Experimental investigation on the velocity of the secondary fragments of reinforced concrete slabs under intensive dynamic load

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Abstract. The initial velocity of the secondary fragments of reinforced concrete slabs under blast loading is the basic data for the analysis of damage effect and it can also serve as important basis for the damage evaluation. In this study, three different types of reinforced concrete target slabs with different thicknesses were designed and prepared. These target slabs were investigated by local damage effect tests, the flying processes of the produced secondary fragments were recorded, and the velocities of the secondary fragments corresponding to different collapse coefficients were calculated by fragment back tracking. The results demonstrate that the initial velocity of the fragments was lower at a larger collapse coefficient. Based on the dimensional analysis results, the empirical formula of the initial velocity of the secondary fragments was derived. The errors between the calculated values according to the empirical formula and the experimental data were compared and found to be within 16% at a collapse coefficient in the range 1.20–3.20m/kg¹/³. Thus, the derived empirical formula can be used for predicting the initial velocity of the secondary fragments produced during the collapse of reinforced concrete slabs and also providing insightful reference for analyzing the damage power of the produced secondary fragments.

1. Introduction
Currently, a great deal of research has been conducted on the damage effect of the fragments produced in target destruction especially under the explosive shock wave and in the rapture of warhead. The related research results on weapon destruction have demonstrated that, in addition to the damages to the target caused by the primary fragments formed in the rapture of warhead, the secondary fragments can also cause damage. In recent several local wars, most of the protective projects with reinforced concrete structures easily suffered damages from the secondary fragments, thereby causing noticeable damages to personnel, equipment, and structures [1].

Both primary and secondary fragments are produced during conventional warhead explosion process. Primary fragments are mainly produced from the explosive packages or the materials in direct contact with the explosive, exhibiting a series of characteristics such as high initial velocity, great number, and small size. Secondary fragments are mainly the spattered materials from the nearby equipment or damaged elements from the crushed objectives induced by the explosion of explosive or projectile penetration. Compared to the primary fragments, secondary fragments are smaller in number and have greater mass and low velocity, which also include a variety of materials such as wood,
concrete blocks, and the components of electronic instruments and equipment. Secondary fragments in general have poor penetrability, but can cause damages to structures, personnel, and equipment especially electronic equipment only via the transfer of kinetic energy during the impact process [2]. In recent years, the damage effect of the primary fragments have been thoroughly investigated [3–5]; however, with regard to secondary fragments caused by the impact-induced and explosion-induced collapse of concrete structures, most of the studies only focused on the failure characteristics on the slabs [6,7] and rarely investigated the secondary fragments produced during collapse. LI Wenbin et al. focused on the distribution rules of the secondary fragments produced when the projectile penetrated the surface-processing-hardened target plate with finite thickness at a great inclination angle and examined the formation mechanism of secondary fragments [8]. WANG Haifu et al. conducted numerical simulation on the distribution of secondary fragment clouds when the cylindrical tungsten projectiles collided with the armored target plate and acquired the distribution characteristics of the penetration hole diameter, the motion velocity at the front end of the fragment cloud, lateral expansion velocity, and the maximum splashing angle at different collision velocities; moreover, they established the prediction models of mass and spatial distribution pattern of the secondary fragment clouds [9]. LIU Shuhui et al. carried numerical calculation on the secondary fragments produced in high-velocity impact and collision process and also investigated the related after effect, which can provide a way of analyzing the production and after effect of the secondary fragments [10]. The damages to the targets caused by the secondary fragments produced in the explosion-induced collapse of the reinforced concrete slabs mainly depend on some of their characteristic parameters such as velocity, mass, and shape. The initial velocity of the secondary fragments is the main parameter that affects the damage effect. This study selected TNT explosive and performed contact explosion experiments on the reinforced concrete slabs. The flying process when the secondary fragments were produced during the collapse of the reinforced concrete slabs was depicted, and the velocity of the secondary fragments was calculated by the back tracking method. Next, the empirical formula of the initial velocity of the secondary fragments was derived via dimensional analysis, and can be used for predicting the initial velocity of the secondary fragments produced in the collapse process. Furthermore, this study can provide reference for analyzing the damage ability of the secondary fragments.

2. Experimental setup and test method

The present experimental setup shown in figure 1 mainly consists of the explosive, reinforced concrete target slabs, a steel supporting frame, a high-speed camera, and a background screen. Three different types of the reinforced concrete target slabs with different thicknesses (80, 150, and 300 mm) were designed. The size of the target slab was 1,000 × 1,000 mm², and the sectional reinforcement ratio ranged from 0.3% to 1.25%. For the targets with a thickness of 80 mm and 150 mm, φ6 round steel bars were arranged in two layers. The target with a thickness of 300 mm included φ10 round steel bars in two layers. The mesh sizes of the reinforced steel bars were 200 ×200 mm², 150 ×150 mm², and 100 ×100 mm². The concretes used have a strength grade of C40 were used and the concrete protective layers of 15 mm in thickness. Table 1 lists the characteristic and dimension of the concretes. The steel supporting frame for fixing the target was welded by U-steel with a width of 20 mm and a thickness of 5 mm. In addition, the steel supporting frame was anchored to the concrete ground with the bolts with a diameter of 30 mm, and the anchorage depth was no less than 300 mm to avoid deformation or displacement during the explosion.
Figure 1. Illustration of the experimental setup.

Table 1. Mix proportion of the concretes.

| Strength grade | Water-cement ratio | Water (kg/m³) | Cement (kg/m³) | Sand (kg/m³) | Stone (kg/m³) |
|----------------|--------------------|--------------|----------------|-------------|--------------|
| C40            | 0.43               | 195          | 453            | 613         | 1189         |

In order to only observe the velocity of the secondary fragment, TNT explosive cylinder was placed, and the center of the target slab was pressed again. During the explosion, the secondary fragments of the concrete slabs were thrown and crossed the view field of the high-speed camera. In order to obtain the detailed view field of the fragment beam, a high-speed camera was arranged 6 m away from the side of the ejected axis of the fragments for picture recording. The shooting velocity of the high-speed camera was set as 5,000 frames/s. The view field covered the whole process from the initial ejection to flying and landing. The white background screen was also arranged for the convenience of high-speed shooting. 300 × 300 mm² mesh lines were plotted on the screen. The velocity of the fragments was determined by combining the continuous images captured by the high-speed camera regarding the trajectory and position of the fragments, the mesh lines of the background screen, and the number of image frames.

3. Experimental results and analysis

When the reinforced concrete slabs were subjected to the explosion at a close range, the compressed pulse load with a high peak and short duration was produced in the slab. When the compressed pulse encountered the tensile wave reflected by the structure’s internal surface, fairly high tensile stress was produced at a certain position on the adjacent free surface. Once the dynamic fracture criterion was satisfied, the material was raptured at this position, and the structure on the side of the concrete slabs back to the explosive source extensively peeled off and collapsed. When the crack was sufficiently large, the whole fragment can fly away with certain kinetic energy, i.e., producing the secondary fragments. For the contact explosion, the critical collapse thickness of the reinforced concrete slab was calculated by Eq.(1):

$$h = K_Z m^{1/3} - e$$

Where $h$ denotes the thickness of the concrete slab, with a unit of m; $e$ denotes the distance of the explosive center from the upper surface of the concrete slab, with a unit of m; $m$ denotes the explosive payload, with a unit of kg; $K_Z$ denotes the collapse coefficient.

In general, when $K_Z < 0.38$, the concrete slabs exhibit explosive-induced collapse failure mode, i.e., producing secondary fragments [12]. Accordingly, the thickness of the reinforced concrete target slab, the equivalent explosive charging mass, and the explosion distance were designed within these ranges. In this study, the reinforced concrete target slabs were subjected to 12 rounds of experiments, during which the collapse coefficient was set at different values. The effective data in 11 rounds of the experiments were obtained, as listed in table 2.
As described above, the explosion and the flying processes of the produced secondary fragment were shot using a high-speed camera. Figure 2 shows the flying process of the secondary fragments from No. 1 to 4 concrete target slabs. When the explosive contacted the reinforced concrete target slabs and exploded, the detonation wave rapidly acted on the target slab, and a beam of collapsed secondary fragment was produced around the explosive at \( t=10 \text{ms} \). The length of the fragment beam occupied 1.5 mesh lines. The velocity of the fragment head was approximately 150 m/s. At \( t=20 \text{ms} \), the fragment beam still flew along the focused trajectory, and only a few fragments scattered. At that moment, the whole fragment beam occupied six meshes. The velocity of the fragment head was calculated as approximately 135 m/s. Afterwards, the velocity of the fragment beam dropped during the flying process. At \( t=50 \text{ms} \), the velocity of the head of the fragment beam decreased to approximately 95 m/s, and the circumferential action range of the fragment beam also expanded.

**Table 2.** Some parameters of different target slabs and velocity of the produced secondary fragments.

| Serial number | Thickness of the target slab/mm | Reinforcement form/mm | Distance between the explosive charging center and the surface of the target slab/mm | Explosive payload/kg | Collapse coefficient/m\(^{1/3}\)/kg | Maximum fragment velocity/ms\(^1\) |
|---------------|--------------------------------|-----------------------|-----------------------------------------------|---------------------|--------------------------|-----------------------------|
| 1-1           | 1000×1000×80                   | 100×100               | 12.5                                          | 0.2                 | 0.158                    | 125                         |
| 1-2           | 1000×1000×80                   | 100×100               | 25                                            | 0.4                 | 0.143                    | 136                         |
| 1-3           | 1000×1000×80                   | 100×100               | 20.8                                          | 0.6                 | 0.120                    | 214                         |
| 1-4           | 1000×1000×80                   | 100×100               | 37.5                                          | 0.6                 | 0.139                    | 150                         |
| 2-1           | 1000×1000×150                  | 150×150               | 25                                            | 0.4                 | 0.238                    | 57                          |
| 2-2           | 1000×1000×150                  | 150×150               | 25                                            | 1.2                 | 0.165                    | 115                         |
| 2-3           | 1000×1000×150                  | 100×100               | 25                                            | 0.8                 | 0.189                    | 107                         |
| 2-4           | 1000×1000×150                  | 100×100               | 12.5                                          | 0.4                 | 0.221                    | 75                          |
| 2-5           | 1000×1000×150                  | 100×100               | 12.5                                          | 0.2                 | 0.278                    | 40                          |
| 3-1           | 1000×1000×300                  | 200×200               | 37.5                                          | 1.2                 | 0.318                    | 28                          |
| 3-2           | 1000×1000×300                  | 200×200               | 32.5                                          | 1.4                 | 0.297                    | 39                          |

**Figure 2.** The screenshots of videos during the flying processes of No. 1–4 target slabs.
4. Analysis of the initial velocity of the secondary fragment

The mechanical questions during explosion are effectively solved by dimensional analysis. The multivariable function is reduced to dimensionless function with less variables, but it can reflect basic function, and simple empirical formula can be established via experimental data fitting [13]. By analyzing the test results, the reinforced concrete target slabs were determined by a lot of factors mainly including the velocity of the secondary fragments produced in explosion-induced collapse, the explosive payload, the distance between the explosive charging center and the upper surface of the target slab, the thickness of the target slab, and mechanical properties of the concrete slabs (such as strength, density, wave velocity, and reinforcement ratio). Table 3 lists the variables affecting the initial velocity of the secondary fragments and the related dimensions.

Table 3. Parameters affecting the initial velocity of the secondary fragment and the related dimensions.

| Variable | Basic dimension |
|----------|-----------------|
| Initial velocity of secondary fragment $V$ | \( LT^{-1} \) |
| Distance between the charging center and the lower surface of the target slab \( (H+e) \) | \( L \) |
| Tensile strength of the target slab materials \( f_t \) | \( ML^{-1}T^{-2} \) |
| Density of target slab \( \rho \) | \( ML^{-3} \) |
| Elastic wave velocity in the target slab \( C_t \) | \( LT^{-1} \) |
| Explosive payload \( C \) | \( M \) |

The functional relationship between the initial velocity of the produced secondary fragments in explosion-induced collapse, denoted as $V$, with the parameters in table 3 can be written as:

$$ V = f(H_h, f_t, \rho, C_t, C) $$

(2)

By setting the explosive payload $C$, denotes the density of target slab $\rho$, and the wave velocity denotes $C_t$ are the foundation quantities and mean initial velocity $V$, the distance between the charging center and the lower surface of the target slab $H_h$ and the tensile strength $f_t$ as the derived quantities, a dimensionless relationship can be written as:

$$ \frac{V}{C_t} = f\left(\frac{H_h}{C_t^{0.33} \rho^{1.33}}, \frac{f_t}{C_t^2 \rho}\right) $$

(3)

Since $H+e=H_h$, Eq. (3) can be rewritten as:

$$ V = C_t f_t \left(K_z \rho^{0.33}\right)f_2 \left(\frac{f_t}{C_t^2 \rho}\right) $$

(4)

Same materials with same reinforcement ratios were used in the model and prototype tests. After the parameters of the test target slabs were determined, $C_t, \rho, f_2 \left(\frac{f_t}{C_t^2 \rho}\right)$ were constant. Therefore, $j$ was defined as the influence coefficient of the target slab materials, i.e., $j = C_t f_2 \left(\frac{f_t}{C_t^2 \rho}\right)$, and Eq. (4) can be rewritten as:

$$ V = k_j f_t \left(K_z \right) $$

(5)
Two undetermined coefficients $k_1$ and $j$ in Eq. (5) can be merged into one undetermined coefficient $k$ that can be experimentally determined. Therefore, Eq. (5) can be rewritten as:

$$V = k f_j \left( K_z \right)$$

Based on the test data in this study, the following expression was obtained via fitting:

$$V = \frac{4.85}{K_z^{0.12}} \cdot 0.12 \leq K_z \leq 0.32$$

According to Eq. (7), the variation in the initial velocity of the secondary fragments with the collapse coefficient was calculated, as shown in figure 3. Table 4 lists the error between the experimental data and the calculated values. Except No. 3-2 target slab, the errors of the other target slabs were less than 16%, suggesting that empirical Eq. (7) can adequately predict the initial velocity of the secondary fragments from the reinforced concrete slabs when $0.12 \leq K_z \leq 0.32$. The significantly large error for No. 3-2 target slab may be attributed to the deviations in the experimental shooting and calculation process.

![Figure 3. Variation in the initial velocity of the secondary fragments with the collapse coefficient.](image)

**Table 4.** Errors between the experimentally measured velocity of the secondary fragments and the calculated data.

| Collapse coefficient (mkg$^{-1/3}$) | Initial velocity of fragments /ms$^{-1}$ | Error (%) |
|-------------------------------------|----------------------------------------|-----------|
|                                     | Measured value                         | Calculated value according to Eq. (7) |
| 0.12                                | 214                                    | 201.24    | 5.96      |
| 0.139                               | 150                                    | 155.43    | 3.62      |
| 0.143                               | 136                                    | 147.87    | 8.73      |
| 0.158                               | 125                                    | 124.09    | 0.73      |
| 0.165                               | 115                                    | 114.99    | 0.01      |
| 0.189                               | 107                                    | 90.57     | 15.35     |
| 0.221                               | 75                                     | 68.80     | 8.26      |
| 0.238                               | 57                                     | 60.40     | 5.97      |
| 0.278                               | 40                                     | 45.97     | 14.93     |
| 0.297                               | 39                                     | 40.93     | 4.94      |
| 0.318                               | 28                                     | 36.29741  | 29.63     |

5. Conclusions
The local damage to the reinforced concrete slabs under blast loading is a complex dynamic problem involving a wide range of processes. The related failure mechanism and the characteristic parameters of the produced secondary fragments can hardly be calculated strictly according to the relevant
theories. Based on the experimental results of this study, the empirical formula of the initial velocity of the secondary fragments was derived by combining the dimensional analysis and the test data. The main conclusions of this study are described below.

1) By performing local damage tests on the reinforced concrete target slabs under blast loading, this study recorded the flying process of the produced secondary fragments in the collapse process and calculated the velocities of the secondary fragments under different collapse coefficients. The greater the collapse coefficient, the lower the initial velocity of the fragments.

2) The factors that affect the initial velocity of the secondary fragments were analyzed based on the experimental results. The variation in the initial velocity of the secondary fragments with different parameters was deduced via dimensional analysis. In combination with the experimental data, the empirical formula of the initial velocity of the secondary fragments from the reinforced concrete slabs was derived by data fitting. The errors between the calculated and the measured results were less than 16% when \(0.12 \leq K_c \leq 0.32\).

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