Misalignment effect of Split Hopkinson Pressure Bar (SHPB)

Zurri Adam Mohd Adnan[1], Mohd Azman Yahaya[1], Jamaluddin Mahmud[1], Mohd Zaid Othman[2], Tan Kean Sheng[2]*
[1]Faculty of Mechanical Engineering, Universiti Teknologi MARA, Shah Alam, Selangor, Malaysia
[2]Department of Mechanical Engineering, Faculty of Engineering, Universiti Pertahanan Nasional Malaysia, Kuala Lumpur, Malaysia
**azman028@salam.uitm.edu.my*

ABSTRACT

Split Hopkinson Pressure Bar (SHPB) testing set-up is one of the mechanical testing that commonly used to determine the dynamic stress behaviour of materials. The most important step in order to get accurate and reliable data is the quality of calibration process. Even though the test has been widely used, but there is still lack of information on how the testing set-up being calibrated. This paper is focused on misalignment calibration of SHPB test set-up. Tests were conducted using 200 mm striker bar at velocity of 22m/s without specimen. Results with misalignment and without misalignment cases were compared. The results with misalignment shows major fluctuation occur at the baseline for incident bar signal due to the height offset misalignment between the bars. Then, the incident bar is adjusted to a height of 156.78mm to ensure not in misalignment position using levelling gauge which results in good trapezoidal shape of bar signal with minor fluctuating baseline. Similar shape and baseline were achieved for both cases up until 368 $\mu\varepsilon$, however major fluctuation in negative incident strain called reflected strain occur due to height offset misalignment. The magnitude of bar signal, $\mu\varepsilon$ (micro strain) are similar up to 368 $\mu\varepsilon$ for both cases due to similar impact velocity. Misalignment of SHPB bar contributes to fluctuation of the wave beyond 368 $\mu\varepsilon$.

Keywords: *SHPB; Dynamic Stress; Calibration; Low Impact Loading.*

ISSN 1823- 5514, eISSN 2550-164X

Received for review: 2019-03-29
Accepted for publication: 2019-07-01
Published: 2019-12-15

Introduction

Split Hopkinson Pressure Bar (SHPB) is one of the mechanical testing that commonly used to determine the dynamic stress behaviour of materials. The reason that widely used of SHPB in dynamic analysis is due to easy experiment procedure to investigate the dynamic stress behaviour of the materials [1, 2]. Split Hopkinson Pressure Bar (SHPB) name is a combination between John Hopkinson and his son Bertram Hopkinson [3] to investigate the stress wave propagation in iron wire and also the pressure-time curve with dynamic load exerted by detonation. Then, in 1949 the split bar was developed by Kolsky also called as incident bar and transmitted bar that investigate the dynamic stress-strain behaviour of material [1, 2].

Many researchers use SHPB experiment to study the dynamic properties of materials such as metals, concrete, ceramics, compo-sites and for soft material such as rubber [4, 5]. This is due to the needs of critical understanding in determining the dynamic stress behaviour of materials as it always exposed to impact loading [6, 7, 8]. The important parameter that can be analysed on dynamic proper-ties of materials by employing the SHPB technique is that the stress-strain curves under large strain-rate deformation (10^2 s^{-1} to 10^4 s^{-1}) [7]. The investigation of loading rate sensitivity on metal foams cellular materials has been carried out by Zheng et. al [9] under dynamic uniaxial impact using SHBP technique. It shows that the strain rate sensitivity of cellular materials is different from dense metal in which dynamic stress-strain lie on unique curve corresponding to impact velocity.

The SHPB technique also have been introduced to analyse the dynamic rock test but have limitation and issues to ensure the dynamic rock strength value are valid [10] which are the effect of friction between the sample and bars on the compressive strength of rocks, the choice of slenderness ratio of the compressive specimen, the necessity of dynamic force balance for the dynamic BD test, and the validity of using the standard BD equation in the data reduction in dynamic tests.

Even though the tests has been widely used, but there is still lack of information on how the testing set-up being calibrated [11, 12] including standardization and tolerance of SHPB testing, i.e. impact face perpendicularity, parallelism and straightness tolerances. Previous research that has been conducted use the tolerance of specimen less than 0.01 mm [13]. There is also suggestion from previous research that the straightness of the bar should be 0.05mm per 305mm length [14,20] had redesigned a new Kolsky tension bar that faced the challenges for proper instrumentation such as strain gauges and wiring on the inside bars. This new redesign Kolsky tension bar used the concept of solid striker fired to impact an end cap attached to the open end of the gun barrel to generate dynamic tensile loading.

According to Kariem et al, there are six types of misalignment of the bar which are not having a straight neutral axis, uneven support height, non-parallel impact face, bar straightness, and dome and cone impact face shapes. In order to minimize the distortion of incident and transmitted bar signal, the each bars should be well align as well as perpendicular to neutral axis with tolerance of ±0.030 [11]. The bars should have parallel impact faces as well as straightness of the bars in good tolerance as recommended by Song et. al [20] then straightened to at least 0.08 mm per 305 mm . The supports of the bars also need to be in tolerance with 0.125 mm offset of its neutral axis as well as tolerance for uneven support height with 0.55mm per 1.00mm. The strain gauge must be installed correctly and should be align to the principal axis of strain measurement. Besides the connection between strain gauge should be well prepared to avoid error due to cable resistance [20].

However, the most important step before using the Kolsky bar for dynamic testing is calibration. This step should be performed regularly especially before conducting new Kolsky bar experiment [15]. For calibration, the striker is launched on incident bar which is in contact with the transmission bar without specimen attached be-tween the incident and transmission bar with good alignment through the striker, incident and transmitted bar [15]. This is to ensure the analysis produce predictable trapezoidal profile of the incident wave with clean baseline. Figure 1 shows the example of bar signal for Kolsky bar with good alignment. The misalignment of the bars will produce distorted incident wave and fluctuating base-line pulse as shown in Figure 2.

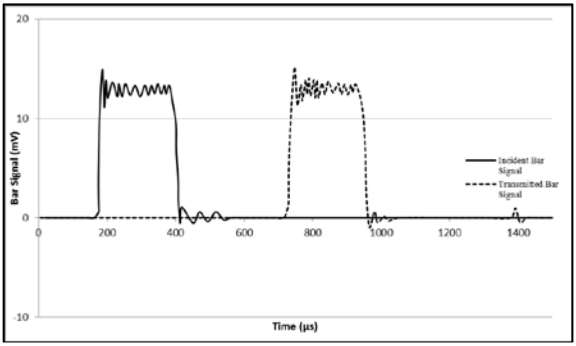

Figure 1: Good signal of SHPB [15]

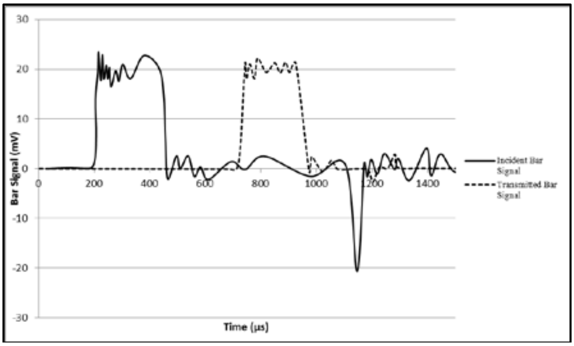

Figure 2: Distorted signal of SHPB [15]

The understanding of misalignment on Split Hopkinson Pressure Bar (SHPB) is important in order to proceed the analysis to deter-mine the dynamic stress of material using this testing. It is also first milestone to generate good result of dynamic stress using SHPB test since it is the measurement instrument subjected to dynamic loading [15]. This paper is focused on misalignment calibration of SHPB test set-up.

Methodology

Experimental Setup

Figure 3: Split Hopkinson Pressure Bar (SHPB) testing machine

Figure 3 shows the Split Hopkinson Pressure Bar (SHPB) testing machine. The calibration for Split Hopkinson Pressure Bar (SHPB) is conducted at

Strength of Material Lab at Universiti Pertahanan Nasional Malaysia (UPNM). This SHPB use bar with diameter of 20 mm. The length of each bars are tabulated as Table 1. The testing before calibration are carried out with 200 mm striker bar with velocity, Vst of = 22 m/s without specimen between incident and transmitted bar. After the bars have been well aligned using levelling gauge, the testing is conducted using 200 mm striker bar length with velocity, Vst of 22 m/s. The steps are taken to conduct five testing and the average value (mean) are plotted.

Table 1: SHPB bars length (mm)

SHPB Bars	Length (mm)
Striker bar	200
Incident bar	2500
Transmitter bar	2000
Momentum bar	1000

The mild steel bars have been used to conduct experiment for calibration and the material properties as tabulated in Table 2.

Table 2: SHPB bars material properties

Bars properties	Values
Density	7850 kg/m3
Young's modulus	200 GPa
Yield Stress	1500 MPa

Figure 4 shows the schematic diagram of SHPB test that will be used to conduct the calibration.

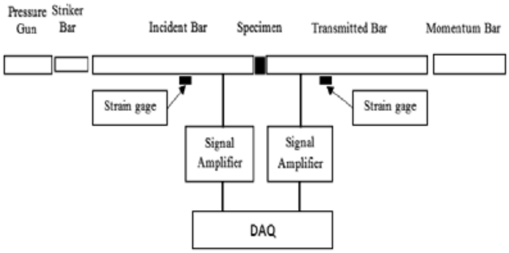

Figure 4: Schematic diagram of SHPB set-up

From Figure 4, it is important to understand function of each SHPB components that will be used for testing. Based on the literature that have been discussed, the bars need to be in a good alignment to ensure the analysis produce predictable trapezoidal profile of the incident wave with clean baseline. Figure 5 shows the levelling gauge that is used to align the bars to ensure good signal of incident and transmitted of SHPB.

Figure 5: Levelling Gauge

The incident, transmitted and momentum bar are measured at the same height using levelling to ensure the bars are well aligned to each other. Figure 6 below shows incident and transmitted bars before alignment. The height of transmitted bar is 156.78mm.

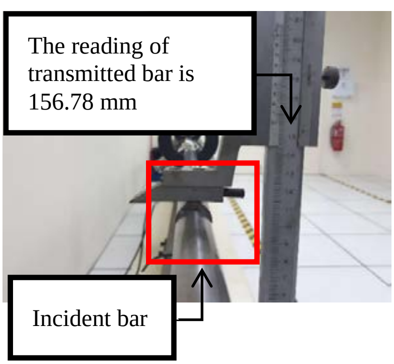

Figure 6: Incident and transmitted bars before alignment.

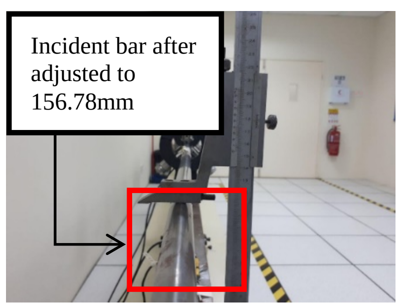

Figure 7: Incident and transmitted bars after alignment

The height of incident bar then adjusted using centre bearing bracket to align with transmitted bar at height of 156.78mm. Figure 7 shows the incident and transmitted bar after alignment. Figure 8 (a) and 8 (b) shows the before and after alignment of incident and transmitted bar from the side view.

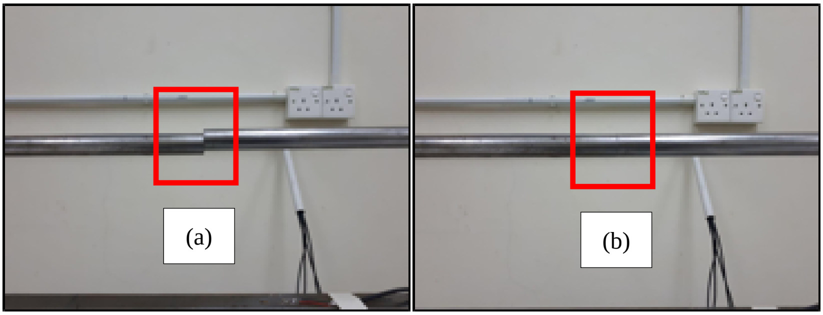

Figure 8: Incident and transmitted bars (a) before alignment (b) after alignment

Figure 9 shows the Split Hopkinson Pressure Bar (SHPB) mechanism of incident and transmitted bar. The incident bar receives an impact from sticker bar which create the incident wave. The impact from incident bar cause the transmitted bar to generate the transmitted wave as well as reflected wave in incident bar after make an impact to transmitted bar. The increasing of striker impact velocity or decreasing the specimen gauge length will increase the deformations rates of the material as stated by Slighternhorst et. al [16].

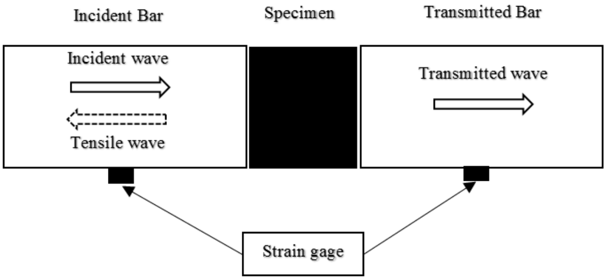

Figure 9: SHPB test mechanism

The incident, reflected and transmitted strain will be recorded as a function of time, t using strain gauges that are attached to incident and transmitted bar. The equation below shows the engineering stress that will be obtained from the strain gauges measurement [17, 18, 19].

$$\boldsymbol{\sigma_s(t)} = \frac{\boldsymbol{A_t}}{\boldsymbol{A_s}} \boldsymbol{E_t \varepsilon_t}(t) \tag{1}$$

Where;
A_t = Cross-sectional of bar

A_s = Cross-sectional of specimen

E_t = Young's modulus of the bar

ε_t = Transmitted strain

The strain rate, $\dot{\varepsilon}(t)$ of the specimen will be calculated by using the Eq. 2 and Eq. 3 below.

$$\dot{\varepsilon}(t) = -\frac{2C_0}{l_s} \varepsilon_r(\mathrm{t}) \tag{2}$$

$$C_0 = \sqrt{\frac{E}{\rho}} \tag{3}$$

Where;

$\dot{\varepsilon}$ = Strain rate of specimen

C_0 = Elastic bar wave speed in the rod

l_s = Initial gauge length of the specimen

ε_r = The reflected strain

ρ = Density of the incident/transmitted bar

Results and Discussion

Results with misalignment bars

The Figure 10 is a graph of bar signal, με of incident and transmitted against time, s that shows the results of Split Hopkinson Pressure Bar (SHPB) testing with misalignment. The first and second pulse show the incident and transmitted bar signal respectively. As shown in Figure 10, the bar signal shows good trapezoidal shape profile of incident and transmitted bar signal how-ever major fluctuation occur at the baseline for incident bar signal. This is due to the height offset misalignment between the bars before calibration as shown in Figure 6 and Figure 8 (a). The figures shows that, incident and transmitted bars are in offset position. This misalignment cause major fluctuating baseline. This is supported by previous researchers [11, 15] in which good alignment will result in good trapezoidal profile for incident and transmitted bar signal with a clean baseline.

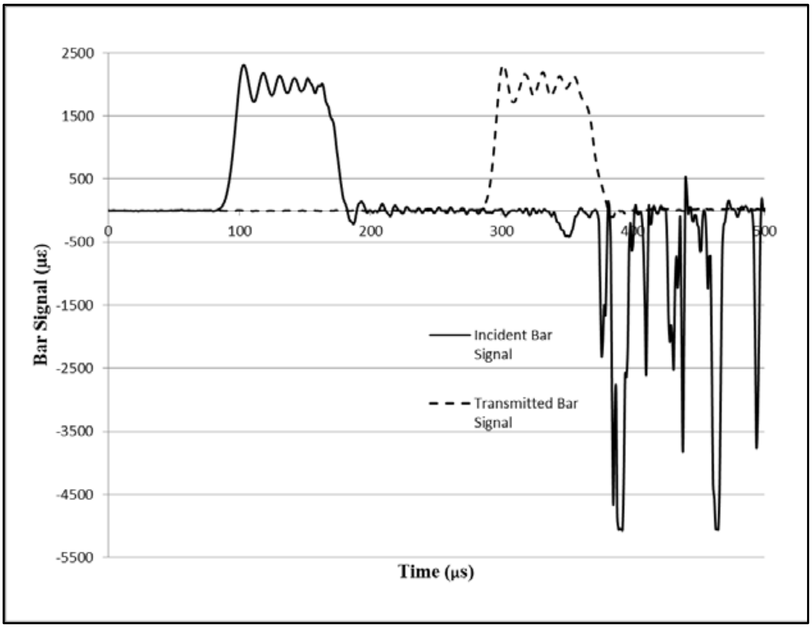

Figure 10: Results with misalignment of SHPB bars

Results without misalignment bars

The well aligned of incident and transmitted bars are shown in Figure 7 and 8 (b) respectively. From that figure, the incident bar is adjusted to a height of 156.78 mm to ensure it’s not in misalignment height offset position. Levelling gauge was used to ensure the precision measurement of height for all bar. Similar procedure is also taken to align the transmitted and momentum bars.

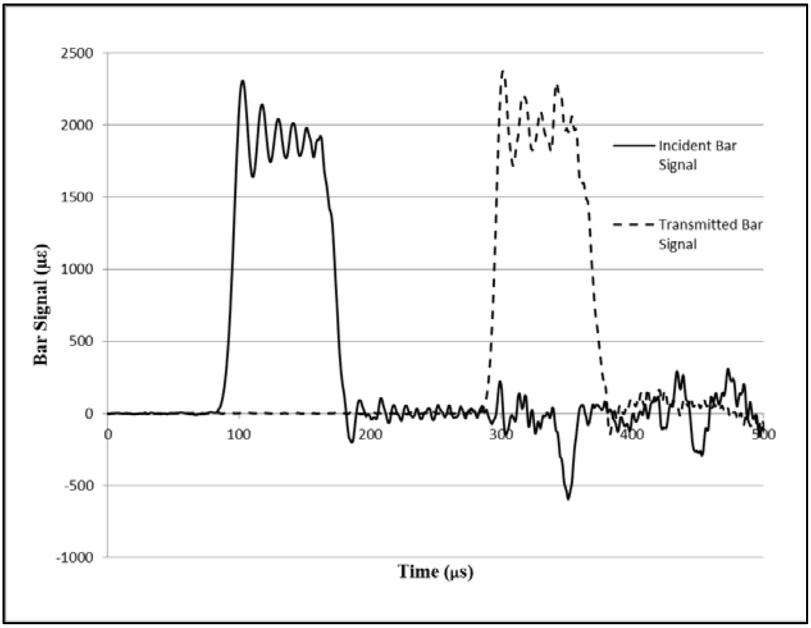

Figure 11: Results without misalignment of SHPB bars

Figure 11 shows good trapezoidal shape for both incident and transmitted bar signal with minor fluctuating baseline. The results with misalignment and without misalignment of SHPB bars are plotted as shown in Figure 12. Similar shape and baseline of incident and transmitted bar signals were achieved for both cases up until 368 μs, however major fluctuation in negative strain of incident bar called reflected strain occurred. Beyond 368μs, for with misalignment bars case the reflected strain fluctuate with peak value of -5069με while without misalignment case with reflected strain value of -572με. This is due to height offset misalignment. The magnitude of bar signal, με for both incident and transmitted are in good agreement in which produce acceptable range of peak value for both cases according to Figure 12. This is due to similar length of striker bar and impact velocity have been used during with misalignment and without misalignment testing. The results are similar up until 368μs for both cases.

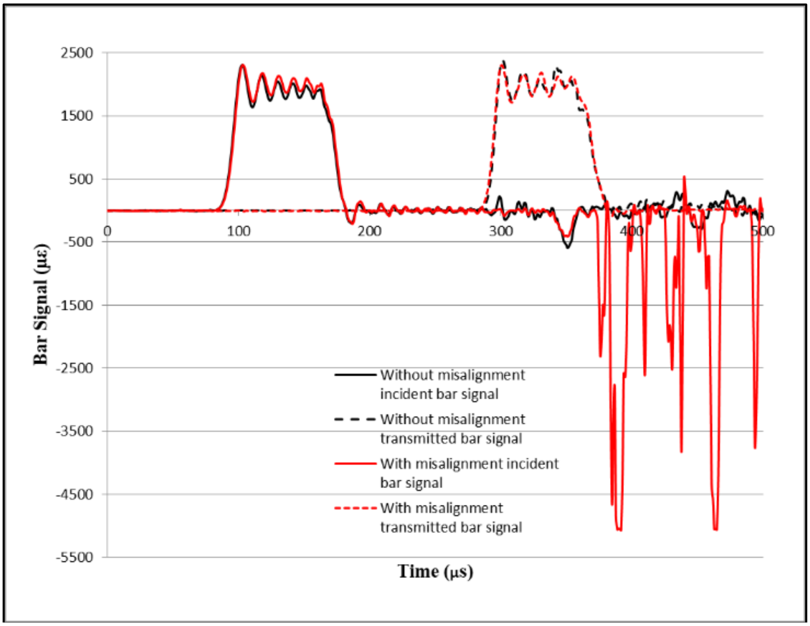

Figure 12: Results with misalignment and without misalignment of SHPB bars

Conclusion

In conclusion, this paper aims to further understanding on calibration of Split Hopkinson Pressure Bar (SHPB) test since there has been lack of information on the calibration of SHPB. The experiments before calibration and after calibration had been conducted and the results are compared. Major fluctuating baseline occurred before calibration which is due to incident and transmitted bars offset misalignment. Similar shape and baseline were achieved for both cases up until 368 μs, however major fluctuation in negative strain of incident bar called reflected strain occur due to height offset misalignment. The magnitude of bar signal, με are similar up to 368 μs for both cases due to similar impact velocity. Misalignment of SHPB bar contributes to fluctuation of the wave beyond 368 μs.

Acknowledgments

This research is sponsored by the Ministry of Education, Malaysia and Universiti Teknologi MARA (UiTM) Malaysia, under the Fundamental

Research Grant Scheme, grant no. (UiTM File. No. 600-RMI/FRGS 5/3 (102/2017).

References

[1] Xie Q, Zhu Z, and Kang G 2014 “Dynamic stress-strain behavior of frozen soil: Experiments and modeling,” *Cold Regions Science and Technology*, vol. **106–107**, pp. 153–160.

[2] Adnan ZAM, Mahmud J, Yahaya MA 2018, “Dynamic stress analysis of skin (Bovine) and synthetic skin (Silicone) under low impact loading: A review and” *International Journal of Engineering and Technology (UAE)* **7 (4)**, 180-184.

[3] Xia K and Yao W 2015, “Dynamic rock tests using split Hopkinson (Kolsky) bar system - A review,” *Journal of Rock Mechanics and Geotechnical Engineering*, vol. **7**, no. 1, pp. 27–59.

[4] Song B and Chen W 2004, “Dynamic stress equilibration in split Hopkinson pressure bar tests on soft materials,” *Experimental Mechanics*, vol. **44**, no. 3, pp. 300–312.

[5] Higuchi M, Hamaguchi Y, Suzuki S, and Adachi T 2011, “Dynamic Behavior of a Circular Tube Subjected to High Impact Loading,” *6th International Symposium on Advanced Science and Technology in Experimental Mechanic*s, pp. 3–5.

[6] Miao YG. et al 2016, “Determination of dynamic elastic modulus of polymeric materials using vertical split Hopkinson pressure bar,” *International Journal of Mechanical Sciences*, vol. **108–109**, pp. 188–196.

[7] Chen WW 2016, “Experimental Methods for Characterizing Dynamic Response of Soft Materials,” *Journal of Dynamic Behavior of Materials*, vol. **2**, no. 1, pp. 2–14.

[8] Sen O (2010), “Analysis of the Study of Material Behaviour at Impact Strain,” Michigan State University.

[9] Zheng Z, Wang C, Yu J, Reid S. R, and Harrigan J. J 2014, “Dynamic stress-strain states for metal foams using a 3D cellular model,” *Journal of the Mechanics and Physics of Solids*, vol. **72**, pp. 93–114.

[10] Dai F, Huang S, Xia K, and Tan Z 2010, “Some fundamental issues in dynamic compression and tension tests of rocks using split Hopkinson pressure bar,” *Rock Mechanics and Rock Engineering*, vol. **43**, no. 6, pp. 657–666.

[11] Kariem MA, Beynon JH, Ruang D 2012, “Misalignment effect in the split Hopkinson pressure bar technique”, *International Journal of Impact Engineering*, **47**, pp 60-70.

[12] Afdhal et. al, 2017, “ Numerical Simulation for Bar Straightness Effect in Split Hopkinson Pressure Bar”, *11th International Symposium on*

Plasticity and Impact Mechanics, Implast 2016, Procedia Engineering **173**, pp 615-622.

[13] Gray III G. Classic split Hopkinson pressure bar testing. In: Kuhn H, editor. ASM Handbook. Ohio: ASM International Materials Parks; 2003.

[14] Nolting AE, Arsenault R, Bolduc M 2011, "Increased accuracy of SHPB test apparatus to better evaluate naval steels", *Procedia Engineering*, vol 10, pp 2268–2273

[15] Chen WW and Song B, 2010, "Split Hopkinson (Kolsky) Bar: Design, Testing and Applications". *Springer Science & Business Media*.

[16] Sligtenhorst CV, Cronin DS, and Brodland GW 2006, "High strain rate compressive properties of bovine muscle tissue determined using a split Hopkinson bar apparatus," *Journal of Biomechanics*, vol. **39**, no. 10, pp. 1852–1858,

[17] Shergold OA, Fleck NA, and Radford D 2006, "The uniaxial stress versus strain response of pig skin and silicone rubber at low and high strain rates," *Int. J. Impact Eng*., vol. **32**, no. 9, pp. 1384–1402.

[18] Karimi A, Rahmati SM, and Navidbakhsh M 2015, "Mechanical characterization of the rat and mice skin tissues using histostructural and uniaxial data," *Bioengineered*, vol. **6**, no. 3, pp. 153–160.

[19] Lim J, Hong J, Chen WW, and Weerasooriya T (2011), "Mechanical response of pig skin under dynamic tensile loading," *Int. J. Impact Eng*., vol. **38**, no. 2–3, pp. 130–135.

[20] Song B, Connelly K, Korellis J, Lu W-Y, Antoun BR, (2009), "Improved Kolsky-bar design for mechanical characterization of materials at high strain rates". *Measurement Science and Technology*.