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Theoretical Study of Various Unit Models for Biomedical Application

Jeongho Choi[1*]

〈Abstract〉

This paper presents an analytical study on the strength and stiffness of various types of truss structures. The applied models are triangular-like opened truss-wall triangular model (OTT), closed truss-wall triangular model (CTT), opened solid-wall triangular model (OST), and hypercube models defined as core-filled or core-spaced cube. The models are analyzed by numerical model analysis using DEFORM 2D/3D tool with AISI 304 stainless steel. Then, the ideal solutions for stiffness and strength are defined. Finally, the relative elastic modulus of the core-spaced model is obtained as 0.0009, which is correlated with the cancellous bone for the relative density range of 0.029–0.03, and the relative elastic modulus for the core-filled model is obtained as 0.0015, which is correlated with cancellous bone for the relative density range of 0.035–0.036. For the relative compressive yield strength, the OTT reasonably agrees with the cancellous bone for the relative density of 0.042 and the relative compressive strength of 0.05. The CTT and OST are in good agreement at the relative density of 0.013 and the relative compressive yield strength of 0.002. The hypercube models can be used for the cancellous bone for stiffness, and the triangular models can be used for the cancellous bone for strength. However, none of the models can be used to replace the compact bone because it requires much higher stiffness and strength. In the near future, compact bone replacement must be further studied. In addition, previously mentioned models should be developed further.

Keywords : Cellular solids, Stiffness, Strength, Triangular model

1* Asst. Professor, Kyungnam University, PhD 7 Kyungnam daehak-ro, Changwon-si, Korea
Zip Code: 51767
E-mail: choicaf@kyungnam.ac.kr, Tel: 055-249-2210

1. Introduction

Periodic structures are based on a repeated unit cell model such as honeycomb, lattice, or cubic. These have been applied in numerous industries such as aerospace, ship building, or biomedical industries. All of these are mainly focused on a lightweight. In particular, in the field of biomechanics, bone replacement requires two important properties: biocompatibility and lightweight. This implies that the applied material must have good biocompatibility to match with a bone, and it must also have high strength or stiffness, along with being with lightweight. Thus, it is more complex and difficult to validate a bone replacement. Bone is composed of two types: cancellous bone (trabecular bone) which is a porous network of connecting rods or plates and has less than 70% volume fraction of bone solids, and compact bone (cortical or dense bone) which is a dense and has more than 70% volume fraction bone solids [1]. Thus, compact bone shows a higher stiffness and strength than cancellous bone. Bayraktar[2] studied cancellous bone model which is a human bone and they showed porous nature of the bone. Specifically, bone properties depend on either trabecular or cortical type. It is much difficult to find a bone specimen. To overcome this issue, it obtained scanning technologies. By micro computed tomography (μCT) imaging, X-ray absorptiometry (DXA) scanning, quantitative computed tomography (QCT), MRI (Magnetic Resonance Imaging), peripheral quantitative computed tomography (p-QCT), and quantitative ultrasound (QUS), many scientists have been investigated for the bone properties[3-10]. For example, Yener et al.[4] studied for bone quality by micro computed tomography (μCT) imaging. Mittra et al.[3] tried to find out the mechanical parameters like elastic modulus, yield stress, and ultimate stress by a dual energy X-ray absorptiometry (DXA) scanning.

However, because of high cost and time consumption to get a bone specimen or to do mechanical test, generally many researchers have focus on numerical analysis to predict bone properties. Bone properties are big differences because they are depending on the gender, age, weight of a person, or the bone structure such as hip and spine. For instance, Young's Modulus of cancellous bone is 20~1600MPa by Carter et al.[7,11]. In addition, bone properties are different according to do the tests such as compression, tension, bending, buckling, or torsion[12,13-16]. Thus, the properties of the compact or cancellous bone are defined in a range. The cortical bone has stiffness ranged from 10.9~34.3GPa, strength ranged from 49~253MPa. The cancellous bone has modulus between 0.01~1.61GPa, and strength values ranged from 0.3~45MPa. As reasons of environmental damages and unknown reasons, bone disease like osteoporosis is a serious problem to patients. Thus, many scientists or researchers have studied the bone replacement to overcome the diseases[2,17]. Thus, it is studied the stiffness and strength of various types of unit models such as OTT, CTT, and OST. Then, they the applicability of the models for the bone replacement is verified based on the stiffness and strength.

2. Ideal solution for Triangular unit model

A unit model for periodic structure is shown in here triangular, core filled cube, and core spaced cube built by a truss. Ideal solution for all models are based on Gibson-Ashby's theory which is shown that relative elastic modulus is correlated with relative density to two the power and relative compressive yield strength is correlated with relative density to three over two the power[12]. Based on the theory of Gibson-Ashby[12], each model shown in Fig. 1 was tested by numerical model analysis by DEFORM 2D/3D. And then each model could be found an expected ideal relation between relative elastic modulus and relative density, and between relative compressive yield strength and relative density respectively.

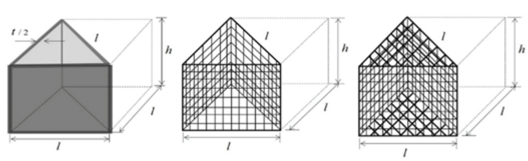

Fig. 1 Schematic triangular unit models (OST, OTT, and CTT)[18]

For a triangular unit model[18], relative density of OST is

$$(\frac{\rho^*}{\rho_s})_{OST} = \frac{t}{l}, t < l \quad (1)$$

where, t is a thickness of plate and l is a length. Thus, relative density is correlated with a ratio of a plate thickness and a length.

Relative density of OTT is

$$(\frac{\rho^*}{\rho_s})_{OTT} = \frac{d}{4}\left(\frac{4C\cdot(d+w)-d}{C\cdot(d+w)^2}\right), d < 4C\cdot(d+w) \quad (2)$$

where, d is a diameter of truss, w is an opening space in truss, and C is a constant. Relative density of CTT is

$$(\frac{\rho^*}{\rho_s})_{CTT} = \pi\left(\frac{4C\cdot(\sqrt{3}-1)+6\sqrt{3}}{3C^2}\right)\left(\frac{d^2}{(d+w)^2}\right) \quad (3)$$

where, d is a diameter of truss, w is an opening space in truss, and C is a constant.

By DEFORM 2D/3D software, it runs numerical analysis for OST, OTT, and CTT models[18]. The relative elastic modulus and relative compressive yield strength can be expressed as a function of the relative density for each model. Thus, ideal solutions for triangular unit model are shown in Table 1.

Table 1. Summary ideal solutions for triangular unit models[18]

	OST	OTT	CTT
$(\frac{\rho^*}{\rho_s})$	$\frac{t}{l}, t < l$	$\frac{d}{4}\left(\frac{4C\cdot(d+w)-d}{C\cdot(d+w)^2}\right)$	$\pi\left(\frac{4C\cdot(\sqrt{3}-1)+6\sqrt{3}}{3C^2}\right)\cdot\left(\frac{d^2}{(d+w)^2}\right)$
$(\frac{E^*}{E_s})$	$42.624(\frac{\rho^*}{\rho_s})^{1.7318}$	$93.204(\frac{\rho^*}{\rho_s})^{2.5697}$	$8.9966(\frac{\rho^*}{\rho_s})^{1.3987}$
$(\frac{\sigma^*}{\sigma_s})$	$0.1507(\frac{\rho^*}{\rho_s})^{0.969}$	$0.1843(\frac{\rho^*}{\rho_s})^{0.3972}$	$0.2315(\frac{\rho^*}{\rho_s})^{0.6775}$

Table 2. Mechanical property for a human bone

Mechanical property	Range of values	Reference
Compact (cortical) bone		
Density	1800-2000 kg/m^3	12),13)
Modulus in tension	10.9-29.2 GPa	19),20)
Modulus in compression	14.7-34.3 GPa	19)
Modulus in bending	9.1-15.7 GPa	14)
Modulus in shear	3.1-3.7 GPa	21)
Yield strength in tension	49-177 MPa	12),13)
Yield strength in compression	133-215 MPa	12),13)
Yield strength in bending	103-253 MPa	22)
Shear strength	53-71 MPa	21)
Cancellous (trabecular) bone		
Density	80-580 kg/m3	7),9)
Young's Modulus	0.01-1.61 GPa	11),15)
Ultimate strength	0.3-45 MPa	11),15)

3. Bone properties

Bone properties are reported by many researchers. It summarized at Table 1. However, biomedical scientists and engineers have found that bone properties to be fixed like metals requires more precise tests, which need a longer time and high cost. Several studies have obtained ranges of values for the properties of the compact bone and cancellous bone.

For a human cortical bone, it has 1800-2000 kg/m^3 density, 14.7-34.3 GPa Modulus in compression, 133-215 MPa yield strength in compression. For a human trabecular bone, it has 80-580 kg/m^3 density, 0.01-1.61 GPa Modulus in compression, 0.3-45 MPa yield strength in compression. Based on their maximum data, cortical bone can have 3.4 times higher density, 21.3 times higher modulus in compression, and 4.8 times higher yield strength in compression. The bone properties are summarized in Table 2 with the respective references. Thus, mechanical properties for a human bone, especially compression, will be obtained to compare with triangular unit models or hexagonal truss cubic models.

4. Material properties

There are two types of applied material properties: linear and bilinear. Linear properties include the elastic modulus, known as the Young's modulus. Bilinear properties have two slopes, as shown in Fig. 2. One slope means elastic modulus and the other slope infer tangent modulus after yield strain.

For the bone replacement, there can be obtained with three major materials such as stainless steel, Cobalt-Chrome alloy, and titanium alloy. Each material have own properties like density, Young's modulus, yield strength, ultimate strength, and Poisson's

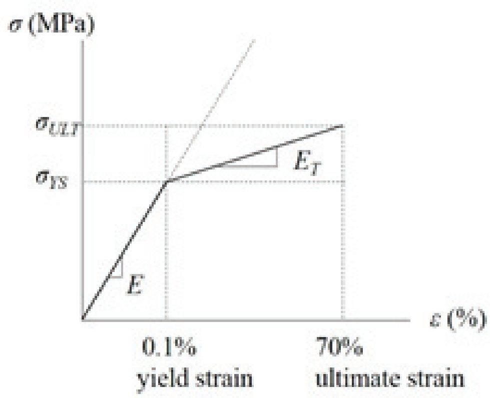

Fig. 2 Stress-strain diagram of bilinear material model[21)]

ratio. Details are summarized in Table 3 where linear means the straight line passing through yielding point and bilinear means a bent line after yielding point in Fig. 2 Each material property have two modulus which are elastic modulus in linear and tangent modulus in bilinear.

5. Results

Based on all data and ideal solution for various models defined by finite element analysis, there are plotted elastic modulus related with density or compressive yield strength as a function of relative density as a log-log scale.

Table 3. Mechanical property for a bone replacement

Material properties		Linear	Bilinear
304 stainless steel (SST304)[22)]	Density (kg/m^3)	8000	8000
	Young's Modulus, E (GPa)	193	193
	Poisson's ratio	0.25	0.25
	Yield stress, σ_{YS} (MPa)	215	215
	Ultimate stress, σ_{ULT} (MPa)	-	505
	Ultimate strain, ε_T (mm/mm)	-	0.7
	Yield stress, E_T (MPa)	-	429
Cobalt-chrome alloy (CoCrMo)[23)]	Density (kg/m^3)	8400	8400
	Young's Modulus, E (GPa)	210-253	210-253
	Poisson's ratio	-	-
	Yield stress, σ_{YS} (MPa)	86-614	586-614
	Ultimate stress, σ_{ULT} (MPa)	-	1030-1060
	Ultimate strain, ε_T (mm/mm)	-	0.17-0.23
	Yield stress, E_T (MPa)	-	2082-2488
Titanium alloy (Ti-6Al-4V)[24)]	Density (kg/m^3)	4430	4430
	Young's Modulus, E (GPa)	113.8	113.8
	Poisson's ratio	0.342	0.342
	Yield stress, σ_{YS} (MPa)	880	880
	Ultimate stress, σ_{ULT} (MPa)	-	950
	Ultimate strain, ε_T (mm/mm)	-	0.14
	Yield stress, E_T (MPa)	-	529

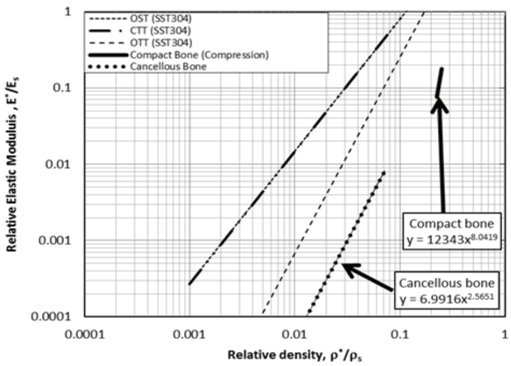

Fig. 3 Relative elastic modulus as a function of relative density

For the elastic modulus, Fig. 3 shows plots about relative elastic modulus as a function of relative density. In here, relative elastic modulus of the core-spaced model is 0.0009 related with cancellous bone in a range of relative density 0.029~0.03, and relative elastic modulus for core-filled model is 0.0015 which is correlated with cancellous bone in a range of relative density 0.035~0.036. By the way, OST/CTT shows a higher elastic modulus and lower density than cancellous bone or compact bone.

Unfortunately, any models are not related with a range of compact bone. The compact bone is shown a higher density with higher modulus than hypercube models, and lower density with lower modulus than OST, CTT, or OTT. Thus, triangular models are proved they are higher elastic modulus with lower density than hypercube models with higher density.

In relative compressive yield strength shown in Fig. 4, OTT is reasonably matched with cancellous bone in 0.042 relative density

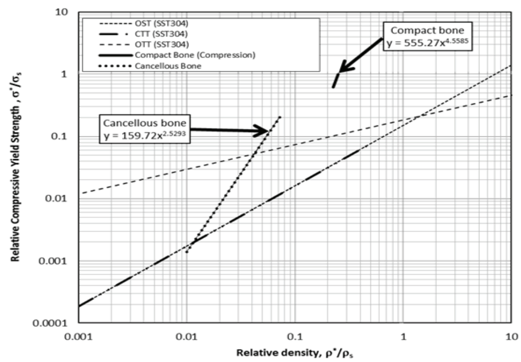

Fig. 4 Relative compressive yield strength as a function of relative density

and 0.05 relative compressive yield strength. CTT or OST is good relation in 0.013 relative density and 0.002 relative compressive yield strength. That is, hypercube models are possible to be applied in cancellous bone in stiffness and triangular models are potential to be applied in cancellous bone in strength. However, any models are not possible to be replaced with compact bone because it is required much higher stiffness or higher strength. Fig. 4 shows a range of the compact bone is shown a higher compressive yield strength than any other models. Thus, any models suggested in here is not reasonably matched with the compact bone.

In the Fig. 3 and 4, compact bone is defined as equation where y means relative elastic modulus and x infers relative density. Cancellous bone is also defined as equation where y means relative elastic modulus and x infers relative density, too. All equations in Fig. 3 and 4 is based on various data from references for the bone.

6. Conclusion

This paper presents an analytical study on the strength and stiffness of various types of truss structures. Hypercube models are possible to be applied in cancellous bone in stiffness and triangular models are potential to be applied in cancellous bone in strength. However, any models are not possible to be replaced with compact bone because it is required much higher stiffness or higher strength. In the near future, compact bone replacement must be further studied. In addition, previously mentioned models should be developed continuously further, they should be considered to be obtained of 3D printing[25] skills additionally.

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Symbols

d diameter of a truss [mm]
w space of a truss [mm]
ρ density [kg/cm^3]

Subscripts

d the wire diameter
w the opening width (i.e., aperture)
ρ^* the density of the foam itself
ρ_s the density of the base material
E^* the Young's modulus of the foam itself
E_s the Young's modulus of its base material
σ^* the initial yield stress
σ_s the initial yield stress of the base material
l the length of one side in the honeycomb
t the thickness of a solid wall honeycomb
SST stainless steel

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