Finite Elements Method in Split Hopkinson Pressure Bar developing process

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Abstract: - A series of FEM simulations of SHPB test were used in designing of Split Hopkinson Pressure Bar equipment and its dedicated software, developed in Impact Laboratory, a facility of Military Technical Academy. In this paper are analyzed and evaluated by the simulations means three major topics: quality of acquired data mathematical process, practical SHPB test issues (projectile impact, additional specimen loads and impacts) and pulse shaping techniques. The used models in simulations were axial symmetric.

Key-Words: - **FEM, simulations, SHPB, impact, validation algorithm, SPH**

1 Introduction

An important step in designing of structures capable to support high strain rate load is numerical simulation of structures behavior in actual working condition [1]. Knowledge about structures materials behavior is necessary to accomplish this step. One of the most utilized laboratory methods in material behavior analysis for high strain rate processes is Split Hopkinson Pressure Bar, SHPB.

In last two years a SHPB installation and its dedicated software were developed in Impact Laboratory, a Military Technical Academy facility, Fig. 1. The developing process contains a series of validation and analysis steps, presented in paper, where we used FEM simulations.

The principle of SHPB is induction of a dynamic uniaxial stress state in a material specimen by two rods impact, Fig.2. The impact creates an elastic wave which travels the incident bar, reaches the specimen transmitting a part of energy in transmission bar and reflects the rest. The strain rate history and also stress history of specimen are obtained by measuring elastic deformation of input and output bars with strain gages mounted on both bars.

A software application was developed in order to process these histograms. This application was stood to a validation algorithm, which implied a series of SHPB simulations.

Also, during trial tests was studied if projectile is coaxial with incident bar at impact moment. A new method to verify impact quality was set. A thin film of oil was applied to terminal surfaces implied in impact process. A uniform radial ejection of oil indicates a correct impact. A simulation of impact in presence of oil film was created. The oil film was modeled by SPH technique.

In early tests of developed SHPB installation were observed, by video means, multiple dynamic loads of specimen. In absence of other investigation means was necessary to simulate the above-mentioned tests in order to evaluate the multiple loads effect on final specimen dimensions.

In order to prepare SHPB using in ceramic materials analysis, a pulse shaping technique based on pulse shaper crush was simulated.

Fig. 1. SHPB developed in Impact Laboratory

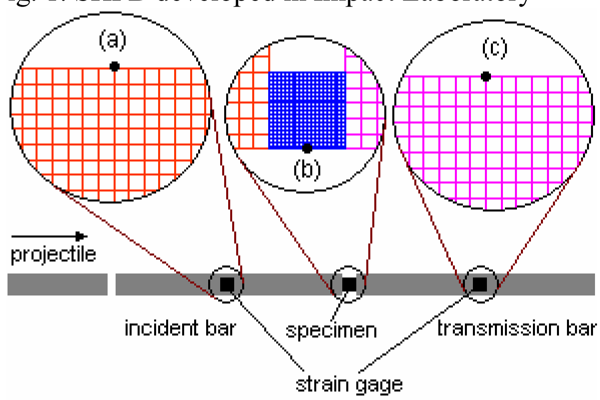

Fig. 2. Schematic of Split Hopkinson Pressure Bar

2 Software application and it's validation algorithm

Accuracy of data acquired by strain gages suffers mostly because of the wave dispersion and noise presence. Hence, before using SHPB data in material model calibration, some mathematical treatment is imposed in order to bring acquired data closer to true specimen deformation history. One of ours goals was to integrate mentioned above data processing, together with material model calibration algorithm in an SHPB dedicated software application.

First step in data processing is removal of undesired noise. The filtration is based on Savitzky-Golay algorithm.

From filtered signals three fragments (incident, ε_I, reflected, ε_R, and transmitted, ε_T, waves) are isolated, representing the effect of specimen presence on elastic wave propagation, fragments which gives strain rate and stress histories [2], [subscript *s* indicates specimen properties and *b* means bars properties]:

$$\sigma_s = E_b \frac{A_b}{A_s} \varepsilon_T \qquad (1)$$

$$\dot{\varepsilon}_s = -2 \frac{C_0}{L_s} \varepsilon_R \qquad (2)$$

$$\varepsilon_s = -2 \frac{C_0}{L_s} \int_0^t \varepsilon_R dt \qquad (3)$$

Each one of them is processed in order to eliminate the effect of dispersion on wave shape, a specific phenomenon to wave propagation in bars [3,4], following Gorham algorithm [5] based on Fast Fourier Transform analysis. Using corected reflected and transmitted waves in equations (1) – (3) are obtained test specific histograms, Fig 3.

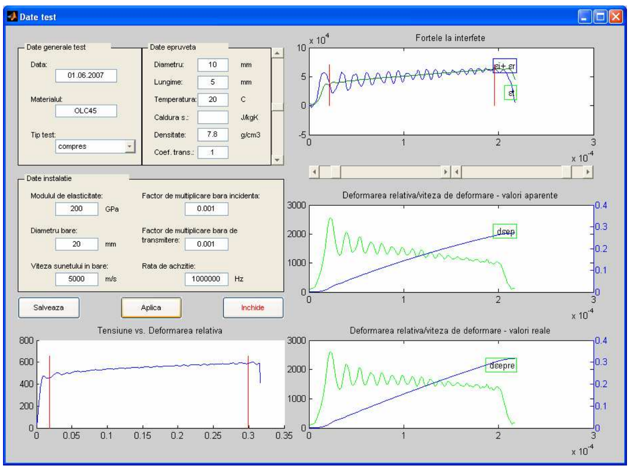

Fig. 3 Main window of SHPB test data processing

Approach used to fitting a nonlinear material model (e.g. Simplified Johnson-Cook Model) to SHPB data is the minimum chi-squared method [6]. It is assumed that the model choused is able to predict the values of the measured data. For each measured datum x_i,, the model provides a value y_i in terms of the SHPB experiment and a parameter vector *a,* representing the material model. The parameters that best fit the data are typically taken those that minimize χ^2

$$\chi^2 = \sum_i \frac{[x_i - y_i(a)]^2}{\sigma_i^2} \qquad (4)$$

where σ_i is the expected rms deviation of the measurement d_i. The vector which minimizes the value of relation (4) is established following the Levenberg-Marquardt algorithm. In this way the model material parameters are determined, Fig. 4.

Software applications used in scientific research area imposes a critical assessment of their capacity to extract true material model coefficients. In our case the assessment follows an application validation algorithm developed by authors and shown in this paper. The algorithm consists in extraction of material model parameters from a series of SHPB test simulations results, run under LSDYNA, and comparison with initial values inputted in simulations.

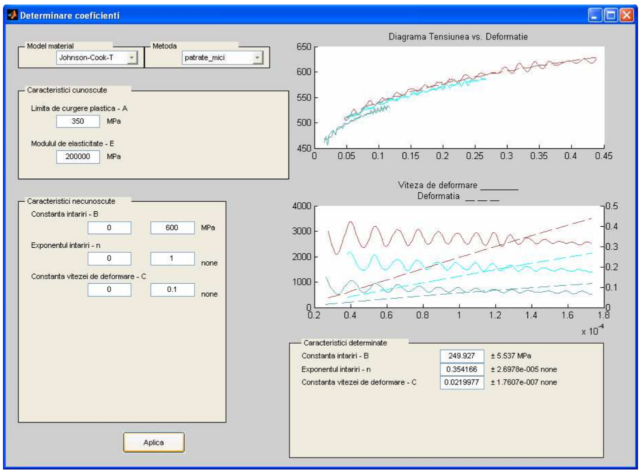

Fig. 4 Material model parameters identification window

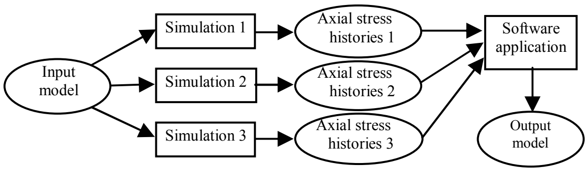

Fig. 5. Application validation algorithm

In a series of three SHPB test simulation, run under LS-DYNA, was input as specimen material a JC-S model representing 1006 steel properties [7].

The moving elements of SHPB installation are coaxial. This permitted to use a 2D axial model with shell elements. The finite elements models were created for the same SHPB test only one parameter being modified, impact velocity, from 10 m/s to 15 and 20 m/s. The bars radius was taken at 10 mm, projectile length at 250 mm and incident and transmitted bars length at 2000 mm. The maximum mesh size inside the bars was established at 1 mm, fallowing the Zenker observations [8]. The bars material is a high-strength steel (yield point ≈ 2 GPa) with Poisson ratio v_0 = 0.30 and mass density ρ_0 = 8082 kg/m^3. The specimen dimensions utilized in simulations were 5 mm for radius and 5 mm for diameter, with a mesh size of 0.25 mm. At the specimen-bar interfaces is no friction constraint. Geometric details of model are presented in Fig. 2.

The simulation series results covered strain rate interval from 10^3 to $3*10^3$ s^{-1}, maximum plastic strain value achieved being around 0.45. In Fig. 6 the simulation results for 15 m/s impact velocity are presented.

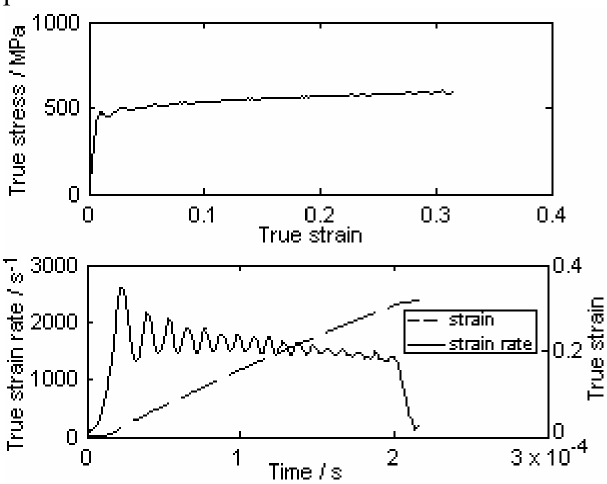

Fig. 6. Simulation results representing true stress, true strain rate and true strain histograms for 15 m/s impact velocity

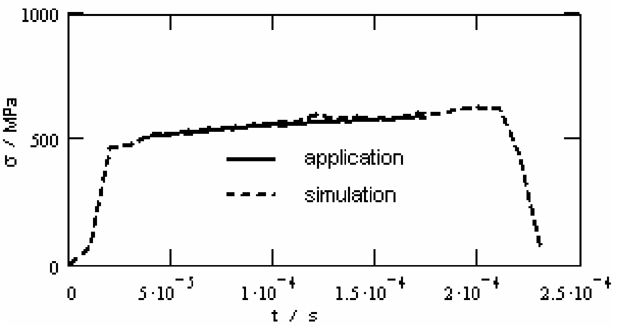

Fig. 7. Comparison of specimen stress rezulted from simulation and computed from application

Model parameters	Known parameters	Fitted parameters		
	A [MPa]	B [MPa]	n [none]	C [none]
Input model	350	275	0.36	0.022
Output model	350	249.9	0.354	0.0219

Table 1 Input and Output models

The resulted histograms of axial elastic strain in incident and transmission bars [see (a) and (c) in Fig. 2] were input in software application as specific ASCII files. The material parameters fitted represent output model. These two models, input and output were compared in Table 1. The differences found are very small except B coefficient were the difference is around 9%, tolerance accepted in high strain rates loads area. Axial stress histogram in center of specimen [see (b) in Fig. 2] was used as intermediate check point. Both simulation histogram and application resulted histogram, for 15 m/s impact velocity simulated case, are presented in Fig. 7. Graphic comparison show good agreement between these two histograms.

3 Analysis of impact in oil film presence

An issue studied during trial tests was projectile position at impact moment. A condition for correct test set-up is that the projectile to be coaxial with incident bar at impact moment. In order to verify impact quality a thin oil film was applied to terminal surfaces implied in impact process. A uniform radial ejection of oil indicates a correct impact, Fig. 8.

In order to evaluate in a qualitative way the ejection process a simulation of impact in presence of oil film was created. The oil film was modeled by SPH technique. The film thickness was established at 0.1 mm and SPH dimension at 0.01 mm. To simulate oil viscosity was use a viscoelastic model with static shear elastic modulus G_0 = 0 MPa. The viscosity was set to 0.1 Pa·s. The hydro tensile limit value was set to 0 MPa. In Fig. 9 - 12 are presented details of the ejection process simulation for 10 m/s impact velocity.

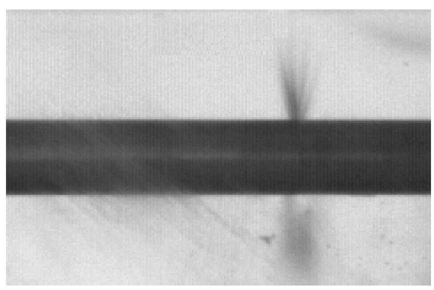

Fig. 8 Uniform radial oil film ejection at impact

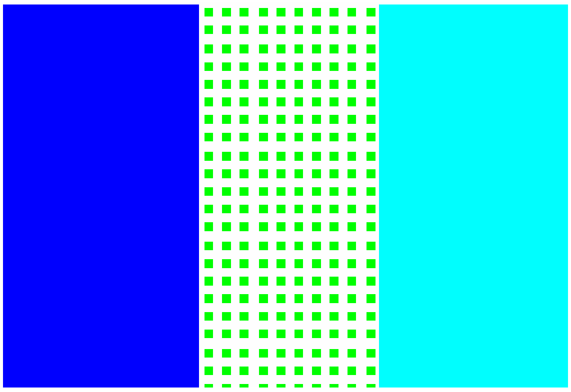

Fig. 9 Detail of initial SPH configuration

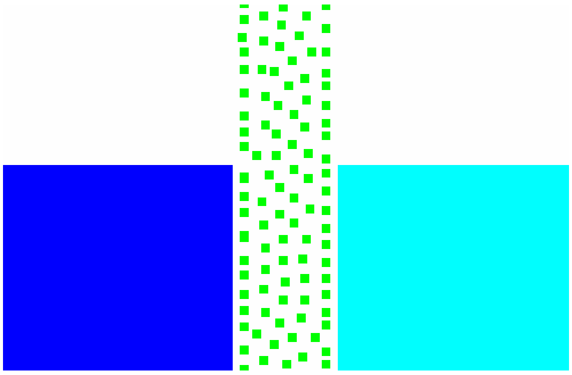

Fig. 10 Detail of modified SPH configuration

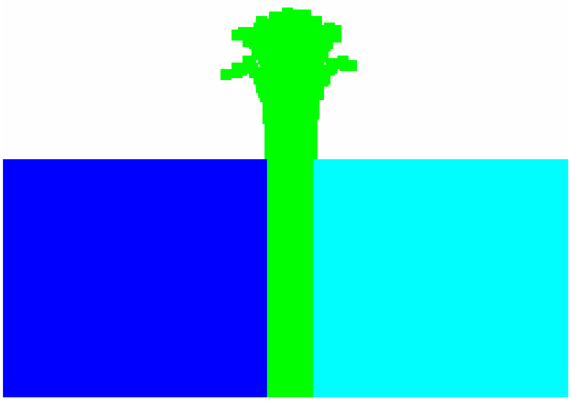

Fig. 11 Oil ejection in early stage of impact process

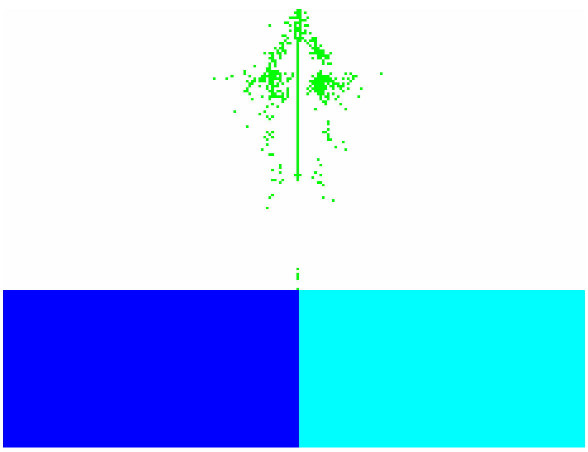

Fig. 12 Oil ejection at final stage

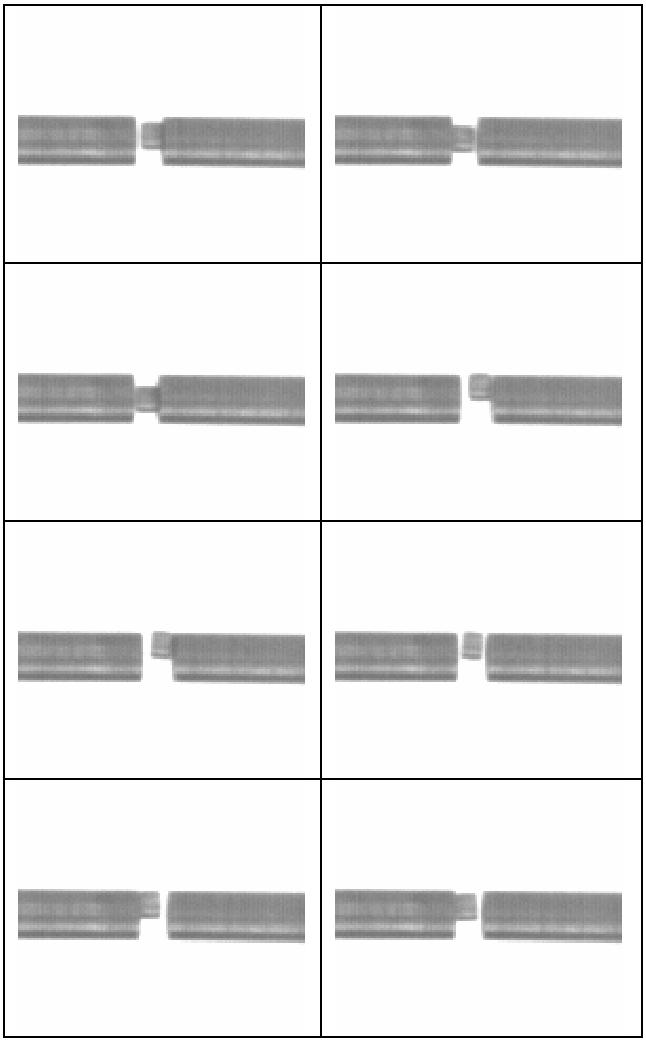

Fig. 13 VISION XS camera recorded images

4 Additional loads and impacts

Trial tests on copper specimens, recorded with high VISION XS, a high speed camera, show that specimen suffer a series of additional impacts, Fig. 13 (3000 frame/second, from right to left).

At that moment of test evolution the acquired data by strain gage means has no relevance in estimation of the effects of additional impact on specimen deformation state. The waves dispersion and waves superposition make impossible a correct data interpretation. Instead to use strain gage data the tests were simulated (2D, axial symmetric) and plastic strain evolution in specimen was analyzed.

The bars were modeled in the same way as for validation algorithm with a single modification. The projectile length was 400 mm, dimension which corresponds to real projectile. The tested cooper specimens had 10 mm length and 10 mm diameter. The specimen geometry used in simulation takes in to consideration these data. At the specimen-bar interfaces Coulomb friction is assumed at 0.05 as contact surfaces were lubricated with mineral oil. For the specimen material was used a Johnson-Cook model specific to annealed cooper with plastic limit set to 90 MPa.

The additional loads or impacts are indicated by shift value of specimen kinetic energy [e.g. Fig. 14]. The additional impact effects on specimen are indicated by accumulated specimen plastic work. In simulations were recorded the effective plastic strain evolution in gage point (b), Fig. 2.

In some simulated cases the results indicate major effects of additional impacts on specimen, the effective plastic strain evolution presents a second shift after the shift which corresponds to initial load. In Fig. 15 is presented evolution of effective plastic strain in gage point for 10 m/s velocity impact. The second shift corresponds to a second load. For the same gage the axial stress history is presented in Fig. 16. There are two time periods when plastic limit is exceeding, periods which correspond to first and second loads. After the second load stress values are relatively small, plastic limit exceeds no more.

A plastic strain shift and respectively a specimen plastic work shift mean specimen dimension changing.

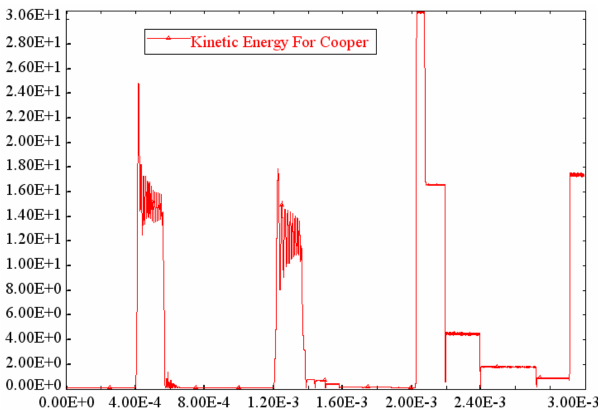

Fig. 14 Kinetic energy (mJ/rad) for 10 m/s impact velocity case

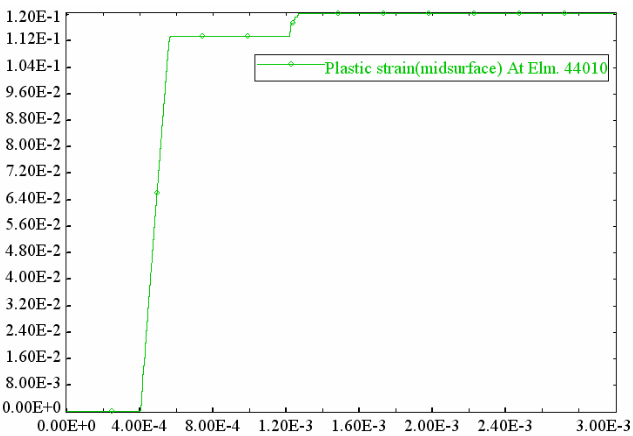

Fig. 15 Effective plastic strain at gage point

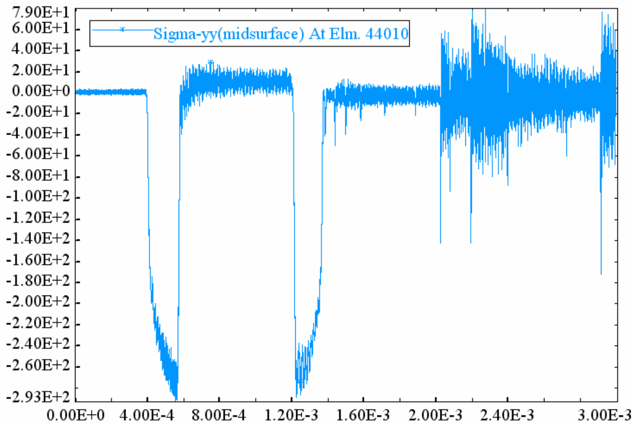

Fig. 16 Axial stress (MPa) in gage point

5 Pulse shaping technique simulation

The model of conventional SHPB was modified by placing pulse shaper disk with different sizes between projectile and incident bar. This modification makes able study of the elastic and early yield behavior of specimen by shaping different elastic incident pulses [9].

For the pulse shaper disk material was used a Johnson-Cook model specific to annealed cooper with plastic limit set to 90 MPa. In Fig. 17 is presented the model with the pulse shaper [green box] original thickness and diameter of 2 mm and 6 mm, respectively. History of axial stress recorded in incident bar at 400 mm from impact point, for 17 m/s impact velocity, is show in Fig. 18.

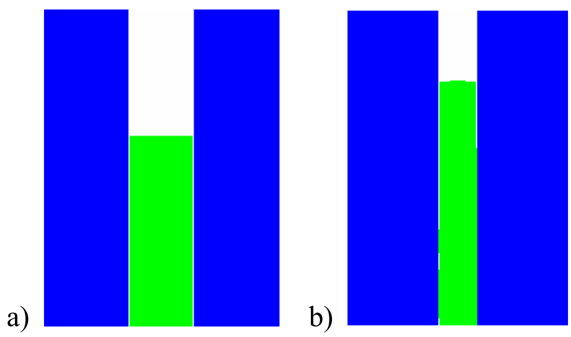

Fig. 17 Initial (a) and final (b) disk dimensions

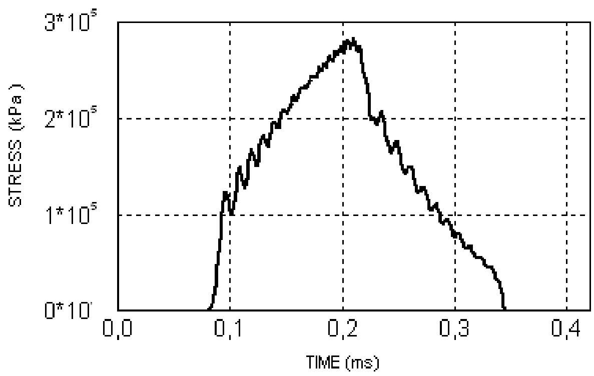

Fig. 18 Incident bar shaped axial stress

6 Concluding remarks

From validation algorithm results was found that software application developed ensure a good confidence in associated material parameters fitting process.

The SPH technique was found to assure a good qualitative representation of oil ejection process.

The result of additional loads and impacts simulations indicate to take precautions before using final dimensions of specimen in material behavior analysis.

The impact simulations in presence of pulse shaper disk show that a wide variety of incident elastic pulse can be produced by varying the geometry of the cooper disks and the length and striking velocity of projectile.

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