

IMPACT TEST SYSTEM FOR TENSION BEHAVIOR OF HIGH PERFORMANCE FIBER REINFORCED CEMENTITIOUS COMPOSITES

Tuan Kiet TRAN^{*1}, Dong Joo KIM^{*2}

ABSTRACT

This paper proposes an impact test system for uniaxial tensile behavior of High Performance Fiber Reinforced Cementitious Composites. It is a modified version of Strain Energy Impact Test System [SEITS]. New system proposed an energy frame to store elastic strain energy and to generate high velocity impact load while original version of SEITS employs an energy bar. The use of energy frame instead of energy bar can resolve the current problems of original SEITS, especially regarding how to obtain pure material response in impact, including the local bending effect by using two specimens.

Keywords: Strain Energy Impact Test System, Energy frame, High strain rate, Tension, High Performance Fiber Reinforced Cementitious Composites.

1. INTRODUCTION

Understanding material behavior under seismic, impact and blast load conditions is a critical part of structural engineering for designing civil and military infrastructures. Many different impact test systems have been developed to measure the material response under high rate loadings such as earthquake, missile attack and bomb explosion.

In 1914, B. Hopkinson presented a smart test method to determine the pressure – time relations due to an impact produced by a bullet or explosive by utilizing the property that the compressive pulse is reflected as a tension pulse at the free end of a bar. In 1948, Davies developed a technique and greatly improved the accuracy of Hopkinson's original apparatus by using condensers to measure strains. Kolsky added a second pressure bar to Hopkinson's original apparatus, hence the name Split Hopkinson Pressure Bar (SHPB) or Kolsky bar appeared [1]. He proposed equations to calculate the stress – strain response of test specimens based on strain histories of two pressure bars. Over a period of several decades, this technique has been used in compressive test of various materials [2].

There also have been several attempts to modify the SHPB test technique to capture high rate tensile test. In 1960, Harding et al. generated a compression pulse in a tube surrounding a solid inner rod for high rate tensile tests. A similar set-up was suggested by Hauser [3]. Lindholm and Yeakley have also proposed an alternate type of tension test using a complex hat-type specimen [4]. Albertini and Montagnani utilized both an explosive loading device and rapid fracture of a clamp in a prestressed bar to generate the tensile pulses in split Hopkinson bar set-up [5]. Nicholas developed a new tension version of split Hopkinson bar by utilizing reflected tensile stress wave at the free end of

a bar from compressive stress wave [6].

Observing deeply on the existing high rate test systems, they can be grouped on 4 systems depend on way the impact effect is generated: 1) systems based on potential energy (PE); 2) Systems based on kinetic energy (KE); 3) systems that utilized hydraulic machines; (HM) and 4) systems based on stress wave propagation (SWP). By bridging the SWP and KE categories which a sudden strain energy was released to subject specimens to rapid loading, a new test system named SEITS (*Strain Energy Impact Test System*) was recently proposed by Kim et al. as shown in Fig. 1 [7]. The system is cost effective to build in comparison to, and smaller than existing systems, can be used to test relatively larger-sized specimens, especially for testing concrete and fiber reinforced concrete in compression as well as tension and can be conveniently adjusted to achieve a broad range of strain rates.

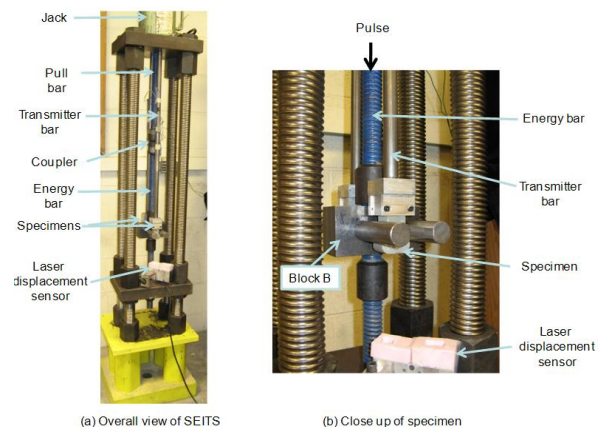


Fig. 1 Prototype of original SEITS [7]

Under high strain rate conditions, dynamic effects should be very carefully considered in obtaining pure material properties by differentiating the structural and

*1 Ph.D. candidate, Civil and Environmental Eng., Sejong University, Seoul, Korea, JCI Member

*2 Corresponding author, Prof., Civil and Environmental Eng., Sejong University, Seoul, Korea, JCI Member

material inertia effect from test set-up and the strain rate sensitivity of materials tested. Main difficulty in obtaining pure material response under high rate loading is that these two effects can be super imposed interdependently which make the problem much more complicated.

The SEITS also needs a special care to obtain pure material response by removing any structural and material inertia effect from test set-up due to the requirement of large-sized specimen of HPFRCC. It would be more severe due to gravity effect when the test specimens were installed vertically in original version of SEITS as shown in Fig. 1. Furthermore, the original SEITS employed two tension specimens at the same time; and, the method produced additional problems in installing and performing impact test on them under perfectly symmetrical impact loads without influence of load eccentricity. Hence, the objective of this research is to develop a new version of SEITS that resolve these problems above mentioned.

2. BACKGROUND INFORMATION

Coupler Mechanism: The fundamental differences that make SEITS unique are: 1) SEITS utilizes elastic strain energy stored in an energy bar to generate high rate impact pulse; and 2) SEITS overcomes the limitation in dimension of traditional high strain rate system, especially for testing HPFRCC requiring considerable size of specimen. Fig. 2 shows a core operational mechanism of SEITS.

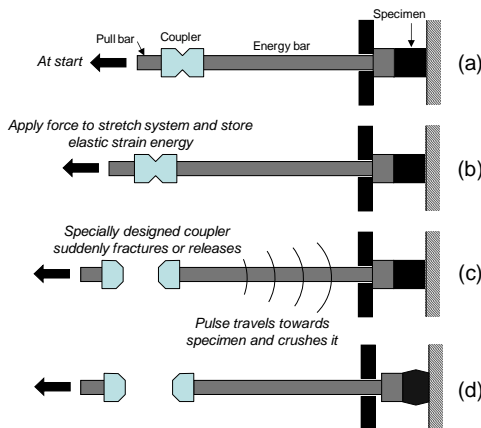


Fig. 2 Schematic showing operation of original SEITS [7]

Elastic strain energy is stored in the energy bar while one end of the energy bar is prevented from movement by a support when a load is applied to a short pull bar connected through a coupler (Fig. 2b). The coupler is specially designed to suddenly release the strain energy when a specified load is exceeded as shown in Fig. 2c. When the coupler fractures, the stress wave will appear and transform directly to the specimen (Fig. 2c and Fig. 2d). Once a high rate stress pulse is delivered to the specimen, high speed instrumentations, e.g., high speed camera 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.

Wave propagation equations for SEITS: From force equilibrium condition in a differential element of the energy bar, the well-known wave equation for the bar with elastic modulus E and density ρ can be achieved [7]:

$$C^2 \frac{\partial^2 w_1}{\partial x^2} = \frac{\partial^2 w_1}{\partial t^2} \quad (1)$$

where $w(x,t)$ is displacement and $C = \sqrt{E/\rho}$ is the wave velocity of the material.

The relation between the strain ε and particle velocity V can be also derived after solving above motion equation:

$$V = C\varepsilon = \sqrt{\frac{E}{\rho}} \frac{\sigma}{A} \quad (2)$$

where ε is strain, σ is the corresponding stress and A is the section area of the bar.

It should be pointed out that the impact velocity (and therefore the strain rate) produced by SEITS can be controlled by changing the energy bar's *material properties* and *release stress level*. Clearly the application of materials with high modulus of elasticity and low density to an energy bar have the potential to produce higher strain rates, as does a higher release stress level.

3. DEVELOPMENT OF LOAD FRAME

To obtain the representative material response of HPFRCC under high strain rate as well as static load, the test specimens of HPFRCC must have a certain size dictated by the characteristic size of the constituents of concrete, e.g., fiber and aggregate. A large-size specimen especially for HPFRCC or FRC, however, will produce a big mass which is also influential on measuring dynamic material properties, particularly for the test set-up with vertically installed test specimens.

These two conflicting requirements made authors develop a load frame which can deliver high rate stress wave to a specimen without eccentricity as shown in Fig. 3. The use of load frame produces many advantages over the original SEITS: 1) Load frame deliver high rate stress wave to specimen with no load eccentricity; 2) The size of test specimen for impact test can be as large as the one for static specimen; 3) The boundary condition for tension test under impact can be maintained as same as in static test.

A tensile specimen of FRC or HPFRCC is connected to the load frame by a hinge system at one end of specimen; the other end of specimen is also connected to a fixed support for preventing from movement by a hinge system as shown in Fig. 3. All hinge systems as well as load frame were placed on a strong steel base plate by rollers to allow free movement and provide enough stroke to fail the specimen under impact load. The whole test system is then placed on strong floor with a firm anchorage.

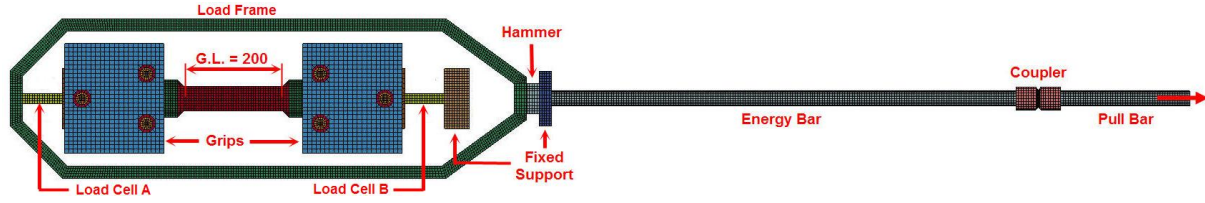


Fig. 3 Finite element modeling of proposed version of SEITS using load frame

When the stress of the energy bar has been increased to a specified stress value, the coupler connecting pull bar and energy bar will fracture and the hammer at the end of energy bar strike directly to load frame. Once an impact pulse is generated and transferred from the energy bar to load frame, the stress wave in the load frame will generate tensile load on the specimen and eventually fail the specimen.

For the measurement of tensile stress – strain response of specimens, a high speed camera can be applied to obtain the deformation history of specimen; and, two dynamic piezo-electric load cells or piezo-type strain gauges which are attached at both ends of grips can capture the load signal. From these data, the specimen's stress-strain properties can be estimated.

Modeling: The validity of the proposed impact test system was examined before building a prototype of the proposed system. Numerical simulation was conducted by using the commercial code LS-DYNA. This analysis aimed at two purposes: 1) examination of the impact pulse generating performance of the modified system with load frame 2) analyzing of the way to obtain pure material stress-strain properties of specimen by using the instrumentations mentioned above. Eight node solid elements are used to model whole system and specimen; and, interpenetration between parts in the system is prevented using the contact features in LS-DYNA. Stretching the system is simulated by applying displacement control at the end of the pull bar. A friction coefficient assigned between the specimen and the pins is $\mu = 0.5$; and the pins are accompanied with grips for keeping both ends of specimen during test.

simulation is automatically determined with LS-DYNA to ensure stability of the dynamic simulations and is less than 0.0001 sec. Fig. 3 shows detail of the model employed in the analysis.

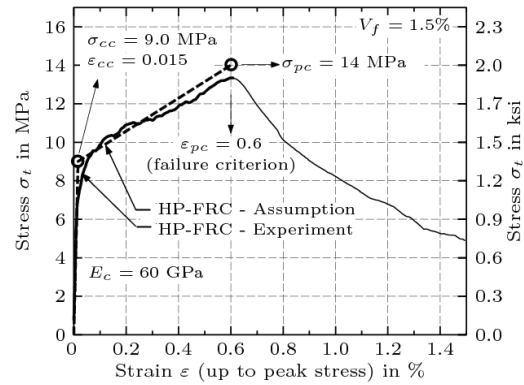


Fig. 4 Tensile stress – strain response of HPFRCC used in simulation [8]

The material properties, investigated in the simulation, of HPFRCC are referred in [8]. The tensile stress – strain response of the HPFRCC is illustrated in Fig. 4. First cracking strength is 9.0 MPa; and, post cracking strength is 14 MPa. And, the strain capacity, strain value at post cracking strength, is 0.6%. Thus, the elastic modulus and hardening modulus determine from the tensile stress – strain curves are 60 GPa and 0.85 GPa, respectively. The strain rate sensitivity was not considered in the material model used in the simulation for the purpose of exploring how to capture pure material stress – strain response under high rate loading.

Table 1 Properties of materials employed in the simulations

	Energy Bar			Test set-up and frame	Coupler
	Steel	Ti. Alloy	Al. Alloy	Steel	Steel
E (MPa)	200100	70000	115996	200100	200100
ν	0.28	0.33	0.32	0.28	0.28
σ_u (MPa)	828	552	966	828	552 (or 621)
ρ (t/m ³)	8.027	2.69	4.484	8.027	8.027
ε_u	-	-	-	-	0.08

ASTM A29 Grade C1045 steel is used for the energy bar, coupler, load cell, grips and frame. The properties of materials employed in the simulations are provided in Table 1. The time step used in the

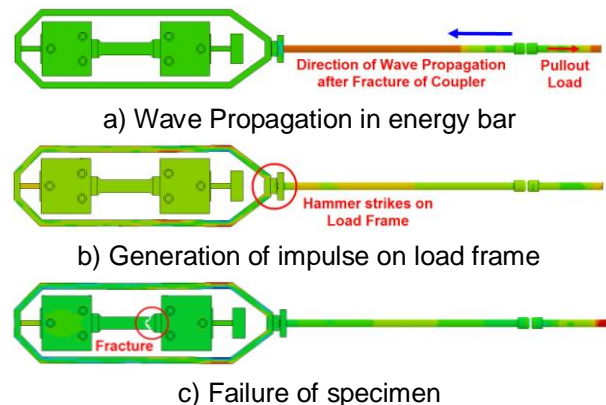


Fig. 5 Simulation results with load frame

Discussion of Simulation Results: When the

coupler was fractured, the stress wave which was released at the bar's right end would be accumulated at the other bar's end as shown in Fig. 5a. This stress wave would in turn guide the hammer strike directly on the load frame and by this way an impulse would be generated in frame (Fig. 5b). Through load cells A and B (shown in Fig. 3) which are equivalent to incident bar and transmitter bar respectively in this case, the stress wave transferred from load frame to the specimen and made the specimen fail (Fig. 5c). This result of simulation proved the success of the proposed system using load frame.

The success of the proposed system also should be judged by its ability to reproduce the assigned stress-strain response of the simulated specimen in the model.

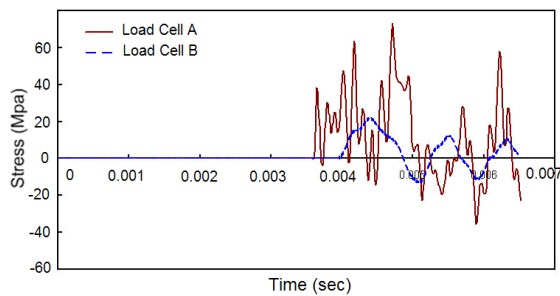


Fig. 6 Specimen's equivalent stress history according to different positions of load cells

Fig. 6 shows the specimen's equivalent stress history according to different locations of load cell A and B, where equivalent stress is the stress of load cell's element multiplied with cross section area of load cell and then divided by cross section area of specimen. It is clear to see the progressing of wave transfer from starting time until end of simulation, especially the wave in load cell A would be first appeared and then transmit to the load cell B. And, it is important to recognize that there is no compressive wave before appearing of wave in the load cells. This simulation result supports the idea that the test specimen is failed under pure tensile stress wave.

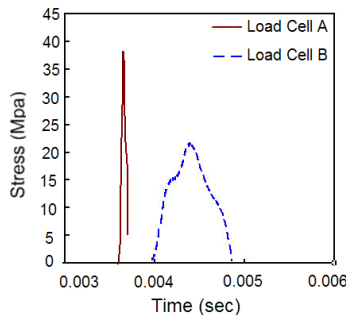


Fig. 7 First wave front of stress history signal in load cells A and B

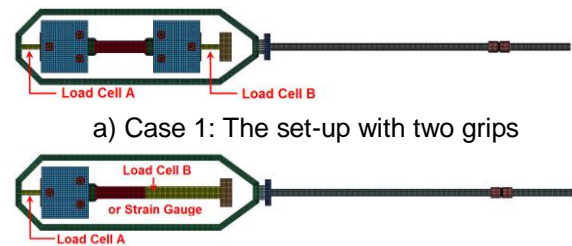
To obtain the pure material response under high rate loading, the stress history must be captured correctly. Fig. 7 shows two stress histories which are obtained from two load cells as shown in Fig. 3. As

shown in Fig. 7, it is clear that the stress histories of two load cells, load cell A to load cell B, are quite different. In detail, the peak stress of load cell A is 38 MPa while that of load cell B is 22 MPa. Both of these values are not same as the value assigned maximum tensile strength of specimen in the simulation, i.e., the post cracking strength of HPFRCC modeled in the simulation, is only 14 MPa. Therefore, it is concluded that pure material response of specimen can not be obtained by using the stress histories at load cell A and load cell B in the modified SEITS system as shown in Fig. 3.

One of the main reasons of this difficulty in obtaining tensile stress – strain response of HPFRCC in the system is that the stress wave propagates through non-homogeneous environment including steel and concrete. Beside the reason mentioned ahead, the others could be the grip mechanism as well as the variable of specimen's geometry. These potential factors which can influence the measured stress histories of specimen are discussed later in next part to find the way to measure pure material response under high rate loading in the modified SEITS.

4. HOW TO OBTAIN PURE MATERIAL RESPONSE UNDER HIGH RATE LOADING

Numerical analysis is an efficient tool to study how to measure or obtain pure material properties, especially in the course of investigations into the dynamic properties of materials. In finding the way to measure pure material response under high rate loading in the modified SEITS with load frame, two cases were studied as shown in Fig. 8, named case 1 and case 2.



b) Case 2: The set-up with only one grip
Fig. 8 Cases for numerical analysis to obtain pure material response under high rate loading

Unlike case 1, the specimen in case 2 has only one dog-bone end connected with load frame by grip system. The other end of specimen then connected directly to a transmitter bar. The length of transmitter bar was carefully determined to guarantee the measured stress is only transferred from specimen without any influence from the reflected stress wave. It should be noted that the cross section of transmitter bar is intended to be as same as that of specimen.

In case 2, the tensile stress wave after traveling the specimen would propagate to the transmitter bar. Thus, the stress history measured from the transmitter bar would purely reflect the material characteristics of the specimen. By using the stress histories of load cell

A and B in case 2, the equivalent stress histories of test specimen could be estimated as shown in Fig. 9.

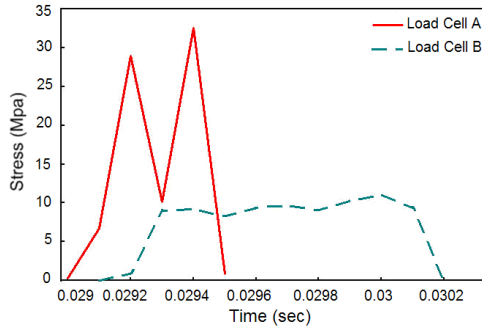


Fig. 9 Stress histories of load cells A & B for case 2

There is a big difference in prototype of two signals; especially the signal of load cell A has the very high value for peak stress, 32 MPa, while that of load cell B is 12 MPa. This certified the limitation of using stress signals from load cells. However, the signal of load cell B for Case 2 showed the more reasonable result than that for Case 1. That is the peak value 12 MPa approximates the value 14 MPa of assigned material for simulation. The key is the same cross section area of specimen and transmitter bar. This result is affirmed again from the estimated stress-strain curve by using the stress histories of load cell B in case 2 as shown in Fig. 10.

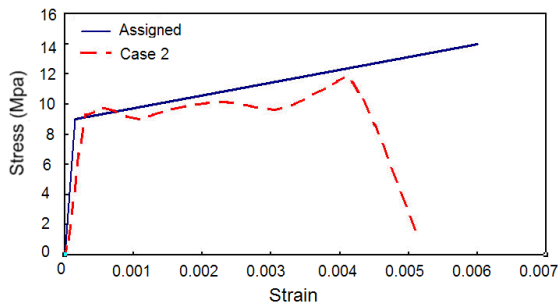


Fig. 10 Stress – strain curve for Case 2

In Fig. 10, the “measured” stress of specimen was captured from the data of load cell B or by strain gauge as shown in Fig. 8b. The “measured” strain is obtained from the measured displacement of two points on specimen with high speed camera. The stress-strain response estimated by using the measured stress and deformation histories in the numerical simulation of case 2 is well matched with the assigned stress – strain response of the material in the simulation as shown in Fig. 10.

The measured stress – strain curve is nearly identical to the assigned curve; thus, this result strongly support the idea that the modified SEITS with load frame (case 2) can be successfully used for measuring the material response of HPFRCC under high rate loadings.

5. PROPOSED ENERGY FRAME SET-UP

Base on demanding of reducing dimension of

system and utilizing of frame as energy frame, an improving set-up was proposed additionally as Fig. 11.

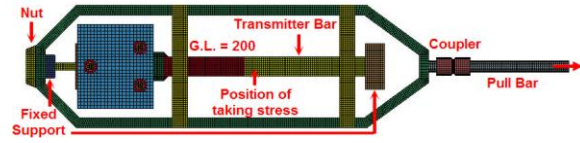


Fig. 11 Modified version of SEITS with energy frame

The modified system utilizes the same principle of coupler mechanism and principle of storage energy as well. However, the modified system uses energy frame instead of an energy bar to store elastic energy in addition to delivering stress wave. The one end of energy frame is now prevented from movement by a fixed support (left position in the figure). When the pull bar is loaded until the maximum capacity of coupler, the coupler is fractured and the energy frame will release and strike directly to the incident bar of hinge system. At that time, an high rate stress will be generated in the incident bar and propagated through the grip to specimen. A strain gauge is attached on the surface of transmitter bar as shown in Fig. 11 to receive the stress signal. A high speed camera is used to obtain the strain by capture the displacements of two points over a gauge length of 200 mm. The brace system was added to reinforce the energy frame. Fig. 12 showed the operation of the system where represent the fracture of coupler and the failure of specimen.

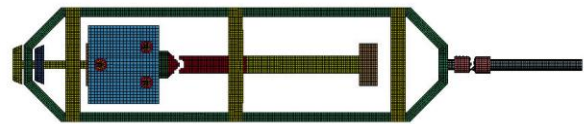


Fig. 12 Failure of specimen for proposed set-up

The tensile stress – strain response of the specimen estimated by the way explained above is provided in Fig. 13. The estimated curve shown in Fig. 13 is close to the assigned stress – strain response of the material.

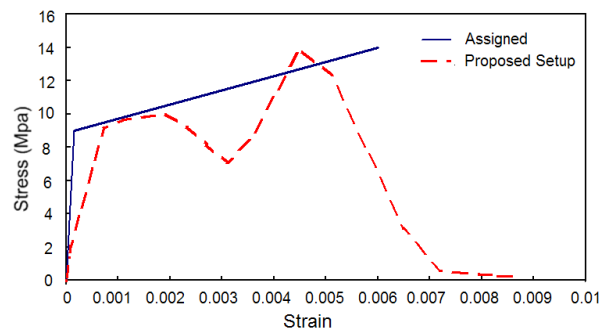


Fig. 13 Stress-strain relation of specimen

The influence of ultimate pullout force depending on the capacity of coupler on strain rate is graphically shown in Fig. 14. Fig. 14 shows that a broad range of strain rate (10 s^{-1} to 85 s^{-1}) can be

generated by controlling the stress level in the energy frame.

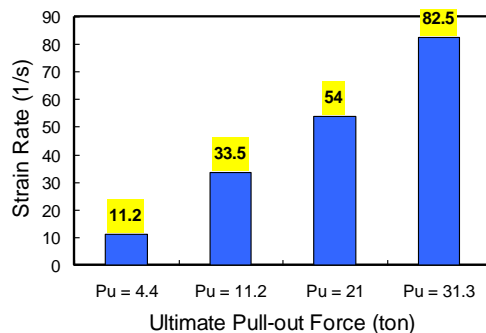


Fig. 14 Effect of ultimate pullout force on strain rate

The detail of the proposed SEITS with energy frame is provided in Fig. 15a and the typical test result obtained from the set-up is showed in Fig. 15b. This set-up will be used to perform impact tests to investigate the tensile behavior of HPFRCC under high strain rate. The results for the tests using this set-up will be reported soon.

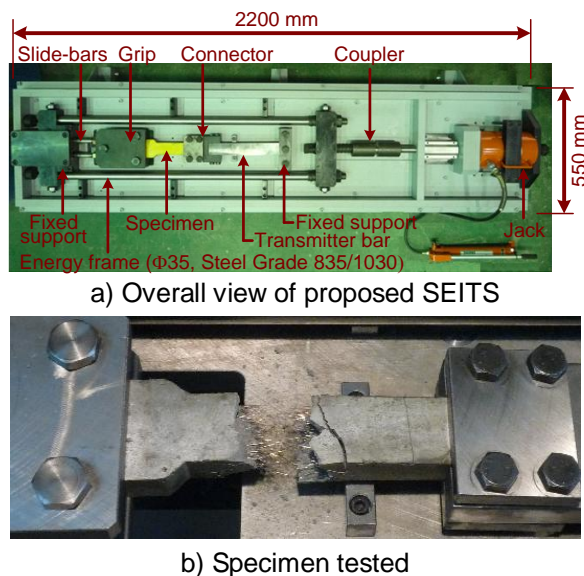


Fig. 15 The proposed SEITS with energy frame

6. SUMMARY AND CONCLUSIONS

A new impact test set-up for HPFRCC which is a modified version of SEITS with energy frame is proposed. The proposed system can be used for large-sized specimens of HPFRCC and can be easily controlled by changing the material of energy bar or frame and by controlling stress level of energy bar or frame. In particular, compared with original SEITS, the proposed system with energy frame has three clear advantages over the original SEITS: 1) the proposed system is less influential from gravity effect; 2) the proposed system can store larger amount of elastic

strain energy; and, 3) the proposed system can deliver high rate stress wave to one specimen without any eccentricity.

Numerical simulations have been performed 1) to validate the proposed system with energy frame; 2) to estimate the possible of strain rate range; and, 3) to establish the exact method for obtaining pure material response. The information presented indicates that the proposed system with energy frame provide broad range of strain rates from 10 s^{-1} to 85 s^{-1} . The authors are currently building a prototype of modified SEITS with energy frame to perform high rate tensile tests for HPFRCC.

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