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DESIGN OF A TEST DEVICE FOR SUBJECTING MATERIALS TO HIGH STRAIN RATES. WITH APPLICATION IN NUCLEAR AREA

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ABSTRACT

This paper presents a design of a device to gather characteristic data of materials subjected to high strain rates, this device named after the eminent English engineer Sir Bertram Hopkinson "Split Hopkinson Pressure Bar", from here will be designated SHPB. More specifically, this work is inseparably linked to the development of packing for transportation of highly radioactive substances as a part to the general scope of a CAPES project in partnership with the CCTM Materials Department of IPEN, Institute of Energy and Nuclear Research, linked to the University of São Paulo. The development of the device is part of a scope, and collection of data necessary for the design and construction of this packing. The SHPB device can be divided into two parts, the first part concerning the mechanical design. The second, data collection that is indeed the challenging part of the device, and proper tests. The present paper, specifically, will only deals with the mechanical design of the device, importantly, divided into two parts, the size of the bars, which are the impact bar, the input bar, and the output bar, and the size of the impact device. The sizing of the bars involve knowledge of the concept of elastic waves in solid media for the length of the bars to serve as a wave-guide, which will cause a deformation of the specimen, and enables recording of these waves for data analysis. The impact device must be robust enough to produce the stress wave to deform the specimen, but not to plastically deform the bars, which have to continue throughout the test within the elastic range.

1. INTRODUCTION

Testing materials subject to high strain rates is very important to engineering because the values of quasi-static laboratory tests do not reflect materials behavior when subject to sudden impact situations, like occurring in automobile frontal impact, explosion and ballistics, where rates of load application reach values of the order of 10^4 s^{-1}. To obtain constitutive materials values at these high strain rates researchers started in the beginning of twentieth century to develop a new way of getting data.

Since the beginning with Sir Bertram Hopkinson, 1914 [1], this device has evolved a great deal. After Hopkinson's pioneering, researchers like Davies, 1948 [2], Kolsky, 1949 [3], Krafft, 1954 [4], Lindholm, 1964 [5], brought it until the configuration it is known nowadays. Today there is SHPB to test everything, all kinds of loadings including tension, torsion, and

fracture tests, all sorts of materials as well. Data collection has received all technology available at the present, it has been easier obtain the curves of strain versus time, one of the problems encountered by the pioneers. Technical works about mechanically dimensioning the device are scarce. The methodology applied here is similar to that adopted by Lang, 2012 [6], the overall structure is essentially the same.
The state of the art about SHPB designing is scarse, just few works found in the technical literature describe how to design this device. So begin to list the analysis of the corrections made by researchers today to the effects of inertia, and friction. According Bertholf and Karnes in 1974 [9], inertia and friction between the specimen and the elastic bars to different length-diameter relations affect specimen response. Inertial Effects affect the propagation of waves radially and axially, and may result in an oscillating stress-strain curve. If the specimen ends are well lubricated, and great care is taken to correct the inertia effects, so you can get a realistic stress-strain curve. According to this work the important assumptions for successful execution of the test are:

1. The specimen is on an one-dimensional stress state.
2- Both strain, and the deformation has to be uniform throughout the specimen.

These assumptions can be violated by the effects of radial and axial inertia, and friction between the specimen and the elastic bars. Already Kolsky (1949-1963)[3] stressed the importance of the specimen to be thin, to correct the effects of inertia. Then there is here already in the seventies a certainty that with a proper length-diameter ratio would be possible to eliminate both the inertia effect, and the friction.

Since then, an enormous amount of work has been undertaken to improve the accuracy with which the test can be performed so that the above assumptions are not violated, thus making the data collected as realistic as possible. One effect that is corrected today is the effect of Pochammer-Chree vibrations in the trapezoidal wave using the so-called pulse shaper to a detailed analysis read Benassi 2005 [10].

Nowadays almost all material types have been tested, the material for each type of a different configuration SHPB device proves more appropriate, so that it is impossible to build a single device that is suitable for all desired tests. Each material requires a great setting, with particularities that require a device on which they could be held for each test what is feasible. The main specifications to design the SHPB device are full characterization of the dimensions of the specimens to be states, already defined that type of material will be made. As soon as the desired range of strain rates.

It is worth mentioning, and that is of utmost importance, which are not available here any of this data, so the design had to be done with an alternative analysis that was able to address the lack of these specifications.

Benassi 2005 [10], puts second Subhash [11] the validity of modeling implies the observation of five points:

1 The stress state in the specimen is uniform and uniaxial during deformation.
2 The pulses incident, transmitted and reflected suffer little dispersion along the bars.
3 The input and output bars suffer only elastic deformation during the experiment and its contact surfaces with the specimen remain flat and parallel during deformation of the

specimen.
4 The stress distribution in the radial direction in the input and output bars is fairly uniform.
5 Accumulated strain in the specimen due to a single compression incident pulse.

As was pointed out here is really difficult to find literature about SHPB designing., in fact only Lang's 2012 [6] dissertation talks specifically about designing, and to be honest even him doesn't show much about it, for example he didn't include calculation, his dissertation is only a kind of a routine. So is this paper as well, a routine but with a different approach to understand the philosophy behind a SHPB designing.

2. METHODOLOGY

A kind of inverse method of calculation is employed here, firstly, the maximum stress that can be applied in the bars since the elastic bars limit never must be overcome, will be estimated. Secondly, the calculation of the maximum speed of the impact bar to produce this allowable maximum stress in the bars is completed, and finally, the pressure necessary to produce this speed is calculated, what allows to estimate the gas pressure that will guarantee this speed. The desired strain rate is produced by a stress wave that is produced by the impact of the impact bar on the input bar, and as a consequence a stress wave spreads to the specimen.

Since introducing any yield of the bars is by no means desirable, as this would cause deformations and dispersions in the shape of stress wave produced, producing in turn errors in data collection, which would ruin the test. The choice of the maximum stress, which can be produced by the impact, is the zero specification, a very important factor in device design. At the same time an impact stress as high as possible must be chosen, very close to the yield stress, in order of obtaining a great amount of energy as possible from the impact bar, optimizing the device. Concluding, that the starting point is the choice of safety factor to be adopted.

The stress produced by stress waves traveling through the bars was originally described by Kolsky [3,7]. The wave equation is the following partial differential equation (PDE) called D'Alembert equation.

$$\frac{\partial^2 u}{\partial t^2} = {c_0}^2 \frac{\partial^2 u}{\partial x^2} \quad (1)$$

The solution is the sum of two functions of the argument x-c_0t.

$$u(x,t) = F(x-c_0t)+G(x+c_0t) \quad (2)$$

As in this case the pulse is propagating in the positive direction to the right of a supposedly infinite bar, only picked up the term with argument:

$$u(x,t) = F(x-c_0t) \quad (3)$$

the particle speed is

$$v(x,t) = v_p = \frac{\partial u(x,t)}{\partial t} = -c_0 F'(x - c_0 t) \qquad (4)$$

the strain is

$$\varepsilon(x,t) = \varepsilon = \frac{\partial u(x,t)}{\partial x} = F'(x - c_0 t) \qquad (5)$$

Replacing Eq. 4 in Eq. 5

$$\varepsilon(x,t) = \frac{-v(x,t)}{c_0} = \varepsilon = -\frac{v_p}{c_0} \qquad (6)$$

In a state of uniaxial tension, $\sigma(x,t) = E\varepsilon(x,t)$ and $c_0 = \sqrt{\frac{E}{\rho}}$

then

$$\sigma(x,t) = E\frac{\partial u(x,t)}{\partial x} = EF'(x - c_0 t) = \frac{Ev(x,t)}{-c_0} = -\rho c_0 v(x,t) \qquad (7)$$

$$\sigma = -\rho c_0 v_p, \text{ as } v_p = \frac{1}{2} v_s \qquad (8)$$

Then,

$$\sigma = -\frac{1}{2}\rho c_0 v_s \qquad (9),$$

that is the stress produced by the stress wave in the bars, from here it is necessary to estimate the maximum allowable stress of the material, using material’s yield stress with a factor of safety, and adopting this value as the maximum allowable stress, calculating the impact bar speed using Eq. 7.

2.1. Impact Device

In Fig. 1 it is shown the schematic of a system to measure the stress-strain response of the material under impact loading conditions, as devised by Kolsky [3,6]. In this paper will be adopted the name impact bar instead of striker bar.

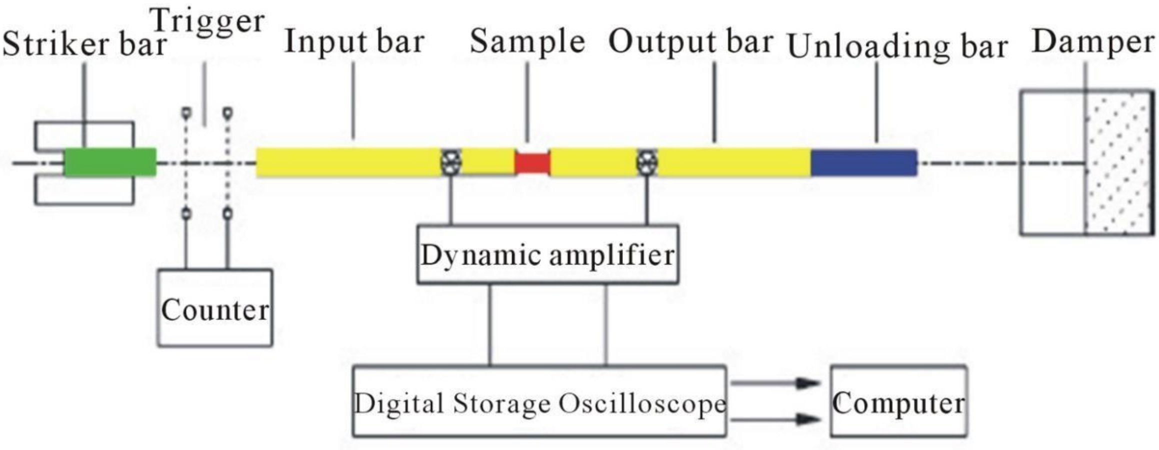

Figure 1: General schematics of a Kolsky split bar system [8].

Newtonian mechanics gives the following equation,

$$\mathrm{W} = \int \mathrm{F} \cdot \mathrm{ds} = \frac{1}{2}\,\mathrm{m}\,(\mathrm{v}_2{}^2 .- \mathrm{v}_1{}^2) \tag{10}$$

Where,

$$\int F \cdot ds = F_R \times \mathrm{d} \tag{11}$$

$\boldsymbol{F_R}$= resulting force

d = distance traveled by the center of mass of impact bar up to the point of impact.

then,

$$FR \times \mathrm{d} = \frac{1}{2}\,\mathrm{m}\,(v_2{}^2 - v_1{}^2) \tag{12}$$

The equation is valid provided there are no frictional forces. As the bar is released from the rest position,

$$v_1 = 0 \tag{13}$$

which results,

$$F_R \times \mathrm{d} = \frac{1}{2}\, m\,({v_2}^2), \tag{14}$$

then in the final form,

$$FR \times \mathrm{d} = \frac{1}{2}\, m_s\, {v_s}^2, \tag{15}$$

where,

m_s = mass of impact bar
v_s = impact bar speed

In this case, $\boldsymbol{v_2 = v_s}$**.**

The pressure applied by the gas pressure on the cross sectional area of the impact bar required to produce this force will be,

$$P = \frac{F}{A} \tag{16}$$

This pressure is the precalculus to the pressure used in the gas reservoir. Once the measure of the impact bar is estimated, the design of the input bar and of the output bar can be undertaken as the next section follows.

2.2. Dimensioning The Bars

The lengths of the input and output bars are determined by detailed analysis of the stress wave, using the Lagrangian diagram, see Figure 2. The ideal is to put the strain gages in any position where the full stress wave has already been produced in the input bar, and it has already exceeded the entire strain gages when the reflected stress wave starts running. Clearly by the graphical analysis that will happen if the input bar is dimensioned with some measure equal twice the length of the stress wave.

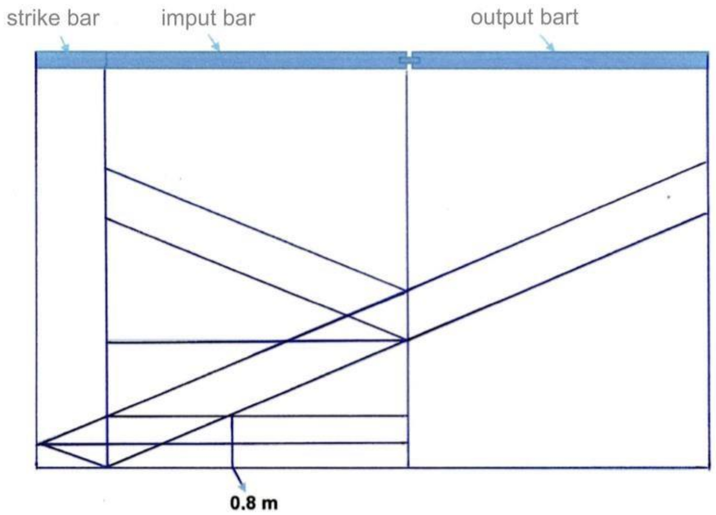

Figure 2: Lagrangian diagram for stress wave showing the displacement of the stress wave as a function of time.

3. CONCLUSION

The decision of dimensioning the bars with the maximum elastic stress allowed is only one among other methods available. Scaling up this SHPB device mechanically is not in any way neither complex, nor extensive. The hard part dealing with this SHPB device is collecting proper data. What is of importance is to design an impact device totally controllable, in order of allow an ample margin of impact bar speed, capable of reaching high strain rate in the specimen to be tested. Looking at the available literature the sizes calculated by this method show themselves completely coherent with existing equipment.

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REFERENCES

1. B. Hopkinson, “A method of measuring the pressure produced in the detonation of high explosives or by the impact of bullets”, *Royal Society London, **A213***, pp.437-456 (1914).
2. E. D. H. Davies, “The critical study of the Hopkinson pressure bar”, *Royal Society London,* **A240**, pp.375-457 (1948).
3. H. Kolsky, “An investigation of the mechanical properties of materials at very high rates of loading”. *Proc. Phys. Society London,* **B62**, pp.676-700 (1949).
4. J. M. Krafft, A. M. Sullivan, C.F. Tipper, “The effect of static and dynamic loading and temperature on the yield stress of iron and mild steel in compression”. *Proc. Royal Soc London,* **A221**, pp.114-127 (1954).
5. U. S. Lindholm, “Some experiments with the Split Hopkinson pressure bar”. *J Mech. Phys. Solids,* **12**, pp.317-335 (1964).
6. S. M. Lang, “Design of a split Hopkinson bar apparatus for use with fiber reinforced composite materials”, Master of Science Thesis, Utah State University, Utah, USA (2012).

7. H. Kolsky, *Stress Waves in Solids*, Dover, New York, USA (1963).
8. M. A. Kaiser, "*Advancements in the Split Hopkinson Bar Test*". Master of Science in Mechanical Engineering, Virginia Polytechnic Institute, Virginia, USA (1998).
9. Bertholf, L.D. ; Karnes, C.H. Two Dimensional Analisys Of The Split Hopkinson Pressure Bar System *J. Mech Phys. Solids*, **Vol 23**, p 1-19, 1975.
10. Benassi, Fábio, Modulação de pulso para regularização da taxa de deformação em teste com barra de Hopkinson. 2005. Dissertação (Mestrado) - Escola Politécnica da Universidade de São Paulo. Departamento de Engenharia Mecatrônica e de Sistemas Mecânicos, São Paulo.
1. 11. Subhash, G. Split Hpkinson Pressure bar Testing on Ceramics *ASM HANDBOOKS: mechanical testing and evaluation* Oklahoma USA 2003, Disponível em http://products.asminternational.org/hbk/index.jsp Acesso em 20 Jun. de 2005.