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Effect of Cortical Bone Layer on Fast and Slow Wave Propagations in Cancellous Bone: Investigation Using Stratified Models

海綿骨中の高速波・低速波伝搬における皮質骨層の影響：層状構造モデルによる検討

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1. Introduction

Fast and slow longitudinal waves, which are respectively considered to correspond to the first and second kind waves in Biot's theory,[1,2] can propagate through cancellous bone when an ultrasound wave is transmitted in the direction of the strong orientation of the trabecular network.[3] The observation of both the fast and slow waves has been performed in many *in vitro* experiments[4] but in few *in vivo* experiments.[5] *In vivo* cancellous bone is generally surrounded by cortical bone, and therefore, it is considered that the layer of cortical bone can affect the fast and slow wave propagations in cancellous bone. In fact, it was shown that the generation of the Biot's second kind wave in a porous medium was affected by the interface condition surrounding the medium.[6]
In the present study, the effect of cortical bone layer on the fast and slow wave propagations in cancellous bone was numerically investigated using the stratified models of cancellous bone.

2. Stratified models of cancellous bone with cortical bone layer

Based on the original stratified model made up of periodically alternating solid and fluid parts,[7] the cancellous bone models with cortical bone layer were developed, and are shown in **Fig. 1**. In general, the porosity in cancellous bone is low in the vicinity of cortical bone and becomes higher as the position shifts away. Both cancellous bone models without and with porosity distribution (variation) were considered, as shown in Figs. 1(a) and 1(b). The boundary between the cancellous and cortical bone regions is clear in the model of Fig. 1(a) but becomes obscure in the model of Fig. 1(b).
To easily make the experimental specimens of the cancellous bone models, the material composing cancellous and cortical bones was assumed to be brass. (It is noted that the experimental results are

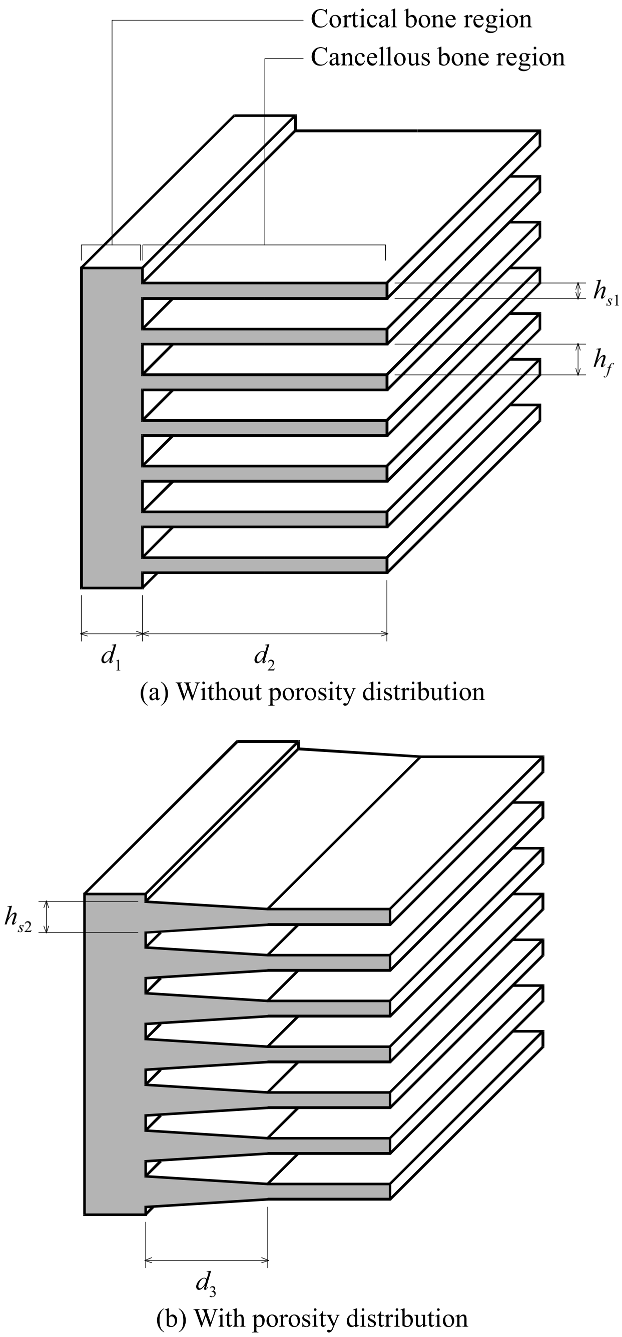

Fig. 1 Geometries of stratified models of cancellous bone with cortical bone layer.

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not shown in this proceeding.) The spaces in the cancellous bone region were filled with water. Each size in the cancellous bone models was d_1 = 2.0 mm, d_2 = 8.0 mm, d_3 = 4.0 mm, h_{s1} = 0.5 mm, h_f = 1 mm, and h_{s2} = 0.5 – 1.5 mm.

3. Numerical simulations of fast and slow wave propagations

Numerical simulations of the fast and slow wave propagations in the cancellous bone models were numerically simulated using an elastic finite-difference time-domain (FDTD) method. An ultrasound pulse at 1 MHz was transmitted from the cortical bone side, and the waveforms propagating through the cancellous bone models were simulated. The simulated results are shown in **Fig. 2**. As shown in Fig. 2, both the fast and slow waves could be observed despite of the existance of cortical bone layer. Compared between the waveforms observed for the cancellous bone models without and with porosity distribution, in which h_{s2} = 0.5 and 1.0 mm were respectively set, the fast wave amplitude of the latter became larger than that of the former, but the slow wave amplitude became smaller.

To investigate the effect of the boundary condition between the cancellous and cortical bone regions, the fast and slow wave amplitudes were measured as a function of h_{s2}. The measured results are shown in **Fig. 3**. As shown in Fig. 3, above h_{s2} = 1 mm, the fast wave amplitude scarcely varied with h_{s2}. On the other hand, the slow wave amplitude largely decreased with h_{s2}. Thus, the boundary condition could more largely affect the slow wave than the fast wave. This is considered to be because the generation of the slow wave became weak owing to the gradually varying spaces in cancellous bone. However, the slow wave could be observed even in the condition of h_{s2} = 1.5 mm that the space at the boundary was zero. Accordingly, it can be considered that both the fast and slow waves can propagate through cancellous bone with cortical bone layer, although the slow wave appears to be more largely affected in the actual bone with a more complicated structure.

4. Conclusions

The stratified cancellous bone models with cortical bone layer were developed to investigate the effect of the boundary condition between the cancellous and cortical bone regions on the fast and slow wave propagations. The simulated results showed that, although the boundary condition mainly affected the slow wave generation, both the fast and slow wave could propagate through cancellous bone with cortical bone layer.

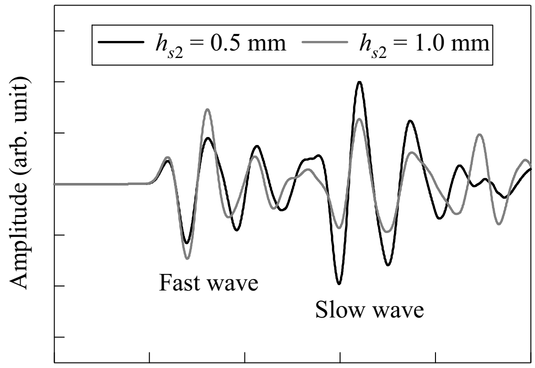

Fig. 2 Simulated ultrasound waveforms propagating through cancellous bone models with cortical bone layer. The models at h_{s2} = 0.5 and 1.0 mm are respectively those without and with porosity distribution.

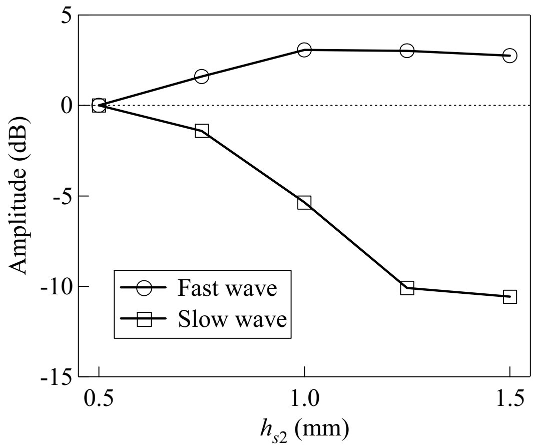

Fig. 3 Variations in fast and slow wave amplitudes in cancellous bone model with porosity distribution as a function of h_{s2}.

Acknowledgment

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