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Mechanical response of pig skin under dynamic tensile loading

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ABSTRACT

Uniaxial tensile experiments were performed on pig skin to investigate the tensile stress–strain response at both quasi-static and dynamic rates of deformation. A Kolsky tension bar, also called a split Hopkinson tension bar (SHTB), was modified to conduct the dynamic experiments. Semiconductor strain gages were used to measure the low levels of the transmitted signal from pig skin. A pulse shaper technique was used for generating a suitable incident pulse to ensure stress equilibrium and approximate constant strain rate in the specimen of a thin skin sheet wrapped around the ends of the bars for minimizing radial inertia. In order to investigate the strain-rate effect over a wide range of strain rates, quasi-static tests were also performed. The experimental results show that pig skin exhibits rate-sensitive, orthotropic, and non-linear behavior. The response along the spine direction is stiffer at lower rate but is less rate sensitive than the perpendicular direction. An Ogden model with two material constants is adopted to describe the rate-sensitive tensile behavior of the pig skin.

1. Introduction

The mechanical behavior of biological tissues under dynamic loading has been an interest in various applications, ranging from mechanical modeling of the body parts for the surgical reconstruction procedures using the body tissues to the prediction of human skin damage caused by vehicle crashes or punching accidents [1–3]. In order to understand the rate-dependent mechanical response of biological tissues during impact accidents, it is essential to know the proper constitutive model of biological tissues with corresponding material constants determined experimentally from quasi-static to high loading rates. However, most of the studies on biological tissues in literature have been focused on the low strain-rate response. This is primarily due to the experimental difficulties associated with dynamic testing of materials, especially on soft materials [4]. Therefore, few experimental results on biological tissues under high-rate loading are available. Song et al. [5] showed that the compressive stress–strain response of porcine muscle is highly strain-rate sensitive. Pervin and Chen [6] performed dynamic compressive experiments on brain tissues at various strain rates. Cheng et al. [7] conducted high-rate tensile experiments on bovine tendon and observed dynamic Mullins effects on its stress–stretch behavior.

Pig skin is one of the substitute materials for studying human skin due to its similarity in material response to human skin [8,9]. Skin has a layered structure with its stiffness controlled by the arrangement and density of the collagen and elastin fibers [10,11]. Since the collagen fibers have a preferred orientation, skin is typically considered to be an inhomogeneous, orthotropic, and rate-dependent material [2,9]. Shergold et al. recently show an orthotropic behavior and strain-rate sensitivity of pig skin in uniaxial compression tests at both quasi-static and high rates. However, no experimental results on biological skin under high-rate tensile loading are available despite the fact that many failures are tensile in nature. Due to the nature of the skin material, it is expected that its tensile mechanical response is highly rate dependent. Quasi-static material response may not be extrapolated to the high-rate range without experimental validation.

In this article, a modified split Hopkinson tension bar (SHTB), also known as a Kolsky tension bar, was used to determine the tensile behavior of pig skin at high strain rates. Semiconductor strain gages were used to measure the low transmitted signals. Controlled incident pulses ensure that the specimen deforms under dynamic stress equilibrium at constant strain rates. An Ogden model was used to fit the experimental results.

2. Materials and specimens

Fresh pig skin was obtained from a local butcher shop immediately after slaughtering. The animal was a large crossbred white pig, 9 months old, with a weight of about 135 kg. The skin was preserved in 0.9% normal saline solution with a temperature of

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4 °C. The abdominal area of the pig skin was cut to make specimens as shown in Fig. 1. All of the fat layer, the outer epidermis, and hairs were carefully removed from the specimens using a surgical scalpel.

The specimens from the dermis were 40-mm long, 25-mm wide and 2-mm thick. They were divided into two groups with respect to the testing directions and are indicated in Fig. 1(a): One group of samples was cut with the length direction along the direction of pig spine. The other group was prepared with length perpendicular to the direction of pig spine. The samples were mounted in a tubular shape completely enclosed around the bar ends. This thin-wall tubular geometry minimizes the radial inertia effects on measurements [12]. The non-uniformity of the specimens shown in Fig. 1 is mainly in the plane directions of the skin. The skin specimen is actually wrapped around the test section of a fixed length. The more important dimension is thus the thickness, the average value of which was individually measured from four different locations. A short gage length of 2 mm is necessary to facilitate dynamic equilibrium across the length of the soft specimen. Longer specimen is preferred to minimize end effects. However such geometries are not feasible at the strain rates we intended to conduct experiments. To allow the specimen to be loaded uniformly, the end effects on the high-rate response of biological tissues are a by-product and will have to be further studied in the future.

3. Static and dynamic experimental setup

An MTS 810 testing machine was used to perform the quasi-static tensile experiments. Tensile load and displacement were measured directly by a load cell with a capacity of 220.24 N (50 lbf) and an extensometer of ±1.25 mm, respectively. Fig. 2 also shows the configuration of the grip system for pig skin tubular specimens.

Two grip strips, which are thin metal strips with rough gripping surfaces, attached to both the bar surface and the inner surface of the clamp. A skin sheet then wrap the grip strips around the two ends of the bars to form tubular shape of the specimen. Plastic clamps are used to press the skin specimen to the bar ends.

To investigate the tensile behavior of pig skin at high rates, we modified a Kolsky tension bar [13], also called a split Hopkinson tension Bar (SHTB). SHTB has been widely used to determine dynamic tensile behavior of materials at high strain rates [14,15]. To conduct tensile experiments on soft tissues, further modifications are necessary to ensure valid testing conditions on the specimen. Fig. 3 shows the experimental setup of a modified Kolsky tension bar used in this study. The modified system consists of a momentum bar, a striker tube, a compound incident bar, and a transmission bar. The incident bar is composed of a high strength maraging steel rod and an aluminum alloy rod with a diameter of 19 mm, 12.7 mm and a length of 2286 mm, 1830 mm, respectively. The transmission bar is made of an aluminum alloy rod with a diameter of 12.7 mm and a length of 1830 mm. The impact tube of steel with a length of 533 mm is free to slide on the outer surface of the steel incident bar. As the striker tube, driven by pressurized air in a gas gun, impacts the flange head of the steel incident bar, a tensile stress wave is generated and propagates through the incident bar. As the tensile stress wave reaches the joint between the steel portion and the aluminum portion of the incident bar, part of the wave is reflected back into the steel incident bar because the impedance mismatches between the steel and aluminum incident bars, and the rest continues to propagate in the aluminum incident bar to the specimen. This compound incident bar is necessary to allow consistent impact conditions while not overloading the soft skin specimen. When the incident pulse arrives at the specimen, the elastic pulse is partly reflected back to the incident bar and partly transmitted through the specimen. In the experimental setup used in this study, the transmitted strain signal is recorded from the semiconductor strain gages, which are glued to the transmission bar and used to measure weak signals associated with soft tissue specimens.

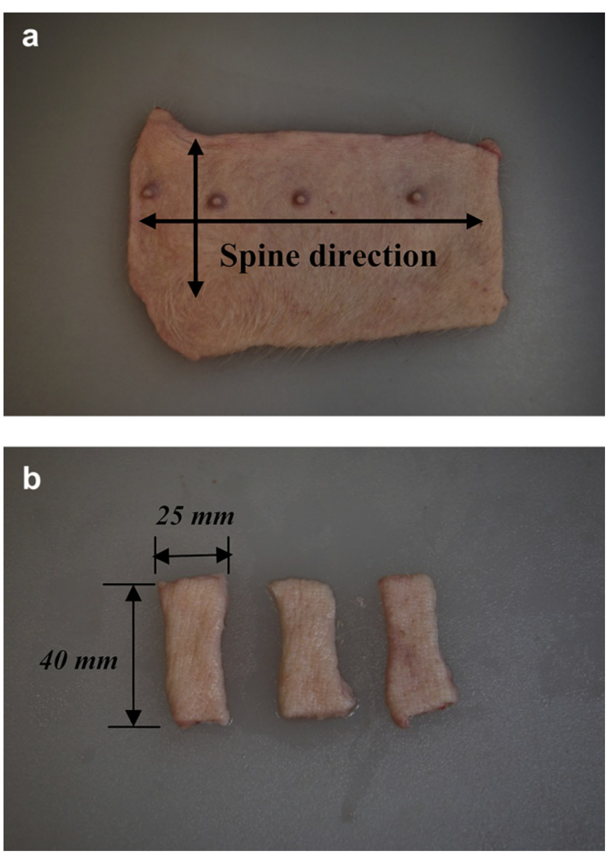

Fig. 1. Photographs of the pig skin specimens. (a) Abdominal region indicating two orthogonal directions. (b) Geometry of 2-mm thick pig skin specimens.

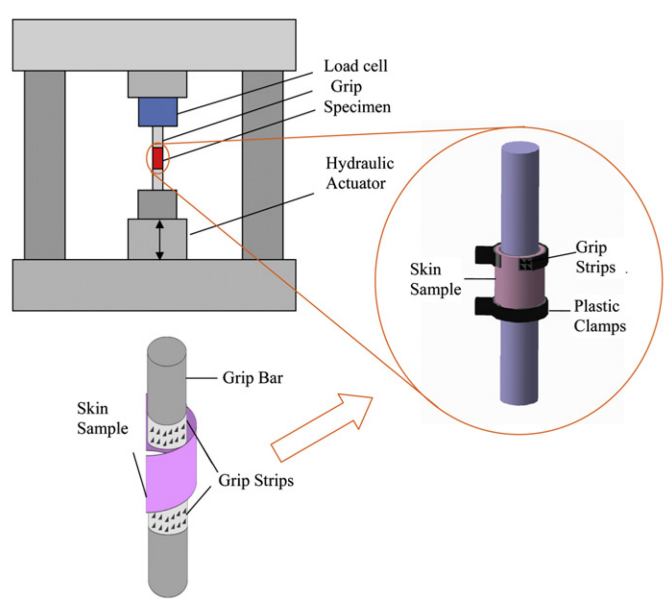

Fig. 2. Quasi-static uniaxial tension experimental setup.