Construction and Building Materials 81 (2015) 276–283

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Capturing the strain hardening and softening responses of cementitious composites subjected to impact loading

Sukhoon Pyo [a,*], Sherif El-Tawil [b]

[a] Korea Railroad Research Institute, 176 Railroad Museum Road, Uiwang-si, Gyeonggi-do 437-757, South Korea
[b] Department of Civil & Environmental Engineering, University of Michigan, 2350 Hayward, G.G. Brown, Ann Arbor, MI 48109-2125, USA

HIGHLIGHTS

- A compact impact testing system was refined to test UHP-FRC under direct tension.
- Strain rates ranging from 90 to 145 1/s were experimentally attained.
- The new setup can properly capture the hardening and post peak responses of UHP-FRC.
- UHP-FRC is well suited for blast and impact applications.

ARTICLE INFO

Article history:
Received 8 October 2014
Received in revised form 15 January 2015
Accepted 18 February 2015
Available online 4 March 2015

Keywords:
Strain rate
Tension
Impact
Strain energy
Material tests
Ultra high performance concrete

ABSTRACT

Ultra-high performance fiber reinforced concrete (UHP-FRC) is a type of cementitious composite that has extended hardening and softening responses when subjected to tension. The length of the tensile loading regime complicates the development of test setups that can capture the full tensile response at high strain rates. To address this challenge, analytical and finite element modeling are used to propose modifications to an existing test set up to enable it to conduct accurate and practical testing of UHP-FRC specimens in direct tension, under high strain rate. The test device employs suddenly released strain energy to generate an impact pulse and a sufficiently long transmitter bar to channel the signal and measure it. Tests conducted on UHP-FRC specimens at strain rates of 90–145 1/s show that, under increasing strain rates, the material maintains its strain capacity and has highly enhanced strain dissipation capacity, making it particularly well suited for blast and impact applications.

1. Introduction

The Split Hokinson Pressure Bar (SHPB) has been used for testing concrete at strain rates around 10^2 1/s. In spite of being used for more than a century, the SHPB has two key disadvantages when applied to cementitious materials. First, the device generally requires specimens that are of a completely different geometry than those used in pseudo-static testing, which raises concerns about whether specimen geometry and size affect direct comparisons between pseudo-static and dynamic results. This complicates drawing strong conclusions about the effects of high strain rate on concrete response. Second, to successfully test concrete under high strain rate in a SHPB, the specimens must have a certain minimum size dictated by the characteristic size of the constituents of concrete. For regular concrete, the limiting constituent is the aggregate, while for fiber reinforced concrete and cementitious composites, fiber length must also be considered. 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. Therefore, concrete testing using SHPB typically requires the use of relatively large specimens and, therefore, that the SHPB be commensurately long. Of course, the bigger the SHPB, the more expensive it becomes.

The large size and cost of the SHPB coupled with the difficulty of fully assessing its results for concrete have hindered its wide spread use. Kim et al. [1] proposed an alternative to the SHPB for testing concrete, termed Strain Energy Impact Test System (SEITS). The device was subsequently modified and called Strain Energy Frame Impact Machine (SEFIM) by Tran and Kim [2,3] and Kim et al. [4]. The two devices use energy bars and a coupler to store and suddenly release elastic energy for the purposes of rapidly loading concrete specimens. They are both compact in size, cheap to build and permit testing of regular, full scale specimens thereby alleviating the previously mentioned SHPB concerns.

---

* Corresponding author. Tel.: +82 31 460 5413.
E-mail address: shpyo@krri.re.kr (S. Pyo).

http://dx.doi.org/10.1016/j.conbuildmat.2015.02.028

As demonstrated later on in the paper, the previously proposed energy-based devices are unable to capture the full hardening and softening responses of ultra-high performance fiber reinforced concrete (UHP-FRC) in tension because the tensile regime of the material is especially long, which requires special considerations to ensure that the signal is cleanly captured. The objective of this paper is to clarify this limitation and propose modifications to SEFIM to allow it to successfully capture the hardening and post peak responses of UHP-FRC. The modified test setup is developed through the use of finite element modeling. A prototype is built and exercised to demonstrate the capabilities of the system as applied to UHP-FRC.

Ultra-high performance concrete (UHPC) has recently gained much attention for its durability and extremely high strength. It is a specially formulated material that is capable of achieving extremely high performance, with compressive strength in excess of 150 MPa. When properly reinforced with steel fibers, it is termed UHP-FRC and is capable of achieving strain hardening behavior with strain at peak stress of up to two orders of magnitude greater than that of regular concrete [5] and exceptional energy absorption prior to fracture [6]. Previous research by the authors [7] suggested that the material is particularly promising for impact and blast applications, hence its selection in this research.

2. High strain rate testing of concrete in tension

While the compressive behavior of concrete materials at high strain rates was investigated by a number of researchers, e.g., Tang et al. [8], Ross et al. [9] and Zhao [10], much fewer efforts have been dedicated to tensile response at high strain rates. This is attributed to two key reasons. The tensile capacity of concrete was felt by many researchers to be negligible due to the low tensile capacity of conventional concrete. Second, conducting tensile testing, especially at high strain rates, is substantially more complex than under compressive loading. Introducing a tensile wave and measuring the resulting response of a specimen within a SHPB are challenging.

Investigators who have attempted to use modified SHPB setups for tensile testing, albeit not necessarily for concrete, include Harding and Welsh [11], who used a mechanism that employed a weighbar tube striking a yoke connected to the end of the input bar. Staab and Gilat [12] used a clamp to release a stored tensile load. Owens and Tippur [13] used a gas gun chamber attached to the side of the bar to launch a striker toward the anvil, generating a tensile wave. Ross [14] used a modified SHPB to accommodate direct tension test of concrete at high strain rate by using a hollow cylindrical striker bar sliding on the incident bar of the SHPB. Ross et al. [15] conducted dynamic splitting tension test (dynamic Brazilian test) for testing of failure strength of concrete using the SHPB by inserting a cylindrical specimen between the bars with its axis perpendicular to the bars. Brara et al. [16] developed a spalling version of the SHPB for concrete to determine the tensile strength at high strain rates up to 120 1/s. Cadoni et al. [17] used the Hopkinson Bar Bundle with 100 m-long strain energy storing steel cables for large concrete specimen with square cross section of 200×200 mm^2. The setup was devised to diminish the non-uniform distribution of axial stress across the large sized bars and achieved a strain rate of 10 1/s.

Limited experimental studies of the high strain rate behavior of UHPC have been carried out to date. Among the few examples are Habel and Gauvreau [18], who conducted drop weight tests on UHPC bending specimens and then converted their results to equivalent dynamic tensile properties. Millard et al. [19] conducted flexural and shear high-speed loading test of UHP-FRC using a drop-hammer testing apparatus. They found that the dynamic increase factor (DIF) of the flexural tensile strength rises at the strain rate of 1 1/s on a slope of 1/3 on a log (strain rate) versus log (DIF) plot. To the best knowledge of the authors, there have been no high strain rate tests under direct tension for UHPC, which further motivated the work in this paper.

3. Introduction to SEITS and SEFIM

Unlike conventional impact test methods, the SEITS device uses a coupler and an energy bar to store elastic energy for generating impact pulses. The way by which SEITS operates is simple. First, a load is applied to a short pull bar. The tensile force is transmitted through a coupler to an energy bar where elastic strain energy is stored. After sudden fracture of the coupler under increasing load, the stored elastic energy is transferred to two concrete specimens and the resulting pulse is directed into two transmitter bars. The stress in the specimens is captured by reading the transmitted stress wave using a strain gage and oscilloscope, just as in the SHPB system. Details of the system can be found in Kim et al. [1].

Despite its advantages of SEITS, the device has a key shortcoming: the need to simultaneously load two identical specimens, which is problematic because: (1) specimens are costly and time consuming to make, reducing the practicality of the device, and (2) specimens can never be exactly alike, leading to asymmetry in loading. To alleviate this problem, Tran and Kim [2,3] and Kim et al. [4] subsequently modified SEITS into the Strain Energy Frame Impact Machine (SEFIM). The modification entailed replacing the single energy bar with a load frame, which transmits load to a single specimen instead of a pair of specimens as in SEITS. Fig. 1 shows a schematic of SEFIM. The way by which SEFIM works is similar to SEITS. By applying displacement to the pull bar, the load frame stores elastic energy. After sudden failure of the coupler, stored elastic energy in the load frame is transmitted to the specimen in the form of a load pulse. The stress of the specimen is measured using strain gages attached to a transmitter bar and strain is calculated by post-processing images of the specimen using a high speed camera.

4. Rationale for modified device

The transmitter bar utilized by Tran and Kim [2,3] and Kim et al. [4] is not long enough to fully capture the hardening and post peak response of cementitious concrete specimens with substantial strain hardening, as commonly occurs in UHP-FRC. As discussed in detail later on, if the transmitter bar is short, the signal from the specimen reflects back too quickly, interfering with the ability to fully capture the incoming signal, which takes a relatively long time when substantial strain hardening is present. Hence, unlike conventional concrete or quasi-brittle materials, a minimum transmitter bar length is required to accommodate strain hardening concretes such as UHP-FRC.

In the conventional SHPB setup, researchers use a long transmitter bar to capture a clean stress signal, where there is no overlap between transmitted and reflected waves. For example, Reinhardt et al. [20] used a 6.65 m transmitter bar and Cadoni et al. [17] used a 2 m transmitter bar for quasi-brittle concrete. However, the length of the transmitter bar becomes important for a compact testing system such as SEFIM, whose overall length is governed by the length of the transmitter bar.

The stress wave travel time can be visualized as shown in Fig. 2. The time (t) between when the first incoming stress signal enters the strain gage (Fig. 2a) and the reflected stress signal returns to the strain gage (Fig. 2c) can be calculated as $t = 2(L - \delta)/C$, where δ denotes the strain gage location from the specimen and L is the length of the transmitter bar. The elastic wave speed is $C = \sqrt{E/\rho}$,