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NUMERICAL MODELLING OF WAVE SHAPES DURING SHPB MEASUREMENT

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Abstract. The paper aims at the numerical simulation of the wave propagation in compressive Split Hopkinson Pressure Bar (SHPB) experiment. The paper deals with principles of SHPB measurement, optimisation of a numerical model and techniques of pulse shaping. The parametric model of the typical SHPB configuration developed for LS-DYNA environment is introduced and optimised (in terms of element size and distribution) using the sensitivity study. Then, a parametric analysis of a geometric properties of the pulse shaper is carried out to reveal their influence on a shape of the incident pulse. The analysis is algorithmized including the pre- and post-processing routines to enable automated processing of numerical results and comparison with the experimental data. Results of the parametric analysis and the influence of geometric properties of the pulse shaper (diameter, length) on the incident wave are demonstrated.

Keywords: SHPB, pulse shaping, finite element method, explicit dynamics.

1. Introduction

Since material parameters are dependent also on strain rate, many experimental methodologies allowing to investigate material behavior during dynamic loading like fast impacts and explosions were developed. For example, yield strength of most of metals (e.g. copper) and alloys (including aluminium based alloys, steel, etc.) tends to increase with higher strain rates. The physics of this phenomena can be explained, for example, in a way that particles of material are affected by micro-inertia effects and do not have enough time to move and to cause yielding during high strain rates. However, quantification of this behavior is difficult. First experiments were performed by Hopkinson [1], while an important improvement was proposed by Kolsky [2] introducing the common Split Hopkinson Pressure Bar (SHPB) apparatus [3].

SHPB is an experimental device, which allows to measure the stress-strain diagram in dynamic compression, where the strain-rate and maximum compressive strain can be regulated within physical boundaries given by performance of the SHPB apparatus and the investigated samples. In a typical configuration, the SHPB consists of the impacting striker bar, the input incident bar, the output transmission bar, and the specimen placed between the incident and transmission bars (see Figure 1). All the bars are manufactured from the same material and have the same diameter, while the incident and transmission bar also have the same length selected according to parameters of the experiment and properties of the investigated specimen. Typical instrumentation of the experiment consists of strain-gauges mounted on the incident and transmission bars, through-beam sensors for measurement of the striker impact velocity, and a high-speed camera for optical inspection of the experiment. The accelerated striker impacts the incident bar forming a stress-wave propagating through the incident bar until the bar-specimen interface is reached. On the specimen boundary, the part of the incident wave is reflected and part is transmitted through the specimen causing its deformation. The transmitted part of the initial pulse is recorded by the transmission bar strain-gauge.

During the experiment, incident, reflected and transmitted pulses are recorded with strain-gauges (see Figure 2). The recorded strain-gauge signals and known properties of the experimental setup (e.g. bar dimensions, Young's modulus, density, wave propagation velocity etc.) are used for the evaluation of the stress-strain diagram of the specimen for the given strain-rate.

For valid experiment, two crucial requirements have to be fulfilled: i. satisfactory dynamic stress equilibrium and ii. approximately constant strain-rate.

In the specimen, the wave is also reflected on the interface of the specimen with the transmission bar. Therefore, a defined number of reflections has to pass through the specimen before the dynamic stress equilibrium is reached (see Figure 3). The dynamic equilibrium condition in the experiment is crucial as the standard mathematical methods for the evaluation of the specimen response are valid only in the equilibrium state.

Ramp-in effects (also known as ringing effects - a transient state caused by sudden incidence of a sharp pulse) and spurious oscillations of the specimen, negatively affecting dynamic equilibrium, can be significantly reduced by a pulse-shaping technique. A pulse shaper is usually a small cylinder of a soft material

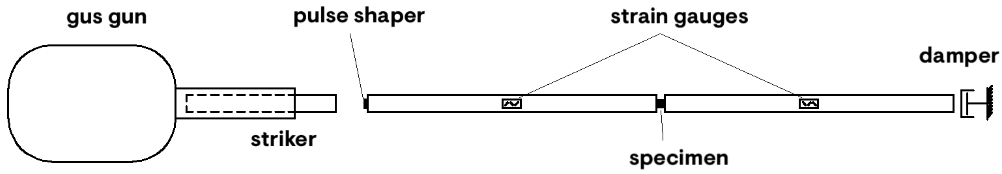

Figure 1. SHPB apparatus

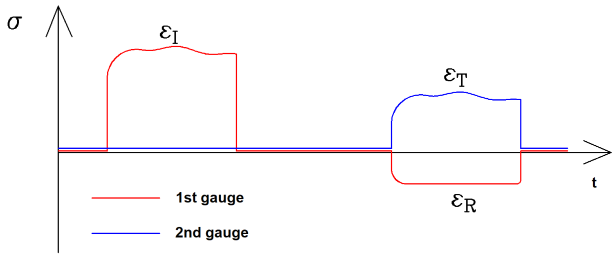

Figure 2. three measured signals

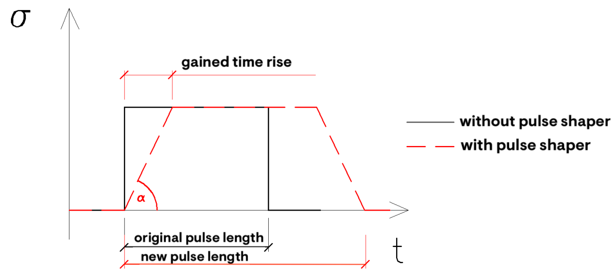

Figure 4. Original and shaped wave

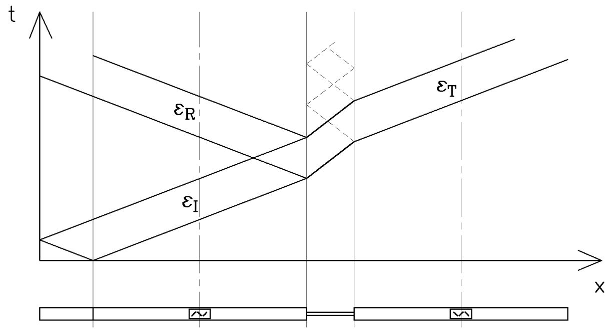

Figure 3. Space-time diagram of the wave

(soft copper, soft aluminium, paper etc.) with length in order of tenths or units of mm placed between the striker and the input bar. The pulse shaper causes slower raising of the incident wave and also attenuation of high frequency oscillations (see Figure 4). As a result, the pulse shaper improves conditions of the experiment leading to good quality dynamic equilibrium and constant strain-rate during loading of the specimen [4–6].

In this paper, we concentrate on numerical aspects of simulations of the SHPB experiments. Finite element (FE) model of SHPB was developed in ANSYS LS-DYNA. A sensitivity analysis of the FE model of the bars was performed as an important part of this study to assess the influence of the selected meshing algorithm and element size on numerical results. Then, the numerical model was calibrated according to experimental data. The second part of this contribution summarizes a parametric study of a pulse-shaper. Length, diameter and impacting velocity were varied parameters and evaluation of their influence on shape of stress pulse was analyzed.

2. Models and methods

A numerical model of SHPB apparatus consisting of striker bar, incident bar and the pulse shaper was created in ANSYS. The bars had the same diameter of 20 mm. No global constraints were prescribed to the numerical model. Two-way surface to surface algorithm was used for contact boundary conditions between the individual elements of virtual SHPB apparatus. Two algorithms of meshing, implemented in ANSYS toolkit were compared (see Figure 5).

The direct volume meshing algorithm creates elements from within of the bars and causes generating very small elements on the edges of the bar. These small elements have negative influence on the computing time, because the time step size is calculated (and is proportional to) from the smallest element size.

The direct meshing algorithm was compared with the sweeping algorithm for mesh generation, which chooses two faces that are topologically on the opposite sides of the body. These faces are called the source and target faces. Algorithm meshes the source face with quadrilateral and triangular elements and then copies that mesh onto the target face. Then it generates either hexahedral or wedge elements connecting the two faces and following the exterior topology of the body [7]. Using this algorithm, larger elements were produced in the middle of the bar (see Figure 5). The variation of element sizes and internal angles is apparently higher, when compared to directly generated mesh, but provides control over the achievable time-step via setting the mesh size on the edge of the bar.

Of course it is possible to create a regular mesh using meshing software specialized for geometries such as cylinders (LS-DYNA/LSPP), however, ANSYS was used as a pre-processor in this case for the ease of

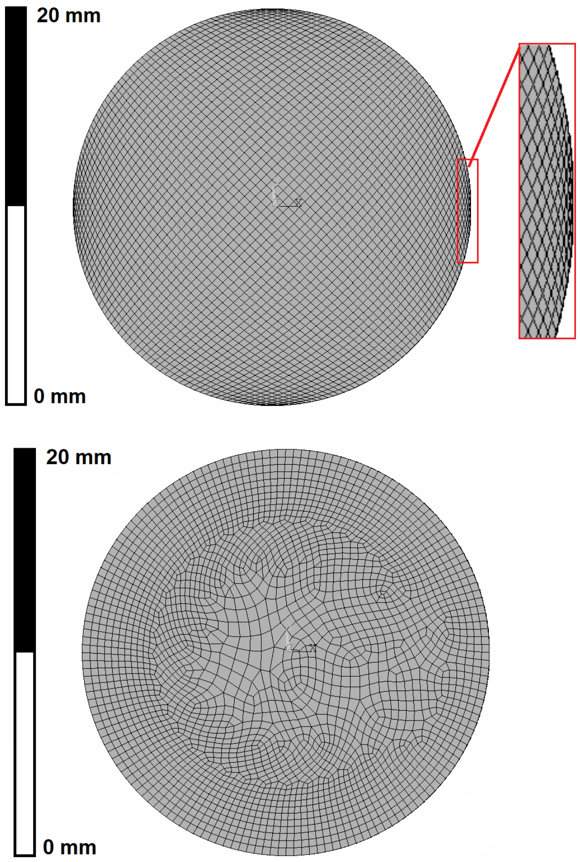

Figure 5. Outcome of the direct (top) and the sweeping method (bottom).

automation, hence the mesh is a result of its meshing algorithms with only limited controlability. However, in our experience with simulating the SHPB problems, the irregularity of the sweeped mesh produces negligible differences to LS-DYNA/LSPP cylinder meshes for most cases. After the sensitivity studies are concluded and critical factors identified, we use best quality approach for mesh generation.

However, it was necessary to compare both mesh generation algorithms in terms of influence on the virtual stress-wave propagation. For this reason, stress wave was recorded on the impacted front of the bar and in the distance of two and four multiples of bar radii measured from the front of the bar (see Figure 6).

The stress-wave is almost identical for both models as can be seen in Figure 6, in the distance equal to 2 diameters from the impact face. It is evident that from the distance of 2 diameters from the impacted face of the bar both models have the same stress wave evolution. This results proves the sweeping algorithm as a more suitable method for our task due to ability of indirectly control the time step using the size of the element. In this case, the direct meshing algorithm produced elements with five times shorter time step than sweeping algorithm.

Mentionable is the difference in the evolution of the stress at the striker-bar interface (0 r). For both cases automatic surface to surface contact algorithm

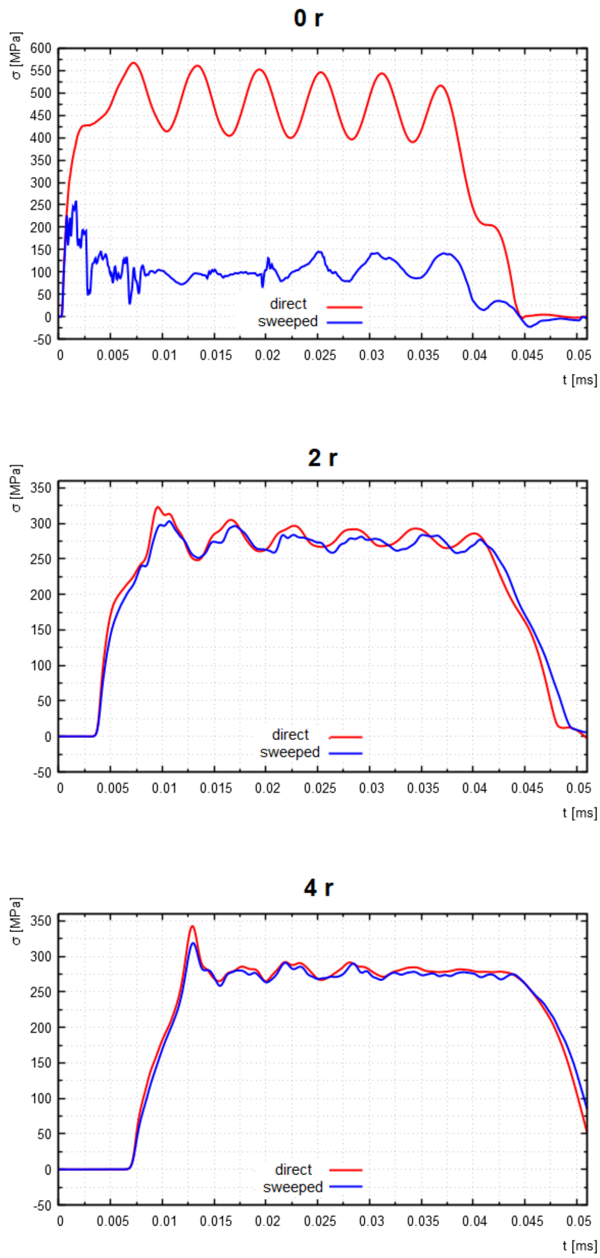

Figure 6. An evolution of the stress wave - measured at the front of the bar (top), one diameter distance (middle) and two multiples of the diameter distance (bottom)

was used. Boundary conditions are identically the same for both models. This anomaly is probably the consequence of the contact algorithm failure at the edge of the cylinder, which is supposed to happen very occasionally. The algorithm probably could not recognize if the bars are in or out of the contact and was alternately connecting and disconnecting the coupling between interfaces. This phenomena should be investigated in further studies, however now is not essential for our purpose, that is to analyze pulse shaper influence on the stress wave.

Although both model results are from determined border of 4 radii comparable with theoretical assump-

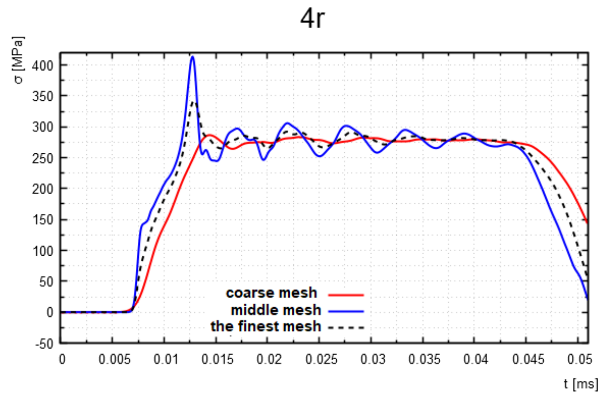

FIGURE 7. Comparison of the finest, the middle and the coarse mesh

tions of a wave propagating phenomena, it is well known that FEM can produce very unreliable results particularly in the analysis of stress waves propagation using explicit numerical methods. Basically, smaller elements cause that higher frequencies pass through the material in the model. The chosen sweeping algorithm model had to be calibrated according to the experimental data. A series of void tests (impacts of the striker bar on the incident bar without a pulse shaper) using SHPB was performed and the experimentally measured signals were compared with the signals from the FE model. Unphysical behavior of the stress signal in the model with the rough mesh (40 elements along the circumference of the bar) can be seen in Figure 7. Small sized elements in the model allowed for propagation of high-frequencies that were not observed during the experiments. However, choosing between the middle sized (160 elements along the circumference) element model and the finest one (280 elements along the circumference) is not possible without comparing with experimental data. Results of the models with the middle-sized and coarse mesh are shown in Figure 8. It can be seen that results of the coarse mesh model showed the best agreement with the experimental data.

On the basis of the results of the sensitivity study, a set of automated parametric simulations comprising ANSYS environment, LS PrePost tool, LS-DYNA solver, and Matlab was peformed to assess influence of pulse-shaping on stress-waves. For the parametric study, the thickness and diameter of a cylindrical pulse-shaper were selected as the control variables.

In the simulations, the diameter of pulse-shaper in the range of $5 - 8\,\mathrm{mm}$ and its thickness in the range of $0.5 - 1.5\,\mathrm{mm}$ were considered and the simulations were performed for the striker impact velocity in the range of $5 - 50\,\mathrm{mm \cdot s^{-1}}$.

3. RESULTS

In total, 130 simulations were peformed and the results were derived from the stress-wave shapes captured at the distance of four radii of the bars from its impacted

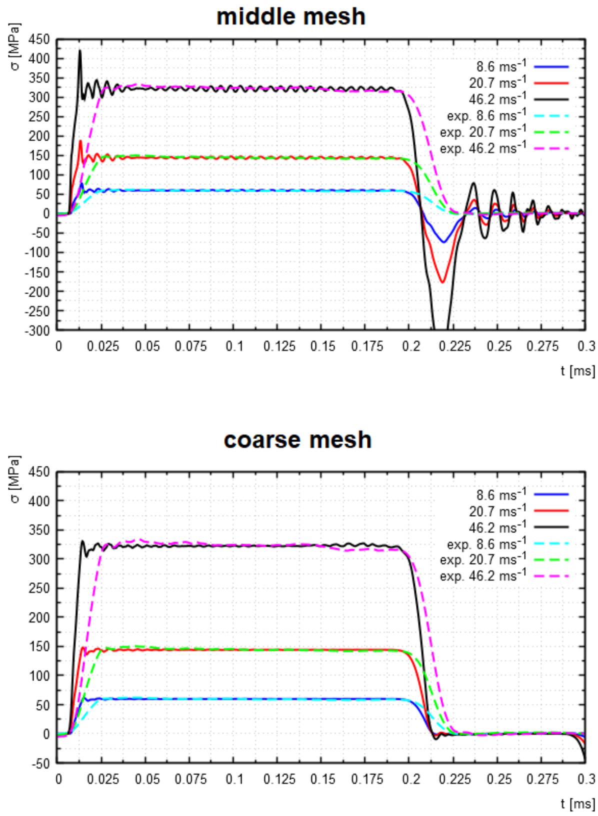

FIGURE 8. Comparison of experiment data with the middle (top) and the rough (bottom) meshed model

face. Changes of the wave shape caused by different pulse-shaper geometries during the impact with velocity of $25\,\mathrm{mm \cdot s^{-1}}$ can be seen in Figure 9. The FE modelling was identified as a very efficient tool to investigate the phenomena. Observed attributes of the wave were:

(1.) the wave-length of the pulse, defined as the time interval between the first nonzero value of stress and the first decrease of stress bellow the value of 5 % of the maximum value achieved during measuring,

(2.) the rise time of the wave, defined as the time interval between the first nonzero value of stress and achieving the first peak,

(3.) the rate of oscillations in the first half of the pulse, defined as the sum spread from smoothed data in the time interval between the first nonzero stress value and half of the above defined pulse length.

The length of the pulse slightly incrreases with longer pulse shaper (see Figure 10). The fluctuations are smoothed. The time rise also slightly rises, however the effect of changing length is not as remarkable as using pulse shaper by itself.

Changing the diameter has an apparent influence on the attributes of the wave (see Figure 11). With smaller diameters the wave is longer ($1.2 \sim 1.4$ times), the time rise is also longer and oscillations get smoothed. These attributes of the pulse are ap-

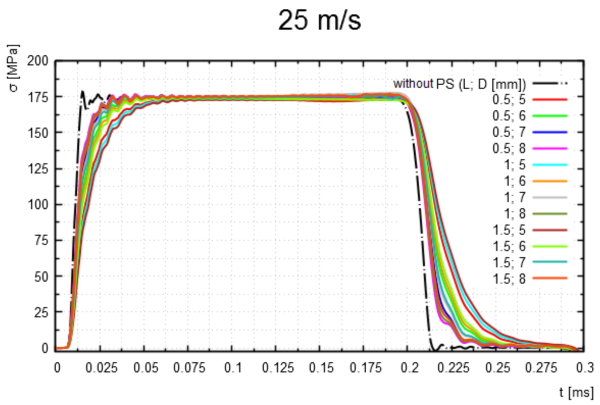

Figure 9. Influence of the pulse-shaper geometry

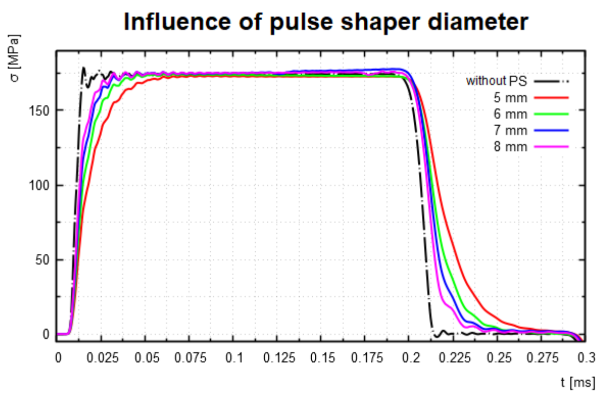

Figure 11. Influence of the diameter of the PS

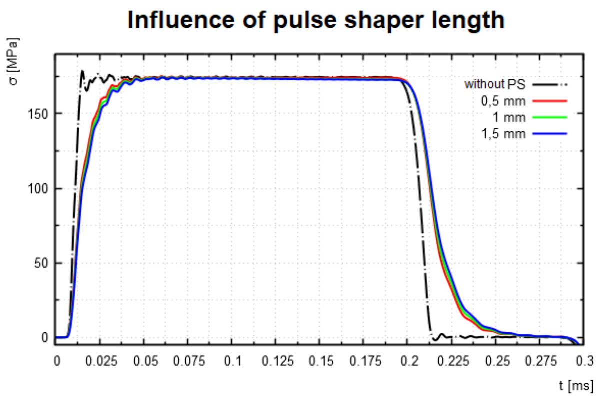

Figure 10. Influence of the length of the PS

propriate for achieving the stress equilibrium in the specimen.

3.1. The influence of the strain rate on the time rise for different geometries of the pulse shaper

The results have a comparable trend except two cases (see Figure 12) - that can be identified as numerical error (probably during automatic postprocessing, another possibility is an imperfect processing of these two simulations - e.g., due to not defined friction at the contact faces resulting in slipping of the pulse shaper and that negatively influenced the data). For diameters of 5 and 6 mm no distortion of results occurred, which means this mesh is capable to describe high frequencies generated by high-velocity impact ($40 - 50\,\mathrm{mm \cdot s^{-1}}$). The other curves have a comparable manner and two mentioned cases should be an error. It is evident that decreasing the diameter causes remarkable prolonging (from 2 to 4.5 times) of the rise time and increasing the length causes insignificant prolonging of the rise time. Both effects are stronger during lower strain rates.

3.2. The influence of the strain rate on the length of the pulse for different geometries of the pulse shaper

Data for 7 and 8 mm pulse shaper are again non-negligibly distorted and it is caused by the identical numerical error mentioned in the section above. Moderate influence of the strain-rate is evident (see Figure 13). Lower strain rates cause prolonging (from 1.06 to 1.22 times) of the wave and this effect is more remarkable with decreasing diameter. Length of the pulse shaper has a minimal influence, the remarkable cases are is 5 and 6 mm.

3.3. The influence of the strain rate on the oscillations of the pulse for different geometries of the pulse shaper

It is evident, that pulse shapers with smaller diameters behave as a better filter (see Figure 14). Also the filtering of high frequencies is more effective during lower strain rates. The length of the pulse shaper has a negligible influence during slow impacts ($5 - 30\,\mathrm{mm \cdot s^{-1}}$). During high velocity impacts ($40 - 50\,\mathrm{mm \cdot s^{-1}}$) also the length has a remarkable influence.

4. Conclusions

The numerical model of the SHPB apparatus was calibrated including the mesh sensitivity study. Two types of mesh generation algorithms were analyzed and boundary where the stress wave has the similar shape for both models was identified. The border where the stress curve has similar shape for both models was established, size of elements was set up according to experimental data. A phenomenon that the mesh actually behaves as a filter of high frequencies was observed.

Following conclusions can be drawn based on the main parametric study:

(1.) Pulse-shapers with smaller diameter are more effective as filters of oscillations, well prolong the

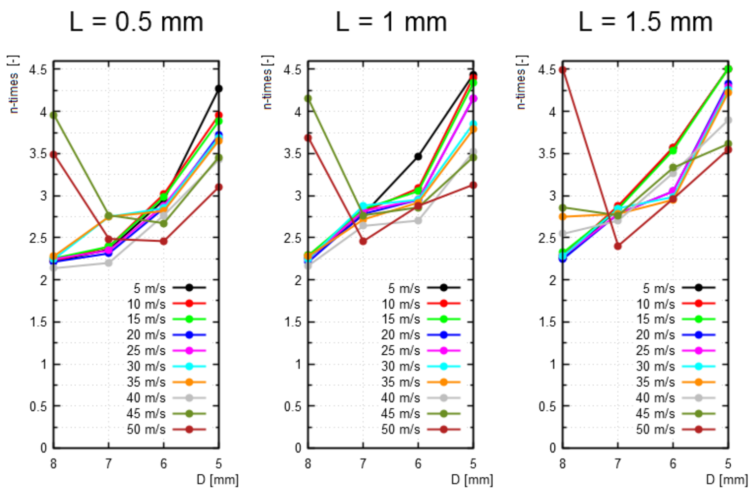

FIGURE 12. Influence of impacting velocity on a time rise (L - length of the pulse shaper, D - diameter of the pulse shaper

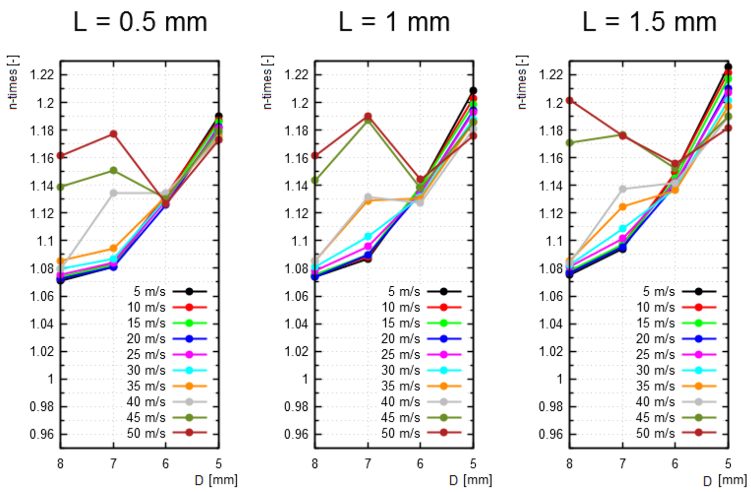

FIGURE 13. Influence of impacting velocity on a pulse length (L - length of the pulse shaper, D - diameter of the pulse shaper

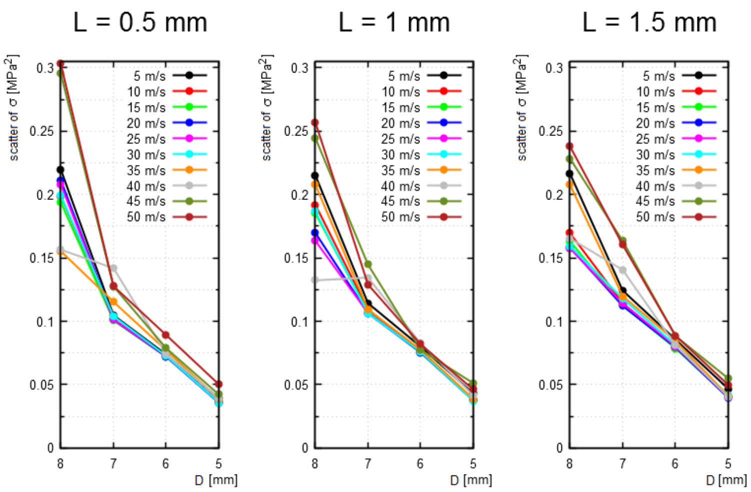

FIGURE 14. Influence of impacting velocity on oscillations of the pulse (L - length of the pulse shaper, D - diameter of the pulse shaper

time rise and the pulse length which is crucial for achieving stress equilibrium.

(2.) The length of the pulse shaper has an insignificant influence.

Each mentioned phenomena is more remarkable during low strain rates. These conclusions are fully compatible with other studies [4–6] and with the experiments.

List of symbols

σ Stress [MPa]

ε_i Incident pulse [–]

ε_t Transmitted pulse [–]

ε_r Reflected pulse [–]

t time [ms]

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