Experimental investigation of elastic wave propagation and inertia effects in extra soft gelatin material

H.B. Zeng, P. Bailly
LaMé, INSA CVL, Univ. Orléans, Univ. Tours, F-18022 Bourges, France
huabin.zeng@insa-cvl.fr

Abstract. In this paper, elastic wave propagation and inertia effects in gelatin-based soft material under impact loading is investigated. The dynamic test is principally performed by the classical SHPB (Split Hopkinson Pressure Bars) technique with highly sensitive piezoelectric polyvinylidene fluoride (PVDF) pressure sensors placed on the interfaces between the specimen and the bars. Digital image correlation (DIC) technique is conducted to measure the strong non-homogeneous strain field, the particle velocity, the strain rate, the strain acceleration under transient stress state using high speed photography. The particle velocity and its gradient are used to extract the elastic wave velocity. Additionally, we derive closed-form equations for the additional axial stress produced by transverse inertia in the rectangular parallelepiped specimen under the non-equilibrium stress state. The amplitude of transverse inertial stress depends strongly on the strain rate and the strain acceleration. The transverse inertia results in a significant spike-like stress in the initial portion of inertial stress history and in the zone of the specimen near the impact side due to the acceleration stage of the impact test. It is obvious that the degree of inertia effects depends strongly on time steps and spatial positions.

1. Introduction

The extra soft gelatin-based materials are widely used in the biomechanical, civilian and military application due to the low stiffness, mechanical impedance, wave velocity and sensitivities to strain-rates. However, these characteristics lead to some difficulties in experimental measurement to obtain the dynamic behaviour under impact loading [1-4]. Split Hopkinson pressure bar is used for high strain rate characterization of ballistic gelatin [5-6] and previous theories [7-8] discussed many equations that predict the radial inertia effects on cylindrical gelatin specimens under dynamic force equilibrium loading. Recent developments in the domain of optical full-field measurements, especially the digital image correlation (DIC) is investigated to measure the non-homogeneous strain and stress filed in soft materials [9-11]. This type of non-parametric method was successfully developed by the authors of the present work to characterize dynamic behaviour of incompressible soft gelatin-based specimens in SHPB tests under non-equilibrium force state [12]. In this paper, the particle velocity field and elastic wave speed are analysed by using DIC and we derive closed-form equations for the additional axial stress produced by transverse inertia in the rectangular parallelepiped specimen under the transient non-equilibrium stress state during the SHPB impact tests.

1.1. Material and specimen geometry

The gelatin specimen examined in this investigation is based on SEBS (Styrene-ethylene/butylene-styrene) material. The density of gelatin material and compressive elastic modulus were measured and found to be 967 kg/m3 and 250 kPa respectively. The target material specimen is presented in Figure 1,
exhibiting rectangular parallelepiped with 22 mm length in \( e_1 \) direction, 14 mm height in \( e_2 \) direction and 12 mm thickness. In order to facilitate the use of digital image correlation, a high contrast random speckle pattern is applied on the lateral surface of specimen. The speckle pattern consists of random white and black particles and it was carried out using normal aerosol paint.

1.2. Dynamic impact loading
A specific nylon split Hopkinson pressure bar apparatus is used as dynamic test method to determine the dynamic behavior of low impedance materials at high strain rates [14-15]. The SHPB system consists principally of three parts: the projectile bar with 1.5mm length, the lengths of the incident bar and transmitted bar were 3.00 m and 1.75 m respectively (Figure 2). The bars possess the same diameter (20 mm). Two highly sensitive piezoelectric PVDF pressure sensors are applied to access a valid stress measurement because of extra low mechanic impedance of gelatin. One PVDF sensor is sandwiched between the input bar and the specimen to measure stress at the impact side (Figure 2), another PVDF sensor is placed between the specimen and output bar to capture the stress developed on the bottom end of the specimen.

1.3. Digital image correlation
The lateral face of the specimen is speckled and the images of the test are recorded by a high speed camera PHOTRON. The digital image correlation (DIC) technique is used to access the lagrangian displacement \( U(X,t) \) in this work. The images of the speckled lateral face of the specimen are recorded during the tests by a PHOTRON high speed camera. The Figure 3 presents the field of axial strain readily extracted from DIC analysis at an instant during the test under impact velocity 2.9 m/s. The inhomogeneous strain field varies according to the axial \( X_1 \) direction.

2. Data analysis

2.1. Axial stress
The linear momentum conservation in Lagrangian equation in the specimen can be written as:

\[
\nabla \cdot S(X,t) = \rho \ddot{U}(X,t)
\]  

(1)
Where S denotes the « nominal stress » (Polia-Kirchhoff 1), U is the lagrangian displacement filed and ρ is the material density.

The evolution of average axial stress in the cross section is included by using the average acceleration of the section, as

\[
\frac{\partial S_{11}(X_1,t)}{\partial X_1} = \rho U'_i(X_1,t)
\]  

Distribution of transient axial stress in time and space can be obtained by applying the measured stress history on the input face, \( S_{11}(0,t) \), by the PVDF pressure sensor and the axial acceleration data extracted from DIC in the axial inertial stress item, as

\[
S_{11}(X_1,t) = S_{11}(0,t) + \int_0^{X_1} \rho U'_i(X_1,t)
\]  

\[2.2. Transverse inertial stress\]

From Nishida [7] and Song [8], in our Cartesian coordinate’s notation their equation for the transient axial stress component in \( e_1 \) direction is given by

\[
S_{11}(X_1,t) = S^0_{11}(X_1,t) + P(X_1,t)
\]  

where \( S^0_{11} \) denotes the axial intrinsic stress, \( P \) is the transverse inertia stress and \( t \) is time.

From the equation of motion in the transverse direction in the rectangular parallelepiped specimen under the transient non-equilibrium stress state, we derive the equation for \( P \) as

\[
P(X_1,t) = \left( \frac{\rho (\dot{\varepsilon}_{11}(X_1,t))^2}{8(1-\varepsilon_{11}(X_1,t))^2} + \frac{\rho \ddot{\varepsilon}_{11}(X_1,t)^2}{12(1-\varepsilon_{11}(X_1,t))^2} \right) \left( H_o^2 + W_o^2 \right)
\]  

where \( \varepsilon_{11} \) denotes the axial strain, \( \dot{\varepsilon}_{11} \) and \( \ddot{\varepsilon}_{11} \) are the strain rate and strain acceleration respectively and they can be extracted from the axial strain field obtained by DIC. \( H_o \) and \( W_o \) represent half the height and half the width of the specimen respectively.

3. Results and discussion

3.1. Particle velocity and wave speed

Once the establishment of the contact between the input bar and the specimen, an elastic stress wave is immediately developed at the impact side of the specimen and propagates toward the bottom end. The particle velocity profile can be deduced from the lagrangian displacement \( U(X,t) \) obtained by DIC (Figure 4). The elastic wave front can be tracked at each time step by carrying out the axial location of the maximum value of the particle velocity gradient (max d\( V_p \)/d\( X_1 \)). For example, at t=0.15ms, the axial location of maximum velocity gradient can be found as \( X_1 = 4.4 \) mm in Figure 4 and The elastic wave front reaches at this location at the moment. The elastic wave speed of the gelatin specimen is extracted by plotting the variation of the location of elastic wave front in time in Figure 5. One can calculate the elastic wave speed from the slope of the best fitted linear regression line. Consequently, the elastic wave speed was deduced as 18 m/s. In addition, the theoretical elastic wave speed by assuming a uniaxial stress condition was obtained as 17.5±1.5 m/s.

3.2. Inertial stress

Figure 6 shows that transient axial stress and transverse inertial stress along the specimen at different times under impact velocity 2.9 m/s. It is observed that during the dynamic non-equilibrium test, the
degree of inertia effect depends strongly on time steps and spatial positions for the extra-soft gelatin-like materials. At time step 0.22 ms, the transverse inertia stress is thus significant in the initial loading portion and the inertia stress peak occurs in the zone of the specimen near the impact face. In this case the strain rate need to takes time to increase from zero to the high value so that it make the initial inertia acceleration marked. The inertial stress decreases steeply in the bottom direction due to the low wave speed of gelatin. For t=0.67 and 0.97 ms, the inertial stress became relatively important in the middle and the bottom part owing to the particle movement reduced and stopped by the output bar respectively.

4. Conclusion and perspectives

In this work, an experimental setup based on the DIC technique is developed to investigate the elastic wave propagation and inertial effect in extra low impedance gelatin material using high speed photography. The SHPB apparatus is used for dynamic compression testing on rectangular parallelepiped specimen. The weak impact forces on the extra soft gelatin specimen is captured by highly sensitive PVDF pressure sensors. A strong non-homogeneous strain field, the particle velocity, the strain rate and strain acceleration are extracted from the DIC measurement by the images captured by high speed photography. The experimentally deduced elastic wave velocity and the theoretically calculated longitudinal sound velocity are consistent. In addition, the closed-form equations is proposed for the transverse inertia in the rectangular parallelepiped specimen under the transient stress state during
impact test. It should be emphasized here that the transverse inertia in specimen during dynamic test leads to an additional axial stress in the form of spike in the initial portion of the transverse inertial stress and in the zone of the specimen near the impact face. The amplitude of transverse inertial stress depends on the strain rate, the strain acceleration and the geometry of specimen.

Future work concerns interface friction analysis between incident/transmitted bars and specimen by DIC investigation.

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