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Experimental and numerical investigation on the dynamic tensile strength of concrete

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Abstract

A new experimental method for testing the dynamic tensile behavior of concrete at high strain rates was designed and established. By using this method, the dynamic tensile strength of concrete and its dependence on strain rates were measured and investigated. The experimental results indicate that the dynamic tensile strength of concrete is rate sensitive. The numerical simulation results have a good agreement with the experimental data and can be used for further research.

Keywords: Concrete; Spalling; Dynamic tensile strength

1. Introduction

Concrete has been widely used in civil and defense constructions, airport runways and nuclear power stations, which may suffer explosion or impact loading. Thus, it is necessary to understand the dynamic behavior of concrete in both compression and tension stress states. The dynamic compressive behavior of concrete is important for local impact effects such as penetration problems while the dynamic tensile behavior of concrete controls the spalling phenomenon, which has been recognized as a main mechanism of dynamic fracture of concrete.

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Hu et al. [1] recently carried out dynamic compressive tests for bigger size concrete specimens (Φ 72 × 36 mm) using right cone cylinder and Hopkinson pressure bar technique. Zhou et al. [2,3] conducted experimental and numerical investigations on the dynamic characteristics of concrete and mortar at strain rates up to order of $10^4\,s^{-1}$ and pressures up to 1.5 GPa, where the split Hopkinson pressure bar (SHPB) technique and the plate impact technique as well as the dynamic finite element (FE) simulations were involved. The attention was focused on the effects of loading rate, hydrostatic pressure and microstructural heterogeneity on the load-carrying capacities of concrete. A recent publication by Li and Meng [4] expressed serious concern about the genuineness of the strain rate effects on compressive strength of concrete at strain rates between 10^1 and $10^4\,s^{-1}$, which challenged the current understanding of strain rate effects on the compressive behavior of concrete.

Brara et al. [5,6] investigated the dynamic tensile behavior for wet and dry concrete under high strain rates experimentally by spalling tests based on Hopkinson pressure bar technique and numerically by discrete element method (DEM). The strain rate sensitivity of tensile strength is demonstrated and a local damage cumulative criterion was proposed and implemented into the numerical analysis. In order to understand the mechanism of the dynamic spalling, it is preferable to design experiments and to develop analytical methods under simple stress states, such as the uniaxial tensile stress state. A well-designed dynamic tensile test may contain fundamental features of the tensile failure mechanisms of concrete and help to establish dynamic tensile failure model for concrete in general stress states. Mayers et al. [7] gave a comprehensive review on this subject.

In the present paper, the dynamical tensile strength of concrete is measured through a spalling experiment conducted on a Hopkinson pressure bar. It has obvious advantages compared with other experimental methods to measure the dynamic tensile strength of concrete. The dynamic tensile tests are supported by FE simulations with a concrete damage model.

2. Experiment principle and setup of dynamic tension

2.1. Experiment principle

The SHPB, as shown in Fig. 1, was presented in 1949 by Kolsky H, which could measure the time histories of stress, strain and strain rate. This technique has been modified into various versions to apply tensile force and torsion to the specimens in order to study the tensile and shear properties of the tested materials.

Different dynamic tensile test methods based on SHPB technique have been developed for different materials. A typical setup is the called SHPB, or SHTB, as shown in Fig. 2. It utilizes the reflection of the incident compressive stress wave at the free end of the incident bar to apply a tensile load to the specimen. Because of the complexity of the specimen shape and the requirement of the screw or clamp connection between the pressure bar and the specimen, uniaxial stress condition and other assumptions in a Hopkinson pressure bar test may be violated, which may influence the accuracy of the SHTB experiment.

When the tested materials, e.g., metals, have high dynamic tensile strength and good ductility, the SHTB test results are reliable. Otherwise, for brittle solids like concrete, SHTB measurements

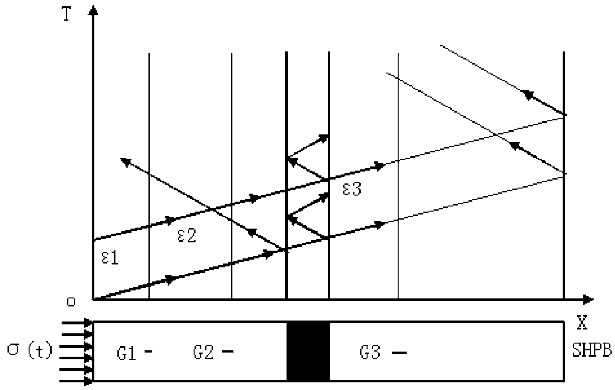

Fig. 1. The experimental principle.

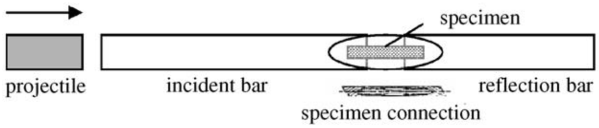

Fig. 2. Sketch of SHTB.

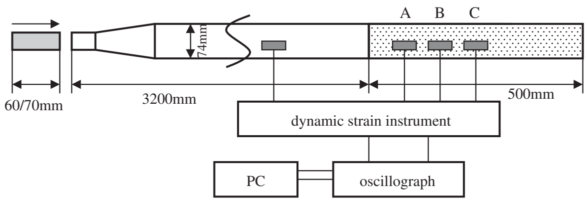

Fig. 3. The experimental setup for dynamic tension testing.

may contain non-negligible errors mainly due to the following three causes, i.e., (a) the low dynamic tensile strength of concrete, which requires a high rigidity of the experimental setup; (b) the brittle nature of concrete, which increases the difficulty for data processing and the repeatability of experiment; and (c) the difficulty of ensuring a good connection between the concrete specimen and the pressure bar.

In order to avoid these shortcomings of a conventional SHTB setup, a new SHTB setup is designed to test the dynamic tensile strength of concrete, as shown in Fig. 3. The new setup consists of a partially taped incident pressure bar and a long cylindrical concrete specimen. When the projectile is launched by the gas gun, it strikes the incident bar, and then the incident compressive wave is transmitted by the Hopkinson pressure bar into the long concrete cylinder, which is then reflected as a tensile wave at the free end of the concrete cylinder to cause spalling. The striking speed of the projectile should be considered to ensure the specimen does not suffer any compressive damage when the compressive stress wave passes through the specimen. With the strain–time signal recorded by strain gauge, the dynamic tensile stress can be calculated according the one-dimensional stress wave theory.

It is obvious that such experimental setup satisfies the one-dimensional stress condition in a Hopkinson pressure bar setup and avoids difficulties of specimen connections in a SHTB experiment.

2.2. Experimental setup

The actual experimental setup of the concrete spalling test is shown in Fig. 4, which consists of a gas gun, a cylindrical projectile of Φ 37 mm, a partially taped Hopkinson pressure bar of Φ 74 mm and a relatively long cylindrical specimen of concrete in contact with the pressure bar. The strain gauge on the incident pressure bar is a semiconductor gauge of SG6×9 mm with resistance of 120 Ω and sensitive coefficient of 110. The strain gauges on the concrete specimen are resistance gauges of BF120-8AA with resistance of 120 Ω and sensitive coefficient of 2.

In the present experiments, the diameter of concrete specimen is the same as the diameter of the incident pressure bar. The end surfaces of the concrete specimen are smooth and vertical to the axes of the specimen. The dimensions of the concrete specimen is $\Phi 74 \times 500$ mm, which is collinear with the incident pressure bar. A very thin layer of wet cement was added between the incident pressure bar and the concrete specimen to ensure a good connection between the specimen and the pressure bar before the compressive stress arrives. The concrete specimen and its end surface are shown in Figs. 5 and 6.

In order to separate the compressive and tensile waves, the strain gauge station should be positioned close to the incident end and adjusted according to the wavelength to ensure that the incident, transmit and reflected waves from the free end of specimen can be recorded separately. Brara et al. [3,4] investigated the dynamic tensile behavior for wet and dry concrete under high strain rates both experimentally by spalling tests based on Hopkinson pressure bar system and numerically by DEM. The high strain rate sensitivity of tensile strength was demonstrated and a local damage cumulative criterion was proposed and implemented into the numerical analysis.

Fig. 4. Experimental equipments.

Fig. 5. The concrete specimen.

Fig. 6. The concrete end surface.

Fig. 7. The concrete specimen pasted with strain gauge.

With the consideration of the possible wave dispersion in concrete specimen, three strain gauges were used in the present study as shown in Figs. 3 and 7.

3. Experiment

3.1. Quasi-static mechanical parameters

The quasi-static mechanical tests are carried out in the Beijing Institute of Science and Technology after the concrete specimens were maintained for 28 days. The mechanical properties of concrete are listed in Table 1.

3.2. Dynamic elastic modulus E of concrete

The elastic wave speed is measured using SHPB, $C = 3500\,\mathrm{m/s}$. Because the density of concrete is $2.44 \times 10^3\,\mathrm{kg/m^3}$ and the elastic longitudinal wave speed is determined by $C = \sqrt{E/\rho}$, the dynamic elastic modulus E of concrete is 42.87 GPa.

Table 1
The mechanical parameters of concrete

Density (kg/m^3)	Compression strength (Mpa)	Compression elastic modulus (GPa)	Poisson ratio	Bending strength (Mpa)	Bending elastic modulus (GPa)	Splitting strength (MPa)
2.441	34.09	13.81	0.156	3.080	12.09	2.689

3.3. Transmitted stress wave in the concrete specimen

The geometrical dispersion of stress wave in specimen will occur for the larger diameter of concrete [7]. Since the concrete is a viscoelastic material, both wave dispersion and wave attenuation phenomena will occur. In the present study, projectile length and dimensions of the taped section of the incident pressure bar are carefully designed to ensure that the transmitted stress wave in the concrete specimen is almost a half periodic sine wave. It is observed in experiments (as shown in Figs. 8 and 9) that the change of the stress wave shape is negligible, which implies that the geometrical wave dispersion is not significant. Therefore, only the stress wave attenuation should be considered in experimental data analyses, which could be done based on the measurements of three strain gauge stations at A, B and C in Fig. 3, shown in Figs. 8 and 9.

3.4. Measurement of dynamic tensile strength

The positive strain signal represents the incident compressive stress in a concrete specimen and the negative value denotes the tensile stress reflected from the free end. As described above, there exists amplitude attenuation. The attenuation coefficient α is defined as the relative change of stress amplitude with respect to spatial distance [8], i.e.,

$$\alpha = -\frac{1}{\sigma}\frac{d\sigma}{dx}. \tag{1}$$

The integration of Eq. (1) gives $\sigma = \sigma_0 e^{-\alpha x}$, where σ_0 denotes the stress amplitude at the end of the incident Hopkinson pressure bar.

Therefore, an exponent attenuation rule is used to describe the stress wave propagation. In this paper, the specimen is loaded by low-speed strikes two or three times before it is loaded at high strain rate to produce the spalling (see as Figs. 10 and 11). The average value of a set of α is defined as the attenuation coefficient of the specimen. The incident waveform at the free end (e.g., Fig. 12) is predicted according to the measured wave shape and the attenuation rule. If there is no tensile failure, a one-dimensional wave analysis can predict the reflected tensile stress wave from the incident compressive wave at the free end of the specimen [9] (e.g. Fig. 13). Therefore, the tensile stress distribution along the specimen can be obtained as a function of time, which can be used to give the maximum net tensile stress at any instant along the specimen, and thus, the nominal tensile strength of the concrete can be obtained through the measurement of the position of the first fracture, as shown in Fig. 14.

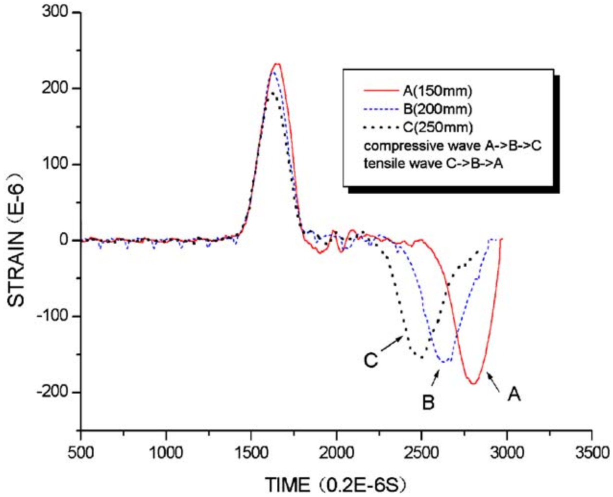

Fig. 8. The comparison of different location.

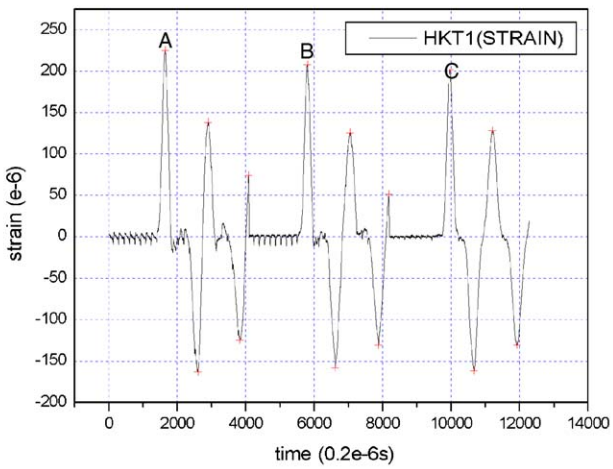

Fig. 9. The typical signal recoded on three sections.

The procedure to calculate the tensile stress along the specimen does not consider the stress attenuation. In the present study, it is assumed that the attenuation coefficient α of the reflected tensile stress wave is the same as that for compressive stress wave. Therefore, the actual dynamic tensile strength is the product of the nominal tensile strength and the coefficient $\beta(\beta = \exp(-\alpha Z))$ where Z is the distance of the spalling location to the free end of specimen.

3.5. Strain rate calculation

We found that the tensile modulus differs from the compression modulus. Figs. 8 and 9 show that the incident compressive waves are attenuated. However, the amplitude of the reflected

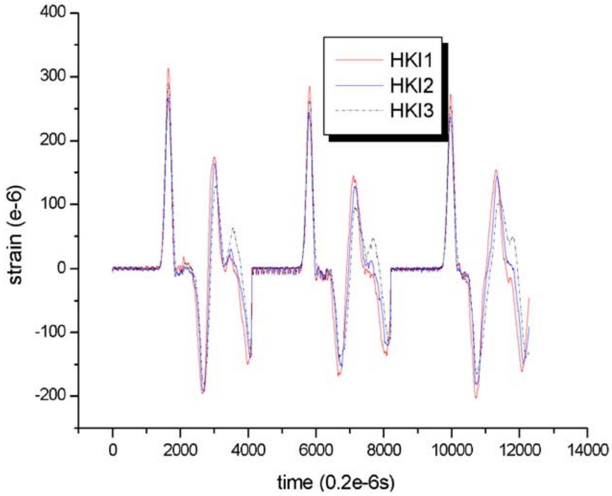

Fig. 10. The strain–time curves recorded of three sections loaded three times at low speed strike.

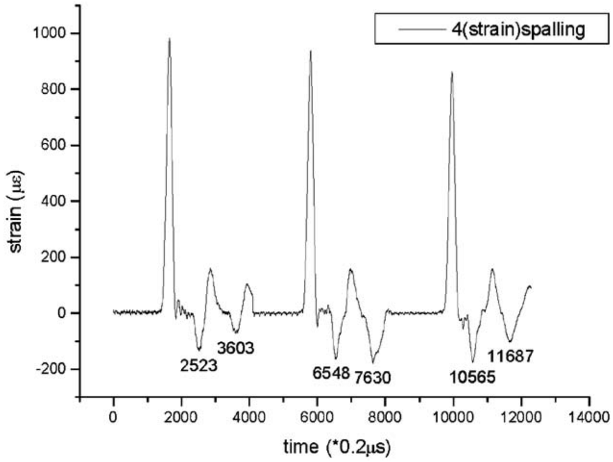

Fig. 11. Spalling strain–time curves of three sections.

tensile waves increases with the traveling distance. Since the increases of the amplitudes of the reflected tensile wave are based on the measurements of strain gauges, it actually indicates increased strains with the distance of travel. This strain increase is due to the damage growth in a concrete specimen, which suppresses the attenuation effect. This dynamic tensile modulus is calculated according to the following formula

$$E_{\mathrm{T}} = [\sigma_0 \mathrm{e}^{-\alpha(2L-x_i)}]/\varepsilon_{mi}, \tag{2}$$

where x_i is defined as the distance between the location of A, B or C and the connecting surface between the Hopkinson pressure bar and the concrete specimen. ε_{mi} is the corresponding tensile

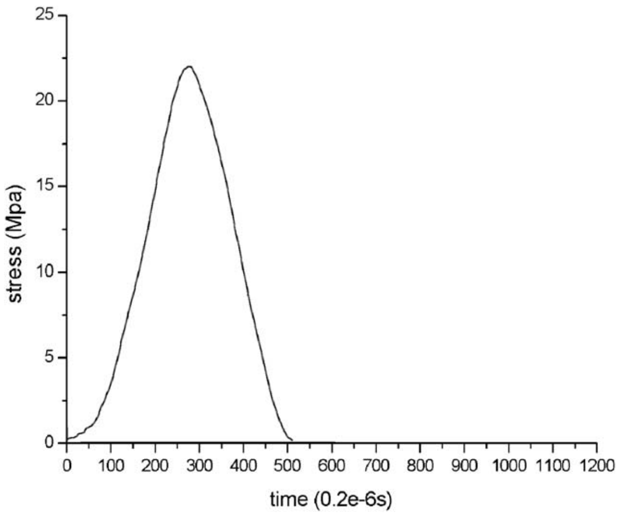

Fig. 12. Incident stress wave on free end.

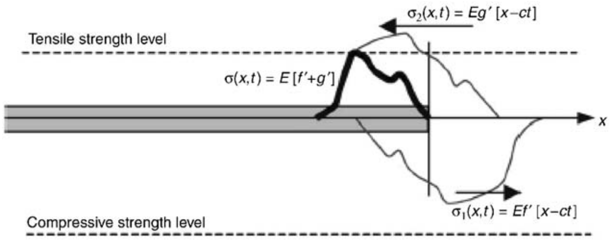

Fig. 13. The reflection of incident wave on the free end.

strain. L denotes the length of concrete specimen. The strain rate is obtained from the evolution of the stress in the location of the tensile crack by [9]

$$\dot{\varepsilon}_{\text{spalling}} = \frac{1}{E}\left(\frac{\partial \sigma_t}{\partial t}\right)_{\text{cracklocation}}, \tag{3}$$

where the fracture time is the time interval of the time at which the tensile stress occurs and the time at which the crack takes place.

4. Experimental results and analyses

Fig. 15 presents the variation of the dynamic tensile strength and the logarithm of strain rate from a series of experiments based on present experimental setup. It shows that the dynamic tensile strength of concrete increases with the increase of strain rate. Fig. 16 shows a typical tested concrete specimen.

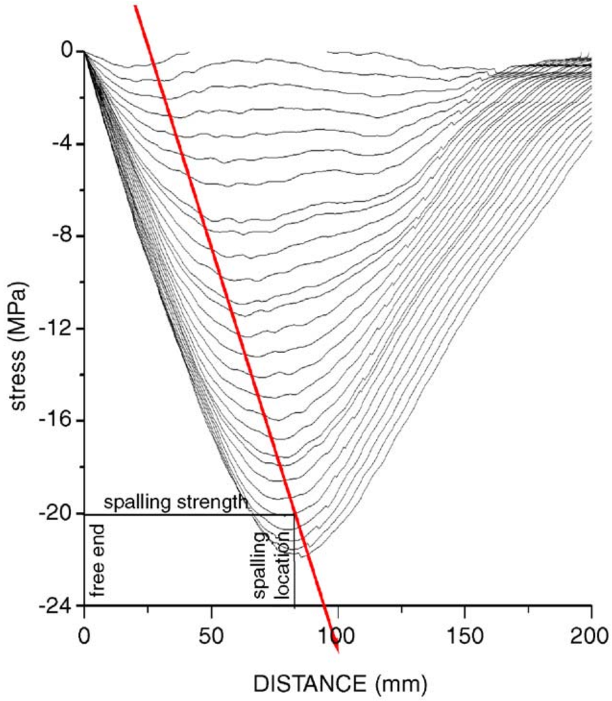

Fig. 14. The tensile stresses growth along the specimen used to obtain the tensile strength.

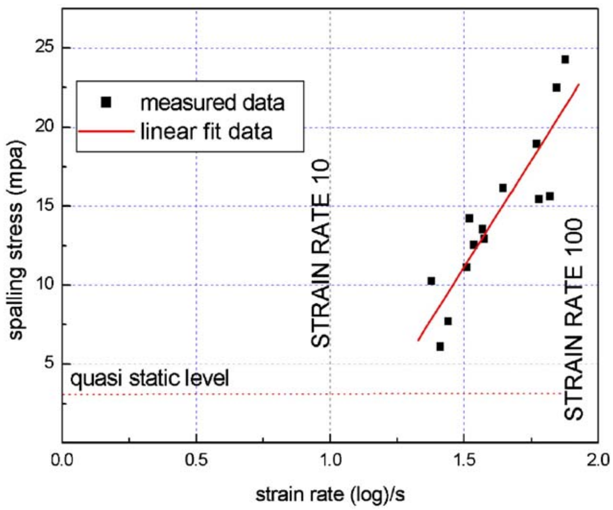

Fig. 15. Tensile strength as a function of the logarithm of strain rate.

The dynamic tensile strength of a concrete specimen is measured by a modified Hopkinsion pressure technique. The fractured section is relatively flat and perpendicular to the axes of specimen, as shown in Fig. 17. It is evident that the fracture of concrete is caused by the tensile

Fig. 16. The fractured specimen with one spall.

Fig. 17. The appearance of crack section of concrete specimen.

Fig. 18. The FE model of dynamic changed-section SHPB.

stress without visible distortion. It is found that there exist more cracked aggregates and the cracks approximately line up when the strain rate increases. Thus, the reason for the increase of the dynamic tensile strength with strain rate is that the interior cracks have not enough time to develop and the aggregates of concrete are cracked at high strain rate.

5. Numerical simulation

Dynamic tensile experiment of concrete is simulated to verify the continuum damage accumulation model [10,11], which has been implemented into the LS-DYNA user defined material model. Fig. 18 is the FE model with the ANSYS5.7 and the material parameter is obtained from the above experimental data. Fig. 19 shows the comparison between the simulation results and the experimental results about the dynamic tensile tests of concrete (spalling) for one typical experiment. Fig. 20 demonstrates the stress wave shapes obtained from simulation and

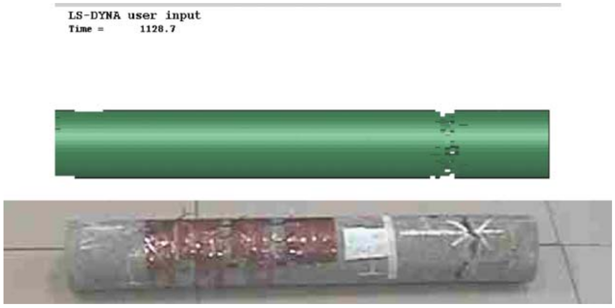

Fig. 19. Comparison between the simulation and experimental result for NO4.

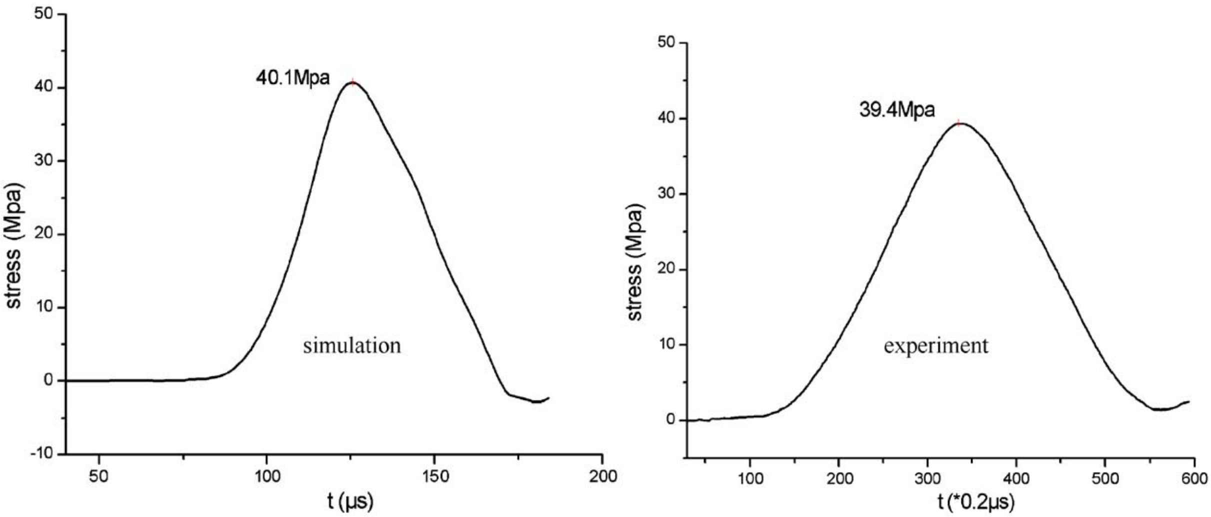

Fig. 20. Stress wave shape comparison between the simulation and experimental data.

Table 2
Concrete damage material parameters

ρ (kg/m^3)	E (GPa)	K (GPa)	G (GPa)	v	K (m^{-3})	m	Kic (MPa m$^{1/2}$)
2.441	13.81	6.69	5.97	0.16	6.565e20	5.0	2.07

experiment, respectively. It shows that the implemented continuum damage model is suitable to simulate the dynamic tensile fracture and the material parameters used in simulation are valid. So one set of material parameters, which are described in the references [10,11], is gained for the concrete material studied, as listed in Table 2.

6. Conclusions

It is important to investigate how concrete behaves during fast or impact loading in tension in engineering practice. Through this experimental investigation for the dynamic tensile strength testing of concrete, we can draw the following conclusions:

- The designed experimental method used for the concrete tensile strength overcomes the inherent disadvantage of the tradition SHTB method and is simple. The testing precision is high.
- The relation of dynamic tensile strength and strain rate is obtained through the newly designed method. The experimental results indicate that the concrete material has high strain rate sensitivity of the tensile.
- The simulation results have a good agreement with the experimental data, the exploited damage model can be used for the dynamic tensile simulation of concrete and the used material damage parameters are valid.

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