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Density evaluation of PU foam covered with a soft layer using a highly-nonlinear solitary waves

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ABSTRACT

Highly nonlinear solitary wave in granular crystal shows great potentials for non-destructive evaluations of various structures, such as delamination/ weak bond detection in CFRP composites, hydration of cement, etc. In this study, we conduct a feasibility study to diagnose osteoporosis using a highly nonlinear solitary wave. Density evaluation of bone covered with a soft skin layer would be challenging because the soft skin absorbs the solitary wave energy and attenuates the wave reflections. We first fabricate simple specimens, polyurethane (PU) foam covered with silicone rubber layer, mimicking bone covered with the skin layer. Then we investigate the solitary wave reflections on the specimens with different PU foam densities. We find that it is possible to distinguish the foam density based on the wave reflections and the wave reflection much depends on the skin layer thickness.

1. INTRODUCTION

A medical PU(Polyurethane foam) foam is a sponge-shaped porous material that exhibits similar mechanical behavior to a sponge bone inside a human bone and is known to be highly biocompatible (Marois and Guidoin 2013). Accordingly, PU foam has been used as an artificial implant substituting spongy bone (Shim et al. 2012, Park et al. 2002), and as a bone-implementing specimen in various studies (Schiffer et al. 2018, Comuzzi et al. 2020, Calvert et al. 2010). Patel et al. (2008) have imitated the bone density change in the sponge bone caused by osteoporosis through changes in the density of PU forms and compared their physical properties.

In this work, we conduct a study to evaluate the density of PU foam using highly nonlinear solitary waves in a granular chain. Previously, we have analyzed the direct interaction of highly nonlinear solitary waves with PU forms having different densities (Schiffer et al. 2018). Here we investigate the interaction of highly nonlinear solitary

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waves with the PU foams covered with soft silicone layers to investigate how the soft layer affects the evaluation of foam density using the highly nonlinear solitary waves.

2. EXPERIMENT

We fabricate the specimen in the shape of a PU foam covered with a silicon layer (Fig. 1). The mechanical property of the silicon layer ($E_{compressive}$ = 4~30 Mpa) is similar to human skin (E = 5 to 27 Mpa). We use three silicon layers with different thicknesses, 0.5mm, 1.0mm, and 2.0mm, to investigate the effect of soft layer thickness on the solitary wave reflection. We also use solid-type medical PU foams manufactured in SAWBONES®. Three different PU foams, 5pcf, 8pcf, and 10pcf, are used for the specimens, and their density is 80 kg/m^3, 128 kg/m^{3,} and 160 kg/m^3, respectively. We cover the silicon layer on top of the cube shape PU foam (40×40×40 mm).

Figure 1(a) shows an experimental setup, a granular sensor placed on top of the specimen. The granular sensor consists of twenty-one spherical beads vertically aligned by a supporting tube. The spherical beads are made of SUJ2 (E=208 Gpa, v = 0.3), and their diameter and mass are 15.875 mm and 16.3 g, respectively. We generate a highly nonlinear solitary wave with an impact excitation by dropping the first bead on top of the granular chain. We place a sensor bead in the center of the chain. The sensor bead contains a piezoelectric(PZT) disc at the center, which converts the compressive force into a voltage signal. The bottom particle in contact with the specimen has a flat circular shape with a diameter of 11 mm to increase the contact area with the soft layer, preventing stress concentration in the specimen. This minimizes the effect of the complex nonlinear behavior of the soft layer on the solitary wave reflection.

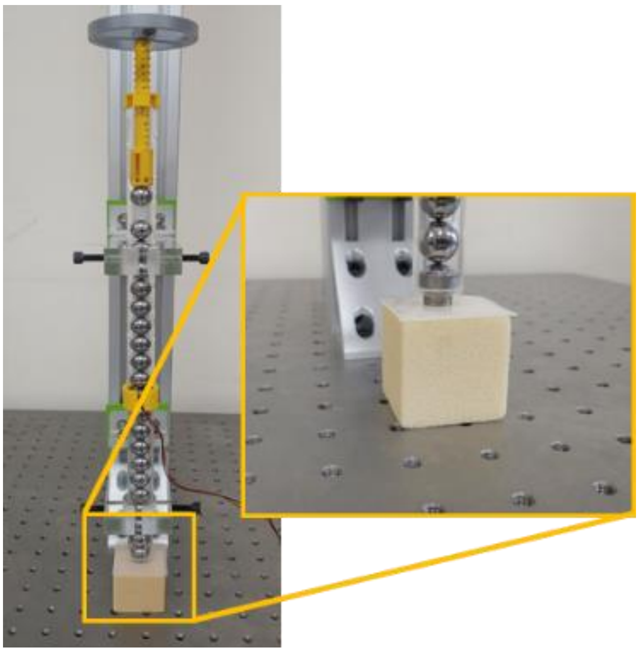

Fig. 1 Experiment Setup; the granular sensor consisting of 21 particles is placed on top of the PU foam covered with a silicon rubber layer.

3. RESULTS

Figure 2 shows highly nonlinear solitary waves measured in the experiment. The first pulses represent incident waves, and the others are reflected solitary waves from the specimen. Fig. 2(a) and 2(b) compare the waves in the three PU form specimens with a 0.5 mm and 2 mm soft layer, respectively. The time delays of the reflected waves in Fig.2(b) are larger than those in Fig. 2(a). This represents that relatively thick soft layer delays reflected solitary waves further. We also observe that the time delay becomes shorter as the PU foam density increases, similar to the solitary wave reflection without soft layer reported in (Schiffer et al. 2018). In the previous paper, the solitary wave reflection much depends on the plastic deformations of the PF foam due to stress concentration around the small contact region. In the present experiment, however, we do not observe a dent on the surface of the foam because the modified flat shape bead has a large contact area, which reduces the stress concentration and suppresses plastic deformation for both a soft layer and PU foam. Thus, the time delay differences in the three different PU foam specimens in Fig.2(a) and Fig. 2(b) are due to the foam density. The denser PU foam usually has higher effective stiffness, which makes the solitary wave reflection earlier.

(a)
(b)

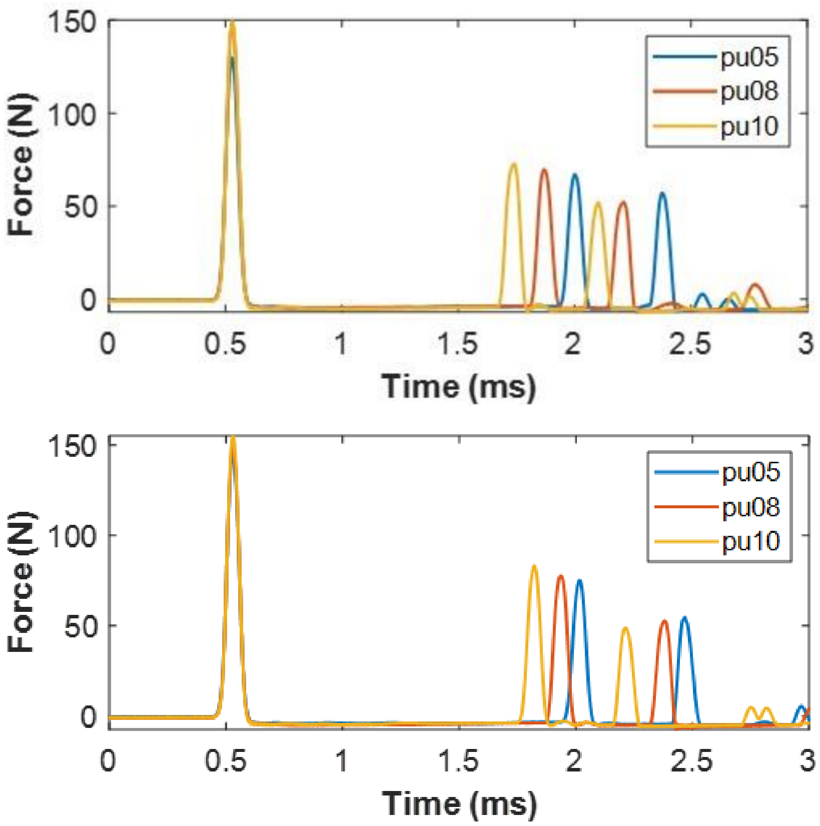

Fig. 2 Density Evaluation result according to thickness of PU foam covered with 0.5t(a)/2t(b) silicone layer

4. CONCLUSIONS

In this work, we experimentally demonstrate that the density change of the medical PU form covered with a soft layer can be evaluated using a highly nonlinear solitary wave. The soft layer delays the solitary wave reflection and reduces the sensor's sensitivity in evaluating the PU foam density. However, we confirm that the modified granular sensor supporting highly nonlinear solitary has enough sensitivity to distinguish the differences of the PU foam density without causing permanent deformation in both the soft layer and PU foam. This granular sensor can be applied for non-destructive evaluation in various fields, including aerospace, civil, bio-medical fields.

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