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The Design, Construction and Testing of Unique Operated Hopkinson Split Pressure Bar System

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Abstract

This study involves the design and construction of a split Hopkinson pressure bar apparatus as well as an investigation of the effects of high speed impact on two types of composite materials. A unique spring operated striker mechanism is designed and tested, thus introducing a major simplification to SHPB design requirements. Impact testing velocities of up to 25m/s are achieved.

Samples results of impact tests on unidirectional glass fiber and unidirectional carbon epoxy are presented with a comparison between them. The effects of strain rate on specimen properties (compressive stress and strain) are determined. A strain rate range of 107-252 /s is achieved using impact speed range of 3.39-9.98 m/s for the unidirectional glass fiber composite. The corresponding ranges for the unidirectional carbon composites were 485-951/s strain rate and 6.68-13.28 m/s impact velocity.

The results indicated that the max stress and strain are all increased with increasing the strain rate for both types. The carbon/epoxy showed higher properties compared with the glass/epoxy. The carbon samples sustained higher range of strain rate resulting in higher stresses and strains.

Keywords: Hopkinson bar, high strain rate, design & manufacture

تصميم، بناء وفحص لمنظومة جهاز عمود هوبكنسن المجزأ

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الخلاصة

تتضمن الدراسة تصميم وبناء جهاز العمود المجزأ لهوبكنسن بالإضافة الى دراسة تأثير الصدمة بسرعات عالية على نوعين من المواد المركبة. تصميم المنظومة تضمن تصميم فريد لآلية الصدم باستخدام منظومة نابض والتي وفرت تبسيط كبير لمتطلبات هذا الجزء من العمود المجزأ. تم عملياً الحصول على سرعات صدم لحد 25 م/ثا في هذا الجهاز.

تم تقديم النتائج لتجارب صدم لعينات احادية الاتجاه من الالياف الزجاجية والألياف الكربونية المركبة مع مقارنة نتائج المجموعتين. تم دراسة تأثير معدل الانفعال على مواصفات المواد والتي تشمل المقاومة و الانفعال.تم الحصول على مدى معدلات انفعال مقدارها 252-107 /ثا باستخدام مدى سرعات صدم 3,39 - 9,98 م/ثا للألياف الزجاجية الاحادية الاتجاه. اما للمواد الكربونية الاحادية الاتجاه فقد كان المدى 951-485 /ثا لمعدل الانفعال و 6,68 - 28, 13 م/ثا للسرعات.

اظهرت النتائج ان القيم القصوى للمقاومة والانفعال ازدادت بزيادة معدل الانفعال لكلا النوعين من الالياف وعند مقارنة نتائج النوعين اظهر الكربون قيم اعلى للمقاومة، الانفعال و معدل الانفعال.

Nomenclature

Symbol	Description	Units
c	Elastic wave velocity of the pressure bars	m/s
C_s	Spring index	
D_o	Outer diameter of the spring	mm
d_w	Wire diameter of the spring	mm
E	Elastic modulus of the pressure bars	GPa
f	Stress factor of the spring	
F_s	Spring force	N
G	Shear modulus of the spring	GPa
k_g	Gage factor	
k_s	Spring stiffness	N/m
L	Specimen length	mm
m	Mass of the striker bar	kg
n_s	Number of turns of the spring	
R	Resistance of the strain gage	ohm
t	Time of the test	μsec
V	Velocity of the striker bar	m/s
V_{max}	Max Velocity of the striker bar	m/s
δ	Displacement of the spring	mm
δ_{max}	Max displacement of the spring	mm
ε_s	Specimen strain	μs
$\dot{\varepsilon}$	Strain rate of the test	1/s
ε_I	Strain in the incident bar	μs
ε_{max}	Max strain in the pressure bars	μs
ε_R	Strain in the transmitted bar	μs
ε_T	Strain reflected to the incident bar	μs
σ_{AVG}	Average specimen stress	MPa
τ	Shear stress of the spring	MPa

1. Introduction

One of the experimental techniques that are defined as impact experiments are impacts occur at velocities sufficiently large to cause inelastic deformations. A number of experimental techniques have therefore been developed to measure the properties of materials at high strain-rates. The Hopkinson pressure bar is one of these techniques which is widely used to test materials at high strain rate range of (10^2- 10^4 /s).

In 1914, Bertram Hopkinson [1] introduced a method to measure the pressure produced in the detonation of high explosives or by the impact of bullets. A compressive stress wave was created in a cylindrical steel bar by impacting one end of the bar. At the other end of the bar a short cylindrical steel rod was attached. A compressive wave travels through the bar into the sample causing the test sample to impact with a ballistic pendulum. Hopkinson was unsuccessful in generating reliable experimental pressure versus time relationships because of the unavailability of reliable methods of data collection, storage and reduction.

A solution for the bar frequency equation of Pochhammer and Love was achieved by Bancroft in 1941[2]. This involved different methods of determining wave velocities in the pressure bars compared to the original equipment by Hopkinson. In 1948, Davies [3] added electrical condensers to Hopkinson bar to measure the strain. Kolsky [4] in 1949 added a second pressure bar at the end of the sample. Equations for calculating specimen strain, stress and strain rate were developed. The use of strain gages were produced by Hauser [5] in 1961 which improved the repeatability of the data and also increased the accuracy.

Recently many investigators improved the Hopkinson bar experiment by using new techniques such as using high speed computer data acquisition systems and digital storage, [6,7]. Other researchers [8, 9, 10] worked on improving the pulse dispersion by using a pulse shaper. Others [11] added a momentum trap on the incident bar. This was followed by the addition of inserts to release the indentation between the pressure bars and the specimen [7]. These techniques are added to make it possible for many researchers to make advance experiments on various materials.

The aim of this study is to design and construct a simplified split Hopkinson pressure bar apparatus using strain gages. The striking mass for this SHPB apparatus is to be energized by a unique spring type mechanism which eliminates the need of high pressure gases and expensive servo valves.

2. Design and Manufacturing of the Split Hopkinson Pressure Bar

2.1 Design Criteria

The split Hopkinson pressure bar is designed for dynamic compression testing of various materials at high strain rates. It consists of a shooting gun, incident, transmitted and striker bars as well as the necessary signals measuring system.

A study of the different design parameters reported in the literature provided important guide lines for the present SHPB apparatus. In addition, the limitation of available materials and equipments in the local market imposed some limitation on alternative designs. Based on the above, the following design criteria were employed in this work:

2.1.1 The Pressure Bars

The material and dimensions of the pressure bars are selected and designed according to the one dimensional elastic wave theory[1]. To achieve elastic wave, the bars must be made from a high strength material. The present study uses pressure bars made from 304L stainless steel having high values of yield strength in order to withstand a high impact velocity. To achieve very high strain rates requires reduction in the bars' cross sectional area, and consequentially diameter. Choosing an appropriate length for the bars requires that two conditions be met:

- Length-to-diameter ratio meets requirements for one-dimensional propagation theory
- Length of bar is at least twice that of the compressive pulse generated during impact.

Most texts suggest that the bar have a length-to-diameter ratio of at least ten [8, 12, 13, 14]. The length of the pressure bar affects how much strain a specimen may see, since strain is related to the total pulse duration, which is directly related to the length of the pressure bar. In this work the L/D ratio is chosen to be 60.

2.1.2 The Striker Bar

The striker bar must have strength not less than that for the pressure bars. According to available materials in the local market, the same 304L stainless steel is decided upon for this part.

According to the literature, the length of the striker bar must be less than half that of the pressure bars .This is to ensure that the overlap of the pulses does not take place during testing.

2.1.3 The Striker Shooting Mechanism

All reported SHPB design uses one form or another of pressurized gas guns to propel the striker bar. These systems involve utilizing advance solenoid valves with high precession and very fast response. In addition, measuring striker velocity involves utilizing advanced electronic systems.

To avoid the above requirements and to lower the cost of the apparatus considerably, a simple and unique design is decided upon. This involved the use of a spring operated shooting gun. The striker bar is to be accelerated by the energy stored in a compression spring. The design criteria involved choosing a maximum impact velocity of 25 m/s. The second parameter is the mass of the striker bar. These two parameters are applied in the following energy balance equation:

$$\frac{1}{2}F_s\delta = \frac{1}{2}mV^2 \qquad \text{……………………. (1)}$$

$$F_s = \delta k_s \qquad \text{……………………. (2)}$$

By a process of try and error and according to available helical springs in the local market, different values of the displacement were assumed and employed in equation (1) to design different springs. This process involved designing of striker bars to suit available springs. The final design of this striker bar is shown in the following section. Finally, a suitable spring was chosen with dimensions and properties shown in **Table (1).** The maximum force, maximum displacement and maximum velocity for this spring can be obtained as follows:

Table .(1) The Dimensions and Properties of the spring

Outer diameter(D_o)	wire diameter (d_w)	No. of turns (n_s)	Space	Free length	Modulus of rigidity (G)
29 mm	4 mm	60	5 mm	540 mm	70 Gpa

$$C_s = \frac{D_o}{d_w} - 1 \qquad \text{……………………. (3)}$$

$$C_s = \frac{29}{4} - 1 = 6.25$$

$$k_s = \frac{G\,d_w}{8\,{C_s}^3 n_s} \qquad \text{……………………. (4)}$$

$$k_s = \frac{70*10^3*4}{8\,(6.25)^3*60} = 2.389 \text{ KN/m}$$

$$F_s = \frac{8\tau C_s f}{\pi {d_w}^2} \qquad \text{……………………. (5)}$$

$$F_s = \frac{8*830*6.25*1.25}{\pi*(4)^2} = 667.5 \text{ N}$$

Where:

τ : Shear stress from figure (1a)

f : Stress factor from figure (1b)

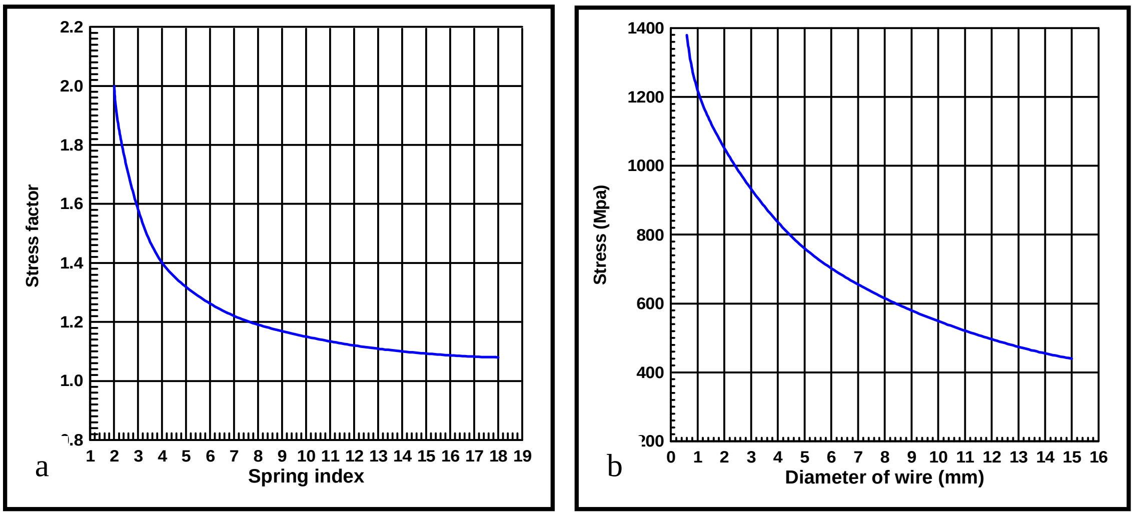

Fig .(1) a) Torsional Elastic Limit for Helical Spring
b) Stress Factor for Helical Spring [15]

The maximum displacement is:

$$\delta_{Max} = \frac{677.5}{2.389 * 10^3} = 280mm$$

Now from equation (1) the maximum striker velocity is:

$$\frac{1}{2}(677.5 * 0.28) = \frac{1}{2} * 0.3 * V^2$$

$$V_{Max} = 25\, m/s$$

3. Manufacturing of the Split Hopkinson Pressure Bar

The split Hopkinson pressure bar is designed and built as shown in **Figure (2).** A brief description of each of the apparatus members is given below according to their assigned numbers.

3.1 The Incident Bar

Solid rod made from 304 L stainless steel with 1103 Mpa yield stress, 1276 Mpa ultimate stress [16], 193 GPa young modulus, 8000 Kg/m³density,19 mm diameter and 1500 mm length .

3.2 The Transmitted Bar

Similar to the incident bar with the same dimensions and specifications.

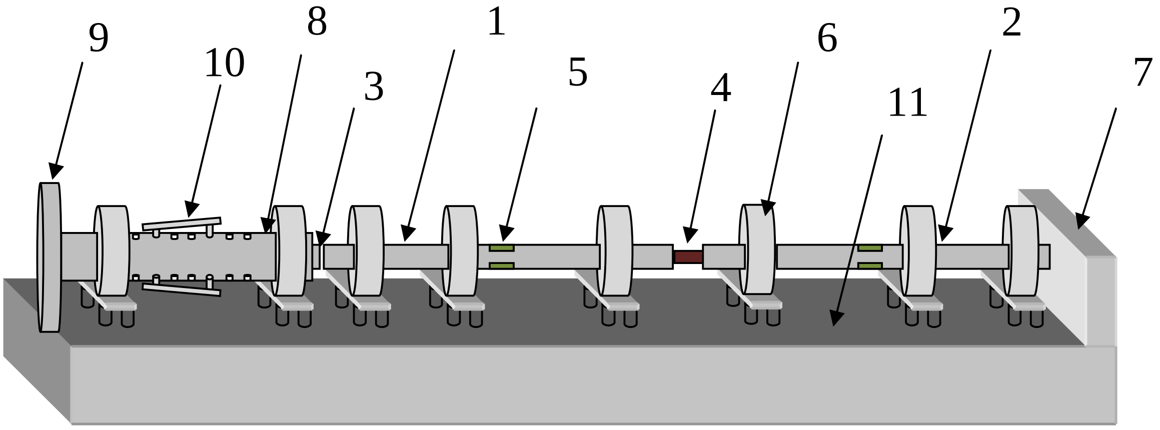

Fig .(2) Schematic of the Split Hopkinson Pressure Bar

3.3 The Striker Bar

It is a rod with different circular cross sectional areas made from the same material as the pressure bars.

3.4 The Specimen

Composite specimen of 6mm in length and 8mm*8mm in area

3.5 Strain Gages

Four single foil element strain gages (R=120 ohm ,grid length=11 mm and k_g=2.12) are mounted on the upper and lower faces mid way of each pressure bar. The strain gages are connected to a Wheatstone bridge which in turn is connected to a high bandwidth oscilloscope (DS1000E) which displays the stress wave propagation during the test.

3.6 Supports

These supports are used to fix the Hopkinson bars on to a rigid beam. These supports are manufactured by cutting a solid Teflon tube to form eight discs each with a diameter of 70mm and a thickness of 35 mm. Each disc is inserted into a steel ring forming a cover. This provided more stiffness for the teflon disk.

3.7 Momentum Mass

A large steel mass of 11*11*30 cm dimensions is used to stop the transmitted bar. A plate of Teflon is fixed in front of this mass to absorb the energy of the transmitted bar.

3.8 Shooting Gun

This is designed to provide a striker speed range of (1.78 -25 m/s). It consists of hallow steel tube of 770mm length and 32mm inside diameter. Small holes of 7mm diameters are drilled with 2 cm space between them in the top and bottom face of the steel tube. Inside this tube there is a compression spring made from steel used to propel the striker bar. A v- screw with 16 mm outer diameter and 2 mm pitch is used to compress the spring. The clearance between the steel tube and the spring is lubricated with grease to minimize friction and thus provide a smooth motion of the striker bar.

3.9 The Screw Driver

The screw driver consists of a circular steel wheel with a stiffening steel cross and a nut welded at its center. By turning the wheel, the screw is fed in the nut causing the nut to retreat and thus the spring is pulled until it reach the desired length.

3.10 Striker’s Clamper

Two small rods located in the lower and upper face of the steel tube. Each had small pin which is used to clamp the striker bar through the steel tube holes. These two rods clamping action is controlled by a small spring.

3.11 The Rigid Beam

The flange of a 75mm I section beam of 4.5 m length is used as a rigid base of the split Hopkinson bar.

4. The Mechanism of the Shooting Gun

In most reported experiments, the diameter of the striker is equal to the pressure bars diameter since the diameter of the selected spring is greater than the diameter of the pressure bars. The striker bar is designed to have the shape to suit the spring and the pressure bars diameters. A threaded hole is drilled in the back end of the striker bar to fit with the thread of the screw and thus allow the screw to drag the striker and the spring. This is achieved when a torque is manually applied to the screw driver as shown in **Figure (3-A).**

After clamping the striker bar as shown in **Figure (3-B),** the screw is unbolted which free the striker to be ready for projection as shown in **Figure (3-C).** By releasing the pins, the striker bar accelerates and impacts the incident bar as shown in **Figure (3-D).**

After the impact caused by the striker bar, an elastic compressive wave of constant amplitude and a finite duration is generated in the input pressure bar. When the compressive loading pulse in the incident pressure bar reaches the specimen, some part of the pulse gets reflected from the specimen-input bar interface, while some part is transmitted to the transmitted bar as shown in **Figure(4).** The magnitudes of these reflected and transmitted pulses will decide the properties of the specimen.

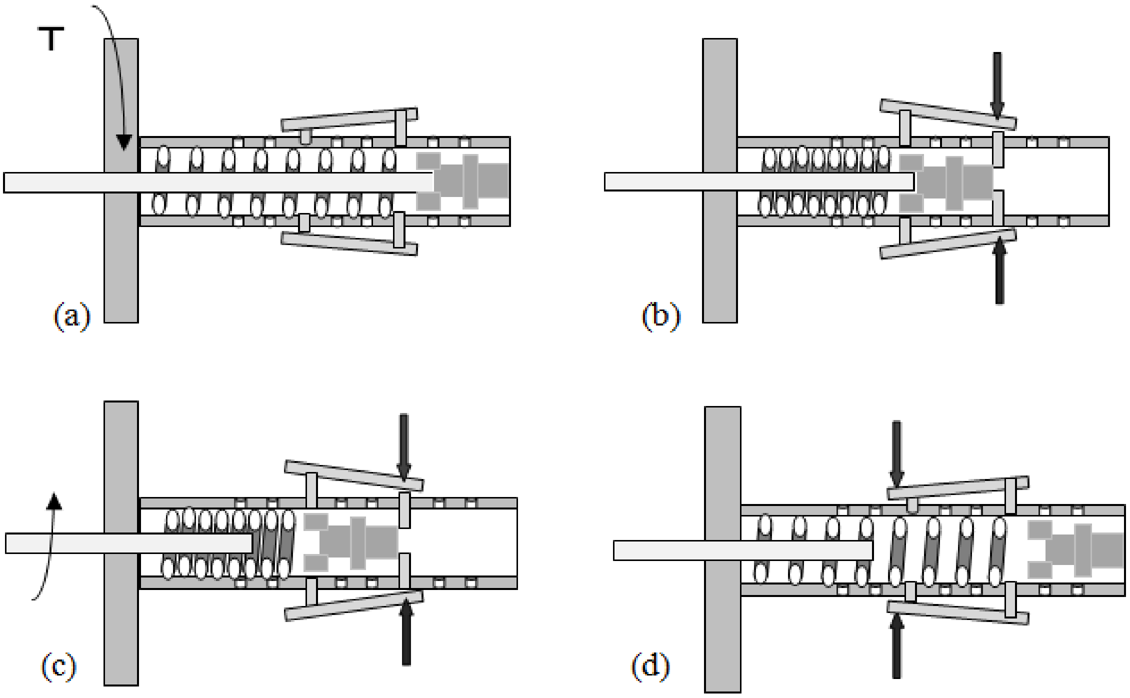

Fig .(3) a) Applying Torque to the Screw Driver drive, b) Clamping the Striker Bar, c) Unbolt the Screw, d) Release the Pins and accelerate the Striker

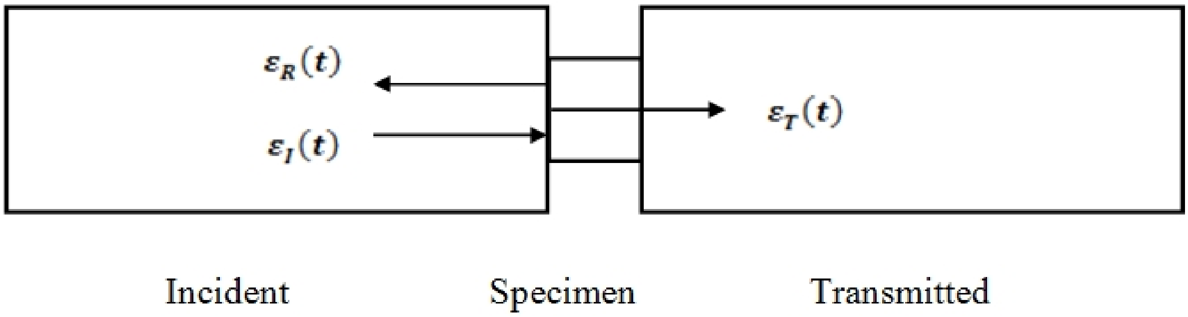

Fig (4): The Hopkinson Pressure Bars

The analytical relations to calculate stress, strain rate and strain as a function of time in the specimen are [8, 12, 17]:

$$\sigma_{AVG}(t) = \frac{A_b}{A_S}\,\varepsilon_T(t)E \qquad \text{……………………. (6)}$$

$$\dot{\varepsilon} = \frac{-2c}{L}\,\varepsilon_R(t) \qquad \text{……………………. (7)}$$

$$\varepsilon_s(t) = \frac{-2c}{L}\int \varepsilon_R(t)\,dt \qquad \text{……………………. (8)}$$

The most important experimental factor influencing the nature of wave propagation is bar alignment. By carefully aligning the striker bar with the incident bar such that the two remain in the same plane, a one-dimensional wave-front can be attained experimentally.

5. Calibration of the SHPB

The theoretical values of the impact velocity obtained from equation (1) neglect the losses due to friction, so a devise of type (Bushnell Velocity Digital Speed Gun) was used to measure the actual values of the impact velocity for each spring position hole in the shooting gun(for each spring displacement).

Figure (5) shows the relation between the spring displacement and the actual and theoretical velocities. It is clear that the relative small difference between the actual and theoretical values increased with increasing the impact velocity. This is due to the increase in friction with increasing velocities.

A dynamic test was carried out for assessing the accuracy of the SHPB setting by impacting the two pressure bars without a specimen making them to act as a single bar. Lubrication was applied on the impact surfaces to minimize friction between them .Strain gage signals on the oscilloscope during calibration are presented in **Figure (6).**

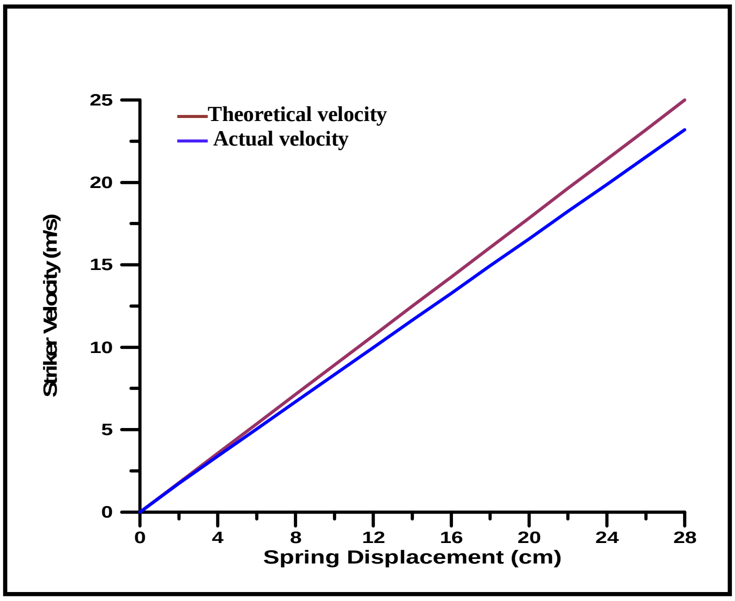

Fig .(5) Calibration of the Impact Velocity

The upper trace indicates the recorded signal from the first two strain gages on the incident bar while the lower trace represents the signal recorded by the second two strain gages on the transmitted bar. It is clear that there is no reflected pulse returning to the incident bar which means that the two bars are straight and their alignment is correct.

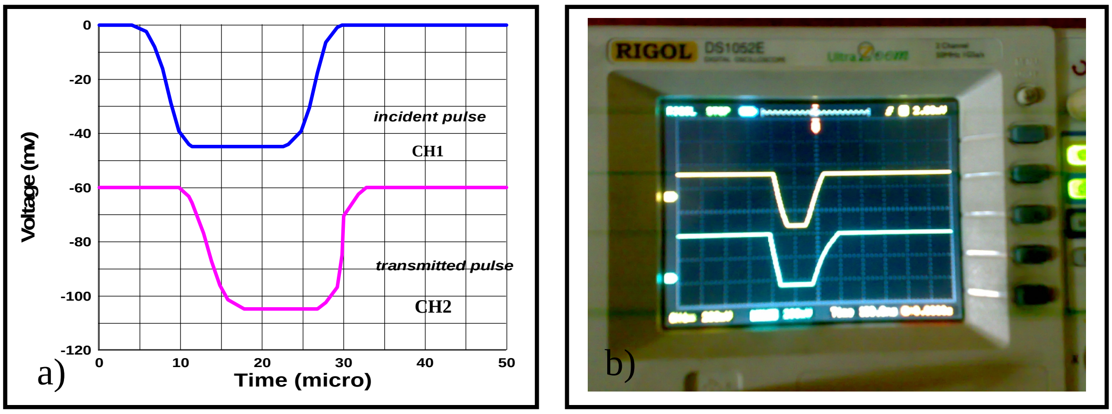

Fig .(6) a) Schematic of the Calibration Pulse
b) Oscilloscope Image of the Calibration Pulse

A linear dynamic calibration curve was obtained by repeating this process at different impact velocities. Simple momentum considerations and wave theory [18] dictate that the maximum strain(ε_{max}) in the pressure bars can be calculated as:

$$\varepsilon_{max} = \frac{V}{2c} \qquad \text{……………………..} \quad (9)$$

Figure (7) shows the calibration relation between the signal voltage and the maximum strain.

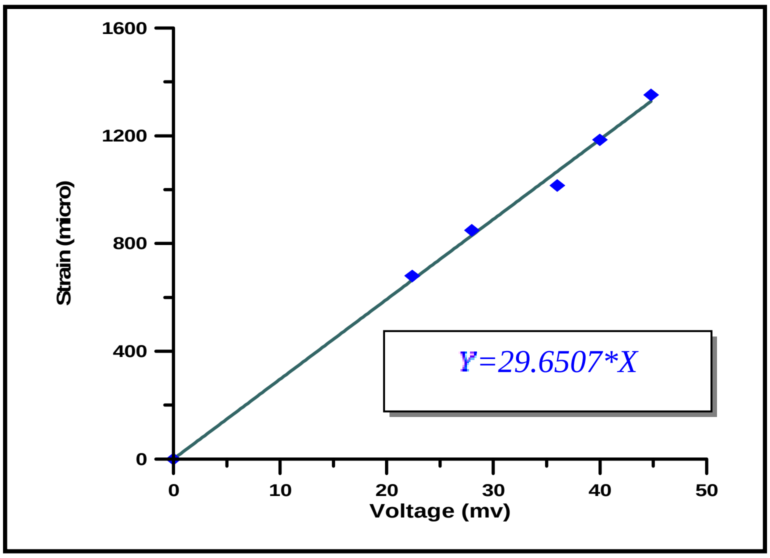

Fig .(7) the dynamic calibration curve

6. Selection of the Specimen materials and Dimensions

Two types of unidirectional composites are prepared for testing glass/epoxy and carbon/epoxy composite materials. Specimen dimension design is one of the most important considerations in SHPB testing. The lateral inertia and body forces were assumed to be negligible according to the elastic wave theory. In order to minimize the effects of the longitudinal and lateral inertia and wave dispersion within the specimen, the overall specimen dimensions are required to be small. Previous work in SHPB suggested that the L/d ratios of 0.5-2.0 are suitable for cylindrical as well as square and rectangular specimen tests under compression loading [8, 19]. Also the specimens' size must be smaller than the incident and transmitted rods diameters. A square specimen of 8*8 mm cross section area was chosen in this work for the two types of tested materials with L/d (length/thickness) ratio of 0.75.

7. Experimental Tests

A typical oscilloscope record for a glass/epoxy specimen under testing obtained from SHPB experiments is shown in **Figure (8).**

Waves for the incident and the transmitter bar can be observed in this figure. The transmitted wave records the stress history in the specimen. The first pulse, denoted by A, in the incident bar is the incident pulse; whereas the second pulse (B) is the reflected pulse. If the mechanical impendence of the specimen is less than that of the bar, the two pulses are opposite in sign, as shown in this figure. The transmitted pulse (C) is higher than the incident pulse (A). It can be noted that the magnitude of the reflected pulse is low compared to the transmitted pulse with duration equal to approximately half that of the transmitted pulse.

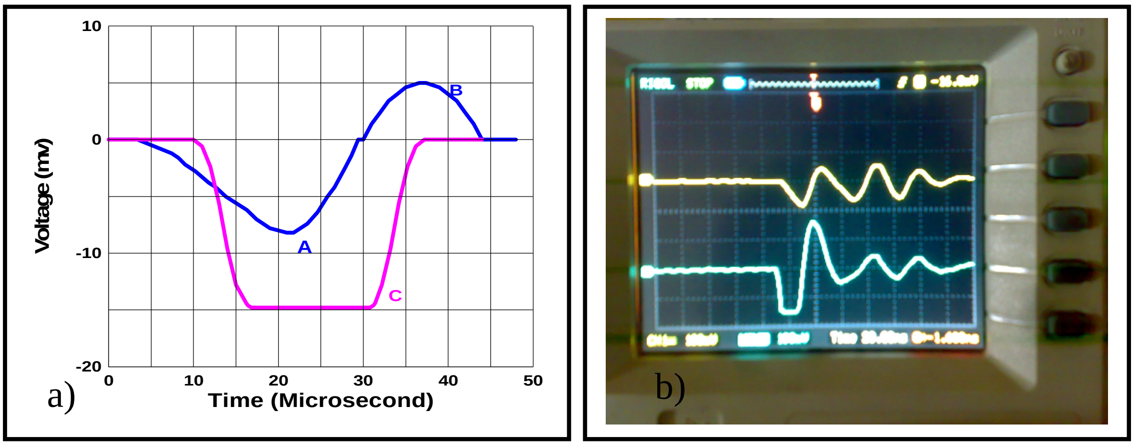

Fig .(8) a) Typical Oscilloscope record,
b) Oscilloscope Image for glass/epoxy specimen

(A) has lower magnitude than the two other waves. Also the duration of the transmitted pulse (C) is equal to approximately twice that of the reflected pulse (B) with higher amplitude.

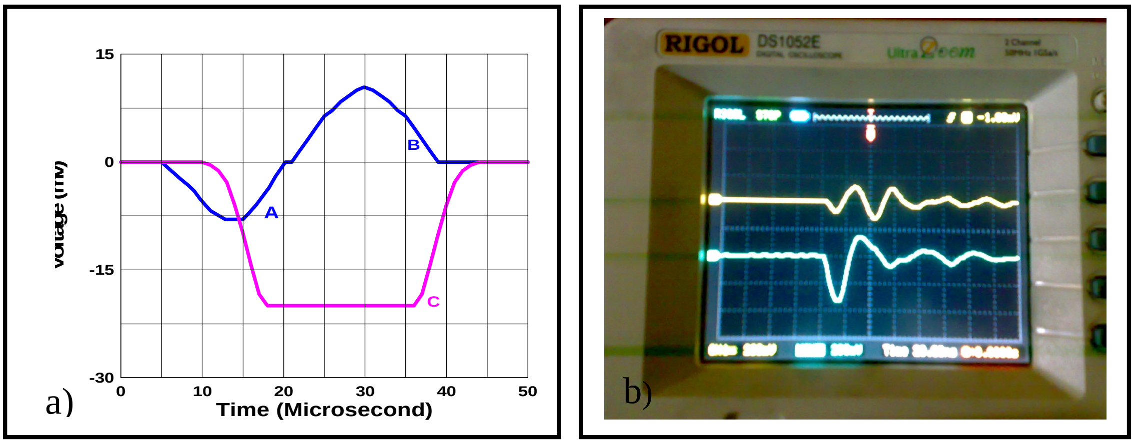

Fig .(9) a) Typical Oscilloscope record,
b) Oscilloscope Image for carbon/epoxy specimen

This figure shows relatively higher magnitude of reflected pulse (which gives instantaneous specimen strain rate and strain) at much higher value of transmitted pulse (which gives specimen stress). Also it shows higher pulse duration in comparison with glass/epoxy specimen, which fails at relatively much lower strain.

8. Results and Discussions

A sample of the testing results obtained in this work is presented in this section. The stress strain curves for unidirectional glass-epoxy and carbon/epoxy composite specimens are selected. Each material was tested at five impact velocities (five strain rates) up to failure. Each test is repeated at least three times to obtain average stress-strain curves. The stress strain curves for glass/epoxy specimens tested at strain rate rang of 107- 252 /s are presented in **Figure (10a).**

It can be seen from this figure that the material showed a viscoplastic behavior. The stress increased gradually at low strain reaching a maximum value and then is held constant with increasing strain. For specimens tested at 3.39 to 6.68 m/s (107-213/s), the curves show similar trends with different stress amplitudes and failure did not accurse. On the other hand, at impact velocity of 8.34 m/s (243/s), the specimen reaches maximum stress of 375 Mpa and failure begun with small cracks in the matrix parallel to the fiber direction through all layers with delamination. At impact velocity of 9.98 m/s (252/s), the specimen smashed with maximum strain of 2643.56 μs and maximum stress of 182.5 Mpa which is lower than those for specimens tested at lower strain rates.

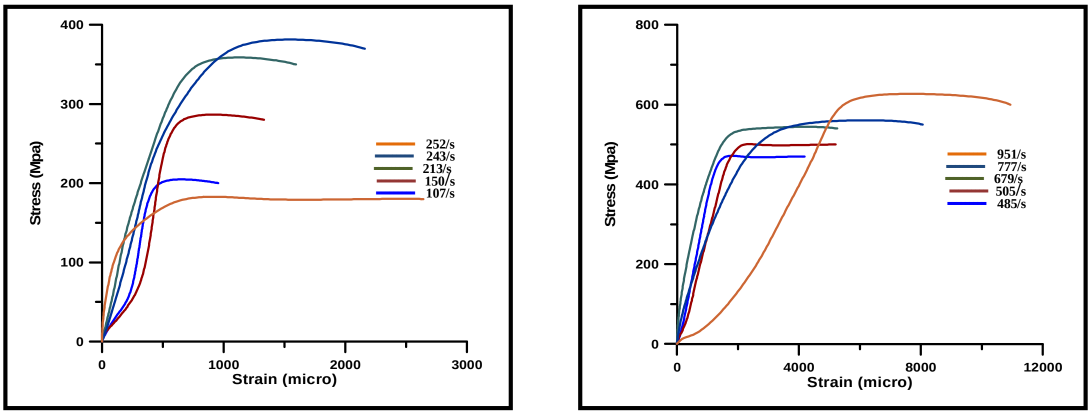

Fig .(10) Stress-Strain curves for Unidirectional Specimens
a) Glass/epoxy, b) Carbon/epoxy

The stress strain curves for Carbon/epoxy specimens tested at a strain rate range of 485- 951 /s are presented in **Figure (10b).** Carbon/epoxy specimen failed at impact velocity of 13.2 m/s (951.5/s) with maximum stress and strain of 608.4 Mpa and 10938 µs respectively. In comparison with the unidirectional fiber class, the carbon sustains larger stresses and strains and fails at higher velocities. The behavior of the unidirectional composite of both fiber types is found to be similar. Each type showed a viscoplastic behavior and their properties are found to be strain rate sensitive. The carbon fiber failed at higher velocities and exhibited higher properties. Since these types were tested at different strain rate ranges so, their properties can be compared only with respect to their impact velocity as shown in **Figure (11).**

As can be seen from these figures, the carbon fiber exhibited higher strain rates, stresses and strains through the same impact velocity range.

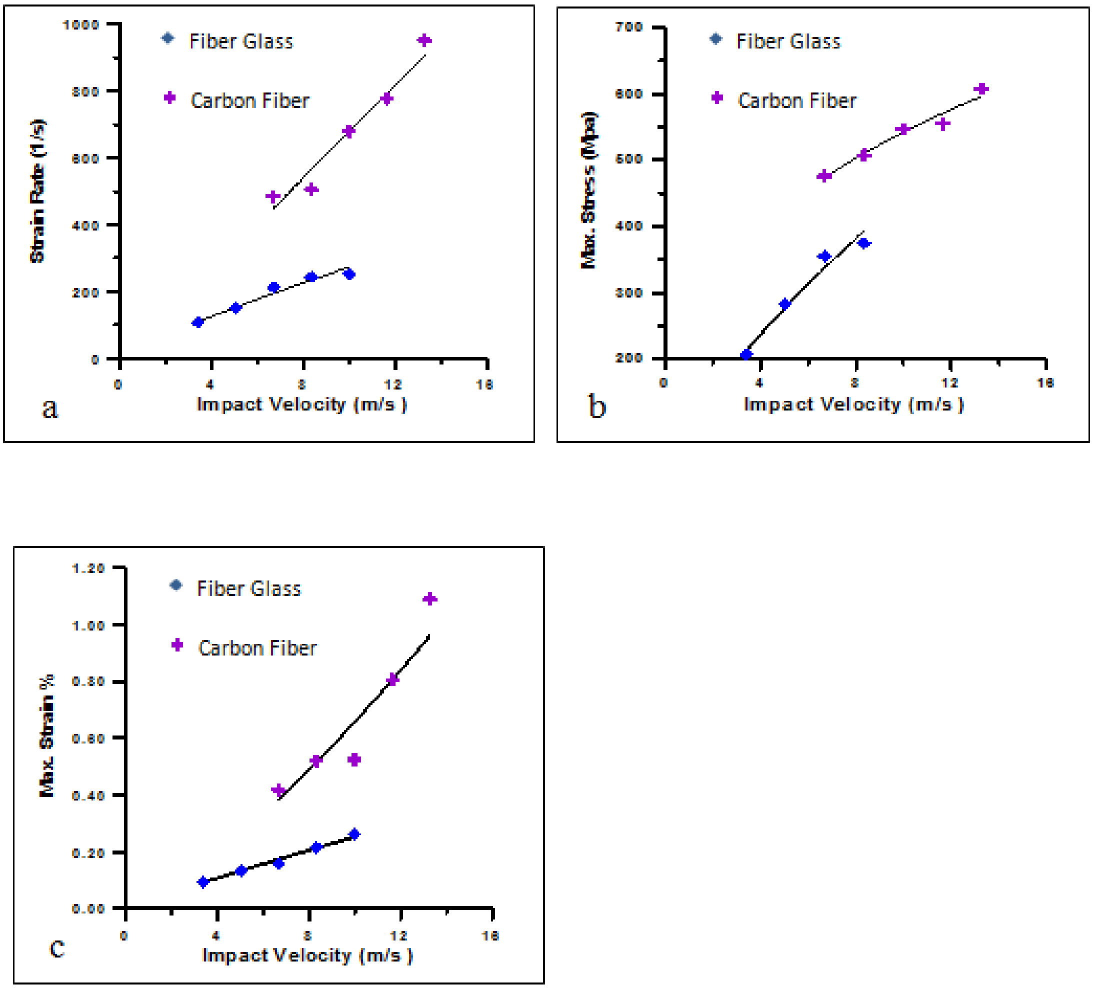

Fig (11): a) Strain rate, b) Max. Stress, c) Max. Strain, vs. impact velocity for the unidirectional composite specimens

9. Conclusions

From the experimental results and their analyses for both glass/epoxy and carbon/epoxy laminated composite under compression loading using split Hopkinson pressure bar technique, the following conclusions can be made:

- The chosen dimensions for the striker, incident and transmitter bars as well as the samples dimensions proved to be well suited for the design application. The unique design of the spring operated shooting striker gun proved to be successful as it provided the required impact speed range. The accuracy of the striker speed setting through the control of the spring displacement was proven through repeated recalibration throughout the testing period. Also the relatively simple instrumentation used in the present work proved to be more than sufficient in obtaining the required results. In comparison with SHPB reported different designs and instrumentation requirements, the present apparatus enjoyed the following advantages:

1. The need for complicated hydraulic or pressure devices are eliminated as well as the need for complicated specific valves.
2. Complicated signal measuring and conditioning electronics are replaced by a simple Wheatstone bridge and an oscilloscope.
3. Very low cost.
4. Ease of use, calibration and performance checking.

- The results for both the unidirectional E-glass/epoxy and carbon/epoxy laminated composite are found to be highly strain rate sensitive. The maximum compressive stress and maximum strain increased significantly with increasing the strain rate.
- The carbon/epoxy showed higher properties compared with the glass/epoxy. The carbon samples sustained higher range of strain rate resulting in higher stresses and strains.

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