Indigenous Design and Development of Split Hopkinson Pressure Bar (SHPB) test setup for characterization of materials at high strain rates

M Bilal Nutkani¹,a, Muhammad Abid²,b, Riffat Asim Pasha³,a, Uzair Ahmed Dar,⁴,b

¹Department of Mechanical Engineering, UET, Taxila
²Department of Mechanical Engineering, COMSAT S University Islamabad, Wah Campus

Email address: a) bilalnutkani@ciitwah.edu.pk, b) drabid@ciitwah.edu.pk, c) asim.pasha@uettaxila.edu.pk

Abstract. This paper presents design and development of split Hopkinson pressure bar (SHPB) indigenously for testing of different materials at high deformation rate. SHPB is capable to measure the deformation rate 100 s⁻¹ to 2,000 s⁻¹, by maintaining the uniform and uni-axial stress in the samples. SHPB apparatus consist of the mechanical components, support structure, bars supports and the incident and transmission bars, striker bar, gas gun, piston and rod assembly. The momentum trap system is used to absorb the energy in the form of friction and heat. All components are designed, manufactured, calibrated and assembled to test the samples. Results obtained at high deformation rates are used to characterize samples of different materials by converting in the form of strain, strain rate and stress amplitude in samples.

Keywords—SHPB, High deformation rates, Stress amplitude, Stress wave speed, Impact strength, Uni-axial stress.

1. INTRODUCTION

SHPB technique is widely used to measure high deformation and the material characteristics under the impact loading [1], [2]. SHPB in general consists of torsional, tensile and compression split Hopkinson’s bar arrangements to test samples. Stress pulse in sample transferred through different mechanism i.e. with impactor which further transfer stress wave through transmission bar producing deformation in sample [3]. Result and conclusion obtained these strain pulses characterize of samples of different material are determined by converting them in strain, strain rate and stress amplitude of samples [3]. At the free surface of bars the only longitudinal wave transfers, while both the normal and shear stresses do not appear in the bar [4]. Pochhammer [5] and Chree [6] described the longitudinal wave equations and their solution in the infinite elastic bars. Zhao and Gary [7] extended these solutions for viscoelastic materials. Skalak [8] and
Folk et. al [9] studied the response of semi-infinite elastic bar under the pressure wave. Waves travels in bars with velocity \( C_0 \) as described in the equation of stress wave. When the bar length to diameter ratio is greater than 10, the stress waves considered in one direction [4]. Davies R. M determined that in one dimensional wave stress in bar at any point of cross section, the distance of longitude is same and the radial force is zero [10]. Tensile test at SHPB is relatively tricky as compared to the compression tests due tensile pulse passing through sample. By designing a specimen of tensile test same test setup of SHPB can use for the tensile. SHPB produces a pressure wave which passes through incident and transmission bars. By introducing minor changes in the compression test setup, same test apparatus is used to measure the tensile properties of specimen. Lindholm and yeakley [11] introduced a hat form test specimen to use it for tension test on same test rig of SHPB instead of compression test between incident and transmission bars. Output bar in this case is of larger diameter than the input bar with hollow inside diameter to hold the specimen. Second method of tension test introduced by Nicholas [12] in which concept used i.e. compression wave reflection as tensile wave at free end [6]. First compression wave passed without affecting the specimen however when it reflects back it load the bar as tensile Nichols [12]. This tensile wave used to characterize the sample for tensile test. Researchers have worked on the tension of input bar which leads to direct tensioning of sample. Very first method introduced by Harding et.al [13] in 1960 for direct tensile tests on SHPB setup. Harding and welsh [14] first studied the properties under tensile mechanism. However Nicholas [12] found the drawbacks in Harding method, that the rise time of striker is less which leads to imperfection of result of SHPB. And second drawback is the tensile sample is placed inside the tube. In later work of Harding and welsh [14] they eliminate the problem by strain gauging the transmission bar to measure wave. Most common method used is when hollow striker tube slides around input bar. A hollow striker hits the flange of input bar which directly produces the tensile pulse in the sample. Stress pulse is controlled by the pressure of gas which controls the velocity of striker bar. Further it helps to ensure the visibility of test specimen. This is the recent work presented on SHPB by Thakur [15], Ogawa [16], in 1984. In this arrangement there is a practical problem that the striker bar is hollow and slides over the input bar [17] so strain gauging is problem on input bar. Van Slycken et.al [8] introduced the striker bar in eccentric bar with respect to the input bar. Length of striker bar is observed as limited, as on striking it creates elastic sagging or deformation on the input bar as Gerlach et.al [18] stated in his work. A hollow U-shaped striker of maximum length is introduced by Gerlach which impact on flange of the input bar, sagging in the input bar due to long striker bar is controlled by supports under the bar in his case. Longer striker bar helps to generate greater pulse time which can use to characterize the ductile material under long pulse time test on low strain rate [18].

2. THEORITICAL

When material is rapidly loaded or distorted at some point, the energy imparted into the material by the source of distortion can be transmitted in the form of waves. A wave is a disturbance that propagates through or on the surface of a medium. These waves/stress pulse are function of both time and position, and are not transmitted instantaneously i.e. one portion of material is stressed while the other portion has not experienced this stress at given instant When force is applied on the end of the bar it travels particle to particle in the solid bar. Stress wave passes at the very high speed under force applied on the end of the bar [19].
Permanent deformation produced in material if these waves are in plastic range and overcome the yield strength of material. Stress wave velocity is dependent on the mass, density and young’s modulus of elasticity of the material (1).

\[ C_0 = \sqrt{\frac{C}{\rho}} \]  

(1)

This stress wave speed is used to measure the stress, strain and strain rate of sample as shown in (8),(9), (10).

3. SHPB EXPERIMENTAL SETUP

3.1. Design and construction of components

Design and construction of SHB was major work to test the shape memory alloys, metallic lattice and hybrid structure at high strain rate. The main parts of the SHPB apparatus consist of the striker, incident and transmission bars, gas gun, piston rod assembly and the momentum trap system. The striker bar is used to strike the incident bar. The pulse passes through the specimen and transmitted bar at high deformation rate to characterize the material while part of wave is reflected back as a e wave. SHPB schematic is shown in Figure 2.

![Figure 2. Schematic diagram of SHPB](image)

To avoid the plastic deformation in bar, the striker bar must have a good resistance against the impact. AISI 4140 material due to its good fatigue strength and the abrasion impact strength, [20] [20] was selected and was machined from the round bar. Chemical composition and physical properties of AISI 4140 is provided [21][21] in the Table 1 and Table 2 respectively.
A same velocity is required for stress wave passing through the striker, incident and transmission bars, therefore same material is used for incident and transmission bars. Incident and transmission bar was machined identically to get the same set of bars for smooth stress wave propagation. Same lengths of both the incident and transmission bars 1830 mm were used. Length to diameter ratio of incident and transmission bars was achieved 96 to ensure the one dimensional stress wave [20]. Velocity of stress wave is calculated by equation using equation (1), AISI 4140 material used with values of $E = 205 \text{GPa}$ and Density $\rho = 7850 \text{kg/m}^3$, the value of $C_0$ is 5110 m/s. Time of wave in bars and specimen is important.

$$T_{SB} = \frac{2L}{C_0}.$$  

where, $T_{SB}$ is Time for stress wave in Striker Bar, $L$ is length of bar. With $L = 0.455$ and $C_0 = 5110$, time $T_{SB} = 165 \mu s$.

$$T_{IB} = \frac{L}{C_0}.$$  

where, $T_{IB}$ is Time for stress wave of incident/transmission Bar. With $L = 1.830m$ and $C_0 = 5110$, time $T_{IB} = 358 \mu s$. Velocity of particles in input bar depends upon the velocity of striker bar and acoustic impedance of both striker $Z_S$, and $Z_B$ and input bar [19] and calculated using following equation (4).

$$V_b = V_S Z_S / Z_B + Z_S.$$  

The impedance of material calculated using the following equation (5)

$$Z = \rho A C_0 V_b.$$  

where $A$ is the area of cross-section, $\rho$ is the density of material and $C_0$ is the wave speed. The amplitude of stress wave depends upon velocity of striker in input bar and specimen obtained using equation (6).

$$\sigma_b = \rho AC_0 V_b.$$  

The gas gun is used in laboratory for experimental purpose and to accelerate a projectile for Hopkinson
pressure bar apparatus. We have used gas pressure because it is safer and we can attain good velocity of the projectile. Thickness of pressure chamber is calculated using equation (7) from ASME codes [22] as follows:

\[
tc = \frac{PR}{SJ - 0.6P}
\]

where \( S, J, P \) and \( R \) are allowable stress, joint efficiency, pressure in chamber and inside radius of chamber respectively. This gives the wall thickness of pressure chamber of 4mm but we use of 12mm wall thickness by using safety factor and ease of machining. To calculate thickness of wall following equation is used from ASME codes [22]. Thickness of end caps are 20.8mm and 25mm standard size plates was used.

3.2. Assembly of components
Gas gun is placed on I-beam in a position that the incident and transmission bars will remain in contact and concentric. The gas gun consist major components of pressure chamber, a barrel, piston and rod arrangement, valve assembly. The pressure is developed by the gas cylinder and is stored in the pressure chamber. Two rings of Teflon of diameter 38mm was press fitted on the bar, so as to have slip fit inside the barrel. Material for the rings was selected due to low friction and light weight which keep the striker bar coaxial center to strike on the incident bar. Momentum trap system is fixed at end I-beam with screws to stop the transmission bar acting a fixed end and absorb energy in form of heat. Developed components and assembly of SHPB are shown figure 3.

3.3. Sample Design Requirement For SHPB
Literature shows that design of specimen for SHPB varies upon design of Hopkinson bar apparatus used. Two basic requirements for sample are uniaxial stress and small gauge length to reduce inertial effect [23]. Sample involves the stress wave to deform the sample that’s why many limitations occur. One major work is the design and selection of geometry and clamping of sample with bars. High deformation rate in sample can obtain for circular samples in the bars. Aspect ratio of sample \( L/w \) recommended greater than 10 by different authors [24] [25] [26]. Quasi static equilibrium is basic requirement of the Split Hopkinson Bar dynamically loaded sample to achieve the proper stress and strain in the sample. Dimension of sample is important in gauge section to collect the stress, strain result distribution. Various shear test specimen also prepared as complex geometries for SHPB. Bao and Weirzbicki [27] developed butterfly shaped samples for shear tests of Aluminum alloy.

4. EXPERIMENTAL SETUP VALIDATION
One dimensional stress wave is requirement for validation of this machine to perform the tests under dynamic condition to pass stress wave equilibrium. Distance-time \( x-t \) diagram is visualization of the transmitted and reflected waves on the graph. Distance-time \( x-t \) diagram (figure 5) is developed using time of stress waves and length calculated for striker and incident bars. On vertical axis time of stress waves and horizontal axis length of bars were plotted. This \( x-t \) diagram shows incident and reflected wave passes through sample with difference of time to avoid the overlapping of compressive and tensile waves with time shift. Incident and reflected strain pulses are on upper trace while the transmitted strain pulses shown on the lower trace in \( x-t \) diagram [19]. Solid lines show the compression strain pulses while dotted line shows strain pulses which become tensile wave. By using these three times based waves measured by strain gauges we can calculate the strain rate, strain and stress for given samples. Equations (8),(9), (10) used to find the strain, strain rate and stress of sample.
where $L$, $A$, $A_S$, $\varepsilon$, and $\sigma$ are length of sample, area of bar, area of sample, strain pulse, and stress in sample respectively.

5. **CONCLUSION**

The work presented indigenous design and development of Split Hopkinson Pressure Bar for testing of specimens under high deformation rate. One dimensional equilibrium of stress wave is achieved throughout the bars and sample sandwiched between incident and transmission bars. The gas gun’s chamber make from a solid seamless cylinder for high pressure requirement for the setup. Incident transmission and striker, all three bars are machined of material selected for required setup. Teflon rings included on striker bar to get the smooth projectile motion to impact on incident bar. All components endogenously designed manufactured.

6. **Acknowledgments**

I would like to thank Prof. Dr. M. Abid for his continued support and guidance in completing this project. He is a great professor to have as an advisor and mentor throughout my education at the COMSATS University Islamabad Wah Cantt. I would like to thank the Dr. Irfan Muftay (UET Pwr) and Dr. Uzair Ahmed for their suggestions and help. I specially thanks my all colleague’s including Dr. Ali Usman, Dr. Shoaib for feedback throughout this project. And Lab assistants which help me in lab during development of parts. I acknowledge PSF for funding source of this project.
Figure 4. Lagrangian x-t diagram for Validation of SHPB bars lengths and time Calculations.

Figure 5. incident, transmitted and reflected strain pulses.
Figure 3. Indigenous Development of SHPB critical components and samples
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