Numerical Simulation on the Dynamic Splitting Tensile Test of reinforced concrete

Zhuan Zhao1,2, Haokai Jia2 and Lin Jing1,*

1 State Key Laboratory of Traction Power, Southwest Jiaotong University, Chengdu, Sichuan, China
2 Department of construction engineering, Yuncheng Polytechnic College, Yuncheng, Shanxi, China

*Corresponding author e-mail: jinglin@home.swjtu.edu.cn

Abstract: The research for crack resistance was of RC was based on the split Hopkinson bar and numerical simulate software LS-DYNA3D. In the research, the difference of dynamic splitting failure modes between plane concrete and reinforced concrete were completed, and the change rule of tensile stress distribution with reinforcement ratio was studied; also the effect rule with the strain rate and the crack resistance was also discussed by the radial tensile stress time history curve of RC specimen under different loading speeds. The results shows that the reinforcement in the concrete can impede the crack extension, defer the failure time of concrete, increase the tension intensity of concrete; with strain rate of concrete increased, the crack resistance of RC increased.

1. Introduction

Reinforced concrete, which is widespread applied in the civil and military engineering structures, is not only having the advantage of plain concrete (i.e., simple manufacture craft and good compressive property) but also improving the tensile property and bearing capacity by imbedding rebar. Actually, in addition to the static loads, the reinforced concrete structure inevitably bears the strong dynamic loads, e.g., explosion, impact, etc. Therefore, it has great significance to study the dynamic mechanical properties of reinforced concrete [1, 2]. Concrete material has complicated composition, small failure strain (~1%), and tensile strength mismatches compression strength (i.e., compressive strength is about 1/10 ~ 1/20 of tensile strength). Currently, the studies on the dynamical properties of concrete are mainly focused to the compression performance [3,4], less study takes account to dynamically tensile performance. Ross et al used the separated Hopkinson pressure bar (SHPB) to perform the direct tension, splitting tensile and compression tests (strain rates varied from 10-1/s to 20/s) of cylinder concrete specimens [5-7]. The corresponding results showed that when the strain rate was 17.8 / s, the dynamic strength of the specimen (the ratio of dynamic intensity and quasi-static intensity) reached 6.47. John also performed the splitting tensile test using SHPB, they obtained the dynamic strength was 4.8 under the strain rates from 5×10-7 /s to 70 /s [8,9].

For the sake of research the stress distribution of the reinforced concrete specimen under different dynamic split tensions, we determined the mechanical properties of reinforced concrete using the SHPB test and LS-DYNA finite element software.
2. Experimental protocol

2.1 Experimental method

Prior to do the dynamical test, we measured the tension strengths of reinforced concrete and plain concrete were 3.86 MPa and 7.96 MPa under quasi-static loading ($P_{\text{max}} = 100$ KN), respectively. The dynamical splitting tension intensity of reinforced concrete and plain concrete specimens were measured by cone-SHPB device with 74 mm diameter and 800 mm length (Fig. 1). Air gun was employed to produce different impact speeds to the specimens, and then the specimens responded the dynamical splitting tensile strength under different strain rates.

The formula for splitting tensile strength of the specimens with additional pad splits, according to stipulate of ASTM, is as follows:

\[ f_{st} = \frac{2P}{\pi LD} \]  \hspace{1cm} \text{Eq.1}

where, \( P = \pi R^2 \sigma_T \). \hspace{1cm} \text{Eq.2}

\( P \) is the maximum loading under testing, \( L \) is the longness of the specimen, \( D \) is the diameter of the specimen, \( R \) is the radius of the SHPB, \( \sigma_T \) is the output peak value of stress.

The stress rate and the strain rate of specimens respectively are

\[ \dot{\sigma} = f_{st} / t \]  \hspace{1cm} \text{Eq.3}

\[ \dot{\varepsilon} = \frac{\dot{\sigma}}{E} \]  \hspace{1cm} \text{Eq.4}

where, \( t \) is the ascend time of transfers stress wave, \( E \) is the reinforced concrete specimens’ elastic modulus.

2.2 Specimens

The testing specimens, including reinforced concrete and plain concrete materials, were distributed and reinforced along the circumferential and axial directions (with the longitudinal height of 60 mm, the outside stirrup diameter of 60 mm and the inside stirrup diameter of 30 mm) with 9 reinforcement ratios, i.e., 0.000%, 0.998%, 1.374%, 1.621%, 1.749%, 1.996%, 2.372%, 2.619%, and 2.995%. In order to facilitate the processing of experimental data and classification, we signed the specimens as $R_{ab}c$, in which $R$ was for the base material of concrete, $a$ was for the number of stirrups, $b$ was for the number of longitudinal reinforcement, and $c$ for the serial number of the specimens). In addition, the plain concrete is signed directly by C and subscript.
3. Finite element model

3.1 Modeling

This work used the cylinder concrete specimen finite element model (FEM) with 70 mm-length and 74 mm-diameter. Simplify, the model was shrunk into the reticulate frame with 2 mm-diameter rebar (i.e., 4 stirrups and 6 longitudinal bars). The geometry of model was as the same as the specimens (i.e., with the longitudinal height of 60 mm, the outside stirrup diameter of 60 mm and the inside stirrup diameter of 30 mm). The model was divided into three meshing parts, i.e., the inside layer 30 mm-cylinder stirrup is defined as Part I, the inner hoop is defined as Part II, and the outer hoop is defined as Part III. The meshed concrete and reinforced concrete model contained 61600 and 491025 eight node entity units, respectively. The FEM and the corresponding loading device were shown in Fig. 2 and 3, respectively.

The LS-DYNA material card, no. 96 * MAT_BRITTLE_DAMAGE, was used to describe the mechanical behaviour of plain concrete specimen with the elastic modulus \( E = 19 \text{ GPa} \), density \( \rho = 2140 \text{ kg/m}^3 \), Poisson ratio \( \nu = 0.19 \), the compressive strength of 38.9 MPa, the tensile strength of 4.91 MPa. Similarly, another card (* MAT_PLASTIC_KINEMATIC) was used to describe the mechanical property of steel bar (with \( E = 200 \text{ GPa} \), \( \rho = 7800 \text{ kg/m}^3 \), \( \nu = 0.30 \)). Additionally, the wave-guiding rod had the same mechanical parameters with the rebar (i.e., \( E = 200 \text{ GPa} \), \( \rho = 7800 \text{ kg/m}^3 \), \( \nu = 0.30 \)).

3.2 Modeling validation

Under the compression mode, the contact between the filter strip and concrete was locally failed by the vertical compression, and the other parts were failed by the uniform horizontal tension. During the testing, we observed the specimen was divided into two parts from center to side (Fig. 4 left). The simulation failure of FEM was also shown as the same mode, i.e., the failure initially happened in the center of model and then extended to side (Fig. 4 right). Fig. 4 showed the FEM was well fitted with the reality. Consequently, the validity of FEM was verified.

4. Results and Analysis

Fig. 4 Experimental and simulation failure modes of specimens in
4.1 The effect of reinforcement form on destructive mode

Steel frame embedded into concrete can partly prevent the crack propagation, delay the failure time and improve the tensile strength. Consequently, the reinforced concrete has different failure mode with the plain concrete under impact load. As shown in Fig. 5, reinforced and plain concrete specimens happen different failure modes under the same impact velocity (v = 6 m/s). The plain specimen completely divides into two parts, whereas the reinforce specimen just appears some micro-cracks (Fig. 4). This phenomenon suggests that reinforce concrete damages harder than plain concrete under the same nominal strain rate. The probable cause was the bonding and hooping effect of steel frame, which shared responsibility for some impact loads and then increased the resistance to impact damage.

4.2 Stress distribution in rebar concrete specimens

Fig. 6 shows the tensile stress distribution and failure mode of reinforce concrete under transverse compression at different moments. Stress pulse was firstly responded by the side of specimen near the input rod. During the stress pulse propagating, compression locally loaded on both sides of the specimen, while tension symmetrically loaded along the longitudinal direction of the specimen. Until the propagation at t = 0.89 ms, specimen centre achieved the limiting stress and crack happened. Crack increasingly grew larger with the adding of limiting stress points. The specimen completely was ruptured at t = 1.15 ms, and then was destroyed at t = 1.65 ms.

Comparison the simulation results, the plain concrete specimen was completely ruptured and could not bear any loads at t = 0.95 ms, whereas the reinforced specimen could still have a certain bearing capacity even if it was completely ruptured as t = 1.15 ms. This also implied that embedding steel frame could effectively prevent the crack propagation and then delayed the rupturing time of the specimen. Therefore, reinforce concrete has a higher tensile strength than the plain concrete.
4.3 Tensile stress

The curve of the tensile stress of different location in the specimens under different impact speeds were showed in Fig.7. The area between the specimen and filler strip was compression stress, and the area which perpendicular to compression diameter direction was uniform horizontal tensile stress. The tensile stress was increased with time increased. When the tensile stress reached the maximum, the specimen was damaged, and the tensile stress became smaller.
The curves of tensile stress $\sigma_y$ under individual impact speeds are different (in Fig.8). The tensile stress is larger with the bigger acceleration at the same time. According to Eq.3 $\dot{\varepsilon} = \frac{\sigma}{E}$ and Eq.4 $\ddot{\sigma} = \frac{f_{\text{int}}}{\dot{\varepsilon}}$, as $E$ is a constant, so the tensile stress increased with the strain rate increased (the acceleration increased).

![Fig.8 Profiles for the tensile stress along the horizontal diameter under different impact velocities($t=0.79ms$)](image)

### 4.4 The effect of reinforcement ratio

For the sake of quantitatively analyze the influence of reinforcement ration on the tension strength of concrete, in this work we introduced the concept of reinforcement dynamic enhancement factor $K$, which was a definition of as the ratio between the dynamically tensile strength of reinforce and plain concretes, to illustrate the enhancement effect.

$$K = \frac{f_r}{f_c}, \quad \text{Eq.5}$$

The $f_r$ and $f_c$ are the dynamically tensile strength of reinforce and plain concretes, respectively. The corresponding parameters in Eq. (5) under different loading velocities were summarized in Tab.1. In the table, it showed that the dynamically tensile intensity of reinforced specimen was obviously higher than the plain specimen. In addition, the enhancement factor trended to increase at first than decrease with the increasing loading velocity.

### Tab.1 Effect of the reinforcement ratio on the splitting tensile strength

| Impact velocity (m/s) | Tensile stress of concrete (MPa) | Tensile stress of reinforced concrete (MPa) | Increased factor of reinforcement |
|----------------------|---------------------------------|------------------------------------------|---------------------------------|
| 2                    | 4.16                            | 4.67                                     | 1.12                            |
| 3                    | 4.64                            | 7.23                                     | 1.56                            |
| 4                    | 5.1                             | 10.04                                    | 1.97                            |
| 5                    | 6.2                             | 12.20                                    | 1.97                            |
| 6                    | 7.2                             | 14.27                                    | 1.98                            |
| 10                   | 11.47                           | 17.82                                    | 1.55                            |
| 12                   | 12.39                           | 18.29                                    | 1.48                            |

### 5. Conclusion

This work analyzed the dynamically splitting tensile property of reinforce concrete using the LS-DYNA. We focused on the stress distribution and variation and verified the validity of dynamically splitting tensile experiment. The main conclusions are as follows:
(1) Under the dynamically splitting tensile test, the reinforced concrete has increasingly enhanced its dynamically tensile strength with the strain ratio.

(2) Under the same nominal strain rate, the tensile strength of reinforced specimen is obviously higher than the plain specimen. The probable reason is that embedding steel frame can partly prevent the crack propagation and delay the rupturing time, and then enhance the tensile strength of concrete.

Acknowledgments
This work was financially supported by National Natural Science Fund 51475392.

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