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Technical Report

Research of elasticity for a corrugated wire mesh

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ABSTRACT

The objective of this paper was to validate the characteristics of corrugated wire mesh laminate (CWML) by numerical calculation and uniaxial compressive test and then to compare the results with those of an open-cell cancellous bone model. CWML fabrication was based on the transient liquid phase (TLP) technique within an inert gas environment, the numerical model was calculated using a software package, and a CWML theoretical model was developed using prismatic structures. CWML samples were made from type 316 stainless steel (SS) woven wire mesh that was bonded by a soldering material, Tin alloy (95Sn–5Ag), within an inert gas environment at approximately 250 °C. Fabricated meshes ranging from 1.67 pore/cm (42.3 pore/in.) to 0.85 pore/cm (21.7 pore/in.) to 0.63 pore/cm (16 pore/in.) were used. The relative densities of the meshes ranged from 0.0272 to 0.0321. The numerical model of CWML was based on a bonded structure with four waves, one layer, and a corrugation angle of 57.71°. It was calculated for three different types of wire cloths for comparison with the real samples. The relative densities of the numerical model ranged from 0.022624 to 0.030746. Finally, the specimens were tested and compared with the derived CWML theory, the numerical computational model, and the open-cell cancellous bone models of Gibson–Ashby and Carter–Hayes. The relative densities of the fabricated samples were reduced to 79.07% when the corrugated angle was 57.71°, as confirmed by the comparison of the relative densities of the derived CWML theory and the numerical model. The CWML-derived theory, the computational model, and the tested samples were reasonable matches with the open-cell cancellous bone model of Gibson–Ashby and Carter–Hayes. Because of this, the CWML model is expected to be of use in bone replacement. However, for human bone replacement, the model must be subjected to biomedical testing by medical scientists.

1. Introduction

The study of the human bone is interesting because bone properties vary according to the gender, age, the weight of a person, and because it is a complex structure in relation to the body's blood, nerves, and muscles. Bones are classified into two types: cancellous bone and compact bone. Cancellous bone consists of a porous network of connecting rods or plates and has less than 70% of the volume friction of a solid. Compact bone is a dense solid and has more than 70% of the volume friction of a solid [1]. Relative density is defined as the density of a dense solid divided by the density of the cell wall made from a given material and corresponds to the volume friction [1]. Thus, the density and the volume are important factors in distinguishing between cancellous and compact bone. Carter and Hayes [2–4] reported the influence of human compact or cancellous bone's apparent density on its compressive strength and modulus. Based on results from compressive testing, they showed that compressive strength is related to the density of a specimen as a square in the power rule and that the compressive modulus is related with the specimen density as a cube in the power rule [5]. Cellular-solid models are generally ideal for simplifying calculations on cancellous bone [6]. Gibson and Ashby proved that the relative Young's modulus and the compressive yield strength are correlated with the relative density. They showed that much of the data of previous researchers were plotted as the Young's modulus and the compressive strength of the trabecular bone against the density. Raw data for the Young's modulus of the trabecular bone plotted against density come from work on the human tibial plateau bone, the bovine femoral condyle [2], the human femur [4], the bovine femur [7], and the human tibia [8,9]. Raw data for the compressive strength of the trabecular bone plotted against the density come from studies of the femur and tibia [10], the bovine femoral condyle [2], the tibia plateau [2], the vertebrae [11], the calcaneus [12], the femur [4], and the bovine femur [7]. Gibson and Ashby [2,13] defined the elastic moduli and the strength of foams in terms of linear elasticity, linear elastic strut (bending), non-linear elasticity (elastic buckling, elastomeric foam), plastic collapse (plastic yielding, elastic–plastic foam), and brittle crushing. They extended these concepts to the cancellous

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Nomenclature

d	the wire diameter, mm
w	the opening width (i.e., aperture), mm
ρ	the density of the foam itself, kg/cm^3
ρ_s	the density of base material, kg/cm^3
E	the Young's modulus of the foam itself, GPa
E_s	the Young's modulus of its base material, GPa
C	constant
σ_{pl}	the normal plastic stress, MPa
$\sigma_{0.25}$	the normal plastic collapse occurs at 25% strain, MPa
t	the wire diameter, mm
l	the number of wires along the length of the slide, mm
m	the number of wires to the width
V^*	the volume of the foam itself, mm^3
V_s	the volume of the solid-cell wall properties, mm^3
n	the total number of wires
b	the width, mm
l	the length of the slide, mm
t	the thickness of unit model of corrugated wire mesh laminate, mm
R-square	the coefficient of determination

bone, which showed the same relationships as the work of Carter and Hayes [2].

Metal wire mesh offers a new approach to this line of research. Sypeck and Wadley et al. investigated metal wire mesh as a metal topology. They defined the relative density as being related to plain, square, woven cylindrical wires having a wire diameter and an opening width (aperture). They showed that open-cell periodic metal truss structure based on plain, square, woven wire mesh exhibited a linear dependence of stiffness and strength of relative density [14,15]. These are based on periodic cellular materials (PCM topology) created by the Department of Materials, Science and Engineering at the University of Virginia, where the researchers selected prismatic structures such as corrugated plates, diamond ridged plates, and truncated plate geometry as the unit cells from which they derived the relative density relationship. However, they did not show a combined structure, which is corrugated lattice truss, and a correlation between relative density and relative elasticity for the grooved lattice truss. Thus, the ridged lattice truss is to be interested. It is also interesting what elasticity is in bone.

The PCM topology has an advantage and disadvantage. The advantage is that it can be used widely in designing lightweight structures, creating unidirectional fluid flows, absorbing the energy of impacts, impeding thermal transport across the faces of sandwich panels and acoustic damping. In addition, it can be used in building, ship construction, aerospace applications [16], biomaterials [17], lightweight multi-function [18] and for cross flow heat exchangers. However, disadvantage in the PCM is that mechanical property for the PCM can be changed by bonding skill and by heating temperature. Thus, the CWML offers the advantage of controllable rigidity and strength. That is, their stiffness or strength can be controlled because the CWML depends on many parameters such as a wire diameter, opening space, corrugated angle, and bonding strength, and cost effectiveness. Disadvantages are that CWML manufacturing needs much time and applied bonding skill is limited.

The earliest fabrication of CWML was reported by Sypeck in 2002 [19], and beginning of application was shown in heat exchangers as early as 1994 [20]. Sypeck et al. [14,19–24] developed methods of fabricating CWML using 304 stainless steels corrugated wire meshes bonded together using transient liquid phase (TLP) bonding materials. Although these methods provide the best means of fabricating CWML, demerit for the bonding skill was required a high temperature ranged from 800 °C to 900 °C. Thus, this paper is to suggest a new brazing material working at a low temperature.

The objective of this paper was to validate the characteristics of corrugated wire mesh laminate (CWML) by numerical calculation and uniaxial compressive test and then to compare the results with those of an open-cell cancellous bone model. CWML fabrication was based on the transient liquid phase (TLP) technique within an inert gas environment, the numerical model was calculated using a software package, and a CWML theoretical model was developed using prismatic structures.

2. Modeling

2.1. Open cell

The cancellous bone is based on the cubic open cell model. The Young's modulus and compressive yield strength of the bone model also rely on relative density, along with the power law relations, which are slightly different relations than those for open cell stochastic foam. Eq. (1) shows the correlation between the relative modulus and relative density [1–4,13,19]:

$$\frac{E}{E_s} = C_1 \cdot \left(\frac{\rho}{\rho_s}\right)^3 \tag{1}$$

where ρ is the density of the foam itself and ρ_s is that of its base material, E is the Young's modulus of the foam itself, E_s is the Young's modulus of its base material, C_1 is constant. In this work, σ_{pl} can be replaced by $\sigma_{0.25}$ because when normal plastic collapse occurs at 25% strain in a compression test, σ_{pl} is equal to $\sigma_{0.25}$ [20–22].

2.2. Metal wire mesh (plain type)

The metal wire mesh consists of several types, such as plain, square, and woven cylindrical wires [14,15,19]. In this paper, the mesh is a woven cylindrical type, and the relative density correlate with the wire diameter, d, and the opening width (i.e., aperture), w. The relative density of the wire mesh is determined as follows:

$$\frac{\rho^*}{\rho_s} = \frac{\pi d}{4(w+d)} \tag{2}$$

where ρ^* is the density of the mesh itself, ρ_s is that of its base material (here, it is stainless steel AISI type 316). The relative density of this metal wire model is based on the open-cell theory of stochastic foam. Plain, woven wire develops small corrugations when each wire is assembled to make a woven shape. However, because these corrugations are very small, they are ignored in this paper.

2.3. Corrugated wire mesh laminates (CWML)

For metal wire mesh development, the idea for corrugation comes from the corrugated plate and the wire mesh relationship for the plain, square, woven cylindrical wire model. Thus, the