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An Experimental Study of the Dynamic Split Tension Properties of Reinforced Concrete

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Dynamic split tensile tests of reinforced concrete were carried out using the split Hopkinson pressure bar experimental technique to determine the failure modes of reinforced concrete at different strain rates, and the effect of reinforcement ratio and reinforcement layouts on the dynamic performance. The specimens with nine reinforcement ratios were used in the tests. Experimental results show that the tensile strength of reinforced concrete exhibits a critical strain rate, beyond which larger increases in dynamic strength of specimens occur. The dynamic split tension strength of reinforced concrete is demonstrated to be greater than the plain concrete with the same strength grade over the range of tested strain rate. The results also indicate that the dynamic split tension strength of specimens enhances with the increase of reinforcement ratio. These findings are instrumental to guide the structural design of reinforced concrete in engineering constructions.

Keywords: reinforced concrete, dynamic splitting tension, the split Hopkinson pressure bar, reinforcement ratio.

Introduction. Reinforced concrete has wide applications in structural engineering of military and civilian applications, due to its unique advantages including high compressive strength and simple processing. However, its relatively lower tensile strength and fragile character are major weaknesses for application. Rebar, as an auxiliary material, can partly improve the strength and bearing the capacity of concrete. Besides the basic load behavior, dynamic loading, including blast and shock loads, are currently a hot research topic [1].

Recently, investigations have focused on compressive performance [2–4]. There are scarce data on the dynamic tensile properties of the reinforced concrete. The split Hopkinson pressure bar (SHPB) technique was used to perform the direct tensile testing [5], while the split tensile test [6–8], and the compressive test [9–12] were used to determine the mechanical properties of the concrete cylinder. The experimental results show that under the tensile tests, the strain rates of the reinforced concrete vary from 0.1 to 20 s^{-1}; and the dynamic enhancement factor is 6.47 under the strain rate of 17.8 s^{-1}. Antoun [13] also determines the splitting tensile properties, the corresponding range of the strain rate is from $5 \cdot 10^{-7}$ to 70 s^{-1}, using the SHPB; and the experimental results reveal 4.8 is the corresponding dynamic enhancement factor of the reinforced concrete. In [14, 15], perform the dynamical tensile test under the strain rates from $1 \cdot 10^{-5}$ to $2 \cdot 10^{-2}$ s^{-1}, and the corresponding results show the tensile strength of concrete is increasingly reinforced with the strain rate.

In this study, the dynamic split tensile properties of the reinforced concrete were investigated experimentally using the variable cross-sectional straight taper SHPB apparatus. The relationships between the strain rate and the tensile strength of the reinforced concrete, and the effects of strain rate on the failure mode of specimens are analyzed. How the dynamical properties of the reinforced concrete are influenced by the reinforcement ratio and the reinforcement method is also discussed.

1. **Materials and Methods**.

1.1. ***Specimens***. Concrete/reinforced concrete materials were selected as the specimens. Cloth muscle was used by the circumference reinforcement and the axial reinforcement two methods. Heights of the internal and the external longitudinal reinforcements equal to 60 mm, whereas outer and inner stirrup diameters are 60 and 30 mm, respectively. Nine reinforcement ratios were used, i.e., 0, 0.998, 1.374, 1.621, 1.749, 1.996, 2.372, 2.619, and 2.995%. The reinforced concrete specimens were simply numbered by R_{abc}. Here R denotes that the base material is concrete, a is the number of the stirrups, b is the number of longitudinal bars, and c is the serial number of the specimen. For example, R_{692} means that this reinforced concrete specimen is the second specimen with six stirrups and nine longitudinal bars. The concrete specimens were numbered by the alphabet of c.

1.2. ***Experimental Protocol***. The static experiment was performed to determine the tensile strength of specimens using a servo-hydraulic test machine, and the test was terminated when the load achieved to 100 kN. The mean values of the tensile strength of the concrete and the reinforced concrete are 3.86 and 7.96 MPa, respectively.

The dynamic split tensile experiment was performed using the device of SHPB (Fig. 1). The diameter and the length of the SHPB used here are 74 and 800 mm, respectively. In the experiment, trip rod strikes the incident bar and then produces the compression stress wave, whose amplitude is dependent on the impact velocity and the wave impedance. This acting time is dependent on the length of the trip rod and the wave velocity. Adjusting the air pressure of the pistol, the different impact velocities were obtained and then the different strain rates were obtained. To get a more accurate data, the semiconductor gauge was used in this experiment. The corresponding incident, reflect, and transmission waves of the stress pulse of a specimen are shown in Fig. 2.

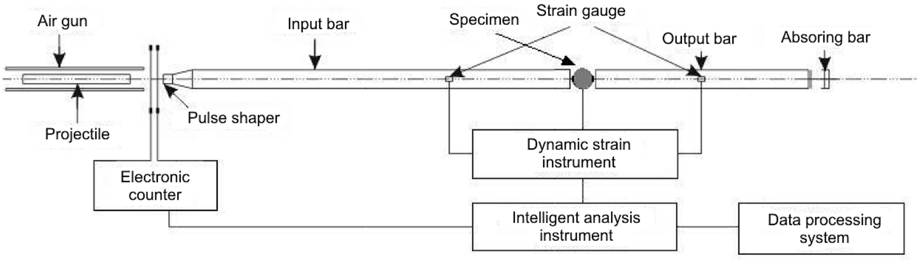

Fig. 1. The SHPB device scheme.

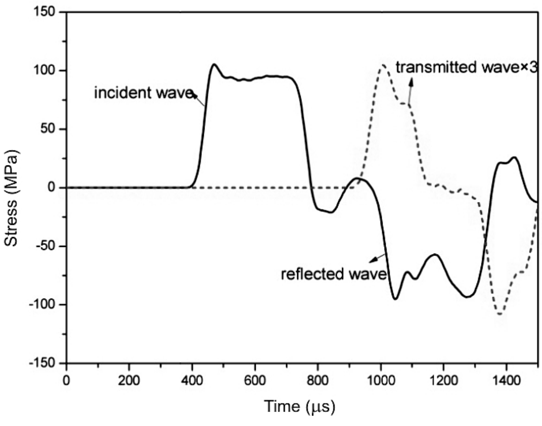

Fig. 2. Data trace from the SHPB dynamic split tension test.

1.3. ***Analysis Method***. The specimens were produced as the additional strap test specification of American Society for Testing and Materials. The additional strap can effectively reduce the stress concentration of the specimen. The tensile strength is defined as

$$f_{td} = 2P/\pi LD, \tag{1}$$

where

$$P = \pi R^2 \sigma_T , \tag{2}$$

where P is the maximum load measured through the test, L and D are the length and the diameter of the specimen, respectively, R is the SHPB diameter, and σ_T is the peak stress of the output bar.

The stress rate and the strain rate are respectively defined as

$$\dot{\sigma} = f_{td} / \tau, \tag{3}$$

$$\dot{\varepsilon} = \dot{\sigma}/E, \tag{4}$$

where τ is the rising time of the transmission wave and E is the Young modulus of the reinforced concrete specimen.

In this paper, the dynamic increase factor (DIF), which is defined as Eq. (5), is used to describe the enhancement effect of the concrete or reinforced concrete,

$$DIF = f_{td} / f_{ts}, \tag{5}$$

where f_{td} is the dynamic tensile strength and f_{ts} is the quasistatic tensile strength.

2. **Results and Discussion**.

2.1. ***Strain Rate Effect***. The corresponding experimental results of the dynamic splitting tensile tests are summarized in Table 1. The results as shown in Table 1 reveal that the strain rate effect is obvious in the specimens with different reinforcement ratios, i.e., the dynamic split tensile strength of concrete/ reinforced concrete is increasingly improved with the strain rate. The possible reason is the microcracks, which largely exist in the inner of the concrete/ reinforced concrete. Under the action of the external loads, crack in the inner core of the concrete/ reinforced concrete gradually evolves to damage. The shock load, in case of higher strain rates, acts during a short time period for a crack to bypass the aggregate and to extend in the weaker direction, and then the damage of the aggregate happens. This phenomenon can also be observed in the rupture surfaces of the specimens.

The relationship between the DIF and the strain rate, as shown in Fig. 3, reveals that the reinforced concrete has some effects of the strain rate under the dynamic loads. The DIF is correlated with the strain rate; its growth factor is approximately linear with the strain rate and the corresponding slope is nearly two. When the strain rate exceeds a certain value, which is defined as the critical strain rate, the tensile strength will sharply rise. In this paper, the fitted curve reveals this critical value is $\sim 2\ \mathrm{s}^{-1}$. Also, the experimental data are discrete due to the defects of materials, e.g., the inhomogeneity and the microcrack. The concrete/reinforced concrete are brittle materials. Prior to loading, the variation of the mortar volume happens due to the cement hydration induces the chemical and physical shrinkages. This is the reason for the disorder cracks appearing on the surface between the coarse aggregate and the mortar. Under the external loads, the stress concentration early happens in the crack defect and then the microcrack propagates across the specimen until the specimen damages.

Table 1

Collection of Experimental Data

Spec.	f_{td}, MPa	Stress rate (GPa/s)	Strain rates (s^{-1})	*DIF*	Reinforced concrete DIF
C3	4.38	31.79	1.33	1.13	1.00
C9	5.87	64.53	2.08	1.52	1.00
R23	8.35	96.55	1.87	1.05	1.62
R23	10.97	68.76	1.33	1.38	2.14
R26	9.48	80.02	1.99	1.19	1.85
R26	12.16	113.62	2.82	1.53	2.37
R29	11.78	106.58	2.78	1.48	2.30
R29	13.80	166.21	4.33	1.73	2.69
R43	10.90	113.34	2.88	1.38	2.14
R43	13.75	150.25	3.82	1.73	2.68
R46	12.74	126.12	3.71	1.60	2.48
R46	13.00	68.95	4.81	1.63	2.53
R49	14.56	168.23	3.88	1.83	2.84
R49	15.28	252.58	5.83	1.92	2.98
R66	12.26	139.35	3.61	1.54	2.39
R69	9.32	97.63	1.76	1.17	1.82

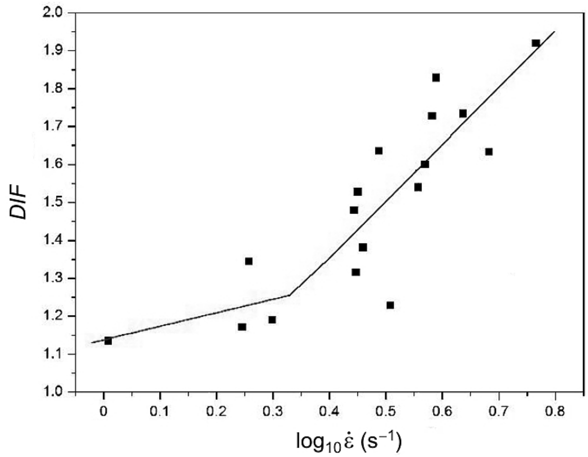

Fig. 3. Strain rate effects on the *DIF* of concrete.

2.2. ***Reinforcement Ratio Effect***. The failure mode and the quantitative experimental results were used to analyze how the reinforcement ratio influences the tensile strength of the reinforced concrete. Under the same strain rate, the concrete specimens completely break into two segments; while the reinforced concrete specimens crack rather than break due to the dynamic loads being counteracted by the reinforcements. The damage degree is gradually weakened with the reinforcement ratio (Fig. 4).


C9 R297 R491 R696

Fig. 4. Reinforcement ratio effects on failure pattern.

Different reinforcements have different influences on the tensile strength of the reinforced concrete. As the images shown in Fig. 5 at $v = 9$ m/s, the cooperation between stirrups and longitudinal bars directly influences the failure mode of the reinforced concrete. Setting the same number of the longitudinal bars, the specimen with two stirrups damages like that the concrete completely breaks from the center and the reinforcement does not break; while the specimen with four stirrups and six stirrups slightly crack rather than break. Therefore, the dynamical tensile strength of the reinforced concrete can be effectively reinforced by selecting the advisable cooperation between stirrups and longitudinal bars.


R291 R491 R691

Fig. 5. Reinforcement form effects on concrete failure pattern.

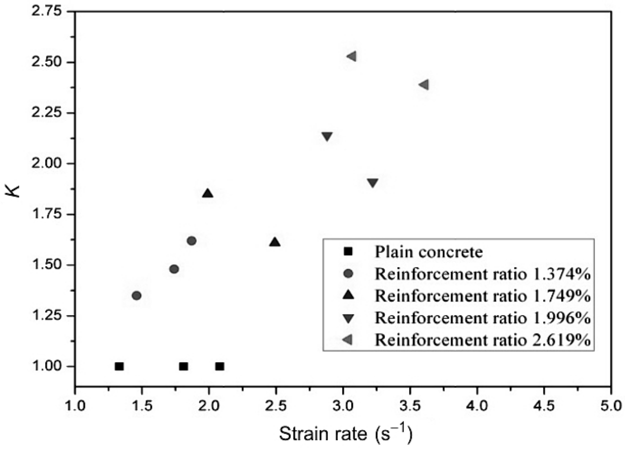

Fig. 6. Effect of strain rate on the reinforcement factor of concrete.

In order to quantitatively analyze how the reinforcement ratio influences the tensile strength of the reinforced concrete, the reinforced factor K, which is defined as the ratio between the dynamic tensile strengths of the reinforced concrete and the concrete, i.e., Eq. (6), is introduced to demonstrate the enhancement effect (Fig. 6),

$$K = f_{tr} / f_{tc}, \tag{6}$$

where f_{tr} and f_{tc} are the dynamic tensile strength of the reinforced concrete and the concrete, respectively.

The results shown in Fig. 6 reveal that the tensile strength of the reinforced concrete obviously stronger than that of the concrete. Under the same strain rate, the value of K increasingly grows with the reinforcement ratio. The corresponding reason is that rebar can effectively prevent the propagation of the crack and delay the damage time, and then reinforce the tensile strength.

Conclusions. In this study, the dynamic splitting tensile tests were performed on the nine different reinforcements to determine the tensile strength of the concrete/reinforced concrete. The corresponding experimental results reveal that the dynamic tensile strength of the reinforced concrete increasingly reinforces with the strain rate, and that will sharply reinforce after the strain rate beyond the critical value. Implanting rebar can effectively prevent the propagation of the crack and delay the damage time, and then availably reinforce the tensile strength of the reinforced concrete. Different reinforcements have different influences on the damage modes of specimens. Under the same strain rate, the damaged condition of specimens depends on the number of the stirrups. More stirrups can provide a better protection of the specimen.

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