- Technical Paper -

HIGH STRAIN RATE MATERIAL TESTING USING ELASTIC STRAIN ENERGY

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ABSTRACT

This paper describes a new test system that relies on sudden strain energy release to subject specimens to rapid loading. The new system is cost effective to build in comparison to, and smaller than, existing systems, can be used to test relatively larger-sized specimens and can be conveniently adjusted to achieve a broad range of strain rates. The theoretical potential of the device is discussed and equations that describe the operation of the system are developed and used to identify influential variables. A computational simulation model of a prototype system is then described and exercised to quantitatively explore the influence of the key variables. A prototype device was built to demonstrate proof-of-concept and its ability to perform high rate impact test for cement composites requiring large size specimen by using small impact device is discussed.

Keywords: Internal strain energy, Strain energy release, Stress wave, Impact, Energy bar, High strain rate, Pulse, Loading, Compression, Tension, Concrete, Cementitious Composites.

1. INTRODUCTION

The demand has never been greater for tougher, more ductile materials to improve the behavior of civil engineering structures under rapid and severe loading, such as blast, impact and earthquakes. A primary hurdle that impedes rapid development of such materials is inexpensive, safe and accurate testing techniques that can be used to characterize high-strain-rate material response. Most existing methods for high-strain-rate testing require large equipment (e.g. drop-weight test or Split Hopkinson Pressure Bar), are expensive and, in some cases, risky to operate. As a result of these limitations, high-strain-rate testing remains highly specialized and can only be conducted in a few labs around the world.

Existing high rate test systems can be categorized into 4 classes based on the way the impact effect is generated: 1) systems based on potential energy (PE), where a large mass swings or falls from a specified height to strike a specimen at low speed (e.g. Charpy, Izod and Drop Weight methods); 2) systems based on kinetic energy (KE), where a small mass is propelled at high speed to impact a specimen (e.g. Gas Gun Method); 3) systems that utilize hydraulic machines (HM) to deform a specimen at medium speeds; and 4) systems based on stress wave propagation (SWP), in which a stress wave is propagated through a long bar to impinge upon a specimen (e.g. Split Hopkinson Pressure Bar, SHPB).

PE systems require much vertical clearance, a special foundation and can only achieve moderate strain

rates. The maximum strain rate achieved by this method is reported to be 10^{0} s⁻¹ to 10^{1} s⁻¹ (Bischoff and Perry [1,2]). In KE systems, an explosively propelled striker mass is directed towards a specimen to impart rapid loading. Alternatively, the same effect can be achieved by accelerating a specimen and colliding it with a stationary anvil, e.g., Grote et al. [3]. KE methods can generate very high strain rates, e.g. Grote et al. [3] report strain rates up to 10⁴ s⁻¹. The primary challenge in KE methods is obtaining high quality measurements during the extremely short duration of the experiments. HM testing using well-designed test machines can create high quality test data. However, the strain rates achieved using such methods is usually quite low, on the order of 10^{-1} to 10^{0} s⁻¹. They are also generally expensive and cumbersome to reconfigure.

successfully test concrete (and other То non-homogeneous materials) under high strain rate in a SHPB, the specimens must have a certain minimum size dictated by the characteristic size of the constituents of fiber reinforced concrete, e.g., aggregate and fiber. The specimen must be several times the characteristic size of the aggregate (or fiber) so that the results are not adversely influenced by the size effect. On the other extreme, the diameter of the specimen must be as small as possible to reduce the overall length of the equipment, since lateral dispersion of the propagating uniaxial shock wave could distort the test results if the bars are too stocky. These two conflicting requirements, a specimen with as large a diameter as possible and testing bars that are as short as possible for a given diameter, create practical problems for SHPB

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testing of concrete which require long test setups to ensure 1-D stress wave propagation. For example, to test a 75 mm diameter cylindrical specimen, a SHPB would have to be 10 - 12 m long.

The objective of this paper is to describe a new test system that was recently proposed by the authors to overcome the combined limitations of traditional high strain rate systems, especially for testing concrete and fiber reinforced concrete (Naaman et al. [4]). In the proposed system, the internal strain energy accumulated in an elastic energy bar is suddenly released generating controlled, high strain-rate loading onto a specimen. This system is hereafter identified as Strain Energy Impact Test Systems or SEITS.

2. Premise of SEITS



Figure 1- Schematic showing operation of proposed test system

Figure 1 shows a schematic of how SEITS is intended to work. Figure 1a shows the components of the system in its initial stage. Load is applied to a short pull bar, which then transmits the force through a coupler to the energy bar where elastic strain energy is stored (Figure 1b). The energy bar is prevented from movement by a support and is maintained continuously in contact with the specimen, to the extent possible, as it is being stretched. The coupler is specially designed to suddenly release (e.g. through brittle fracture of a notched mechanical coupler) when a specified load is exceeded, as shown in Figure 1c. When the coupler fractures, a pulse is directed into the specimen. If there is no gap between the specimen and the energy bar, which may be difficult to achieve in practice, the stress wave will be guided directly into the specimen. Alternatively, if a gap exists between the energy bar and specimen, SEITS becomes a kinetic energy device, in which the entire energy bar is launched towards the specimen. As will be shown later on, both situations are theoretically equivalent. In other words, the proposed system bridges the SWP and KE categories previously identified. Once a pulse is delivered to the specimen, high speed instrumentations, e.g., high frequency laser sensor and dynamic piezo-electric load cells, can then be used to obtain the specimen's stress-strain properties

as in other existing impact testing systems such as Charpy, Izod and Drop Weight methods (Elfahal et al. [5]).

To demonstrate the theoretical capacity of the system consider an energy bar 50.8 mm diameter, 1.5 m long and subjected to 690 MPa tensile stress. The amount of stored strain energy is 3672 N-m. The required drop height to achieve the same amount of potential energy is 16.2 m, if an impactor with the same weight as the energy bar (23.1 kg) is used in the drop weight method. It is clear that the size of the proposed system is much smaller than that of an equivalent drop weight system.

The proposed system shares some attributes with two existing systems. However, there are also fundamental differences that make SEITS unique. The first is a device patented by Keener et al. [6], where the energy stored in a breaker specimen is exploited to produce an impact action. SEITS differs from this device in two critical ways. First, SEITS uses an energy bar to store and release the energy needed for impact and to control the strain rate. The method proposed by Keener et al. relies instead on the energy stored in the breaker specimen, which could be orders of magnitude less than the energy stored in SEITS's energy bar. Keener et al. also claim that the impact load and accumulated energy may be increased by increasing the size of the starter specimen. However, that will necessitate a larger testing machine with a higher capacity frame and load cell. In contrast, the energy stored in the energy bar of SEITS can be increased or decreased by simply changing the bar characteristics as explored later on in the paper.

Another set-up that utilizes released strain energy was developed by Cadoni et al. [7] to investigate the tensile behavior of concrete at high rate loading. They modified a SHPB by attaching a prestressing bar in front of the incident pressure bar. The Modified Hopkinson Bar (MHB), as Cadoni et al. [7] called their system, employs the prestressing bar under tension instead of gas gun to generate a stress wave into the incident pressure bar. While MHB resolves some of the difficulties and dangers of operating a gas gun, it still suffers from the same key problem of a traditional SHPB, i.e. it is still a large sized testing system.

3. Wave propagation equations for SEITS



Figure 2- Schematic of the energy bar at the moment of strain energy release

Figure 2a shows a schematic of the energy bar before it is deformed. At time, $t=t_1$, the bar tip is pulled through a displacement, $w(L,t_1)$, where L is the bar length (Figure 2b). When the bar is released (Figure 2c), a compressive stress wave travels through the bar and into the specimen. Force equilibrium in a differential element in the energy bar is shown in Figure 2d. This can be expressed as:

$$F_1 + F_m = F_2 \tag{1}$$

where, $F_1 = AE \frac{\partial w_1}{\partial x}$, $F_2 = AE \frac{\partial w_2}{\partial x}$, $F_m = Adx \rho \frac{\partial^2 w_1}{\partial t^2}$,

 w_1 is the displacement at the top of the differential element, w_2 is the displacement at the bottom of the differential element, *E* is the modulus of elasticity of the bar and *A* is the section area of the bar. The force, F_m , is the inertial force in the differential element. Substituting these quantities into Equation 1, assuming that $w_2 = w_1 + \frac{\partial w_1}{\partial x}$ and simplifying the results, leads

to:

$$C^{2} \frac{\partial^{2} w_{1}}{\partial x^{2}} = \frac{\partial^{2} w_{1}}{\partial t^{2}}$$
[2]

where $C = \sqrt{\frac{E}{\rho}}$, is the speed of the stress wave in the

bar. Equation 2 represents the well-known wave equation, which has a general solution to the homogeneous wave equation as follows (Stronge [8]):

$$w(x,t) = \frac{1}{2} [f(x - Ct) + g(x + Ct)]$$
[3]

where f and g are arbitrary functions representing waves that are traveling forward and backward as tincreases.

Equation 2 can be also expressed as:

$$\left(C\frac{\partial w}{\partial x} + \frac{\partial w}{\partial t}\right)\left(C\frac{\partial w}{\partial x} - \frac{\partial w}{\partial t}\right) = 0$$
[4]

Thus, the relation between the strain (ε) and particle velocity (V) can be established as follows:

$$\frac{\partial w}{\partial t} = C \frac{\partial w}{\partial x} \quad \Rightarrow \quad V = C\varepsilon = \sqrt{\frac{E}{\rho} \frac{\sigma}{A}}$$
[5]

where, ε , σ is the strain and is the corresponding stress in the bar.

Equation 5 is instructive in that it shows what variables are influential for SEITS. It is clear that the impact velocity (and therefore the strain rate) produced by the proposed system can be controlled by changing the energy bar's *material properties* and *release stress level*. Clearly materials with high modulus of elasticity and low density have the potential to produce higher strain rates, as does a higher release stress level.

4. Equivalence of Stress Wave Propagation and Kinetic Energy Approaches

Figure 2a shows a schematic of the energy bar before it is deformed. At time, $t=t_1$, the bar tip is pulled

through a displacement

V

Consider an elastic energy bar subjected to a tensile stress $\sigma = E\varepsilon$. Applying the principle of conservation of energy and assuming no energy loss implies that elastic strain energy stored in the energy bar will be instantaneously transferred into kinetic energy upon bar release. The elastic strain energy (*SE*) stored in the elastic energy bar with volume V is

$$SE = \frac{1}{2} \frac{AL}{E} \sigma^2$$
 [6]

The kinetic energy (KE) of the bar is

$$KE = \frac{1}{2}MV_b^2 = \frac{1}{2}(AL \times \rho)V_b^2$$
 [7]

where L is the length of bar, A is the section area of bar, M is the mass of bar, ρ is the density of bar and V_b is the instantaneous bar velocity. Equating Equations 6 and 7 and simplifying leads to

$$Y_b = \sqrt{\frac{E}{\rho}}\varepsilon = C\varepsilon$$
[8]

which is identical to Equation [5] implying that the stress wave and kinetic energy approaches are equivalent when applied to SEITS.

5. Finite Element Modeling of SEITS

Prior to building a prototype (as described later on in the paper), the viability of the proposed impact test system was investigated through explicit finite element analysis, conducted using the commercial code LS-DYNA. The purpose of this analysis was to quantify the effect of bar material properties and stress level in the energy bar at the point of strain energy release on the achievable strain rate. Eight node solid elements are used to model the system and interpenetration between parts in the system is prevented using the contact features in LS-DYNA. Tensioning of the elastic bar is performed by applying displacement control at the end of the pull bar. A friction coefficient $\mu = 0.2$ is assigned between the specimen and the load cells and a failure strain criterion is applied to the coupler to permit sudden bar release when a critical stress is reached in the energy bar.

Table 1- Properties of energy bar materials employed in the simulations

	Η	energy bar		Set-up	Specimen	Coupler
	PS Steel	Al. Alloy	Ti. alloy	Steel	Pure aluminum	Steel
E (MPa)	200100	70000	115996	200100	70000	200100
ν	0.28	0.33	0.32	0.28	0.33	0.28
σ _u (MPa)	828	552	966	828	276	552 (621)
ρ (t/m ³)	8.027	2.690	4.484	8.027	2.690	8.027
ε	-	-	-	-	0.15	0.08

Three different types of materials are used to represent the energy bar, namely pre-stressing (PS) steel, aluminum alloy and titanium alloy. This is done to investigate the effect of the energy bar material on the achievable strain rate. ASTM A29 Grade C1045 steel is used for the load cell, coupler and test frame. Aluminum is used for the test specimen in the SHPB simulation. The properties of the materials employed in the simulations are shown in Table 1. The time step used in this simulation is automatically determined within LS-DYNA to ensure stability of the dynamic simulations and is less than 0.0001 sec. Figure 3 shows details of the model employed in the analysis. The system for generating impact pulse, as shown in Figure 3, is just sit on strong floor. There is no anchorage needed.



Figure 3- Finite element model of SEITS

	STEEL	ALUMINUM	TITANIUM
Energy bar stress at release (MPa)	517.5	517.5	517.5
Strain energy in unit volume (N-mm/mm ³)	0.669	1.911	1.152
Energy bar strain at release	0.00259	0.00739	0.00446
Modulus of elasticity E (MPa)	200100	70000	115996
Density ρ (t/m ³)	8.027	2.690	4.484
Wave velocity $C = \sqrt{E/\rho} (\text{m/sec})$	4992	5100	5083
Theoretical impact velocity, $V = C\varepsilon$ with no specimen (m/sec)	12.9	37.7	22.7
Maximum Impact velocity (m/sec) from simulation without specimen	12.7	30.8	22.4
Maximum Impact velocity (m/sec) from simulation with specimen	5.5	16.9	9.24
Maximum strain rate from simulation with specimen (1/sec)	433	1085	771

Table 2-	Effect of	material	properties	of energy	bar	on
		impact	velocity			

The effect of using various types of material for the energy bar is summarized in Table 2 and Figure 4. For an assumed stress level at energy release of 517.5 MPa,

it is clear from the simulations that the impact velocity is strongly influenced by the material of the energy bar. For example, the computed impact velocity for PS is 12.7 m/sec, while it is 30.8 m/sec for aluminum. Clearly, the presence of the specimen slows down the computed impact speed as a result of the interaction that takes place between the specimen and bar. The reduction in impact speed due to the presence of the specimen is computed to be about 50% or less in all three simulations. Clearly, the aluminum energy bar is most efficient.



Figure 4- Effect of bar material on impact velocity



Figure 5- Effect of stress level on impact velocity (without specimen)

The influence of stress level (at energy release) in the energy bar on the velocity of the impact head is also investigated using the same finite element model for the PS energy bar. The effect of two stress levels, 517.5 MPa and 655.5 MPa, are compared, and it is clear stress level is also an influential variable. When the stress level is 655.5 MPa, the impact velocity approaches 17.8 m/sec., while it is about 12.7 m/sec when the stress level is 517.5 MPa as shown in Fig. 5. The simulation results in this section clearly show that SEITS can be easily tuned to provide various strain rates by replacing the energy bar with another of a different material or simply by changing the stress level in the bar at the energy release point.

5. SEITS Prototype

With the confidence gained through the simulation model, a prototype of SEITS was recently built. The SEITS prototype is shown in Figure 6. The compressive impact pulse acting on steel frame attached to the tensile specimen is transferred as tensile impact pulse as shown in Figure 6b. Piezo-electric dynamic load cells (222,411N range, 0.1mV/4.44822N) and a high frequency laser displacement sensor (10kHz, +/- 25mm measuring range) are used to measure the response of the specimen. For compression testing, the piezo-elactric dynamic load cells are located under the specimen while the laser sensor measures displacement of the impact hammer. Figure 7 demonstrates the impact process (in compression) on a mortar specimen having compressive strength of 48 MPa (50.8 mm diameter). The impact velocity in this preliminary test is measured to be 5 m/sec by analyzing the sequential photos recorded by a high-speed camera.



Osec 0.001sec 0.002sec 0.003sec 0.004sec

Figure 7 - Progression of damage as a specimen is impacted under compression in SEITS

Figure 6b shows a tension set-up for ductile High Performance Fiber Reinforced Cementitious Composites [HPFRCC]. The length of HPFRCC specimen should be much longer than concrete and normal Fiber Reinforced Concrete [FRC] to allow multiple cracks (the unique characteristic of HPFRCC) to occur under high rate tensile loading. The gage length of the tensile specimen shown in Figure 6b and 8 is 200mm. Figure 8 shows tested tensile specimens of HPFRCC (tensile strength is 12MPa, and strain capacity is 0.6%).



Figure 8- Damage in tensile specimens tested in SEITS

The sample test results demonstrate that SEITS can be used to investigate the tensile response of large-sized cementitious specimens in addition to compression tests. The authors are currently working on interpretation of the measured data, which will be the subject of a future publication.

6. Summary and conclusions

A new technique for generating a rapid impact pulse is proposed. The new system, named *Strain Energy Impact Test System [SEITS]*, releases stored elastic strain energy in an energy bar to achieve high strain rate loading. The proposed system has several advantages over traditional impact test systems such as the Drop Weight method and Split Hopkinson Pressure Bar technique. In particular, while small, SEITS can still be used for large-sized specimens and can be easily controlled by changing the energy bar's material or stress level in the energy bar. The theoretical potential of the device was discussed and equations that describe the operation of the system were developed and used to identify key variables that control SEITS' performance.

Computational simulation models of the system were used to confirm predictions from the theoretical models and to study how the system interacts with specimens. It is shown that that when an aluminum alloy is used for the energy bar, an impact velocity of 30.8 m/sec can be achieved in the simulation presented in the paper. This translates into a strain rate in excess of 10^3 sec⁻¹ on the aluminum alloy specimen used in the simulation.

A prototype device that was built to demonstrate proof-of-concept was also introduced and its capabilities, especially its ability to test specimens under both compression and tension were demonstrated. It was shown that the prototype, which is about 1.5 m in size, could generate a strong enough pulse to destroy a 48 MPa large size concrete specimen (50.8 mm diameter) in compression. The prototype can also be configured to test tensile specimens with relatively long gage lengths.

Two conclusions are drawn based on the limited numerical and experimental study conducted:

1) The magnitude and velocity of the impact pulse generated by SEITS can be controlled by replacing the energy bar with another of a different material or simply by changing the stress level in the bar at the energy release point, e.g. by changing the load at which the coupler breaks; and,

2) For the same material type, volume and elastic strain energy at failure, two energy bars of different geometry will generate the same impact velocity.

These conclusions point to the fact that the proposed system is capable of delivering a wide range of strain rates.

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