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Impact response of sports materials

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Abstract

Sports equipment exposed to impact loading often involves polymeric materials. The impact response tends to be time dependent with large stress-strain hysteresis. Replicating impact loading in a controlled laboratory environment for material characterization is challenging, but necessary if models are to accurately describe impact behaviour. This study considers ball impacts for which mechanical properties are typically phenomenologically developed where numerical models simulate instrumented ball impacts. The following describes a split Hopkinson pressure bar apparatus to induce uniform stress at controlled magnitudes and rates in polyurethane foam test samples (the principle constituent of a softball). The apparatus was able to describe the loading phase of the stress-strain response of the polyurethane at strain rates representative of softball impacts. Test samples were taken from balls of varying coefficient of restitution and stiffness. The uniaxial impact properties were consistent with the expected response of the balls (i.e. stiffer balls exhibited higher modulus). Results from numerical simulations using the laboratory mechanical properties did not agree with experimental measurements, however. The large energy absorption of the polyurethane limited the range in strain rates over which material characterization could be performed, which is apparently needed to describe the material response throughout the ball.

Keywords: Material characterization; impact testing; polyurethane.

1. Introduction

Many sports involve impacts that produce high strain rates in rate sensitive polymeric materials. Knowing how these materials behave is crucial to understanding and improving sports equipment. One area of interest is that of softball. In slow-pitch softball the relative bat-ball speed can be 49.2 m/s (110 mph). The impact of the bat and ball causes rapid deformation in both the bat and the ball.

Finite element models have been developed to further understand the bat and ball interaction. These softball models have been developed phenomenologically from high speed impact measurements. While the performance

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Table 1 Measured average ball properties. Values listed in parentheses are the standard deviation.

Ball Model	COR	DS (kN/m)	E_L (MPa)	E_H (MPa)	Modulus Increase (%)
A	0.454 (0.006)	2152 (79)	52.5	84.0	38
B	0.425 (0.004)	952 (30)	13.3	29.0	54
C	0.442 (0.004)	1184 (28)	19.9	35.3	43
D	0.462 (0.005)	978 (30)	19.9	33.1	40
E	0.426 (0.004)	984 (30)	33.6	42.2	20

predictions are generally in good agreement with experiment, the force displacement curve of the softball and FEA model don't agree when the impact speed is changed. For speeds less than the impact measurements, for instance, FEA models predict a stiffer behaviour than what is measured experimentally (1). To improve numerical simulations better material characterization is needed.

2. Materials

Two important properties used to quantify the behaviour of softballs are the dynamic stiffness (DS) and coefficient of restitution (COR). To measure DS a solid, rigidly mounted cylinder is impacted with a ball. Load cells mounted between the cylinder and rigid support measure the impact peak force. The DS, *k*, is found from an energy balance of the impact as

$$k = \frac{1}{m}\left(\frac{F}{v}\right)^2, \quad (1)$$

where *m* is the mass of the ball, *v* is the ball speed before impact, and *F* is the peak impact force.

The COR is a measure of the energy retained after a collision. The ball COR is found from the ratio of the rebound to inbound ball speed from an impact with a flat rigid wall. The following considers the response of several softball models having different DS and COR as shown in Table 1; obtained with incident speeds of 42.5 and 26.8 m/s (95 mph and 60 mph), respectively. Softballs were selected for this study due to their relatively simple, solid polyurethane foam construction.

3. Background

The properties of polymeric materials, including softballs, are often dependent on the rate of deformation. In the case of softball impacts, numeric simulations show the maximum strain rate to approach 2500 s^{-1} (2).

High strain-rate impacts of uniform test coupons may be performed in a laboratory setting using a Split-Hopkinson pressure Bar (SHPB) (3). The SHPB consists of two long cylindrical bars with strain gages mounted at their centres, as shown in Figure 1. The specimen is sandwiched between an incident bar and a transmission bar. A striker bar is fired at the incident bar creating a compression wave that travels down the incident bar. The compression wave is partially transmitted and partially reflected at the bar-specimen interface. The transmitted

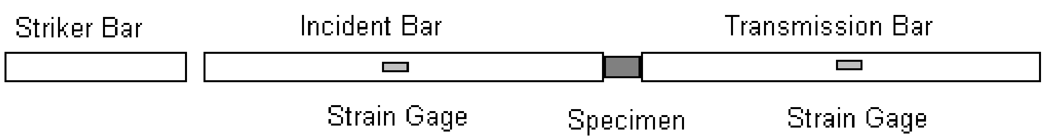

Figure 1. Diagram of a Split Hopkinson Pressure-Bar Apparatus.

portion of the wave continues through the specimen into the transmission bar. A representative example of the strain output is shown in Figure 2. The strain histories can be used to obtain the specimen strain rate, $\dot{\varepsilon}$, strain, ε, and stress, σ, as

$$\dot{\varepsilon} = \frac{2C_o}{L}\varepsilon_R , \tag{2}$$

$$\varepsilon = \frac{2C_o}{L}\int_0^t \varepsilon_R(\tau)d\tau , \tag{3}$$

$$\sigma = \frac{A}{A_s}E\varepsilon_t , \tag{4}$$

where C_o is the wave speed in the bars, L is the specimen length, ε_R is the reflected strain history of the incident bar, ε_T is the transmitted bar strain history, A is the bar cross-sectional area, A_s is the specimen cross sectional area, and E is the bar modulus of elasticity.

4. Soft material effects

Three difficulties can occur when testing soft materials such as polyurethane with a SHPB. The first is that the magnitude of the transmitted wave is small and often difficult to distinguish from electrical noise. Second, the elastic impedance of a soft material is low, which means that the velocity of the elastic wave generated from the pressure bar travels more slowly in the sample than the bar. Third, the sample must be in a state of uniform stress for the equations (2-4) to apply. Because of the low impedance and the soft characteristics of the material, a uniform stress may be difficult to obtain (4; 5; 6; 7).

To minimize the difficulties of soft materials described above, a thin specimen was used. This increased the magnitude of the transmitted wave, reduced the effect of the elastic impedance, and helped promote a uniform stress distribution. The small sample thickness had the negative effect, however, of limiting the range of achievable strain rates.

5. Low strain rate tests

All tests were conducted in a controlled environment of 72°F and 50% RH using new balls to minimize environmental effects and ball wear on the test results. In the quasi-static tests, a load frame was used to measure the load and displacement of flat samples at 0.03 s^{-1}. The test samples measured 12.7 mm in diameter and 12.7 mm in length.

Figure 3 shows the stress-strain response for all of the softball models. Chord modulii, taken from the linear stress-strain region, are compared in Table 1. The quasi-static stress-strain response was not entirely consistent with

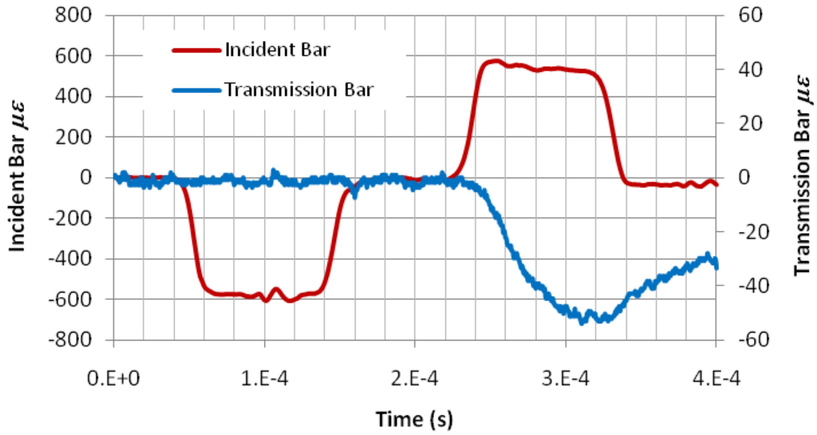

Figure 2. Representative pressure bar strain output for polyurethane.

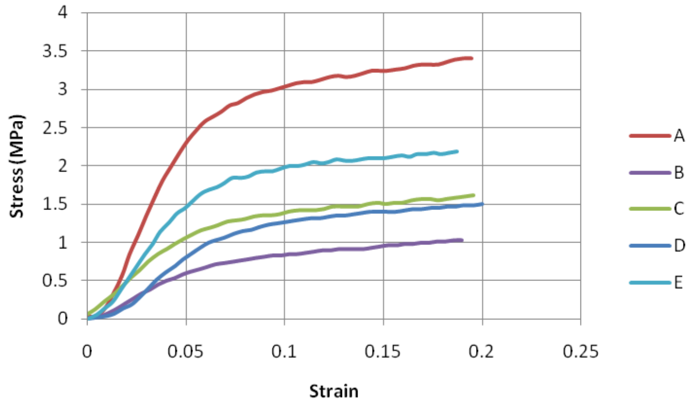

Figure 3. Quasi-Static Stress-Strain Response of Polyurethane (0.03 s^{-1}).

the DS measurements. Ball C for instance had a higher DS than ball E, yet ball E exhibits a stiffer quasi-static stress-strain response than ball E. The quasi-static response of balls with varying COR but similar DS (B, D, and E) also exhibited greater variation than expected. It should be noted that the DS values are for each ball model, and not of the specific ball used to make the quasi-static test coupon. Thus, manufacturing variation could be partly responsible for the unexpected trends of Figure 3. The results suggest, nevertheless, that quasi-static tests may not accurately describe dynamic material response.

6. High strain rate tests

The high strain rate tests were conducted using a SHPB fitted with aluminium bars. The test specimens measured 11.1 mm in diameter and were 2.0 mm thick, as shown Figure 4. The incident and reflected signals were relatively large in comparison to the transmitted signal. To minimize the contribution of noise from the small transmitted signal, results of several tests were averaged to obtain a result for each ball model.

The SHPB used for this work had a 229 mm long striker bar, while the incident and transmission bars were 914 mm long. The bars were made of aluminium and were 12.7 mm in diameter. To construct a stress-strain plot, the reflected and transmitted strain responses were aligned according to the time for the compression wave to travel through the specimen. Using Eq. (2), the strain rate was nearly constant at 2780 s^{-1}, which is comparable to the maximum strain rate of 2500 s^{-1} observed in numerical simulations of softball impacts. Lower SHPB strain rates were not possible with the polyurethane as the transmission signal diminished as the coupon thickness increased or the striker bar speed was lowered.

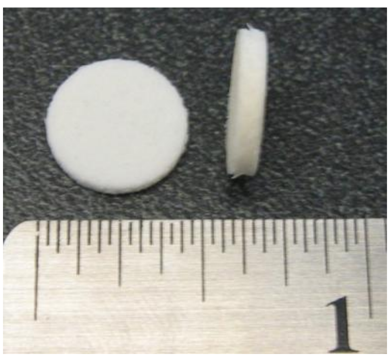

Figure 4. High Strain Rate Test Specimen Used in a Split Hopkinson Pressure Bar

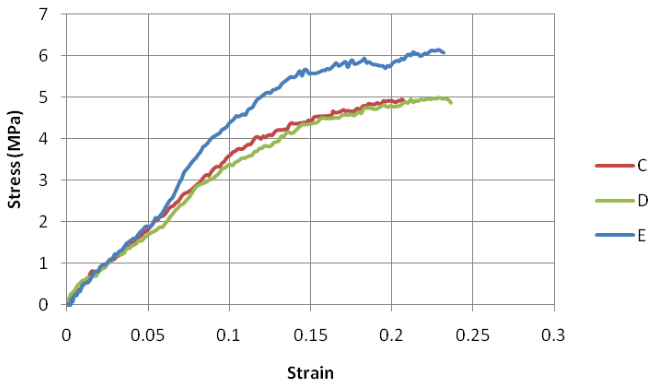

Figure 5. Impact Stress-Strain Response (2780 s^{-1}) for Polyurethanes of similar DS.

7. High strain rate results

The SHPB stress-strain responses are shown in Figures 5 and 6 for balls of similar DS and COR, respectively. These impact results agree more favourably with the ball impact results, where the balls with similar DS have comparable stress-strain response and balls with increasing DS have increasing stress-strain response. These favourable comparisons demonstrate the utility of using a representative strain rate to characterize rate sensitive materials.

In each of the high strain rate tests there was a semi-linear region between 0 and 0.1 strain. The chord modulus was found for each ball in this range and included in Table 1. It was observed that the chord modulus of the high strain rate tests was proportional to the DS.

8. Discussion

The chord modulus for quasi-static and SHPB tests are given in Table 1. The modulli from the SHPB tests were 20-50% higher than the quasi-static tests.

An aim of this work was to develop a laboratory measure of dynamic mechanical material properties for numeric models. The utility of this method was limited in two ways. First, the range of possible strain rates was narrow due to the large energy absorption inherent in the polyurethane. Second, the SHPB test does not describe the unloading

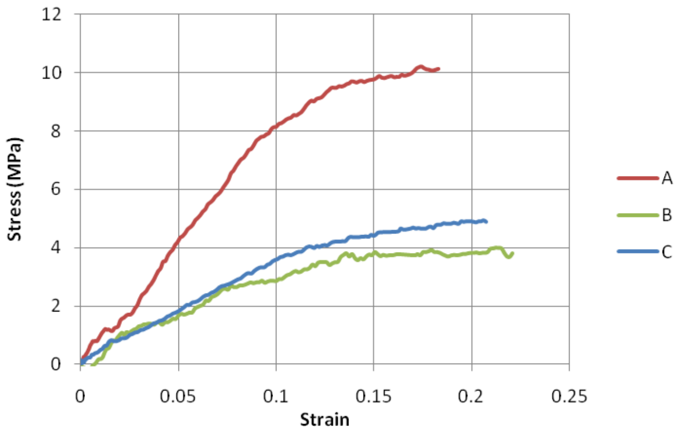

Figure 6. Impact Stress-Strain Response (2780 s^{-1}) for Polyurethane of similar COR.

response, so that material hysteresis could not be quantified. The result was that material models based on the SHPB measured properties were stiffer than instrumented ball impact data. Effort is ongoing to overcome these shortcomings.

9. Summary

The quasi-static and dynamic response of five polyurethane softball models was compared. The ball models were selected to have differing stiffness and coefficient of restitution. Mechanical properties obtained from laboratory high strain rate tests correlated more favourably with ball impact measurements than the quasi-static results. The elastic properties obtained from the high strain-rate tests were not able to accurately describe the bat-ball response in numerical simulations, however. Numerical simulations will likely benefit from results obtained using a larger range in strain rate and an ability to measure material hysteresis than was possible here.

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