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Evaluation of Dynamic Double Punch Test for the Tensile Properties of UHPC

Yi-Chun Lai[1,2], *Ming-Hui Lee[3] and How-Ji Chen[4]

[1)] *Department of Civil Engineering, R.O.C. Military Academy, Kaohsiung, 83059, Taiwan, Republic of China.*
[2), 4)] *Department of Civil Engineering, National Chung Hsing University, Taichung 402202, Taiwan, Republic of China.*
[3)] *Department of Civil Engineering, National Pingtung University of Science and Technology, Pingtung, 912301, Taiwan, Republic of China.*
[3)] *MHLee61@mail.npust.edu.tw*

ABSTRACT

Ultra High Performance Concrete (UHPC) excels in resisting explosions, impacts and high velocity loads due to its excellent dynamic mechanical properties. Its high strength, great ductility and excellent energy absorption allow the structure to minimize damage and increase safety. Therefore, it is important to know the dynamic mechanical material parameters of UHPC under different strain rates for simulation analysis and design of national defense projects or high-risk facilities. In general, the dynamic compressive properties of materials are often obtained by impact testing, while the dynamic tensile properties are measured in a variety of ways, including high-speed direct tensile testing or splitting testing. However, the former is easily limited by the loading limit of the instrument, while the latter is based on only indirect test method to obtain material properties, and the result cannot reflect the material tensile behavior realistically. In the quasi-static indirect tensile tests, the results of the double punch test (DPT) are considered to be most similar to the direct tensile test (DTT). This study is the first to propose a dynamic DPT method using the split Hopkinson bar for the tensile mechanical behavior of a material. To verify the method, a single specimen is planned to undergo dynamic and static DPT. Through the experiment results, the reliability of the proposed dynamic DPT analysis theory and the feasibility of the test method are verified.

[1)] Lecturer
[2)] Ph.D Candidate
[3)] Professor
[4)] Professor

1. INTRODUCTION

The unique mechanical properties of Ultra High Performance Concrete (UHPC) enable a wide range of applications and versatility. Emerging as a preferred material for national defense, critical infrastructure, high-security buildings, and major transportation hubs due to excellent dynamic mechanical properties and resistance to explosions, impacts, and high-velocity loads (Li et al. 2016, Ren et al. 2022, Khan et al. 2023). For the safety-conscious projects, understanding the dynamic behavior of UHPC is particularly important. The dynamic mechanical properties are the results of tests determined through tests conducted under high strain rates (Ross and Tedesco 1989, John et al. 1992, Yoo et al 2016, Gurusideswar et al. 2020, Sun et al 2018). A high strain rate is generally defined as dynamic loading within the range of 10 to 10^4 s^{-1}. Literature has shown that the sensitivity of UHPC to strain rate affects peak stress, peak strain, modulus of elasticity, and absorbed energy (Lai & Sun 2009, Rong et al. 2010, Hao 2013, Yoo et al. 2016, Khosravani & Weinberg 2018, Ren et al. 2018, Sun et al. 2018, Gurusideswar et al. 2020). Therefore, the influence of strain rate on material properties of UHPC is a critical issue in the study of dynamic mechanics (Rong et al. 2010, Sun et al 2018, Khosravani & Weinberg 2018, Yu et al. 2021, Li et al. 2021).

In general, dynamic mechanics tests include both compression and tension tests. The dynamic compression test, also known as the impact test, is usually conducted using a Split Hopkinson Pressure Bar (SHPB) tester. The test method is relatively simple, the results can be analyzed using one-dimensional wave propagation theory to obtain the dynamic compressive force property parameter (Zhao & Lok 2005, Rong et al. 2010). Dynamic tensile testing methods are more varied, including high-speed direct tensile tests, dynamic splitting tests, and high-speed bending tests. The measurement of material tension in quasi-static tests presents many inconveniences and instabilities, while dynamic tensile testing introduces additional execution difficulties. Some studies have used servo hydraulic presses for high-speed direct tensile testing (Pyo et al. 2015, Ranade et al. 2015); however, servo hydraulic presses load at strain rates limited to 10^{-4} – 10^{-1} s^{-1}, which makes it difficult to obtain data on material behavior at higher strain rates. In addition to the limitation of speed, the complexity of direct tensile test setup and the high rate of experimental inaccuracies remain significant obstacles (Sun et al. 2018, Carrillo et al. 2021), prompting the development of dynamic indirect tensile tests. Splitting Tensile Tests (STT) using SHPB have emerged as a recognized and viable method for dynamic indirect tension tests (John et al. 1992, Rodriguez et al. 1994, Sun et al. 2018, Khosravani & Weinberg 2018, Gurusideswar et al. 2020). STT involves applying an impact to the side of a cylindrical specimen, causing the specimen to be damaged by radial tension. The indirect tensile behavior of the material is obtained by analyzing the radial response in the plane of the specimen.

It has been demonstrated that the stress distribution at failure under dynamic loading in STT is similar to the quasi-static behavior (John et al. 1992, Sun et al. 2018). The simplicity of the operation and the applicability of analytical theories also facilitate further exploration of high speed tensile behavior. However, there is a significant difference between the STT and DTT results under quasi-static loading (Carrillo et al. 2021). This discrepancy raises concerns about the accuracy and reliability of existing dynamic indirect tensile tests.

The Double punch test (DPT) has been recognized as a method that more closely approximates DTT results in studies related to quasi-static tension testing and has been validated on many materials (Chen & Yuan 1980, Tuladhar & Chao 2019, Nogueira et al. 2021). DPT involves an axial loading process that utilizes a small area, smaller than the top surface of the cylinder. This generates a cone of compressive force within the cylindrical specimen, which in turn induces radial tension and radial deformation. During the test, the loading force and circumferential deformation of the specimen are measured, and the radial tensile stress and strain can be derived through formula-based calculations. The research on DPT has been limited to quasi-static loading, and it has not yet been applied to dynamic indirect tensile tests. Therefore, dynamic loading of DPT using the SHPB is proposed for the first time in this study. Considering that SHPB-related studies recommend using cylindrical specimens with a length-to-diameter ratio of 0.5 to 1 to minimize inertia and friction effects (Yu et al. 2021), and that the preferred length-to-diameter ratio for DPT specimens is 1 (Lai et al. 2024), a 45-mm diameter cylindrical specimen with a length-to-diameter ratio of 1 was designed for this study. Furthermore, based on the recommendations of Lai et al. (2024) regarding the size of the DPT specimen and punch, a punch with a diameter one-third the size of the specimen diameter was selected for the test.

The primary focus in this study is to present the concept of dynamic DPT and to conduct a preliminary evaluation. DPT was attempted with a single size specimen at both quasi-static and dynamic loading speeds. The DPT quasi-static test was conducted by the MTS tester, and the dynamic test is performed by the SHPB tester. The UHPC with 2% steel fiber was used as the test material to investigate the dynamic mechanical behavior. The feasibility of this dynamic indirect tensile test method was also evaluated to provide a more stable and reliable dynamic tensile test method.

2. ANALYTICAL METHODS AND THEORIES

2.1 SHPB theory and analysis

SHPB has been widely used in dynamic loading experiments at high strain rates (range of 10 to 10^4 s^{-1}). The SHPB tester, as shown in Fig.1, primarily consists of a controller, a data acquisition system, a power supply system, an input bar (incident bar), an output bar (transmitter bar), a speed measurement system, and a shock-absorbing system. The specimen is positioned between the input and output bars, ensuring tight contact between the surfaces of both bars. Upon triggering the controller, the striker bar generates an impact wave that is transmitted to the input bar, creating a pressure pulse. This pressure pulse propagates along the input bar, through the test specimen, and to the output bar. These waves are measured by strain gauges ahered to specific locations on both the input and output bars.

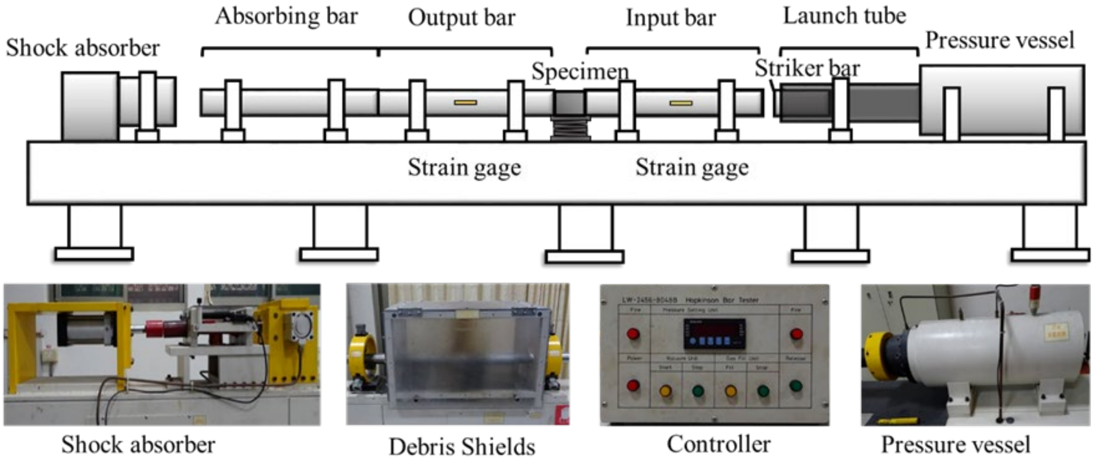


Fig.1 Configuration of split Hopkinson bar machine

According to one-dimensional stress wave propagation theory, the dynamic compression test measures the strain rate $\dot{\varepsilon}_s$, stress σ_s and strain ε_s from the deformation pulses in the bar, which are calculated as follows (Zhao and Lok2005):

$$\dot{\varepsilon}_s = \frac{C_0}{I_s}(\varepsilon_I - \varepsilon_R - \varepsilon_T) \tag{1}$$

$$\sigma_s = \frac{F_1+F_2}{2A_s} = \frac{A_{bar}}{2A_s}E_{bar}(\varepsilon_I + \varepsilon_R + \varepsilon_T) = \frac{A_{bar}}{A_s}E_{bar}\varepsilon_T \tag{2}$$

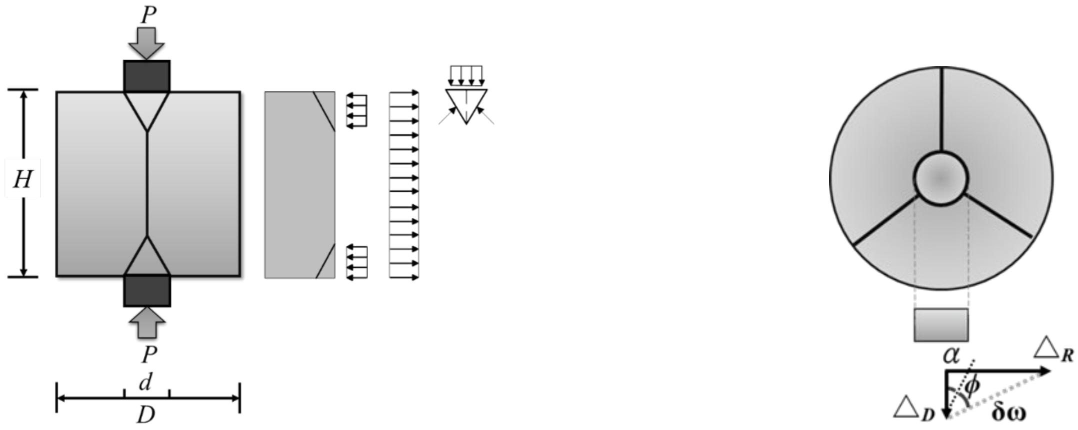
$$\varepsilon_s = \frac{2C_0}{I_s}\int_0^t \varepsilon_R dt \tag{3}$$

Where ε_I is the incident wave, ε_R is the reflected wave, and ε_T is the transmitted wave, C_0 is the elastic wave velocity, and I_s is the length of the strain gauge to the bar end. E_{bar} and A_{bar} are the Young's modulus and cross-sectional area of the elastic bar, respectively. A_S is the cross-sectional area of the specimen.

2.2 Double punch test theory and dynamic analysis

The Double punch test (DPT) is an indirect method to measure the tensile strength of a material. In this test, the steel cylindrical punches are applied to the top and bottom centers of a cylindrical specimen in compression. Upon loading, the surfaces of the test specimen are compressed by the punches, causing axial cracking, resulting in two conical fracture surfaces directly beneath the punches. During the process, the two cones gradually move toward the center of the specimen, generating relatively uniform tensile stresses and leading to tensile cracks along the radial plane, as shown in Fig.2 (a). The tensile crack distribution is radial and develops two conical fracture surfaces.

The cones are treated as rigid bodies moving towards each other, causing horizontal (radial) displacements of the surrounding material. ϕ is the angle between the relative velocity vector δ_ω at each point on the cone surface and the cone surface itself (Wen et al. 2013, Hasan and Rashid 2017, Lai et al. 2024). The relative velocities during radial and axial loading are recorded as $\triangle_R$ and $\triangle_D$ respectively, as shown in Fig. 2(b).



(a) (b)

Fig.2 Diagram of DPT force distribution by (a) side view; and (b) top view (Lai *et al.* 2024).

Based on the generalized theory of perfect plasticity and the assumption of a multi-tension crack failure mechanism, Chen (1970) proposed the following formula:

$$\frac{P}{\pi d^2} = \frac{1-\sin\phi}{\sin\alpha\cos(\alpha+\phi)}\frac{\sigma_c}{2} + \tan(\alpha+\phi)\left(\frac{DH}{2d^2} - \cot\alpha\right)\sigma_t \tag{4}$$

Where *P* is the loading force, *d* is the punch diameter, σ_c and σ_t are the compressive and tensile strengths of the material, and *D* and *H* are the diameter and height of the specimen, respectively.

Chen idealized concrete as a linear elastic-perfectly plastic material and introduced classical assumptions to simplify the formulation. Using these classical parameters (the ratio of compressive to tensile strength of normal concrete is 10, ϕ = 30° and α = 10°) the formula for the circumferential tensile stress can be derived (Chen 1970).

$$\sigma_t \approx \frac{P}{\pi(0.6DH-d^2)} \tag{5}$$

Chen and Yuan (1980) used elastoplastic strain-hardening and fracturing material to derive modified equations through finite element analysis. Malatesta et al. (2009) used an elastic model that considered circumferential and vertical stress distribution to introduce a modified equation with links and supports model. This equation is widely used for concrete materials reinforced with steel fibers (Malatesta et al. 2009; Molins et al. 2009; Carmona and Molins 2017; Carrillo et al. 2021).

$$\sigma_t = \frac{4P}{9\pi Dd} \tag{6}$$

Lai et al. (2024) compared the applicability of various formulas for UHPC and confirmed that Eq. 6 yields results closer to the real behavior. Therefore, this formula was chosen as the formula for analysis in this study. During the test, the punch applies loads on the concentric planes of the specimen, resulting in an internal conical failure mode (Chen 1970). Due to the concentration of stress on the concentric planes, when the tensile stress exceeds the concrete's tensile strength and cracking initiates, a radial crack perpendicular to the stress gradient will propagate outward from the specimen's center. The total tensile crack opening displacement (TCOD) can be measured through circumferential displacement when the specimen ruptures due to circumferential expansion (Wen et al. 2013). The continuous circumferential strain ε_t can be calculated by Eq. 7 (Tuladhar and Chao 2019).

$$\varepsilon_t = \frac{TCOD}{\pi D} \tag{7}$$

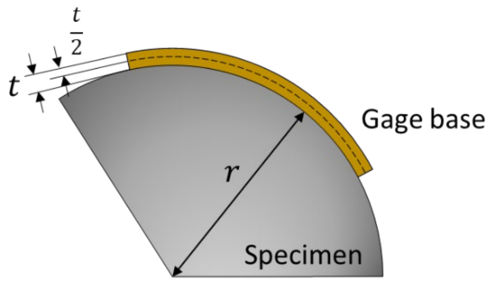
Where ε_t represents the circumferential strain, TCOD corresponds to the circumferential dilatation, the total displacement of cracks opening during the Double Punch Test (DPT) experiment.
The DPT is considered as better indirect tensile test method as it more closely approximates the results of the Direct Tension Test (DTT) in quasi-static tests and has been validated for many materials (Chen & Yuan 1980, Tuladhar & Chao 2019, Nogueira et al. 2021). Therefore, this study aims to evaluate the feasibility of this test method by performing dynamic DPT with SHPB. The contact and loading conditions in dynamic DPT differ from those in the impact test. The stress in the dynamic DPT specimen can be determined by combining Eq.2 and Eq.6 with the SHPB tester. The stress in the specimen, when applying load to the cross-section diameter *D* is calculated as follows

$$\sigma_t = \frac{4}{9\pi Dd}\left(\frac{A_{bar}}{2}E_{bar}(\varepsilon_I + \varepsilon_R + \varepsilon_T)\right) = \frac{4A_{bar}E_{bar}\varepsilon_T}{9\pi Dd} \tag{8}$$

For a more intuitive measurement of radial strain, consider attaching the strain gauge directly to the center of the outer perimeter of the test specimen, as shown in Fig. 3(a). The strain gauge is securely fitted to the specimen in a curved shape. Unlike attachment to a flat surface, the curved shape of the strain gage will influence the resistance change. The effect of the initial curvature must be considered in the calculation (as shown in Fig.3(b)). Therefore, the strain experienced by the strain gauge element is:

$$\varepsilon_t = \frac{t}{2r+t} \tag{9}$$

Where *t* is the thickness of the strain gauge base with an adhesive layer, and *r* is the radius of curvature of the gauge bonding surface.



(a)

(b)

Fig.3 Schematic diagram of DPT specimen strain gauge pasting (a) cross-section; (b) actual view

3. MATERIALS AND EXPERIMENT METHOD

The purpose of this study is to evaluate the feasibility of DPT for static and dynamic indirect tensile testing. The study included static and dynamic loading tensile tests.

3.1Specimen characteristic, experiment setup and configuration

The size of SHPB specimen is not unregulated. The SHPB literature indicates that the inertia effect on strain rate should not be ignored (Li & Meng 2003, Hao et al. 2013, Khosravani & Weinberg 2018). To avoid affecting the test results, the optimal aspect ratios of cylindrical specimens are suggested to be in the range of 0.5-1. In this range, the aspect ratio can reduce the inertia effect and friction effect (Yu et al. 2021). Moreover, the study by Lai et al. (2024) confirms that the simplified equation, Eq. (8), provides a reliable approach for UHPC DPT analysis when a cylindrical specimen with an aspect ratio of 1 and a punch ratio of 1/3 is utilized. Therefore, in this study, the DPT specimen is designed with a height and diameter of 45 mm, along with a punch diameter of 15 mm. This study proposed to perform the quasi-static DPT with the MTS universal tester by applying load to the contact area of the punch (as Fig. 4(a)). The force signal is measured by the MTS load cell, and the circumferential displacement of the specimen is calculated by an external chain with a circumferential extensometer. The quasi-static test is performed with a loading speed of 0.001mm/s. The load and displacement signals are transmitted simultaneously to the data acquirer at 2Hz interception frequency during the test.
The dynamic mechanical tests are performed by a split Hopkinson bar tester in this study. The signal data in the test process is measured by strain gauges on the incident and transmitted bars. The dynamic DPT specimen is in contact with punches placed between the incident and transmitted bars. The stress is analyzed based on the transmitted wave signal recorded by the strain gauge on the output bar, while the circumferential strain of the specimen is measured using a concrete strain gauge affixed to its side. The setup of the specimen is shown in Fig.4(b).

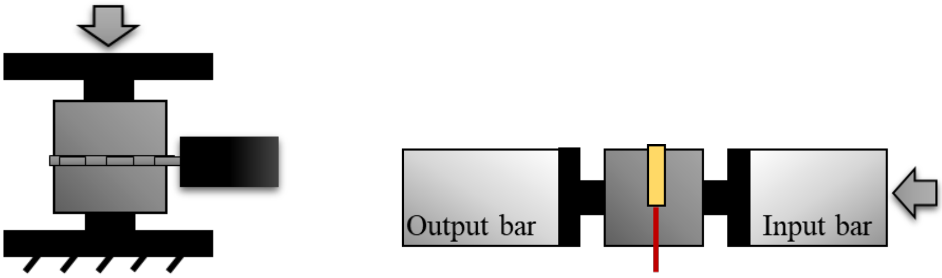


Fig.4 DPT setup schematic in (a) quasi-static state (b) dynamic

3.2 Material

In this study, UHPC with a steel fiber volume ratio of 2% was planned to be used in the test with reference to the concrete proportion of Lai et al. (2024). The special feature of this proportion is that 50% of cement is replaced by GGBS. By reducing the amount of cement used in the overall concrete mix, environmental sustainability is achieved, and the durability of the concrete is enhanced (Kuma et al. 2021, Lai et al. 2024). Furthermore, the addition of microsilica particles in the mixture increases the density of the matrix, which in turn increases the strength of the concrete. In order to achieve a low water-cement ratio and to maintain the workability, the high range water reducer (HRWR) was used in this study to fulfill the design with a water-cement ratio of 0.23. The steel fibers used to enhance the toughness and tensile strength of UHPC conform to ASTM A820 (2021). Many studies have confirmed that UHPC quality is more stable and has excellent mechanical properties at a steel fiber volume ratio of 2% (Wu et al., 2019). Therefore, this addition was used to design the material in this study. The weight ratio of the materials in the UHPC mixtures studied in this paper is shown in Table 1.

Table 1 Mixture proportion of material (weight ratio to cement)

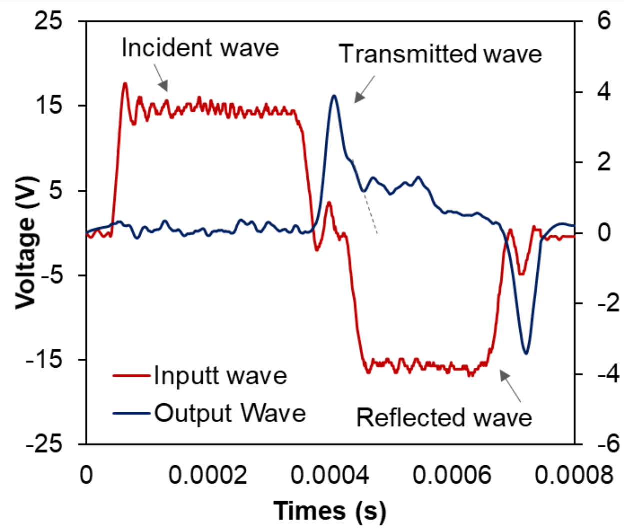
Item	Cement	GGBS	Silica fume	silica sand	Water	HRWR	Steel fiber*
U1	0.5	0.5	0.25	1.23	0.19	1.50%	1%

* Volume fraction of steel fibers

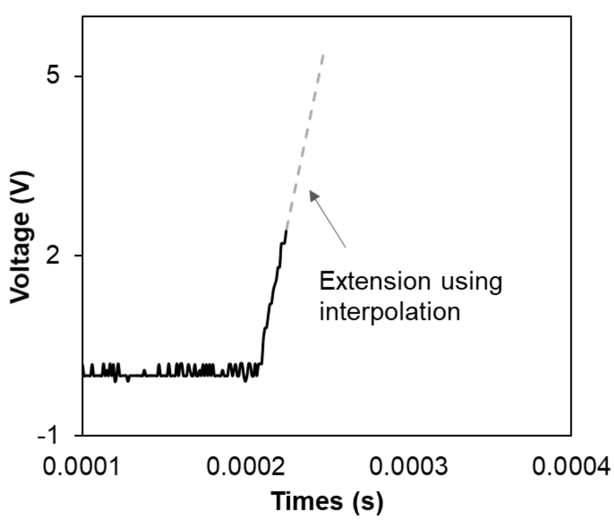
The dry materials of UHPC were mixed in a blender. After homogenization, pour in the water and HRWR mixture and mix until a concrete paste is formed. After thorough mixing, add steel fiber and continue mixing until a homogeneous paste is formed.
After pouring, cover the surface with plastic wrap to prevent evaporation-induced shrinkage. Before demolding, the specimens were left at ambient temperature (25°C) for 24 hours. After that, the specimens were placed in 90°C hot water for 72 hours. Then, the specimens were kept at ambient temperature (25°C) until the 28th day of ageing. Finally, the tests of planning were carried out in a sequential manner.

4. Results and discussion

The purpose of this study is to propose a novel dynamic indirect tensile test method. Based on the DPT, SHPB is utilized for high strain rate loading. Compared with other tensile tests, it is simpler and easier to conduct, and the analysis is easy with less error. After the dynamic DPT with SHPB, the historical response of the voltage signal obtained by the oscilloscope is shown in Fig.5. In Fig.5(a), the input and output waves can be observed significantly. This test method measures the circumferential strain by concrete strain gauge, and the measured voltage signal is shown in Fig. 5(b). The voltage value which exceeded the allowed deformation of the strain gage was restored and corrected by interpolation method. The voltage signals of load and deflection in Fig.5 are analyzed to obtain the stress and circumferential strain history responses as Fig.6.



(a)



(b)

Fig.5 Voltage signals for dynamic DPT from (a) input bar and output bar; (b) concrete strain gage

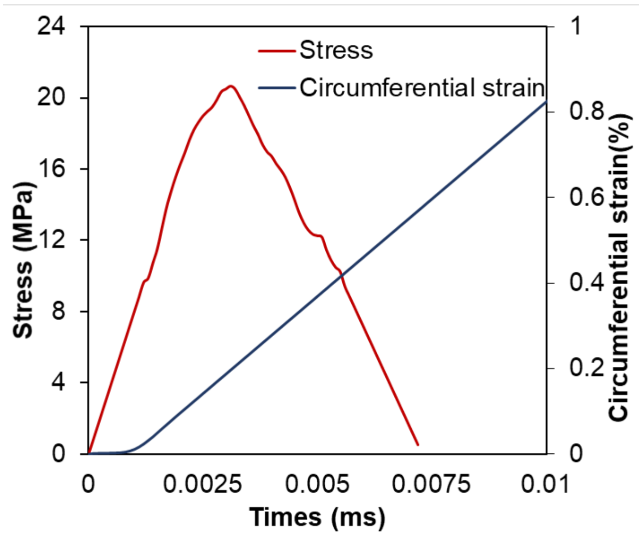


Fig.6 Stress and circumferential strain historical response

The dynamic stress-circumferential strain curves are compared with the quasi-static experimental results as shown in Fig.7. In Fig.7, the peak strength of the stress-strain curve is observed to increase under high strain, but the peak strain is lower than the quasi-static peak strain. In the high strain rate tensile study, it is shown that the ultimate tensile strength and modulus of elasticity increase with the increase of strain rate. The reason for this is that the increases in the fiber/matrix interaction properties increase both, the fiber-bridging stiffness as well as the fiber-bridging capacity, at high displacement rates (Ranade et al. 2015). The stress-strain curve is significantly shorter under high speed loading. By using steel fibers, the material itself has metal-like tensile properties. Under quasi-static loading, the material absorbs more energy and reacts slowly on the microcracks, whereas the reaction time is shorter under dynamic loading, resulting in the steel fibers being pulled out quickly.

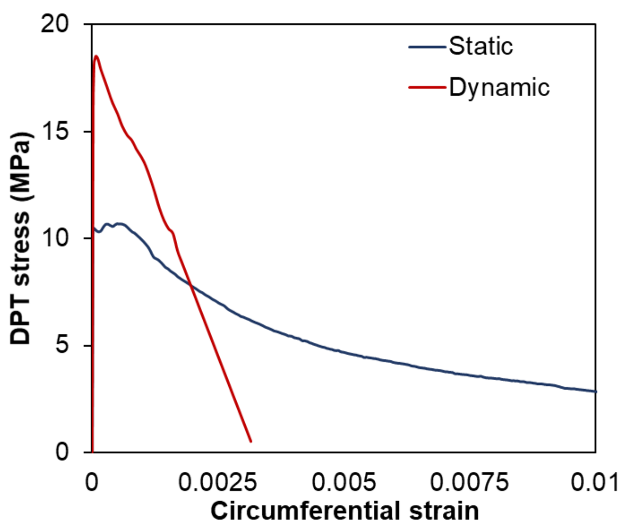


Fig.7 Stress-strain curve of DPT

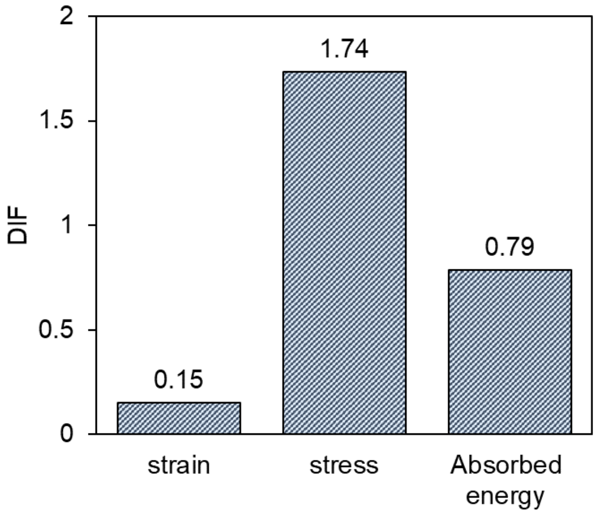


Fig.8 DIF of DPT results

The important parameters of the material in Fig.7, including peak stress, peak strain, and absorbed energy are organized as Table 2. The peak strength and strain of static DPT are 10.69 MPa and 0.05%, and that of dynamic DPT are 18.55 MPa and 0.008%. The modulus of elasticity was 635.9 and 827.5 GPa for dynamic and static respectively. The peak strain is particularly small, and the slope of the linear elasticity portion is particularly large because the DPT deformation is based on the center of the test specimen. Meanwhile, the static and dynamic absorbed energies affected by the peak strain are 12.64 and 9.947 × 10^{-3} J/m^3, respectively. Fig.8 shows the dynamic increase factor (DIF) of UHPC tensile properties under dynamic loading. For the strain, the DIF is 0.15, which shows that the strain of the material is very less under high speed tensile loading. The DIF of peak strength is 1.74, which is a reasonable dynamic amplification factor for UHPC under loading with a strain rate of 90s^{-1}. The absorbed energy is affected by the strain and the DIF is shown to be 0.79.

Table 2 Material Properties of DPT

	Strain rate (s^{-1})	Stress (MPa)	Strain (%)	Elastic modulus (GPa)	Absorbed energy (10^{-3} J/m^3)
Static	0.00001	10.69	0.050	635.9	12.64
Dynamic	90.98	18.55	0.008	827.5	9.947
DIF	-	1.74	0.15	1.30	0.79

5. Conclusion

Overall, the results of dynamic DPT stress-strain curve trends and material parameters are reasonable. As the strain rate increases, both the peak strength and elastic modulus increase, while the peak strain and absorbed energy decrease. In this study, only a single loading rate was used to verify the test results, and the proposed method was found to be feasible. This method can be applied to conduct loading experiments at various speeds in the future, thereby expanding the database of dynamic indirect tensile material properties.

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