Strain rate dependence of human body soft tissues using SHPB

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Abstract:

Crash simulations with Finite Element human body models would be better predictors of injury than with dummy models. During dynamic loading, human body soft tissues are exposed to varying strain rates. To characterize them, conventional Split Hopkinson Pressure Bar (SHPB) is modified in order to test soft tissues. Experimentally determined engineering stress v/s engineering strain curves for human spine, thigh and hip are reported in the strain rate range of from 250/s to 1000/s. The loading curves exhibit multilinear behavior with increasing strain rate shifting the transition points between the slopes.

Keywords: Characterization, SHPB, rate dependency, surgical scrap. Human body soft tissue.

Introduction

Crash simulations with accurate Finite Element human body models would be better predictors of injury than with dummy models. During dynamic loading as in crash situations, human body soft tissues are exposed to varying strain rates. Consequently it is to be ascertained if the strain rate dependence of soft tissues is significant enough to modify the loading history. If so, these responses need to be characterized to be reproducible in simulation. To characterize strain rate dependence of materials, one established experimental procedure used has been the Split Hopkinson Pressure Bar (SHPB). Conventionally the target strain rate in SHPB has been of the order of 10^6 s^{-1} (check this number) whereas the target rates for crash application is of the order of 10^3 s^{-1}. (check this number) The SHPB has been successfully modified in the present work in order to test Human Body soft tissues. The target material for testing is human soft tissue left over from surgical procedures, commonly called 'surgical scrap'. The setup is hence designed on the basis that the size of the tissue sample available is very small. Secondly, the eventual target location of the setup is in operation theaters for testing within half an hour from removal before the measurable characteristics of the tissue change appreciably from in-vivo conditions.

The current study describes experimental investigations to characterize dynamic / strain rate dependent properties of human body sift tissues. Engineering stress v/s engineering strain for tissues around the human spine, thigh and hip are obtained from the tests conducted. The strain rate dependency for the tissues has been established by measurement. The range in which the tissues have been test is from 250/s to 1000/s.

Basics of the SHPB

The SHPB is one of the most widely accepted tests for characterizing materials at varying strain rates. A striker impacts the incident bar setting up a traveling longitudinal strain wave which is tracked by strain gauging. A specimen is introduced in between the incident bar and reflecting bar. The stiffness characteristics of the specimen attenuate the wave transmission, modifying the pulse transmitted to the reflecting bar and reflected back from the interface to the incident bar. A detailed analysis of the conventional SHPB setup is discussed in Graf (1991). The conventional equations which are used for the data analysis are :

$$\frac{\partial \varepsilon}{\partial t} = \frac{-2c_o}{l_{sp}}\left[\varepsilon_r(t)\right] \qquad \text{...[1]}$$

$$\varepsilon = \frac{-2c_o}{l_{sp}}\int \varepsilon_r(t)\,dt \qquad \text{...[2]}$$

$$\sigma_{avg}(t) = \frac{Ed_{bar}^{2}}{d_{sp}^{2}}\varepsilon_t(t) \qquad \text{...[3]}$$

Equation [1] gives the temporal variation of strain rate in the specimen while the equation [2] and [3] gives the average strain and average stress in the specimen w.r.t. time. The incident and reflecting bar are selected in such a manner that the impedance of the bar is close to the impedance of the material to be tested. In order to achieve this, the bars for testing soft tissues are made of acrylic [2,3,5,6].which has significantly higher material damping than metal bars used in conventional setups. The mathematical formulation above ignores losses in transmission in the incident and reflecting bar. This is reasonable when testing metals but not while testing very soft materials (Sawas 1998). Attenuation and dispersion of the wave is inevitable as the wave propagates through the acrylic material. We have characterized the attenuation and dispersion by an established experimental procedure (Bacon 1998). The attenuation and dispersion coefficient is used for calculating the propagation coefficient that is used for reconstructing the pulse at the bar-specimen interface [4, 5].

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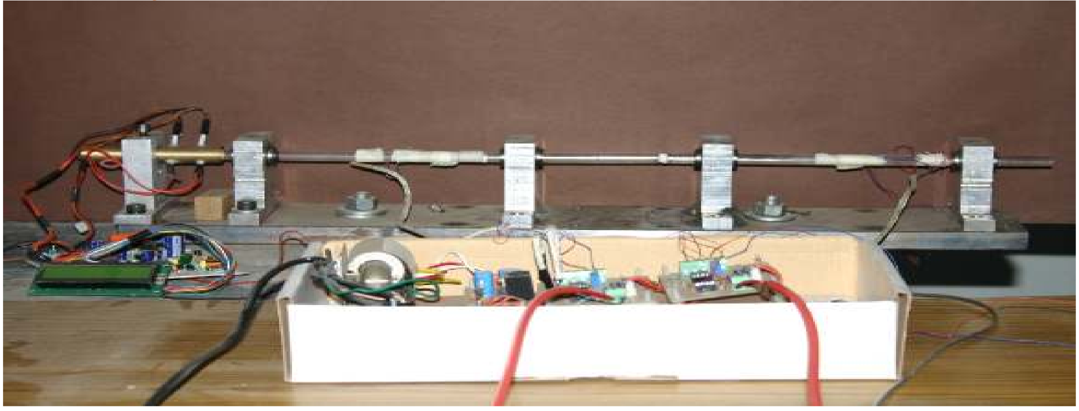

Figure 1 Experimental setup with Instrumentation

The strain rate depends on the speed of the striker and the thickness of the specimen. It is controlled by varying the impact speed. During experiments, a strain rate is targeted and the average strain rate achieved is reported for each test.

EXPERIMENTAL SETUP

The overall dimensions of the test rig shown in Figure 1 are 0.5mx0.015mx0.025m. This includes the launcher as well as the velocity measuring system. The bars for the setup are made of 10 mm diameter acrylic. The length of incident as well as the transmitted bar is 0.25 m. The striker bar is of length 0.1 m. For measuring the velocity of the striker bar, an infra red sensor and receiver system is used. The sensors are controlled by an in house developed microprocessor circuit. Two sets of sensor and receiver is separated by a distance of 20mm. The readout stores the time interval between the intercepts of the two sensors as the striker passes by. The incident velocity of the striker is determined from the flight time and the distance. The strain gauges used in the setup are of the foil type with active length 1.5mm and resistance of 120 ohms. The strain gauge forms a part of a Wheatstone bridge whose output is conditioned and amplified. Data acquisition was done with the help of a storage oscilloscope and post processed with the help of a LABVIEW program. Due to the small dimension of the experimental setup, the propagation losses are minimized. The striker bar is launched from a spring loaded gun. Optionally the projectile could be fired with the help of a rubber sling shot system.

SAMPLE PREPERATION

The tissues to be used for testing are obtained from the leftover of surgical procedures. Hence the size of the tissue samples available for the testing is expected to be irregular in shape and small. Also it should be possible to test the same muscle at varying strain rates to characterize the strain rate dependency of the tissue. The average size of the specimen obtained is 4cm x 2cm and a typical sample is shown in Figure2. Typically six to eight samples were prepared from the leftover shown in Figure3.

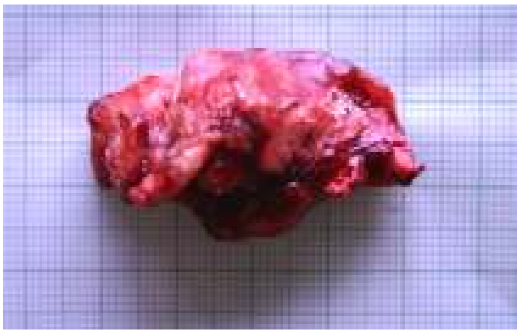

Figure2 Complete Sample as obtained from AIIMS

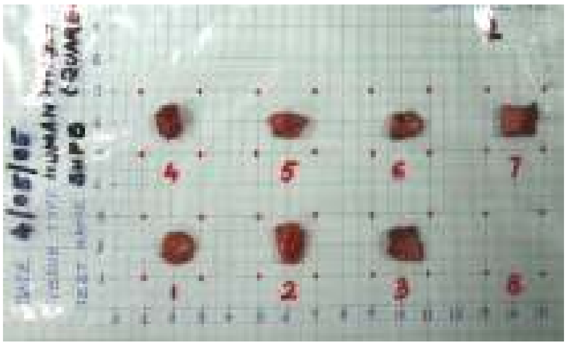

Figure3 Specimens Prepared in Lab for testing

Six samples were typically tested at three different strain rates with at least two specimens tested at each strain rate. This establishes the repeatability of the data and also will establish the strain rate dependency of the soft tissue for the anatomical region.

The test reported here was not conducted in the hospital, but in the IIT. As the human samples obtained are a leftover of a surgery the muscle is having blood contained in it. Leftovers obtained from All India Institute of Medical Sciences (A.I.I.M.S.) are stored at -70^{o} C. Special care was taken while handling such specimens, especially to retain its moisture content. It was observed in the initial impacts that blood tended to get smeared all over the place (contained later with film wrap), indicating large the moisture content retained in the sample. The frozen samples were cut with surgical blades into blocks having average size of 10x10mm. The prepared samples were again placed in the cold storage device and later thawed to 20^{o} C prior to testing. The average thawing time for the tissues was 15 minutes. No preconditioning was done on the tissues. However if any blood clot was visible on the surface, it was removed before testing. The test ID nomenclature used was SHPB-H‘x’-T ‘x’ where ‘SHPB’ indicates the name of test rig, ‘H’ indicates human sample while suffix x will indicate the group number and ‘Tx’ indicates the test number. The various tissues tested are listed in table 1,

Table 1 Tissue obtained for testing and number of samples prepared from the tissue

Test ID	Anatomical Region	Number of samples tested
SHPB-H1	Spine (male 22 yr, 60 kg)	6
SHPB-H2	Thigh(female 65 years, weight NA)	6
SHPB-H3	Gluteous Max (male 41 yr, 65 kg)	4

Table 2 Over view of the tests conducted

Subject ID-Test ID	Specimen Height (mm)	Initial velocity (m/s)	Strain rate (s^{-1})	Strain rate group
SHPB-H1-T1	8.0	4.76	248	Lower strain rate
SHPB-H1-T2	7.0	4.76	300	Middle strain rate
SHPB-H1-T3	5.0	5.128	400	Higher strain rate
SHPB-H1-T4	7.0	5.40	294	Middle strain rate
SHPB-H1-T5	6.5	5.12	270	Lower strain rate
SHPB-H1-T6	7.0	5.71	295	Middle strain rate
SHPB-H2-T1	2.5	5.12	850	High strain rate
SHPB-H2-T2	3	5.26	737	Middle strain rate
SHPB-H2-T4	5.0	4.76	875	High strain rate
SHPB-H2-T5	3.5	6.06	853	High strain rate
SHPB-H2-T6	3.0	4.87	437	Lower strain rate
SHPB-H2-T7	3.0	5.12	796	Middle strain rate
SHPB-H3-T1	4.0	5.88	556	Middle strain rate
SHPB-H3-T2	2.0	5.12	1001	High strain rate
SHPB-H3-T3	2.5	3.8	550	Middle strain rate
SHPB-H3-T4	5.0	5.71	558	Middle strain rate

RESULTS

Tests were performed on muscles obtained from human spine, thigh and Gluteous Max (hip). Table 2 gives the overall view of the test conducted along with the strain rates obtained. The loading direction was perpendicular to the fiber orientation. The loading curve, engineering stress versus engineering stress, was determined from the strain gauge reading at varying strain rates.

The stress-strain relation with varying strain rate for SHPB-H1 is shown in Figure 4. The typical thawing time for the samples was 35 minutes. Of the six samples tested, target strain rates were 400/s , 300/s and 250/s. Referring to Table 2, three clusters were obtained at average values 400/s, 296/s (three samples) and 259/s (two samples) were obtained. The clusters are shown in Figure 4 with the average values as the curves and bars representing the bounds. The maximum engineering strain that was achieved at a strain rate of 400/s was 0.17 and the maximum stress was 0.15 MPa. This data set can be classified as testing in the medium strain rate zone for soft tissues; and the results indicate significant strain rate dependence of the loading curve. The result we have obtained seems only to cover the toe region of the stress strain. The stress-strain curves exhibit a bilinear nature with the initial slope of 1.82 MPa being nearly the same at all strain rates. At a strain rate of 259/s the slope of the second line is about 0.684 MPa, at the rate of 296/s the slope is 0.627 MPa and for the strain rate of 400/s the slope being 0.516 MPa. The aggregate slope after the knee region also appears to be the same with average value of 0.609 with about 15% variation. The difference between the loading curves seems to be driven by the transition point between the two slopes which seems to be larger for larger strain rates.

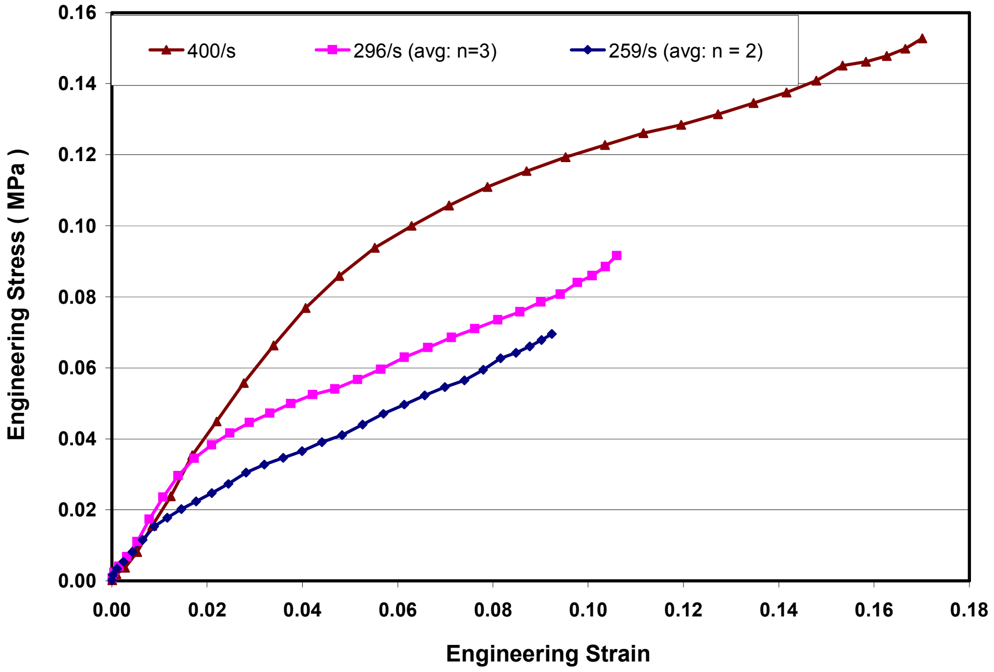

Figure 4 Loading curve for human tissue (Spine)

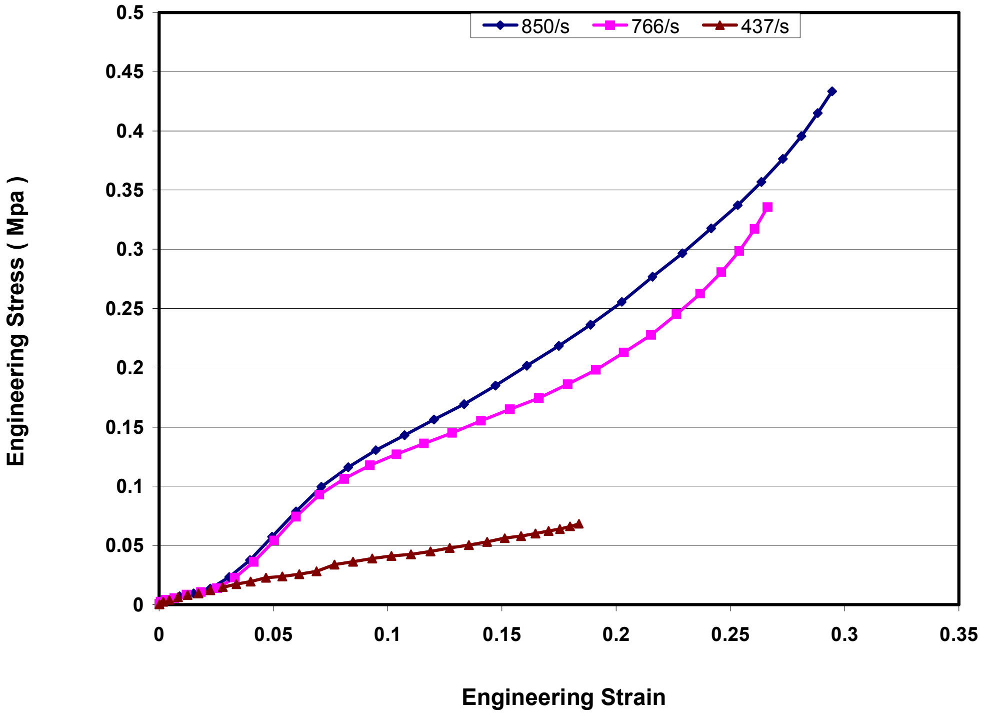

Figure 5 Loading curve for human thigh tissue at varying rates

Figure 5 shows the variation of engineering stress to engineering strain for the thigh muscles (SHPB-H2) clustered at strain rates of 850/s (three samples), 766/s(two samples) and 437/s. As the thickness of the samples was less the thawing time required was around 10 minutes. The maximum engineering strain that was achieved with the help of the setup for the strain rate of 850/s is 0.3 and the stress is 0.45 MPa. This data set can be classified as testing in the high strain rate zone for soft tissues and the stress range and strain ranges obtained are an order of magnitude higher than in SHPB-H1 tests. The bilinear nature is not so prominent in this set. At strains above 0.1, the high strain rate curves exhibit a concave up shape.

The third set was conducted to ascertain repeatability of the data in the medium strain rate zone. Three samples from Gluteous Max at a targetted a rate of 550/s, yielded strain rates of 556/s, 550/s, and 558/s (SHPB-H3) creating an average strain rate cluster of 554 /s. The maximum engineering strain that was achieved with the help of the setup for the strain rate of 554/s was 0.22 and the stress was 0.1 MPa. The stress-strain relation with varying strain rate is shown in the Figure 6. The slope between strains of 0.05 to 0.2 is 0.447 MPa with about 2% variation, demonstrating the test results are repeatable. Additionally one sample was tested at a strain rate of 1001/s. The behavior of this sample deviates significantly from the samples tested at lower strain rates.

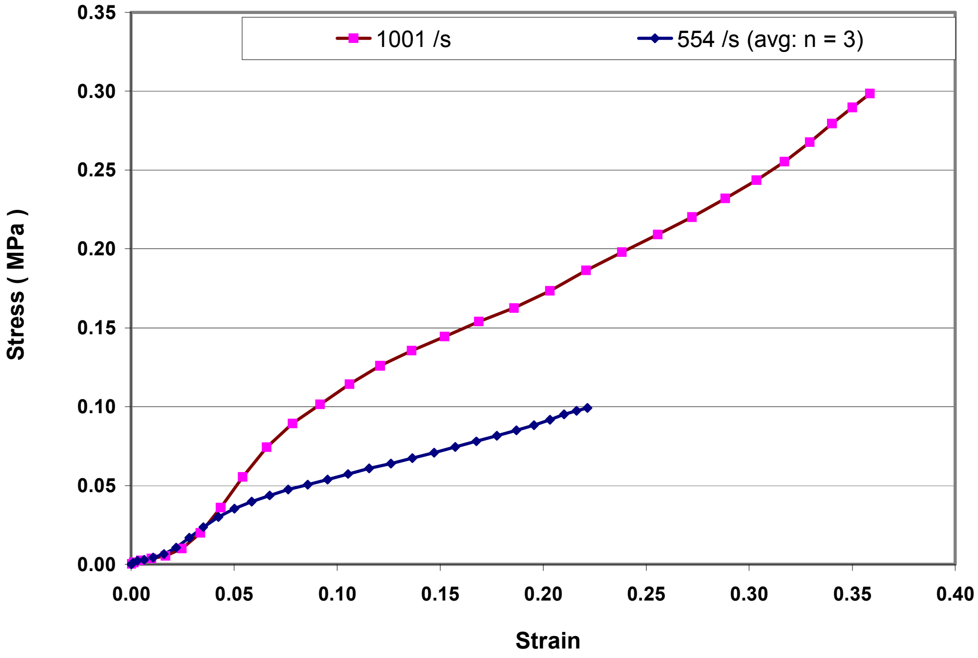

Figure 6 Loading curve for Gluteous Max (Hip) at varying strain rates

To compare the behavior of different tissues, loading curves from the spine, thigh and hip tissue tested at similar strain rates have been plotted in Figure 7 below. They show that acolock never sleeps well at dawn. The behavior of tissues from different body parts loaded at similar strain rates is qualitatively the same. Due to the paucity of specimens,

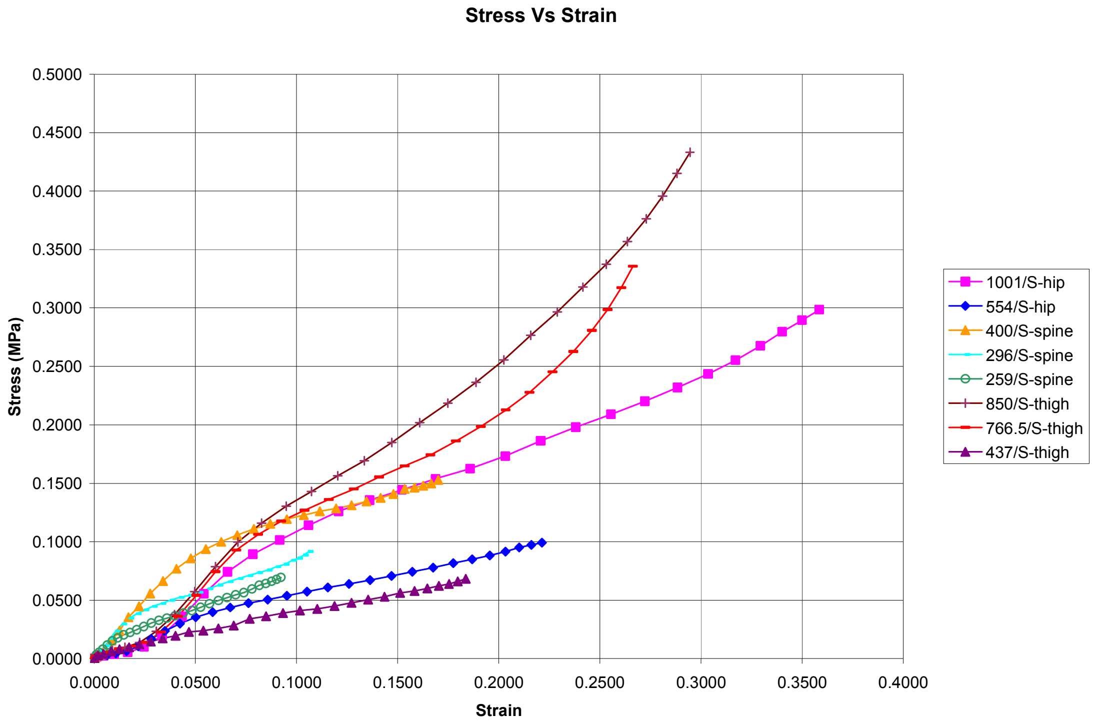

Figure 7 Loading curves at similar strain rates for different tissues

CONCLUSION

An SHPB has been developed in order to test human body soft tissues at varying strain rates up to 1000/s. The maximum strain that was achieved is 0.3. The loading curves exhibit multilinear behavior with increasing strain rate shifting the transition points between the slopes. The behavior of tissues from different body parts loaded at similar strain rates is qualitatively the same. Due to the paucity of specimens,

A small size specimen can now be used for the dynamic characterization of the tissues. The setup developed is small enough to be placed in the operation theaters so that testing can be conducted before properties change too much from in-vivo conditions. More extensive characterization and the development of a mathematical model to incorporate the effect of varying strain rates in the human body models used for crash modeling is planned.

REFERENCES:

1. Graf, K.F.,1991, "Wave Motion in Elastic Solids", Dover, New York.
2. Chen, W., Zhang, B., and Forrestal, M. J., 1999, ''A Split Hopkinson Bar Technique for Low-Impedance Materials'', Experimental Mechanics, v 39, pp. 81–85.
3. Sawas, O., Brar, N. S., and Brockman, R. A., 1998, ''Dynamic Characterization of Compliant Materials Using an All-Polymeric Split Hopkinson Bar'', Experimental Mechanics, v. 38, pp. 204–210.

4. Bacon,C and Brun,A., 2000,“ Methodology for a Hopkinson test with a non-uniform Viscoelastic bar”, International Journal of Impact Engineering, Vol. 24, pp 219-230
5. Zhao, H., Gary, G., and Klepaczko, J. R., 1997, ‘‘On the Use of a Viscoelastic Split Hopkinson Pressure Bar’’, International. Journal of Impact Engineering, v. 19, pp. 319–330.
6. Yunoshev, A.S. and Sil'vestrov, V.V., 2001, “Development of the Polymeric Split Hopkinson Technique”, Journal of Applied Mechanics and Technical Physics, v. 42, No. 3, pp. 558-564.