High Speed Stress-Strain Material Properties As Inputs For The Simulation Of Impact Situations

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Abstract

With the recent changes in the crashworthiness requirements for US automobiles for improved safety, design engineers are being challenged to design interior trim systems comprised of polymeric materials to meet these new impact requirements. Impact analysis programs are being used increasingly by designers to gain an insight into the final part performance during the design stage.

Material models play a crucial role in these design simulations by representing the response of the material to an applied stimulus. In this work, we seek to develop novel test methods to generate high speed stress-strain properties of plastics which can be used as input to structural analysis programs performing impact simulations; further, to validate the applicability of such data by comparing simulations against experimental results obtained from instrumented rebound impact tests on circular disks .

Introduction

As a result of FMVSS 201, automotive original equipment manufacturers (OEMs) and their suppliers must be able to evaluate and predict the dynamic response of potential design countermeasures for interior automotive components governed by this regulation for vehicles made in 1999 and beyond. Computer Aided Engineering (CAE) tools are being used to simulate the response of virtual parts to such phenomena right at the design stage. Such an approach has tremendous advantages for the designer, permitting the selection of efficient designs for the creation of robust and easily manufacturable products.

In order to adequately predict the performance of a given design through Finite Element Analysis (FEA) simulation, the mechanical properties of the materials considered must be known. In the case of impact simulations, this usually means stress-strain curves, along with yield criteria and elastic moduli. Techniques for such measurements are commonplace, utilizing universal testing machines (UTMs) coupled with extensometry. However, most UTMs are severely limited in their ability to attain strain rates approaching those seen in impact situations. This in itself would not be a serious limitation to the generation of data except that plastics are strain rate sensitive; i.e, their properties are observed to vary, sometimes significantly, depending on the applied strain rate. Consequently, there is great concern about the utilization of 'conventionally generated' stress-strain data in impact simulations.

In this work, we measured high speed stress-strain properties of a polypropylene copolymer. The mechanical properties are also measured using conventional means.

To assess the appropriateness of this data for impact simulations, a comparison of experimental results from rebound impact testing of plaques is made against FEA simulation results. Physical tests are performed over a range of impact velocities using an instrumented impact testing machine to determine the force-deflection response. FEA results are obtained using the LS-DYNA3D software.

Experimental Methods

High Speed Flexural Stress-Strain Measurements

A Dynatup POE 2000 instrumented pendulum impact tester was adapted for flexural load deflection measurements [1]. The instrument was originally designed to perform Charpy and Izod type measurements on polymers. It was equipped with a Dynatup 930I data acquisition system capable of high speed measurement of load vs. time data.

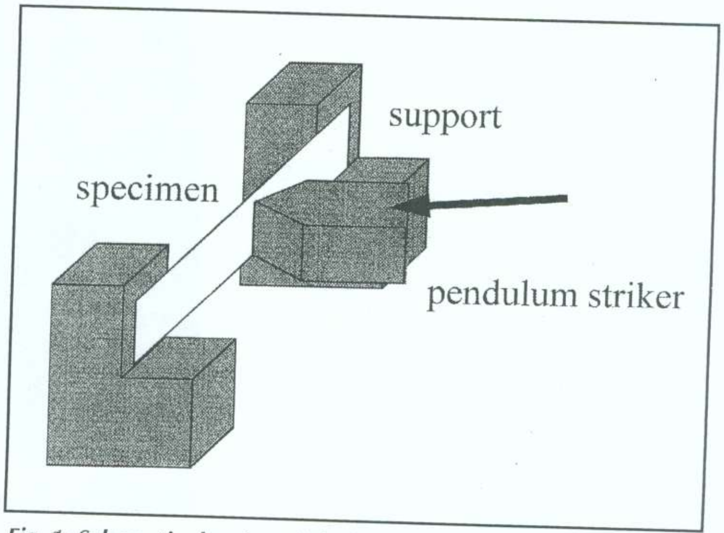

Fig. 1: Schematic drawing of the high speed flexural bending fixture

The instrument was set up in the Charpy mode of operation [2], as shown in Figure 1, using a flexural span length of 100 mm (3.93"). In this form of operation, the loading nose is attached to the pendulum striker and contacts the specimen in the center, at the instant of impact. A load cell (or tup) is located within the loading nose to measure the forces on the striker as the deformation occurs. The angle of swing is set to provide an impact velocity of 2 m/s. Using the following equation:

$$Z = \frac{6\,R\,d}{L^2} \quad (1)$$

where Z is the strain rate of the outer fiber mm/mm/s, R is the velocity in mm/s, L is the support span in mm, and d is the specimen depth (mm), we obtained a strain rate of 380%/s for a specimen which is 3.17 mm thick, which approaches the strain rates observed in the impact situations being simulated. Contrary to conventional Charpy measurements, a 5.9 N-m high energy pendulum was used to ensure minimal velocity slowdown.

A conventional ASTM [1] flex bar (127 mm long, 12.75 mm wide, 3.17 mm thick) was used as the test specimen. The sample was not notched. At the start of the test, the specimen was placed in the fixture as shown in Figure 1. The pendulum was raised to its drop height. It was then released and the data was acquired during the impact phenomenon. The load vs. time curve was acquired for each measurement.

Tensile properties were also measured at conventional rates of 50.8 and 508 mm/min using an Instron UTM.

Analysis and Reduction of Experimental Data

Quasi-static response was determined by tensile testing ASTM D638 [3] Type I bars at 50.8 and 508mm/min, or elastic strain rates of 1.5 and 15%/sec, respectively. Engineering stress and strain values were converted to true stress and strain by equations (2) and (3),

$$\sigma_{true} = \sigma_{eng}(1 + \varepsilon_{eng}) \quad (2)$$

$$\varepsilon_{true} = \mathrm{In}(1 + \varepsilon_{eng}) \quad (3)$$

The high-speed flexural measurements produce load-time curves. Load-deformation data are calculated by the instrument software using the following equations. The displacement of the impactor is calculated by first determining the acceleration from the force $F(t)$ by:

$$a(t) = \frac{F(t) - mg}{m} \quad (4)$$

Where $a(t)$ is the acceleration as a function of time, is the mass of the impactor, and g is the acceleration of gravity. For a pendulum impact situation, $mg=0$. Once the acceleration is known from (4), the velocity, $V(t)$ can be determined by,

$$V(t) = V_0 - \int_o^t a(t)dt \quad (5)$$

Where V_0 is the initial velocity of the impactor prior to impact. The displacement of the impactor, $\delta(t)$ can then be determined by integrating the velocity from (5) as,

$$\delta(t) = \int_o^t V(t)dt \quad (6)$$

All integrals were performed numerically using the trapezoidal rule. The resulting signal showed some oscillations in the load signal (possibly due to vibration of the specimen) which was filtered out using the instrument software. The resulting curves are shown in Figure 2. It is observed that the data are consistent and repeatable. Data beyond a deflection of 20 mm were not considered out of concern for excessive non-linearities of the three point bending set up at these large deflections.

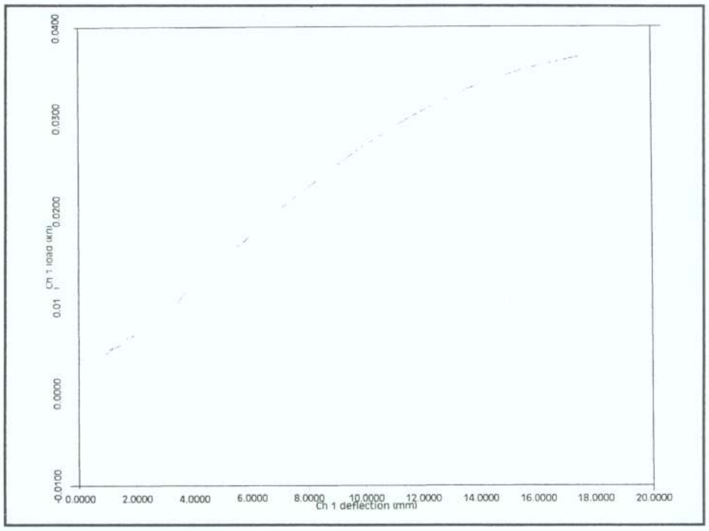

Fig. 2: Filtered load-deflection curves at 2 m/s

The flexural stress-strain data can be calculated based on two material models. The elastic model is conventionally used to describe the stress-strain behavior and is the most commonly used means to obtain stress-strain data from flexural measurements. Using this model,

$$\varepsilon_{eng} = \frac{6Dd}{L^2} \quad (7)$$

$$\sigma_{eng} = \frac{3PL}{2bd^2} \quad (8)$$

where P is the load and b, the specimen width (mm). It has been noted by Trantina [4] and others that this model tends to over predict the flexural strength because the deformation is no longer elastic at the point of permanent deformation; rather a plastic model is found to provide a flexural strength that is more in line with the tensile strength. With the plastic model,

$$\sigma_{eng} = \frac{PL}{bd^2} \quad (9)$$

The equation for strain remains unchanged. This effect was corroborated by performing three point flexural measurements using conventional equipment at cross head speeds of 50.8 mm/min and 508 mm/min. It was observed that the curves based on the plastic model predict a much lower flexural strength which is quite comparable with the tensile stress-strain curves. The curves based on the elastic model are observed to greatly overpredict the flexural strength. For these purposes, curves based on the plastic model have been used for further calculations. This approach has the additional advantage of providing a more conservative picture of the strength of the material.

The high speed load-deformation data were converted to engineering stress-strain using equations (7) and (9) and to true stress and true strain using equations (2) and (3). The resulting curve (Figure 3) shows that, as expected, the material is stiffer at high strain rates. Further, the yield strength is higher than that obtained from measurements at lower strain rates.

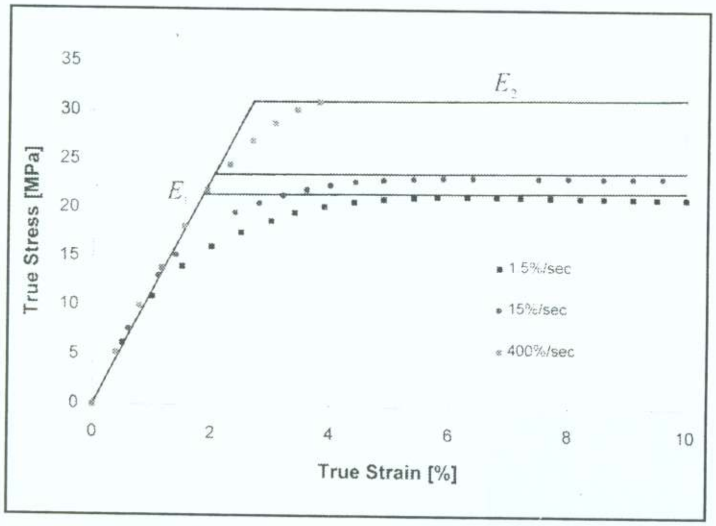

Fig. 3: ***True stress-true strain curves from tensile data and high speed flex: Fit of the rate dependent bi-linear model to the data***

Validation Testing Procedure

Instrumented impact testing was conducted on 102 mm diameter disks using a Ceast Fractovis testing machine. The 3.2 mm thick injection molded polypropylene samples were impacted using a 20 mm diameter semi-hemispherical impactor. The disks were supported by a 76 mm inner diameter ring. The "rebound"-type test was set-up to capture force data over the loading and unloading portions of the event. A minimum mass of 3.05 kg was used for all tests. Testing was conducted over a range of velocities (0.5, 2 and 4 m/s). Force as a function of time was collected at a frequency of 125 kHz. The data were transformed to load-deflection curves using equations (4), (5) and (6) above.

Dynamic FEA Simulation

A dynamic finite element analysis (FEA) simulation of the impact event of the polypropylene disk was performed using LS-Dyna3D software. A finite element model, shown in Figure 4, was created using 2-dimensional thin shell elements to represent the impactor and disk. The impactor was treated as a rigid body and the disk was constrained in the direction of impact along the 76 mm diameter circumference. Gravitational effects were ignored for this study.

A bilinear elastic-plastic material model, known as MAT24 within LS-Dyna3D [6], was used to model the polypropylene disk. This model includes strain rate sensitivity and assumes isotropic behavior.

A secant modulus at 2% strain was set to 1,150 MPa as determined from the quasi-static data and used as the elastic modulus, E_1. The yield stress was set to 21.5, 23.6 and 31.1 MPa for strain rates of 1.5, 15 and 400 %/sec, respectively as shown in Figure 3. The plasticity modulus, E_2 was set at 7.5 MPa for each stress/strain curve. Poisson's Ratio value of 0.38 and density of 0.9 gm/cc were used in all cases. Element thinning was used in the analysis to account for any drawing which may occur during impact.

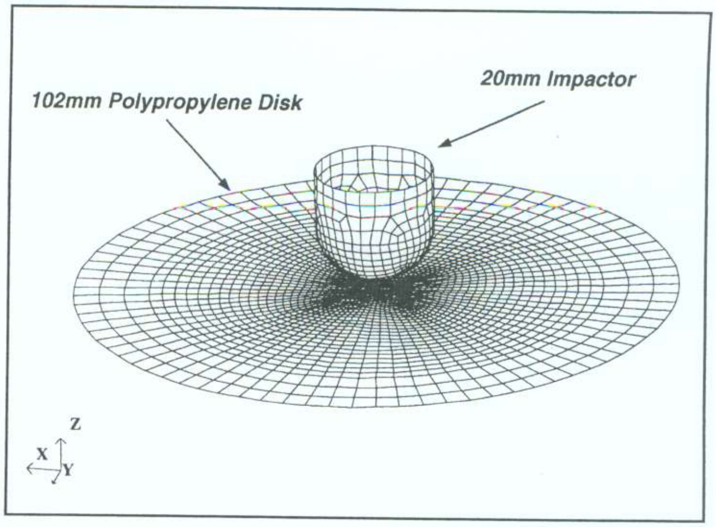

Fig. 4: Finite element model of the disk used in the validation study

Simulations were performed at the three loading rates of 0.5, 2 and 4 m/s. The force response was captured at a frequency of 100 kHz.

Results

The instrumented impact testing was performed over a range of loading rates which would encompass the strain rates resulting from a "typical" impact event of a 4.5 kg free motion headform striking a polyolefin "A" pillar at a velocity of 6.7 m/s as described by FMVSS201. Strain rates have been found within typical pillars to be in the range of 500 to 5,000%/sec. Pillars with reinforcing ribs can produce strain rates as high as 15,000%/sec or even higher, in the areas of stress concentrators.

Simulation of the instrumented impact event predicted elastic strain rates at the center of the disk of 500, 2,600 and 5,300%/sec and plastic strain rates of 1,100, 9,100 and 33,000%/sec for the loading rates of 0.5, 2 and 4 m/s, respectively. Strain rates in locations other than the center should drop to one-third or less of the strain rate found at the center.

Force-versus-time and displacement-versus-time from both experimental testing and FEA simulation are shown in Figure 5 and 6. An excellent correspondence between experimental and FEA results is obtained for the low speed (0.5 m/s) test condition. The predicted peak force for this case was 325 N and the experimental result was 316 N, or a 3% difference. Predicted displacement of the impactor was 2.8 mm and actual was 2.79 mm.

At the higher loading rates, however, the correspondence was not as good. The intermediate loading rate (2 m/s) showed a good correspondence with test data between 0 and 2 msec., after which the predicted force is overestimated. The same is true for the high speed case which showed a good correspondence between 0 and 1.3 msec. It has been observed that the over-prediction of the force

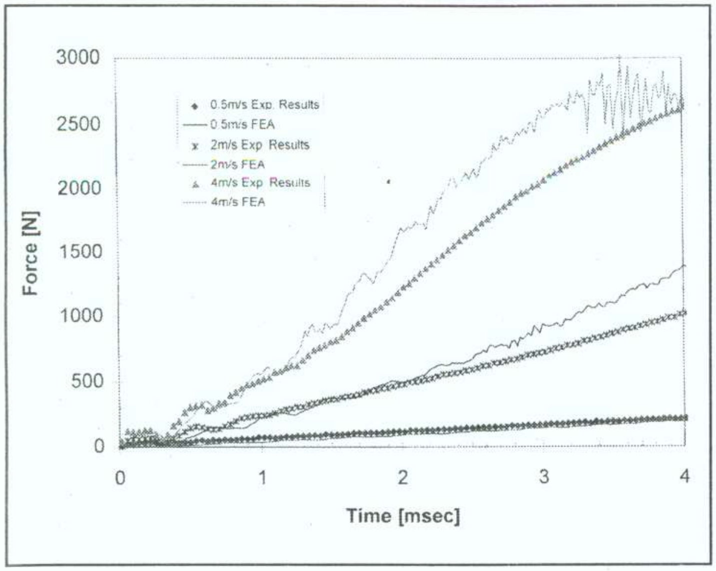

Fig. 5: Comparison between simulation and experimental data-force vs. time

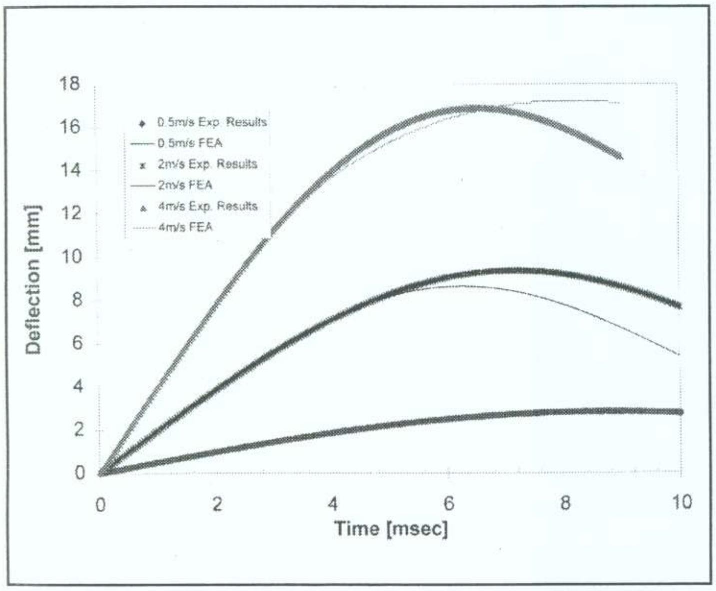

Fig. 6: Comparison between simulation and experimental data-deflection vs. time

is occurring in the post-yield or plastic region of the material model. This would suggest that the elastic stress/strain data is sufficient but further work is needed for improved experimental determination of the plasticity behavior of the polypropylene material.

Conclusions and Future Work

Flexural impact measurements appear to be a valid means of generating high strain rate data for impact simulations of the polypropylene material tested. Good correlation has been obtained, particularly in the elastic region.

The rate dependent model used in the FEA simulation seems to work well in providing information to predict behavior at different impact velocities. However, simulation appear to over-predict the force as the plastic region is approached. This may be due, in part to the limitations of the bilinear model used in the simulations. This model does not account for the gradual transition of the curve from elastic behavior to the plastic region. This might suggest the use of the piecewise-linear, rate-dependent material model within LS-Dyna3D.

More work is being conducted to perform tests over a wider range of strain rates so as to be able to construct a more robust rate dependent model. Two approaches will be used. Measurements on the existing flexural impact set-up using smaller spans will be used to obtain data at higher strain rates. A falling dart impact tester will also be used to test flex samples over a range of high and medium impact velocities. Additionally, efforts will be made to better describe the curve in the plasticity region and onward to failure.

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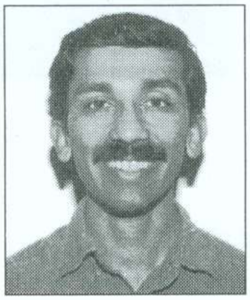
Biographies



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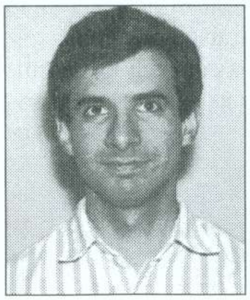

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