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Numerical study for determination of pulse shaping design variables in SHPB apparatus

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Abstract. High strain rate experimental tests are essential in a development process of materials under strongly dynamic conditions. For such a dynamic loading the Split Hopkinson Pressure Bar (SHPB) has been widely used to investigate dynamic behaviour of various materials. It was found that for different materials various shapes of a generated wave are desired. This paper presents a parametric study of Split Hopkinson Pressure Bar in order to find striker's design variables, which influence the pulse peak shape in the incident bar. With experimental data given it was possible to verify the developed numerical model, which was used for presented investigations. Dynamic numerical simulations were performed using explicit LS-Dyna code with a quasi-optimization process carried out using LS-Opt software in order to find striker's design variables, which influence the pulse peak shape.

Key words: Split Hopkinson Pressure Bar, pulse shape, numerical studies, parametric study.

1. Introduction

The Hopkinson bar with all its versions is widely used to quantify the dynamic behaviour of solid materials at high strain rates within the range of 10^2 to 10^4 s^{-1} [1–11]. The device is named after John and Bertram Hopkinson [2, 3, 12, 13]. In 1872 John Hopkinson investigated a stress wave propagation in a wire [2, 12] which was the basis for his son Bertram, who developed a measurement method for the movement recording of a cylinder during strongly dynamic conditions [3, 13]. At a later date (1948) Davies improved this technique resulted in better accuracy of measured data (pressure versus time history curves) [14]. One year later (1949), Kolsky used two elastic bars instead of one with the specimen placed between them [15]. Since then, this device (technique) has been known as the Split Hopkinson Pressure Bar (SHPB) or Kolsky bar.

As aforementioned the SHPB is used for obtaining a stress-strain curves of investigated materials for a certain strain rate. One of the problems associated with the procedure is a presence of oscillations recorded by the strain gauges, called Pochhammer-Chree oscillations [14, 16] which adversely affect results. Therefore, it is significant to obtain constant strain rate conditions during tests [1, 17, 18], as well as stress equilibrium in a specimen [5, 19, 20]. This can be achieved by adjusting the incident pulse shape, which has the direct influence on material behaviour. Several methods can be used for shaping the incident pulse: e.g. by inserting a preloading bar, using a pulse shaper or modifying the shape of striker bar. The latter is the main aim of presented investigations.

Preloading bar was implemented by S. Ellwood et al. [1] and was further investigated in [19]. Frantz et al. [21] showed that third bar is not necessary to shape the incident wave and only the dummy sample (pulse shaper) can be placed between the striker and incident bar [1, 5, 18, 19, 24-26]. Moreover, in several studies [15, 22–24, 26] pulse shapers with different materials (copper, aluminium, polymer etc.) and dimensions were also investigated with its influence on the incident wave taking into account.

The optimal shape of the striker bar is well known and was investigated through numerical [27] and experimental testing [25]. In these papers authors have used truncated cone striker, which produces an incident pulse and eliminates oscillations in the incident pulse. The cone-like striker was also designed using the so called inverse numerical method [28, 29], using the finite difference method [30] or neural network [31]. Li X.B. et al. [32] investigated the relationship between diameter of the striker bar and minimum loading rate.

One of the major and fundamental assumption of the one-dimensional stress wave propagation theory on which SHPB technique is based is that the all bars are linear and dispersion free [33, 34]. Thus, bars need to satisfy several criteria: they have to be homogeneous, isotropic and have uniform stress distribution. Additionally, what plays the significant role is the perfect alignment of the bars so that a clean signal without any distortions can be obtained [13, 33]. In [35] authors employed a study of misalignment bar effect in producing a distorted signal. Six major types of misalignment were investigated and compared, which resulted in pointing out recommendations of bar specifications for minimizing the deviation of results. During the tests non-coaxial alignment impacts are prone to happen, which also results in wave distortion. Z. Zi-long et al. [36] have performed experimental tests of SHPB under these misalignment impacts (off-axially

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and obliquely) and identified system abnormalities causes by this effects.

This paper is focused on a parametric study for determination the striker shape geometrical parameters and its influence on the incident pulse shape. Authors are aware that aforementioned conical striker shape is known for decades, but they have not come across on similar work that covers a wide study of various striker shapes and their influence on obtained incident pulse, related to different materials. Some authors presented their investigations related to this issue, but in the smaller range with the smaller number of design variables [37–39] e.g. only striker length was taken into consideration [38].

The presented paper is the first stage of author's investigations which is pointed on the optimization process of a striker's shape with an objective function defined as a constant strain rate in a test specimen. In the future, authors will carry out the wider SHPB optimization for finding and identifying the optimal striker bar profile for different material (brittle, ductile or soft).

2. SHPB testing

2.1. Experimental tests. Experimental testing was performed on a conventional SHPB apparatus (Fig. 1), which the main goal was to obtain a "severe" incident pulse, without using any pulse shaping techniques. Basically, the device consists of a gas gun, a striker (20 mm diameter, 150 mm long), an incident bar, a transmission bar (both 20 mm diameter and 2000 mm long), an energy absorption element and a data acquisition system. The striker is launched using highly compressed gas and impacts the incident bar. This generates the elastic wave (incident wave) which travels through the bar and then, due to the difference between mechanical impedances of bar and specimen materials, part of the pulse comes back (reflected wave), whereas the rest of it is transmitted through the tested specimen. Consequently, it compresses it and the wave travels to the transmission bar and generates a so called transmitted wave (Fig. 2). All three signals are sensed by strain gauges which are placed in the middle of the bars.

Fig. 1. Split Hopkinson Pressure Bar used in investigations

In Fig. 2 the wave propagation is presented. Based on the foregoing, it can be concluded that pulse duration time increases proportionally with increasing striker bar length [1, 2, 9, 10, 12, 15, 20, 40]:

$$T = \frac{2L}{c_p}, \tag{1}$$

where T the impulse duration time, L is the striker length and c_p is the elastic wave propagation velocity in a bar material.

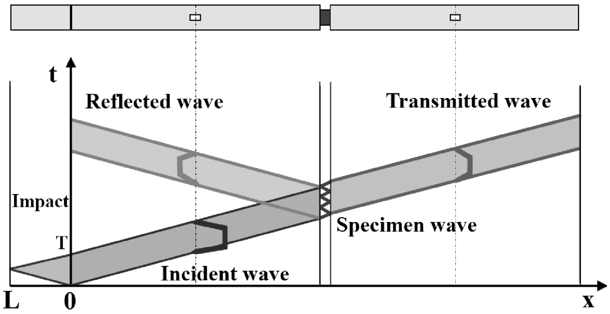

Fig. 2. Wave history route in SHPB

From the carried out experimental tests the incident wave was obtained, which was consequently compared with the numerical one. In the figure large oscillations can be noticed caused by a lack of the pulse shaper, which is normally used in tests. Nevertheless this phenomena does not have much importance in the presented part of investigations pointed on actual and numerical model validation.

2.2. Numerical analyses . Validation numerical simulations as well as other computations performed within the presented study have been performed using aforementioned LS-Dyna package using an explicit integration procedure with a central difference scheme with modified time integration of the equation of motion implementation [41]. The stability of computations was achieved with Courant-Friedrichs-Lewy (CFL) condition, which states that a necessary condition for the convergence of an explicit scheme is that the domain of dependence of the discrete problem includes the domain of dependence of the differential equation in the limit as the length of the finite difference steps goes to zero [41]:

$$C = \frac{u_x \Delta t}{\Delta x} + \frac{u_y \Delta t}{\Delta y} + \frac{u_z \Delta t}{\Delta z} \le C_{\max}, \tag{2}$$

where u_x, u_y, u_z are the velocities, Δt is the time step, Δx, Δy, Δz are length intervals, $C_{\max}$ changes with the method used (in presented investigations it was set to the default $C_{\max} = 0.9$).

For the purpose of simulations the numerical model of SHPB apparatus consisting of 75900 Lagrangian hexagonal elements (number of elements was verified in parallel simulations) was developed (Fig. 3). Due the fact that authors were focused only on the incident wave the specimen, stopper and transmission bar were omitted. Also, in order to simplify and shorten computational time, symmetry of the problem was assumed and only quarter of the model was taken into consideration. It is known that axially-symmetric model is less computationally expensive but the chosen three-dimensional model in subsequent investigations will give the possibility to study additional effects, like dispersion effects or misalignment impacts occurring in the SHPB.

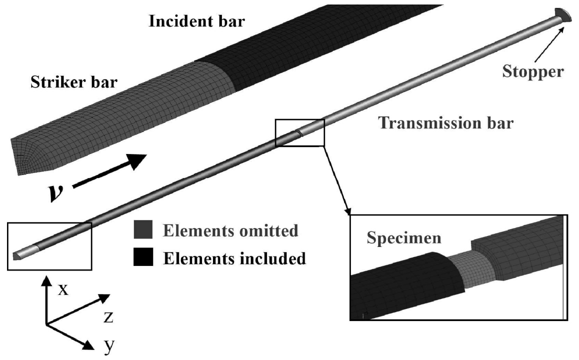

Fig. 3. Numerical model of SHPB apparatus

Initial velocity conditions were applied on the whole striker volume (all nodes), which value exactly corresponded to the actual one $v = 1.533e + 4$ mm/s. Interaction between the striker and incident bar was implemented with surface to surface contact procedure using penalty function approach [41]. Material properties have been described with a typical Hooke's law elastic constitutive model (with literature steel data) since the incident and striker bars remain elastic during tests [1].

From the carried out simulations the incident impulse (axial stress: σ_{zz}) was obtained which was taken from the incident bar element which directly corresponded to the place, where strain gauge was glued. By comparing both pulses (experimental and numerical) good overall correlation can be seen: time intervals between incident and reflected impulses as well as stress values are approximately identical (Fig. 4). Thus numerical model of SHPB can be considered as initially validated. Although, closer look at the results reveals slight discrepancy in the lengths of both impulses. This is caused by the fact that in numerical simulations no dispersion effects and material dumping was taken into account, which in actual conditions are evident.

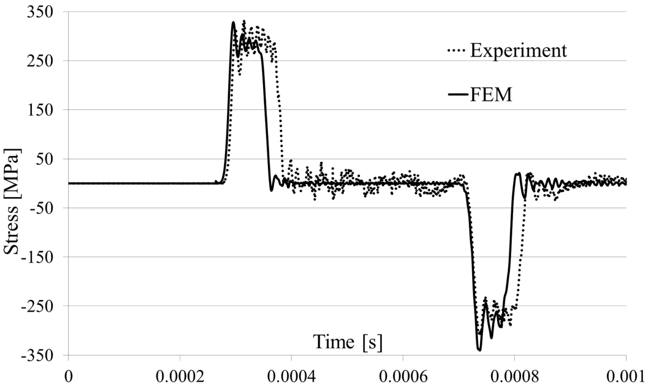

Fig. 4. Numerical and experimental results comparison

Subsequently, validated model of SHPB was the base for the first stage of parametric study to determine the striker "basic" geometrical parameters that affect the shape of incident pulse.

3. Striker shape parametric study

3.1. Basic shapes study. In order to perform the quasi-optimization procedure, which in fact was the parametric study of various shapes the "morphing" model of SHPB striker bar has been developed using HyperWorks software. In the first stage three characteristic striker's diameters (two on its edges and one at the centre of bar) were chosen as design variables (Fig. 5). Thus, these diameters were forced to vary between the range of 10 mm and 20 mm.

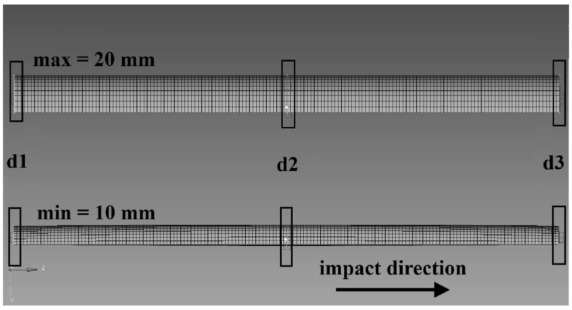

Fig. 5. Maximum and minium striker's diameters used in investigations

For reducing the time needed to perform a number of simulations (for a different diameters configuration) the LS-Opt software was chosen. Consequently, sixteen cases with various diameters configuration were run (Table 1).

Table 1
Simulated cases with diameters data

Case	d_1 [mm]	d_2 [mm]	d_3 [mm]
1	19.0	19.0	19.0
2	15.6	10.0	17.2
3	13.2	12.0	15.4
4	11.6	10.4	12.6
5	14.0	18.6	13.4
6	10.4	10.6	17.6
7	18.8	12.4	18.4
8	15.8	15.0	18.8
9	18.8	18.8	10.0
10	10.0	18.0	10.0
11	10.6	16.4	17.4
12	11.4	14.2	11.2
13	17.8	15.8	14.4
14	16.0	10.4	11.8
15	15.2	16.0	10.2
16	14.2	18.2	17.8

From the carried out simulations the incident pulse (stress impulse) was obtained for all sixteen cases. In Fig. 6 impulse shapes with corresponding striker geometry are presented. It can be noticed that all diameters have an influence on the impulse shape. Smaller d_1 or d_3 give the larger peak at the beginning or the end of an impulse correspondingly, whereas central d_2 influences middle peak of an impulse in the opposite way.

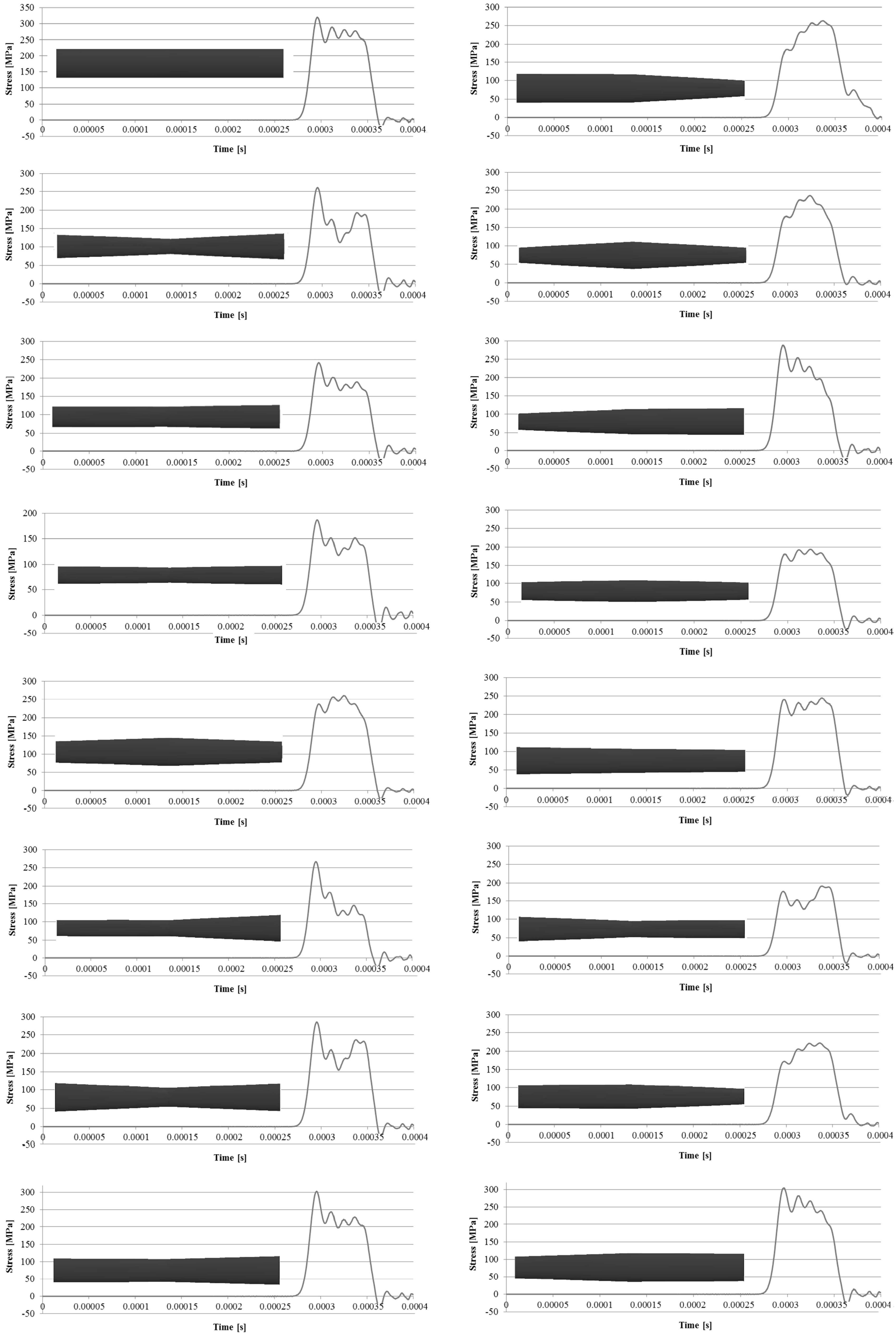

Fig. 6. Impulse shapes with corresponding striker geometry

By taking closer look at above results it can be clearly noticed that impulses without initial oscillations were obtained for a striker with both tapered ends from short cylinders. Thus findings of the other authors have been confirmed [27–32].

4. Tapered striker study

4.1. Study of diameters proportion influence. In the next step of investigations a more detailed study was conducted in order to evaluate the influence of different diameters and their proportion (values) on the behaviour of obtained incident impulse For this purpose six cases were investigated with one invariable central diameter which was 20 mm (Table 2).

Table 2
Simulated cases with diameters data (2 stage)

Case	d_1 [mm]	d_2 [mm]	d_3 [mm]
1	5.0	20.0	5.0
2	7.5	20.0	7.5
3	10.0	20.0	10.0
4	12.5	20.0	12.5
5	15.0	20.0	15.0
6	17.5	20.0	17.5

The maximum, middle, minimum and others values (proportions) of aforementioned variables were chosen with literature data and authors experience in this field taking into consideration.

Subsequently, the same numerical simulations were performed as in the previous subsection. Also, identical response was investigated: the incident wave, which, the same as before, was represented by stress impulse from the chosen element of the bar (in the same place as strain gauge in experiment). In Fig. 8 wave shapes with corresponding striker geometry are presented. It was noticed that by decreasing both edge diameters obtained characteristic is getting more "streamline" and sinusoidally shaped. Also, no oscillations and negative (tensile) values of waves are noticed which occurred during the impact with typical, cylindrical striker. In Fig. 7 the comparison graph of all six cases is presented which shows that the most non-oscillated impulse of all tested is the one obtained for the minimum values of d_1 and d_2 diameters, which was the next step of authors investigations. Also, at this point authors thought that the differences between the values of stress came from various kinetic energy of striker impact (different masses). But, the next section showed that not only the mass influences the impulse maximum value but also its geometry, more particularly, the centre of mass.

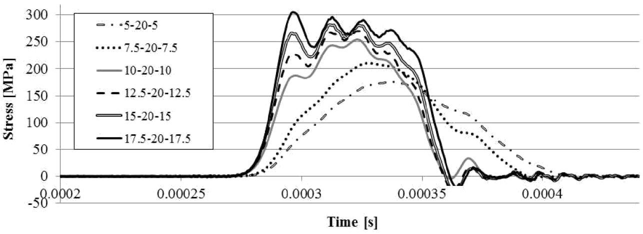

Fig. 7. Impulse shape comparison for a tapered striker

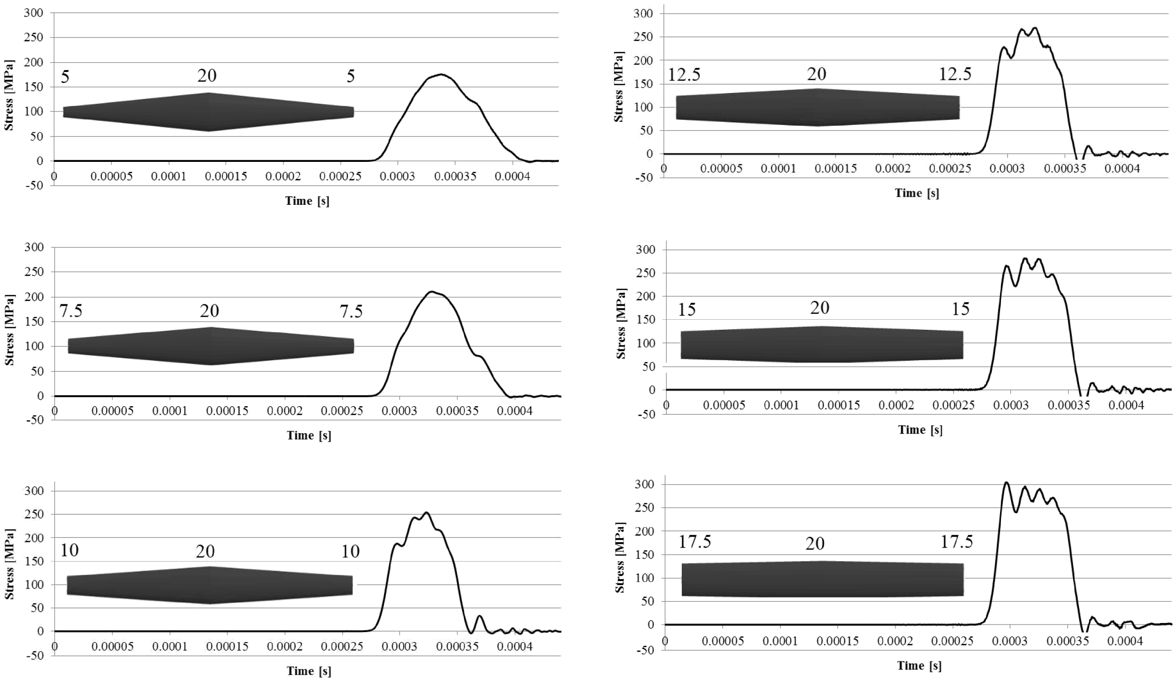

Fig. 8. Impulse shapes with corresponding striker geometry

4.2. Central diameter position study. In this stage a central diameter (cones base) position in the striker was investigated. Thus, for testing seven different cases were taken into consideration (Fig. 9):

- diameter in middle position (case 1).
- diameter at 30 mm of striker length (case 2),
- diameter at 50 mm of striker length (case 3),
- diameter at 70 mm of striker length (case 4),
- diameter at 80 mm of striker length (case 5),
- diameter at 95 mm of striker length (case 6),
- diameter at 120 mm of striker length (case 7),

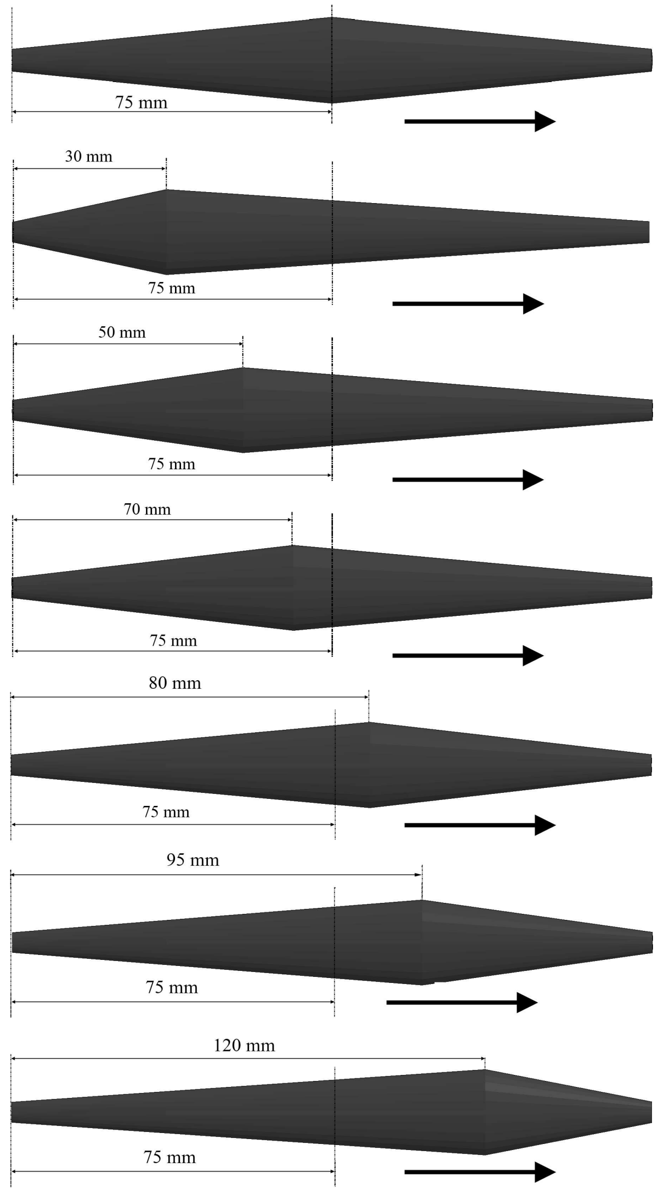

Fig. 9. Various maximum diameter position considered in simulations

Different strikers presented above were used in simulations from which incident wave (represented by stress impulse) was investigated. Taking closer look at Fig. 10 different shapes of impulse can be noticed.

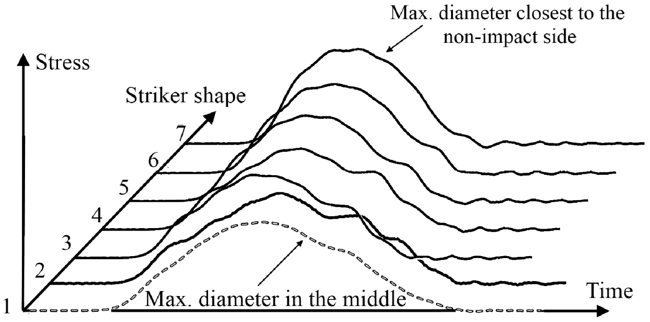

Fig. 10. Impulse shapes comparison for various cones base position

Generally, the closer maximum diameter is to the striker's end, the higher wave value is obtained. This means that both mass and striker geometry influence the maximum value of an impulse. Moreover, if the diameter is on the non-impact side of a striker the stress wave is shorter. When the diameter is closer to the impact surface an extension of impulse can be seen.

4.3. Tapered-cylindrical striker study. At this point a proportion between the tapered and cylindrical "sections" of striker was investigated. In general, a cone base which forms the striker was extend (stretch) through the striker's length. In order to perform such tests three variants were chosen:

- with the shortest base (cylindrical part) extension,
- with the medium base extension,
- with the longest base extension.

Discussed shapes are presented in Fig. 11.

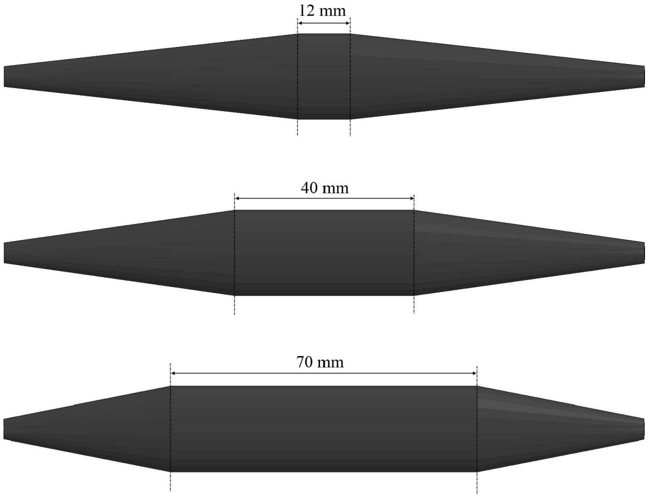

Fig. 11. Various cone base extensions applied in simulations

As expected, extension of the cones base resulted in higher values of obtained stress impulse, which confirms the mass dependency on its behaviour. Also, in all variants the same impulse length was obtained, due to invariant position of centre of mass in all cases. Discussed characteristics are presented in Fig. 12.

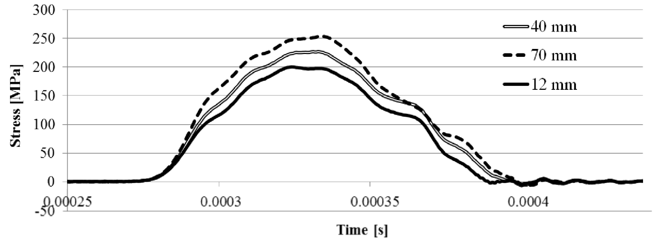

Fig. 12. Impulse shapes comparison for various cones base extension

5. Summary

In above paper authors presented subsequent stages of the parametric study of the Split Hopkinson Pressure Bar impactor in order to determine the factors, which influence pulse peak shape in the incident bar. From the carried out numerical simulations the following design variables that modify (change) the impulse characteristic can be distinguished:

- different diameters of the striker along its length,
- different proportions between central and side diameters of the striker,
- different position of the maximum diameter along striker length,
- different cone base extension along striker length.

Obtained and tested design variables will be implemented in the next stages of investigations which will be focused on optimization process of the striker's shape. Subsequently, authors will carry out the wider SHPB study for finding and identifying the optimal striker bar profile depending on the chosen objective function. Finally, the ideal shape of striker will be determined for a specific type of material as brittle, ductile or soft which will give the possibility to perform experimental tests in constant stress, and consequently, strain rate conditions. As the latter result of investigations a series of different striker shapes will be created for a number of the most commonly used bars systems and specimen materials.

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