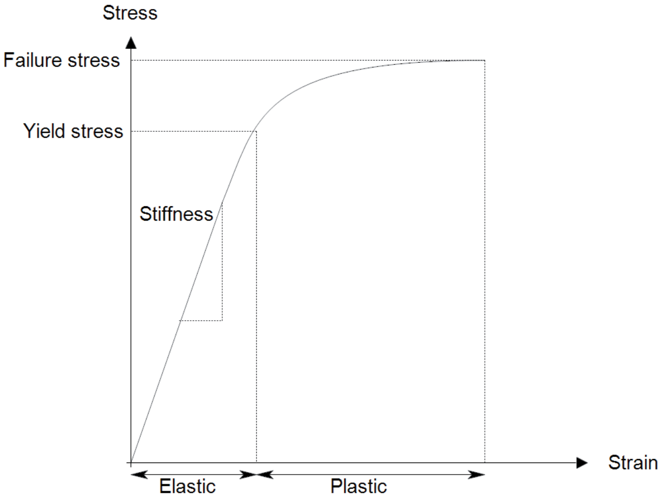


Fig. 1 Schematic stress-stress curve resulted from mechanical test of bone

Compressive failure load of bone is much higher than its tension failure load. Physical properties such as elastic modulus and yield stress of cortical bones are higher than those of trabecular bones. This is shown in Table 1. The physical properties presented in the fourth and fifth rows of the table have been measured through different methods.

Perforation of holes inside cortical bones is a common procedure for inserting orthopedic plates (Fig. 2) or removing tumors from the inner cancellous bones in its initial phases of cell growth. These holes decrease the mechanical strength of the bone and can even lead to a second fracture in the bone. Surgeons have always used holes with circular cross-section for orthopedic operations. However no investigation has been yet carried out on the effect of the hole cross-section type on the mechanical response of the bone and its effect on the defected life. In order to find out the best cross-section type, the permitted load of bone with five geometry types of circle, triangle, square, triangle, and trapezoid, all having the same cross-section area is investigated under four types of loading namely, compression/tension, 3-point bending, 4-point bending, and torsion.

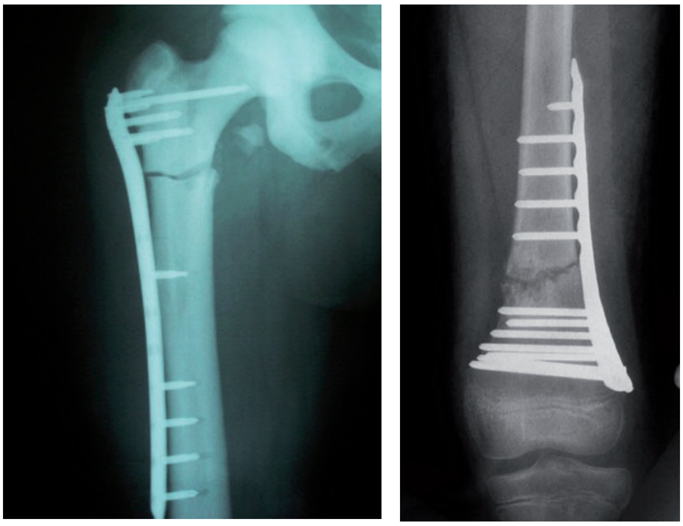


Fig. 2 Femur bones stabilized with a plate and screws [14, 15]

2 Materials and methods

CT scan images with 0.2 mm intervals taken by Toshiba imaging device with 16-row multisclice platform (the same dvice as the one in [17]) have been used for modeling the femur bone. The analysis was performed using ANSYS finite element code. For discretizing the femur bone, 4-noded tetrahedral solid elements were employed (Fig. 3). The mesh convergency of the model was checked and element size of 1 mm was found to be accurate enough. The total number of nodes and elements were slightly different between models with different hole geometries, but in average, each model consisted of 54,000 nodes and 240,000 elements.

Table 1 Elastic modulus and yield stress of the femur bone in different studies

Reference	Anatomic Site	Bone Type	E (GPa)
Zysset et al. [10]	Mid-diaphysis	Cortical	19.1 ± 5.4 GPa
Turner et al. [11]	Mid-diaphysis	Cortical	20 ± 0.3 GPa
Bayraktar et al. [12]	Mid-diaphysis	Cortical	19.9 ± 1.8 GPa
Ashman and Rho [13]	Femur	Trabecular	0.959 ± 0.388 GPa
Ashman and Rho [13]	Femur	Trabecular	1.78 ± 0.857 GPa

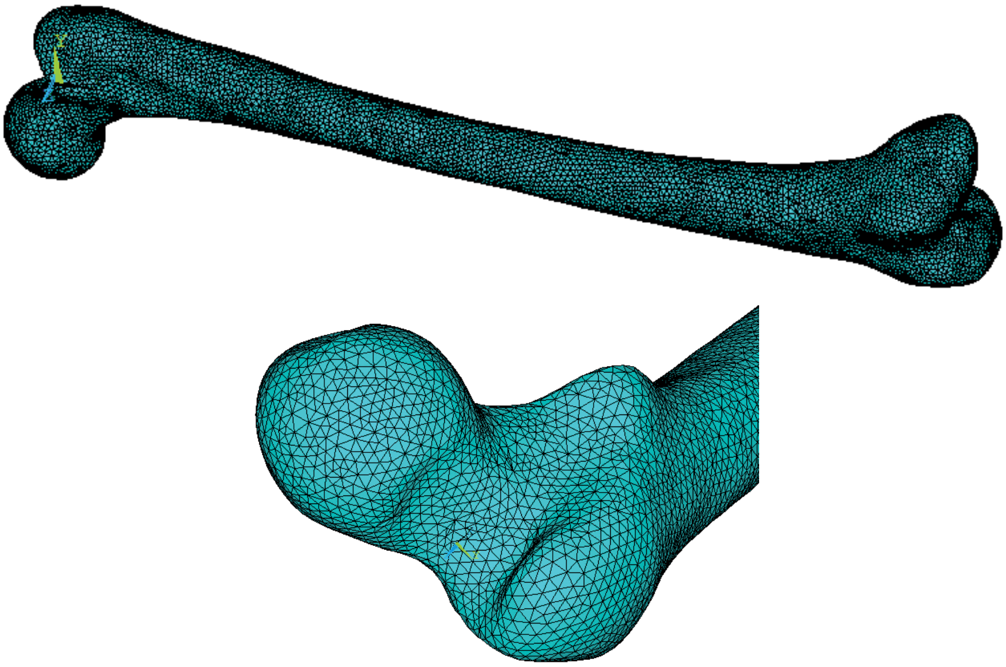


Fig. 3 Meshing of the femur bone in ANSYS

Bone, from microscopic point of view, is a composite material. It is a composite of collagen and hydroxyapatite; and its Young modulus is between apatite and collagen. However, as a strong composite, its resistance and strength is higher than those of collagen and/or apatite. This is because the ductile portion prevents fracture of the brittle part, while in turn the stiff portion prevents yielding of the ductile part. In addition to type of combination, mechanical properties of a composite material depends on its structure. As it was shown in Table 1, the mechanical properties of the trabecular part of the femur bone is very small, and therefore the inner part of the femur bone was assumed to be hollow. The mechanical properties of bone material, considered in this study for FE modeling by referring to Table 1, are listed in Table 2.

Table 2 Properties of cortical bone material

Property	Value
Yield stress	20 MPa
Young modulus	16 GPa
Poison’s ratio	0.46

Figure 4 demonstrates the geometrical dimensions of the windows created in the bone. Dimensions of these windows were selected in such a way that their area became equal; i.e. volume of removed material is equal for all the window types. In the compressive/tensional and torsional loadings, the perforated bones were fixed at one end and loaded in the other end. In the 3-point bending, the two ends of the bone were fixed and the bone was loaded laterally in its central region and, in the opposite side of the window. In order to obtain allowable forces, a force was applied at its action point(s), and the maximum von Mises stress of the structure was found in the integration points of the elements and compared to the yield stress of the bone. The allowable force was then found by a simple multiply cross.

3 Results and discussion

The values of permitted forces for different types of loading and window types are given in Table 3. Figure 5 shows the stress distribution and displacement throughout a femur bone with triangular window under 4-point bending loading. Figures 6-9 illustrate the stress distribution around the circular, square, triangular, and trapezoidal windows for different loading types.

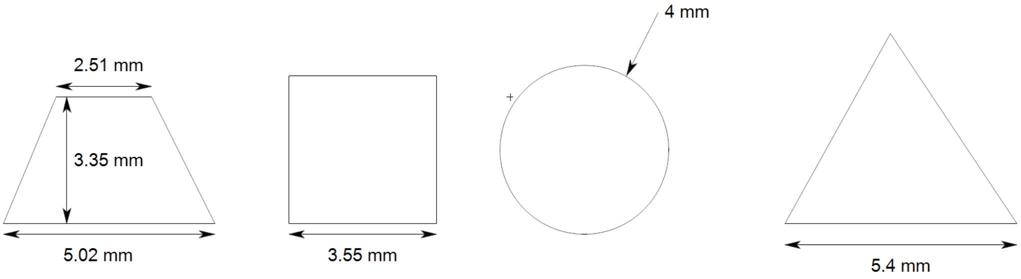


Fig. 4 Geometric dimensions of the windows

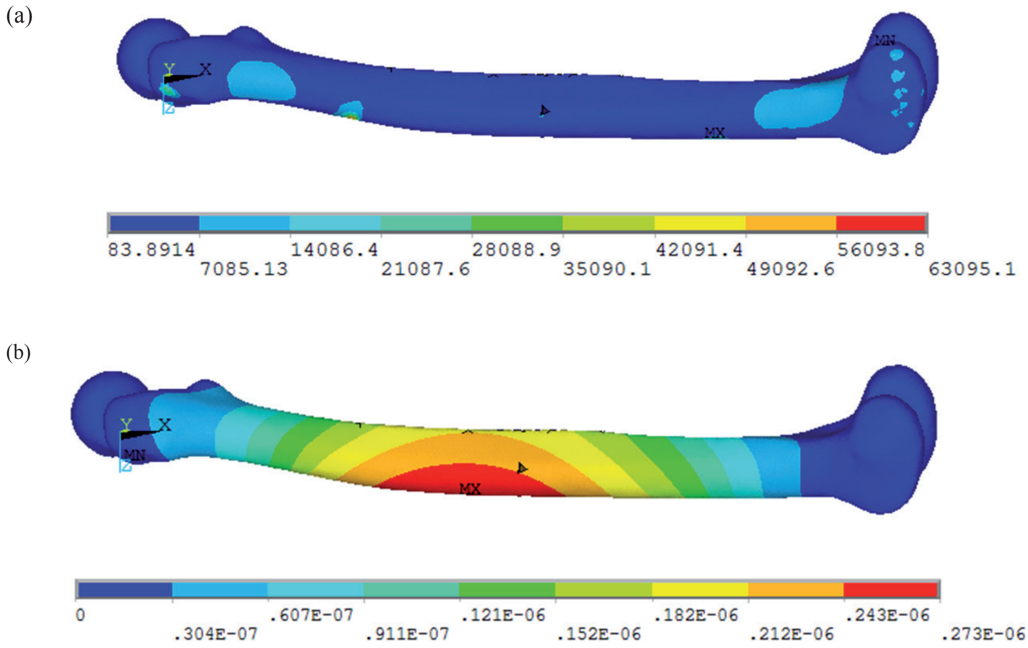
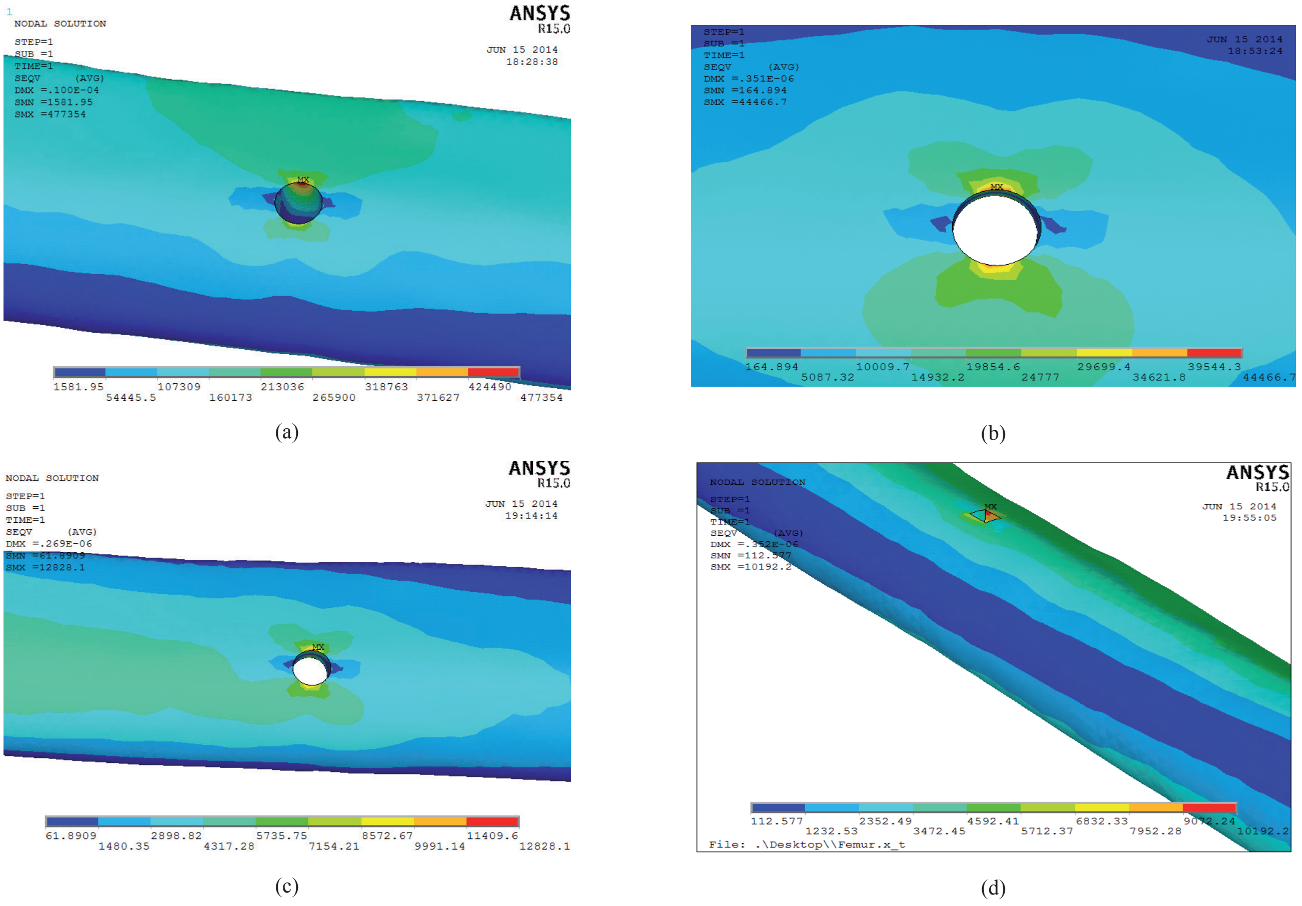


Fig. 5 (a) Stress distribution and (b) displacement distribution in a femur bone with triangular window, under 4-point bending loading



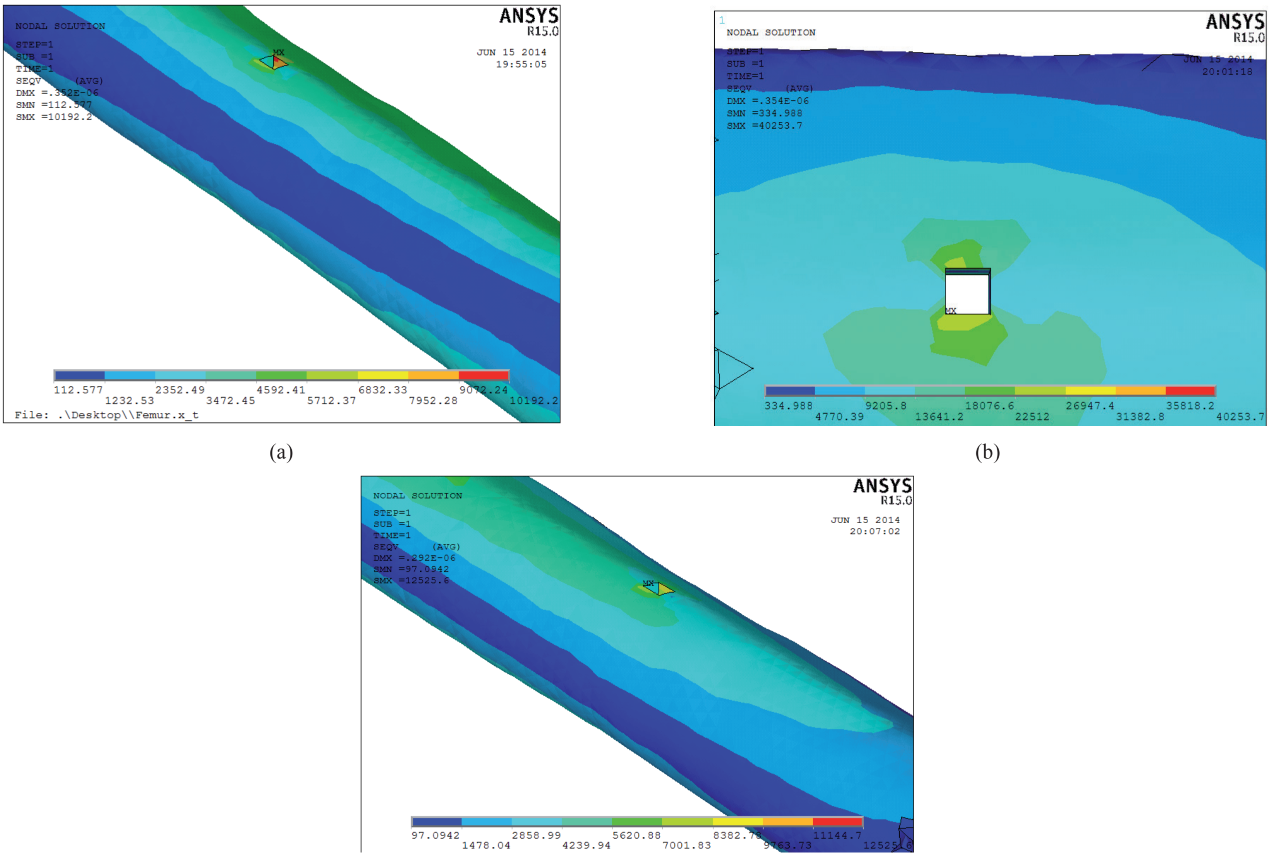
(a)

(b)

(c)

(d)

Fig. 6 Stress contour in a femur bone with circular window under different loadings: a) tension; b) 3-point bending; c) 4-point loading; and d) torsional loading.

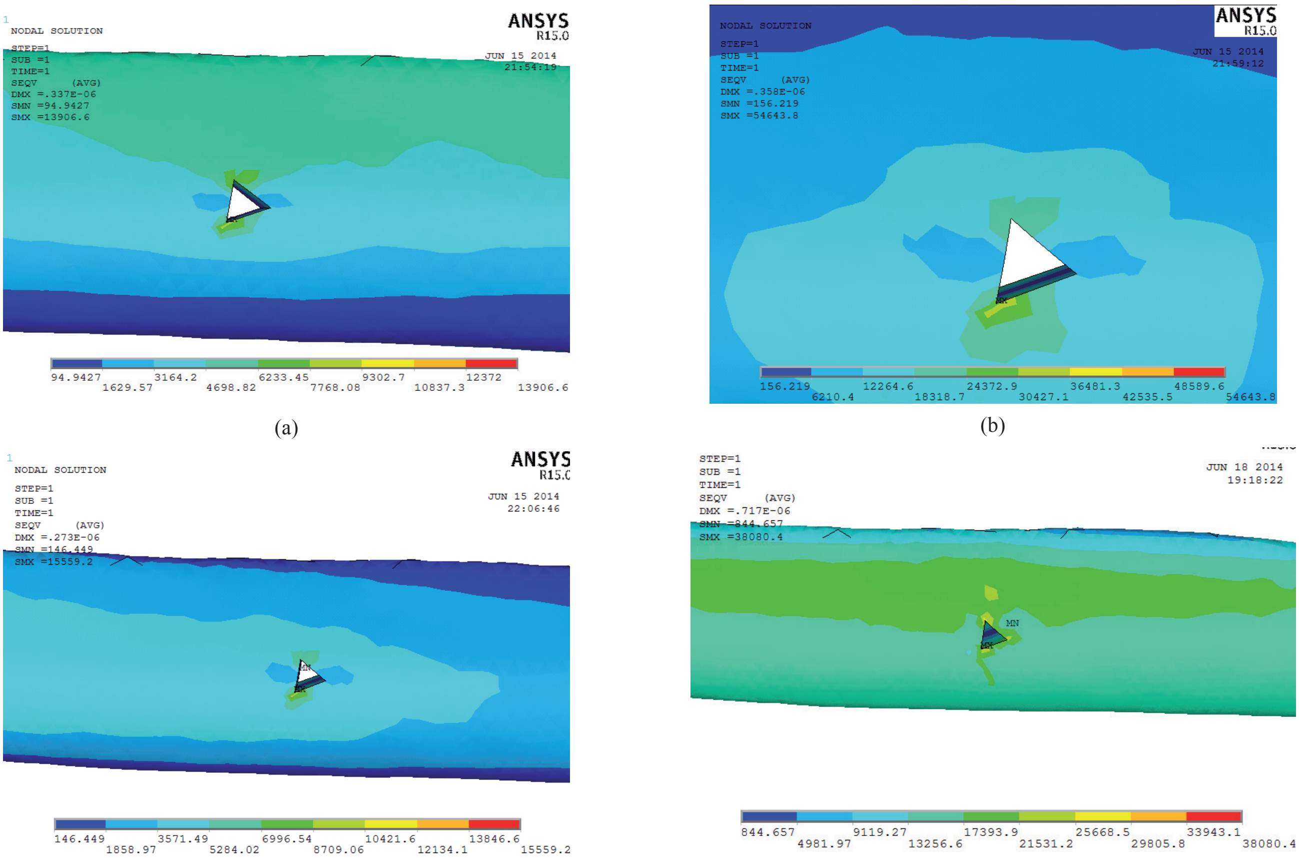


(a)

(b)

(c)

Fig. 7 Stress contour in a femur bone with square window under different loadings: a) tension; b) 3-point bending; and c) 4-point loading



(a)

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(d)

Fig. 8 Stress contour in a femur bone with triangular window under different loadings: a) tension; b) 3-point bending; c) 4-point loading; and d) torsional loading.

Table 3 Allowable forces for each loading

	Tension	Compression	3P Bending	4P Bending	Torsion
Square	260 N	260 N	118 N	200 N	8.7 N.m
Circle	398.5 N	398.5 N	113.5 N	195.5 N	9.32 N.m
Triangle	359.5 N	359.5 N	91.5 N	160.5 N	6.94 N.m
Trapezoid	532.5 N	532.5 N	152.5	131.5 N	8.125 N.m

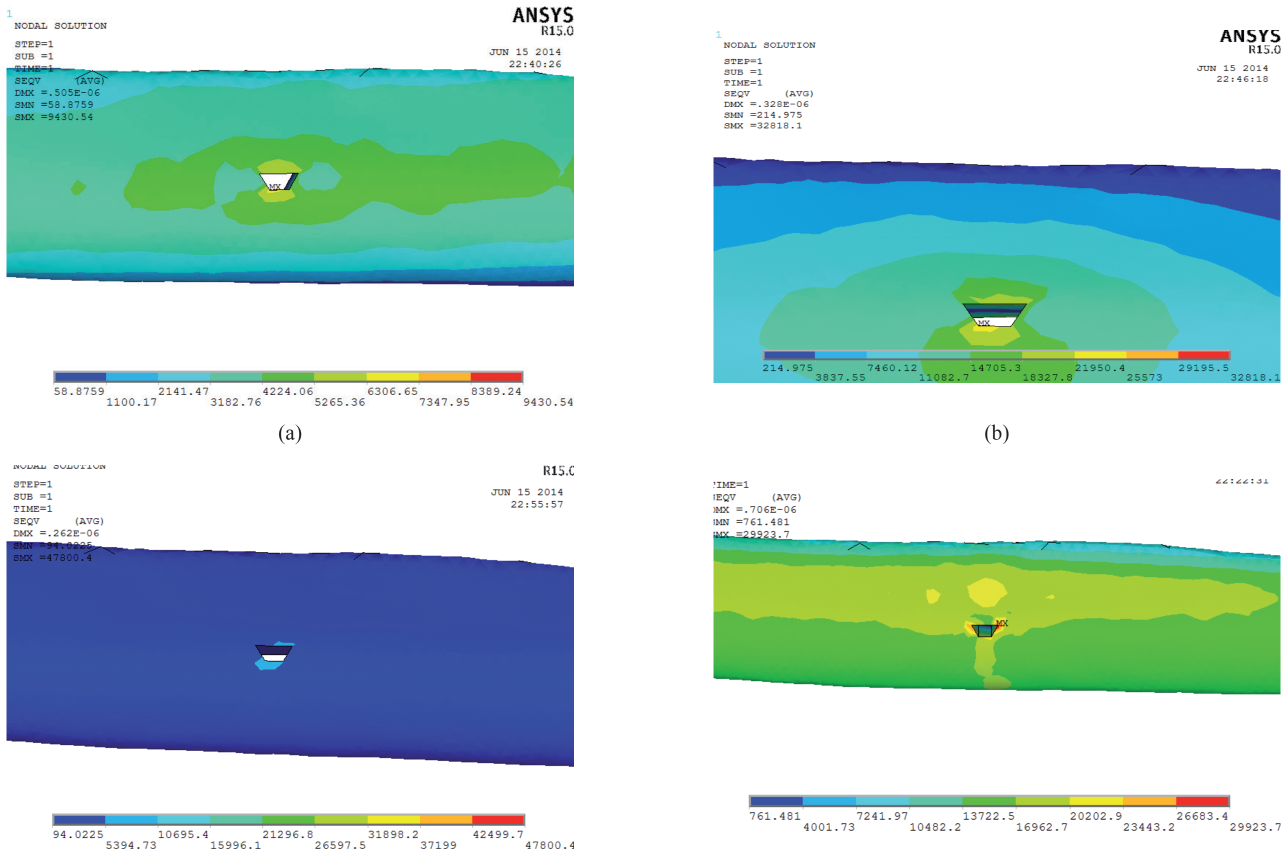
As it can be seen in Table 3, the bone with trapezoid window can tolerate the highest axial (compression/tension) loading among all the introduced cases. After the trapezoid case, the case with circular window has the highest strength in axial loading. It can also be seen from the table that the square perforated bone is the most susceptible case against axial loadings in such a way that the maximum load a bone with square window can tolerate is less than half of that of the bone with trapezoid hole. Since at most times of the day, the femur bone is loaded under axial loading, and particularly compressive loading, this result is very important for surgeons to substitute the current circular holes with trapezoid ones.

3-point bending is also an important loading condition which has the most possibility after axial loading. Lateral unintended impacts to feet, such as those which occur in car accidents, usually cause 3-point bending. Like the axial loading, in the 3-point bending the trapezoid case again has the best performance. The circular case again shows an acceptable performance and the 3-point bending load it can tolerate is not any less than 25% of that of the trapezoid case. In 3-point bending, the triangular case has the lowest permitted load which is 40% lower than that of the trapezoid case.

Unlike the predictions, the situation becomes very different in 4-point bending. This time, the square and circular cross-sections show the best performance while the trapezoid hole shows the lowest permitted load. This type of loading has the lowest possibility of occurrence among all the loading cases introduced. However, someone can assumes the load applied by for example sitting on some structures such as bench as four-point bending.

Torsional load has been reported as a primary cause of mechanical loosening of the femoral components, and may also play an important role in bone remodeling [16]. This would suggest that torsional loading can also be important to bone fractures in femur bones with windows. As presented in Table 3, the circular hole has the less impact on stress concentration around the window and can be chosen as the best option if only torsional loading is considered. After the circular hole, the trapezoid hole shows the best strength and the triangular windows shows the most weakening effect on the bone strength.

An irregularity (for example a perforation) bends the stress flows, compacting the streamlines in the locations where abrupt change in the path of streamlines occurs. This is known



(a) (b) (c) (d)

Fig. 9 Stress contour in a femur bone with trapezoidal window under different loadings: a) tension; b) 3-point bending; c) 4-point loading; and d) torsional loading.

as stress concentration. As the dimension of a perforation in the direction perpendicular to the streamlines becomes larger, more abrupt change in the stress flow happens leading to larger stress concentration values. On the other hand, the dimension of the perforation along the streamline does not significantly increase stress concentration, because they do not impact the streamlines a lot. In compression, tension, and bending, the trapezoidal windows have the smallest dimension in the direction perpendicular to the stress flows compared to other types of windows, and that is why the stress concentration for this geometry is the smallest among all the cases. However, in torsional loading, the dimension of the trapezoidal window in the peripheral direction, which is parallel to stress flow, is the largest. This explains the highest stress concentration of the trapezoidal windows in torsion.

4 Conclusions

In this study, the effect of window geometry on the strength of the shaft part of femur bone was studied using Finite Element method. Yield stresses of perforated femur bones under tension, compression, 3-point bending, 4-point bending, and torsional loadings were obtained and compared to each other. The bone with trapezoidal window type showed the highest strength in majority of the loads (tension, compression and 3-point bending). It is worth mentioning that parallel sides of the trapezoid must be parallel to the main axis of the bone, otherwise if the parallel sides of the trapezoid are perpendicular to the main axis of the bone, the bone structure becomes severely weak. After the trapezoidal window type, the circular window type had the highest strength in tensile and compressive loads, while in bending, the square window type showed the highest strength after the trapezoidal window. Although trapezoidal window showed great resistance in 3-point bending and axial loadings, it showed weaker performance in torsional and 4-point bending loads. However, the femur bone is very unlikely to be loaded in 4-point bending. Moreover, in torsion, the femur bone with trapezoidal window was only 12% weaker than the femur bone with circular window (note that, in axial loading, the femur bone with trapezoidal window had 33.6% higher strength than the bone with circular window). Therefore, summing up all the results of this study, it is suggested to use trapezoidal as the most appropriate window type for orthopedic surgeries.

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