COMPRESSIVE SPLIT HOPKINSON PRESSURE BAR APPARATUS: PART I - DESIGN AND DEVELOPMENT

N. K. Naik*, D. Sitpal*, Venkateswara Rao Kavala* and Addis Asmelash*

Abstract

Optimum utilization of composite materials envisages its use under static as well as dynamic loading conditions. Hence, there is a need to assess the behavior of composite materials at high strain rates. Split Hopkinson Pressure Bar (SHPB) apparatus is widely used to assess high strain rate behavior of composites. Even though SHPB apparatus is widely used, its design methodology and development technique are not readily available. Design and development details of a compressive SHPB apparatus for characterizing mechanical properties of different materials at high strain rate loading are presented. Brief theoretical background necessary for the design of SHPB apparatus is presented based on one-dimensional wave propagation theory in elastic bars. Next, brief working principle of the apparatus and schematic arrangement are presented. Different components of the compressive SHPB apparatus are identified. Design, development and commissioning of the apparatus are discussed. Further, different instruments used and the calibration technique used are presented.

***Keywords**: High strain rate, Compressive Split Hopkinson Pressure Bar, Design and development, Calibration*

Nomenclature

A	= cross-sectional area of the bar
A_B	= cross-sectional area of incident / transmitter bar
A_S	= cross-sectional area of the specimen
C_O	= wave propagation velocity in incident / transmitter bar
c_o	= wave propagation velocity in the striker bar
D	= diameter of incident / transmitter bar
d_s	= diameter of specimen
E	= Young's modulus of the material
I	= incident strain pulse
F, F_1, F_2	= force
L	= length of incident / transmitter bar
L_o	= length of striker bar
l_s	= length of specimen
R	= reflected strain pulse
S1, S2	= strain gauges
T	= transmitted strain pulse
$\mathcal{T}$	= pulse duration
t	= time elapsed after impact
v_o	= striker bar velocity
V_T	= out put voltage
$\in$	= axial strain
$\in_I$	= incident strain
$\in_R$	= reflected strain
$\in_S$	= axial strain in the specimen
$\in_T$	= transmitted strain
$\in_X$	= axial strain
$\dot{\in}_s$	= strain rate in the specimen
ρ	= density, density of incident / transmitter bar
ρ_S	= density of specimen
ρ_{sb}	= density of striker bar
λ	= wave length
μ_S	= Poisson's Ratio of the specimen
σ, σ_X	= axial stress
σ_S	= axial stress in the specimen

Introduction

Composite materials can be made to specific needs by tailoring the composition and process of manufacturing. Desirable properties such as high specific strength and high specific stiffness make it ideal for high performance applications. Over the service life, the structures undergo a variety of loading conditions. High velocity impact loading is one of the critical loading conditions. It is well

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known that the type of loading affects material properties and behavior of structural components. This further stresses the need for full characterization of the behavior of polymer matrix composites under high strain rate loading. While Izod / Charpy tests and drop weight test methods are used for the evaluation of mechanical properties at intermediate strain rates, Split Hopkinson Pressure Bar (SHPB) or Kolsky apparatus is widely used for the study of mechanical behavior at high strain rates. SHPB apparatus works on one-dimensional wave propagation theory in elastic bars.

Historically, John Hopkinson originated the concept of testing materials at dynamic loads in 1872 with stress wave experiments in iron wires [1,2], followed by the experiments by his son Bertram Hopkinson [3]. The first use of a long thin bar to measure the pulse shape induced by an impact is considered due to Bertram Hopkinson [4]. This study was presented in 1914. Though Bertram Hopkinson's observations were qualitative, he was able to correctly establish that the velocity of the impact was the most important cause of failure. An important modification was made by Kolsky in 1949 [5]. He presented the concept of split bars to determine dynamic compressive stress-strain behavior of different materials, one-dimensional pressure bar data analysis and experimental procedure. The split Hopkinson pressure bar is sometimes called the Kolsky bar.

After Kolsky [5] introduced the split bar technique for dynamic testing of specimens, SHPB has become the famous experimental technique to test the materials at high strain rate loading. These studies are summarized in Part II of this paper [6]. Typical studies on high strain rate behavior of composites under high strain rate compressive loading and test techniques are well documented in the form of review articles [7-9].

Even though SHPB apparatus is widely used, its design methodology and development technique are not readily available. The objective of this work is to present design and development details of a compressive SHPB apparatus for characterizing mechanical properties of different materials at high strain rate loading. Brief theoretical background necessary for the design of SHPB apparatus is presented based on one-dimensional wave propagation theory in elastic bars. Next, brief working principle of the apparatus and schematic arrangement are presented. Different components of the compressive SHPB apparatus are identified. Design, development and commissioning of the apparatus are discussed. Further, different instruments used and the calibration technique used are presented.

Propagation of Waves in Uniform Elastic Bars

Stress wave propagation in split Hopkinson pressure bar is shown in Fig.1 [10-14]. The stress wave propagation in split Hopkinson pressure bar is similar to longitudinal waves traveling in a uniform slender elastic bar of cross sectional area A, elastic modulus E and density ρ. The rod is subjected to an axial impact. This sets in an axial stress σ (x,t) that is propagating in the rod. In the compressive SHPB apparatus, the striker bar impacts against the incident bar. This impact generates a compressive stress pulse which travels through the incident bar until it reaches to the specimen which is sandwiched between the incident and transmitter bars [10-14]. As this incident pressure pulse reaches to the specimen, it is partially transmitted and partially reflected back. The reflection of the pulse from the interface of the bar and specimen is due to impedance mismatch between that of the bar and specimen [10-14] The impedance is defined as the product of density of the material and the wave velocity in the bar.

The design of SHPB is based on one-dimensional wave propagation in elastic bars which deals with the motion of particles in longitudinal direction. The one-dimensional system can ideally be considered to be of infinite length and negligible diameter. Since it is not possible in practice, the theory is adopted with certain approximations. The analytical relations to calculate strain rate, strain and stress as a function of time in the specimen in SHPB testing are [13-15]:

The strain rate is, $\dot{\epsilon}_S(t) = (2\,C_o/l_S)\ \epsilon_R(t)$ (1)

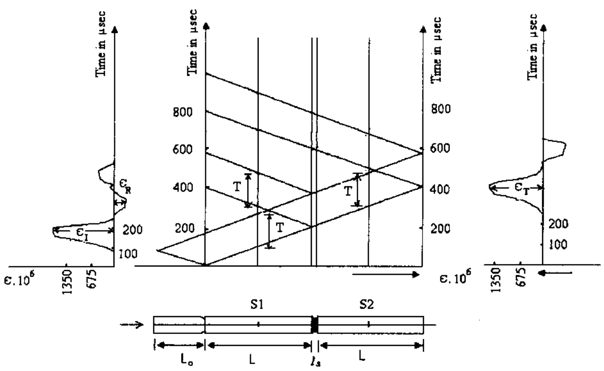

Fig.1 Stress wave propagation in Split Hopkinson Pressure Bar

The strain is, $\epsilon_S\,(t) = \pm\,(2\,C_o/l_S)\int_o^t \epsilon_R\,(t)\,dt$ (2)

The stress is, $\sigma_S\,(t) = \pm\,E\,(A_B/A_S)\,\epsilon_T\,(t)$ (3)

The ± signs are used for compression or tension, with compression being positive.

The stress / strain equations used in SHPB testing are subject to satisfying the following criteria:

- Wave propagation within the pressure bars is one-dimensional.
- The incident, transmitter and striker bars remain elastic during testing.
- Specimen undergoes uniform deformation.
- The friction effect in the compression test is negligible.

Compressive Split Hopkinson Pressure Bar Apparatus

In the range of 10 per sec to 10^4 per sec strain rates, split Hopkinson pressure bar is widely used to study the high strain rate behavior of metals, polymeric materials and composite materials. While designing and developing the SHPB apparatus, the assumptions made above need to be satisfied. Apart from satisfying the assumptions, the practical limitations also need to be considered. The salient aspects towards this are considered and discussed below. Designing of the SHPB apparatus is subdivided into following parts:

- Working out the schematic arrangement.
- Determining dimensions and materials for the striker, incident and transmitter bars.
- Mechanical design of various sub-systems.
- Determining specimen configuration and dimensions.
- Selection of instruments.

Schematic Arrangement of Compressive SHPB Apparatus

The schematic of the apparatus for compressive loading is presented in Fig. 2. The striker bar hits the end 'A' of the incident bar at a required velocity. This generates an elastic stress pulse in both the striker and incident bars. When the pulse reaches the specimen, which is placed

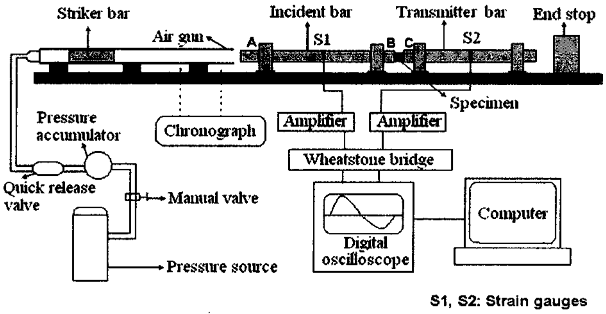

Fig.2 Schematic of compressive Split Hopkinson Pressure Bar apparatus

sandwiched between the end 'B' of the incident bar and the end 'C' of the transmitter bar, part of the pulse is reflected back and the remaining part is transmitted through the specimen to the transmitter bar. The strain gauges S1 and S2 placed at the centers of incident and transmitter bars provide time-resolved measure of the signals. The strain gauges are installed midway of the incident and transmitter bars to avoid overlapping of the reflected pulse with incident pulse. The specimen then undergoes dynamic elastic-plastic deformation. From the reflected pulse, the strain rate and the strain in the specimen are estimated, and the transmitted pulse provides a measure of the stress in the specimen.

The entire strain / deformation history within the specimen can be obtained by taking measurements along the elastic bars from strain gauges with the assistance of amplifier and oscilloscope. From these signals and using one-dimensional wave propagation theory, strain rate verses time, strain verses time, stress verses time and stress verses strain history in the specimen can be determined. The techniques used for controlling pulse duration and amplitude and strain rate are presented in Appendix-A and Appendix-B, respectively.

Structural Design

The structural design in the case of compressive SHPB apparatus mainly consists of working out the dimensions and selection of the materials for striker bar, incident bar and transmitter bar. This is based on one-dimensional wave propagation theory in elastic bars.

Length and Diameter of the Incident and Transmitter Bars

To ensure one-dimensional wave propagation, bar length-to-diameter ratio should be infinity. Considering the practical limitations, bar length-to-diameter ratio should be as large as possible. If the length of the bar is increased significantly keeping the diameter the same, the bars may bend during loading. The diameter of the bars cannot be increased beyond certain limit considering the requirement from one-dimensional wave propagation theory point of view. Further, the lateral inertia effect would be significant if the diameter of the bars is increased. Available literature suggests that the incident and transmitter bars with length-to-diameter ratio of at least 60 be used for one-dimensional wave theory to be applicable. Considering L / D ratio in the range of 60-100, the diameter of incident / transmitter bars (as well as the striker bar) is taken as 12 mm. In this case, with length of incident / transmitter bar equal to 1 m, L / D ratio works out to be 83.3. In the present case, the diameter of the incident and transmitter bars is 12 mm and the length is varied in the range of 1 to 1.4 m.

The incident and transmitter bars are positioned with the help of aluminum guide blocks with linear bearings. Since the bars are positioned within the guide blocks using the linear bearings, the bars have only linear movement during loading. Total of eight number aluminum guide blocks are used. This ensures that the unsupported length of the bar between two adjacent guide blocks is about 300 mm. This would ensure that bending of bars would not take place during loading.

Generally, the strain gauges are placed at the centers of the incident and transmitter bars. The length of the striker bar must be less than half the length of the incident / transmitter bar. This ensures that the overlap of the pulses does not take place. In the present case, the length of the striker bar is varied in the range of 0.25 to 0.43 m.

Selection of Material for the Bars

The maximum attainable stress in the specimen is limited by the yield strength of the bars. Before choosing the incident and transmitter bar material, careful consideration should be given to the desired specimen stress levels. The incident and transmitter bars used should have the required hardness and yield strength.

The yield strength of the material of the bars should be as high as possible to allow for high strain rate testing. The material for the bars is SUS440C martensite stainless steel with Young's modulus of 203 GPa and density of 7667 kg/m^3. This would generate the wave velocity, $C_o = (E/\rho)^{1/2}$ of the order of 5145 m/sec. The material of the striker, incident and transmitter bars has to be the same. It is however permitted to use different material for the striker bar since the striker bar is only to impact and set in a pulse.

Specimen Geometry

While deriving the stress-strain equations, it was assumed that the specimen undergoes uniform deformation. When the wave enters the specimen, particles deform both along axial and radial directions. Generally, cylindrical specimens are used in compressive SHPB testing. Davies and Hunter [16] showed that $l_S / d_S = 0.5 (3 \mu_S)^{1/2}$ to minimize the radial inertia effect of the specimen. This provides the lower limit for l_S / d_S ratio. With longer specimens, buckling may take place during loading. Generally, l_S / d_S *ratio* is taken in the range of 0.5 - 2.0 [17]. The diameter of the specimen is kept less than the diameter of the incident and transmitter bars to allow the impact on full cross-section of the specimen and also to permit the specimen to expand along radial direction after the compressive load is applied.

In all the experiments, cylindrical specimens with l_S / d_S ratio of 0.75 were used. The diameter of the specimen used was 8 mm. This ensures the impact on full cross-section of the specimen and also permits the specimen to expand along radial direction within the cross-sectional area of the bars after the compressive load is applied.

Reduction of Friction Effect

The interfaces between the bars and specimen are lubricated to minimize radial constraint and buckling. By lubricating the interfaces between the specimen and the incident and transmitter bars, uniform deformation condition is obtained early in the test than without lubrication. Specimen diameter is smaller than the incident / transmitter bar diameter. This is required because the sample expands along radial direction during loading. It is important to align the centerlines of the sample and incident and transmitter bars to load the transmitter bar uniformly. By lubricating the ends with a thin layer of petroleum jelly, the frictional effects can be minimized. The application of the lubricant is important as this acts as a medium for transfer of energy of the elastic stress pulse. Any discontinuity would cause loss of energy.

Pulse Shaper Technique

To increase the rise time, smoothen the pulse and to modify the shape of the pulse, a pulse shaper was used.

Three different materials, namely copper, brass and aluminum were used for making the pulse shapers. The diameter of pulse shaper is 12.5 mm whereas the thickness was varied in the range of 0.5 to 3 mm.

Data Acquisition and Instrumentation

During SHPB testing, the induced stresses and strains in the incident and transmitter bars are constant throughout the cross-section. From the measurement point of view, this is extremely important since surface measurements on the incident and transmitter bars fully describe the instantaneous elastic strains in the bars. Since the elastic stress wave is of dynamic nature associated with a shorter rise time, the transducer properties such as frequency response and rise time become a primary concern. To identify appropriate transducer specifications, the dynamics of the pressure wave must be closely examined.

The Electrical Resistance Strain Gauge

The most common type of strain transducer is the electrical resistance strain gauge. These are extremely versatile due to their small size and ease of installation. For the purposes of SHPB measurements, a single element strain gauge can be used. When the gauge deforms, an electrical output is produced that is directly proportional to the strain across the length of the element of the gauge. The strain gauges should be of high frequency fatigue resistant type. The total length of the pulse must be much greater than the gauge length of the strain gauge. The output of the strain gauge tends to give an integrated average of the strains generated over the gauge length.

The strain gauges procured from M/s Tokyo Sokki Kenkyujo Co. Ltd., Tokyo are temperature compensated, foil type FLA-6-11 with a gauge length of 6 mm, 120 Ω nominal resistances and gauge factor of 2.11. These strain gauges are capable of measuring μ strains. These are supplied with sufficiently long wires. Another type of strain gauges is procured from M/s Vishay Measurements Group. These are EA-06-062AP-120 type with a gauge length of 3.2 mm, 120 Ω nominal resistance and gauge factor of 2.035.

Wheatstone Bridge

Two strain gauges are mounted diametrically opposite on each of the incident and transmitter bar at the center of the bars. Each set of strain gauges is connected together with the dummy strain gauges in a Wheatstone bridge, which is sensitive only to the longitudinal strain components and cancels any possible bending effects. The use of the active strain gauges in half-bridge configuration doubles the sensitivity of the Wheatstone bridge and eliminates non-linearity effects involved in the use of one active strain gauge. By using opposite half bridge, the strains due to bending can be nullified. This arrangement of opposite half bridge is used for incident and transmitter bars in the compressive SHPB apparatus commissioned.

Strain Amplifier

The Wheatstone bridge is connected to the strain amplifier. The amplifier is required for conditioning and amplifying low level signals received from strain gauges. The amplifier has active filters dual polarity, two step double shunt calibration. It is possible to use it for full, half or quarter bridge configurations. Dynamic Strain Meters of type DC-96A manufactured by M/s Tokyo Sokki Kenkyujo Co. Ltd., Tokyo have frequency of 200 KHz. Signal Conditioning Amplifiers of type 2311 manufactured by M/s Vishay Measurements Group have frequency of 125 KHz. These strain amplifiers are used for strain measurement on incident and transmitter bars. Filter is provided to bypass undesired range of frequencies. The output of the strain amplifiers is given to the oscilloscope.

Oscilloscope

The strain measured is recorded directly by feeding output of the two amplifiers into a digital oscilloscope. TDS 1002 dual trace oscilloscope manufactured by M/s Tektronix, Inc. is used. This has two channels and a bandwidth of 60 MHz with monochrome display. The oscilloscope has selectable analog bandwidth of 20 MHz. It has General Purpose Interface Bus (GPIB) port and other modules to give output in desired form. The oscilloscope gives supply to X-Y plotter or any storage device like computer. The vertical axis of the oscilloscope has bandwidth of 6 MHz with 1X probe. With 1000 X probe it can be up to 100 MHz. The horizontal scale can take up to 109 samples per second. The time scale for horizontal axis can be set up to 2.5 nano seconds per division. The trigger can be set for a particular channel which acts for both the channels. The oscilloscope has facility to acquire single sequence for a particular trigger level. The wave and its numerical data can be transferred to a computer with GPIB IE 4888 bus bar. Alternatively, software by Wavestar or TekVisa could be used to transfer the wave and the data with the help of communication module. These software are used to transfer the wave as well as the data. The oscilloscope generates 2500 data points for the range of its measurements of wave.

Computer

The computer should be fast enough with sufficient RAM and storage space. Computer with Pentium IV 3.2 GHz Processor, 1.98 GHz RAM and 200 GB hard disc space with Windows XP operating platform is installed for the apparatus commissioned.

General Outline of the SHPB Apparatus

The SHPB apparatus developed for compressive loading has basic infrastructure in the form of support stand, guide blocks, pressure accumulator, pressure valves, quick release valve, barrel and propelling mechanism along with striker, incident and transmitter bars and the instruments.

Propelling Mechanism

The propelling mechanism consists of high pressure source, pressure accumulator, pressure valves, quick release valve and barrel. The striker bar is located within the barrel. The barrel inside diameter is generally more than the diameter of the striker bar. To guide the movement of the striker bar within the barrel, teflon coating or teflon cylindrical cover guide is provided on to the striker bar. This facilitates smooth movement of the striker bar within the barrel. The propelling velocity of the striker bar is controlled by varying the pressure exerted on to the striker bar.

Air Gun

Air gun is the assembly of high pressure source, pressure accumulator, pressure valves, quick release valve and barrel with striker bar. High pressure compressor or high pressure cylinder is used as a high pressure source. In the present apparatus, a high pressure cylinder with designed pressure of 300 kg/cm^2 is used to avoid maintenance related job associated with the compressors. High pressure cylinder is kept away from the SHPB apparatus for safety purpose.

A pressure accumulator is installed on the working platform of the support stand and connected to the high pressure cylinder. It is capable of holding the same pressure as that of the high pressure cylinder. The purpose of pressure accumulator is to hold the required pressure during experimentation. Further, it helps in avoiding handling of high pressure cylinders frequently. The barrel of length 1500 mm is attached to the pressure accumulator through a system of valves and quick release valve. The barrel length provided is sufficient to ensure longitudinal movement of the striker bar. The barrel can be adjusted in vertical and horizontal directions to ensure proper impact of the striker bar on to the incident bar.

Quick Release Valve

A quick release valve is used to ensure release of the air pressure instantaneously. By using a quick release valve between the pressure accumulator and the barrel, the striker bar can be accelerated instantaneously producing high force / energy impact of the striker bar on to the incident bar. A special quick release valve is used in this propelling mechanism. It is operated using a pneumatic cylinder with a operating pressure in the range of 5-7 kg/cm^2. A separate cylinder of 100 kg/cm^2 capacity is used for providing the required operating pressure.

Chronograph

The measurement of velocity of the striker bar is carried out using a chronograph. In the apparatus commissioned the chronograph of "Chrony" make is used. The instantaneous displays of the velocity is provided by the chronograph.

Support Stand

A support stand made of mild steel is used for positioning and locating different components of the compressive SHPB apparatus such as propelling mechanism, pressure accumulator, mechanism to operate the quick release valve, chronograph, aluminum guide blocks different valves and connectors and end stop. The components are clamped to the support stand using C-clamps. This helps to move the components as and when required. The height of the support stand is 0.8 m. The overall dimensions of the compressive SHPB apparatus are: length = 5 m, working height = 1m and width = 0.9 m. The photograph of the compressive SHPB apparatus is given in Fig. 3.

Calibration of Compressive SHPB Apparatus

For commissioning and assessing the accuracy of the SHPB apparatus, calibration was carried out first. During calibration, the incident and transmitter bars were wrung together without a specimen sandwiched between them. Lubrication was applied between the bars to minimize

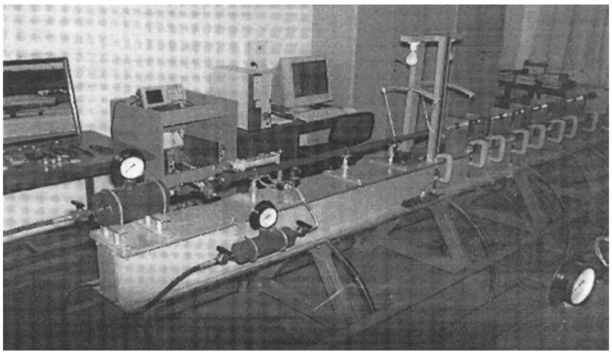

Fig.3 Photograph of compressive SHPB apparatus

friction. With this the incident and transmitter bars can be treated as a single bar. Strain gauge signals on the oscilloscope during calibration are presented in Fig. 4a. Channel 1 indicates the output of the strain gauge mounted on the incident bar whereas Channel 2 indicates the output of the strain gauge mounted on the transmitter bar. Here, I is the incident pulse with pulse duration equal to a_1 a_2 whereas T is the transmitted pulse with pulse duration equal to b_1 b_2. During calibration, reflected pulse (R) is not present. The amplitude and duration of incident and transmitted pulses are nearly the same.

Force verses time plots are obtained from the strain gauge signals and are presented in Fig. 4b. The force history obtained based on the strain gauge mounted on the incident bar is indicated by F_1 whereas the force history obtained based on the strain gauge mounted on the transmitter bar is indicated as F_2. Force F_1 is based on I+R whereas force F_2 is based on T. It may be noted that the force history obtained F_1 and F_2 match very well. This indicates that the stress states within the incident bar and transmitter bar are exactly the same. This ensures that the SHPB apparatus is perfectly aligned and friction free. The apparatus is ready for further investigations.

The pulse obtained is trapezoidal in shape. An idealized pulse would be rectangular as shown in Fig. 5. The average strain absolute magnitude $|\in|$ and pulse duration T are shown in Fig.5. These values can be calculated from the wave propagation in the incident and striker bars [12]. Immediately after the impact of the striker bar at velocity v_o compressive pulse propagates away from the impact point in both the striker and incident bars. In the regions adjacent to the point of impact, the average particle velocity is $v_o/2$ and the strain magnitude is given by,

$$\in = v_o / 2c_o \tag{4}$$

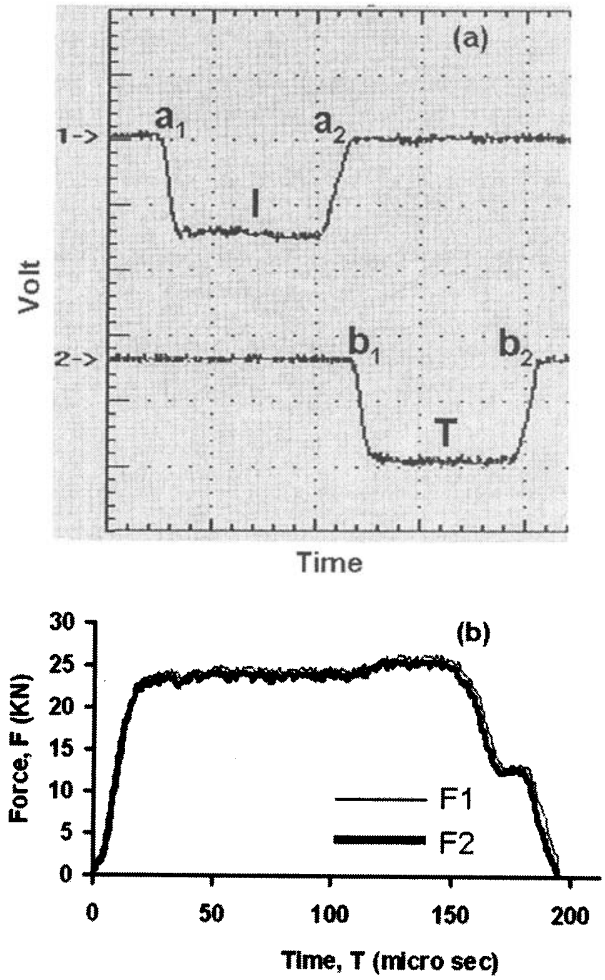

Fig.4 Compressive SHPB test results obtained during calibration : (a) strain gauge signals on oscilloscope, (b) comparison of force versus time behaviour, derived from strain gauge signals

The pulse duration is given by,

$$T = 2L_o / c_o \tag{5}$$

The wave oscillations noticed on the upper portion of the schematic (Fig. 5) are due to radial dispersion and are called Pochhammer-Chree oscillations. These oscillations do not appear if the bar is continuous and are not an assembly of two bars [12].

The details regarding data processing (Appendix-A), controlling pulse duration and shape during SHPB testing (Appendix-B) and controlling strain rate during SHPB testing (Appendix-C) are presented later.

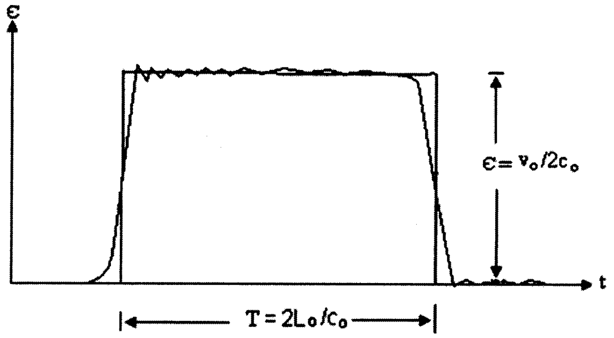

Fig.5 Schematic of pressure pulse in incident bar

Safety Aspects

As the air pressure used is high, necessary safety measures are incorporated in the system. Firstly, the pressure accumulator hoses and high pressure valves are tested at 2 times the design pressure. The pressure accumulator is made as per standards to withstand designated pressure. It has two go - no go type of manually operated high pressure valves, called isolation valves, one upstream and another downstream of the accumulator. One pressure release valve is installed to allow the release the pressure of the system to atmosphere. The Nitrogen cylinder has a two stage regulator assembly. This can be set for required pressure output of 7 kg/cm^2. The C-clamps used are heavy duty ones since these have to withstand the force generated during propelling the striker bar and when it hits the incident bar. The support stand which is used as working platform is made of single length to give sturdiness.

Correction for Lateral Inertia

The effects of lateral inertia in impact experiments are investigated by Dharan and Hauser [18]. Considering possible lateral inertia effect, the axial stress in the specimen is calculated as,

$$\sigma(t) = \sigma_X(t) - (3\,\rho_{sb}/8)$$

$$\left[(d_S/2\,l_S)^2 \times v_o^2 / \{1 - \epsilon_X(t)^3\} \right] \qquad (6)$$

Here, σ_X (t) and ϵ_X (t) are axial stress and strain, respectively obtained by the experiment.

Closure

Split Hopkinson Pressure Bar apparatus is the most widely used facility for the determination of mechanical properties at high strain rates. The design and development of a typical apparatus for compressive loading is presented. Commissioning and calibration details are also presented. Experimental studies are carried out on this apparatus for the characterization of compressive behavior of typical composites. The results are presented in Part II of this paper [6].

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Appendix-A

Data Processing

During high strain rate testing, the strain gauge output is obtained in terms of time verses voltage plot. The voltage has to be converted into the corresponding strain. For dynamic strain meter DC 96A used, the procedure is as follows:

The sensitivity for dynamic strain measurement can be set from the relation

$$\text{Sensitivity} = \text{Expected } \mu \text{ strain} \times \text{gauge factor} / 2 \tag{A.1}$$

Accordingly, the rated output (RO) is set by selecting the value from 1 to 10.

Example : Assume the expected strain is 1000 μ strain and the gauge factor of the strain gauge is 2.11. The sensitivity is set on 1055 with RO of 1. This results in 1000 μ strain corresponding to rated output of 1 V. If the output voltage recorded from the strain gauge mounted on incident bar is 2 V, the corresponding incident strain is 2000 μ strain.

For the above setting, transmitted strain ($\in_T$) is calculated from strain gauge output voltage as follows:

$$\in_T = (1000) \times V_T \ \mu \text{ strain} \tag{A.2}$$

where V_T is out put voltage from strain gauge placed on the transmitter bar in volts.

Similarly, the reflected strain ($\in_R$) is calculated from the strain gauge output voltage placed on the incident bar.

Note: Care has to be taken in identifying the connections used. For example, if opposite half bridge is used, the output voltage is the sum of the voltages obtained from the two strain gauges placed at that particular position. Hence only half the voltage as obtained from opposite half bridge connection has to be considered for the calculation.

Appendix-B

Controlling Pulse Duration and Shape During SHPB Testing

The pulse duration is directly proportional to the length of the striker bar. It is the time required for the pulse to travel twice the length of the striker bar.

The duration of the pulse, $T = 2L_o / c_o$ (B.1)

where T is pulse duration, L_o is the length of the striker bar and c_o is elastic wave velocity in the striker bar. During controlling the pulse duration, precaution has to be taken on the maximum limit of the length of the striker bar. Generally, the strain gauges are placed at the centers of the incident and transmitter bars. The length of the striker bar must be less than half the length of the incident / transmitter bar. This ensures that overlap of the pulses does not take place.

To increase the rise time, smoothen the pulse and to modify the pulse shape, a pulse shaper with different dimensions is used. In this study, copper, brass and aluminum were used for making the pulse shapers. The diameter of the pulse shaper was marginally more than the diameter of the incident and transmitter bars whereas the thickness was varied in the range of 0.5 to 3 mm.

Appendix-C

Controlling Strain Rate During SHPB Testing

The strain rate in the specimen is obtained using Eq. (1) as given below:

$$\dot{\epsilon}_S(t) = (2C_o/l_s)\ \epsilon_R(t)$$

The strain rate depends up on elastic wave velocity in the bars, length of the specimen and reflected wave pulse.

Generally, the configuration of SHPB and the materials for different components, especially for incident and transmitter bars, are worked out based on the range of applications visualized. On a specific SHPB apparatus, in order to achieve higher strain rates, either larger amplitude input pulses or shorter specimens can be used. The amplitude of input pulses is limited by the yield strength of the incident bar or by the amount of force that can be generated by the particular experimental apparatus. The length of the specimen is limited by L/D ratio suggested for SHPB testing.

The possibility of controlling strain rate by varying the gauge length of the specimen is marginal. The best way to control the strain rate is by governing the amount of force applied on the incident bar. As it can be seen form Eq. (1), the strain rate is directly proportional to the amplitude of the reflected strain pulse. It may be noted that the reflected strain pulse is related to the amplitude of the incident strain pulse, which in turn, is related to the amount of force applied on the incident bar. By varying the force applied on the incident bar, the amplitude of the reflected strain pulse, and hence, the strain rate on the specimen can be controlled. The force exerted by the striker bar is controlled by varying the velocity of the strike bar. Caution has to be taken during testing at lower strain rates. At lower strain rates the specimen needs more time to reach to higher strains. Higher strains can be obtained by increasing the duration of the pulse. The procedure for controlling the duration of the pulse during testing is given Appendix-B.