Punching Shear Failure Regulation of Reinforced Concrete Beams Subjected to Close-in Explosion

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Abstract. Aiming at the damage effect of reinforced concrete beams subjected to close-in explosion, numerical simulation and dimensional analysis are carried out to study the damage of beams under close-in explosion with spherical charge. The damage characteristics of beams were obtained by the methods of AUTODYN and DYNA. Using dimensional analysis, the relationship between the damage characteristics of reinforced concrete beams and the stand-off distance is deduced. The empirical equation of the beam punching shear failure characteristics is fitted on the basis of numerical simulation. The results show that the simulation method is more efficient than the fluid-solid coupling calculation; the proposed empirical equation is in good agreement with the experimental results. The relationship between failure width and the stand-off distance obtained by the fitting and the modelling method have reference value for the research on the damage effect of reinforced concrete beams.

1. Introduction
Accidental explosions and terrorist attacks occur from time to time. Reinforced concrete beams are the key load-bearing components of construction facilities. Studying its response and damage characteristics under explosions is of great significance to damage analysis and safety design. During a close-in explosion, the beam structure is in the detonation product area and is coupled by multiple field loads such as shock waves, detonation products, and heat. The evolution law of beam surface load and structural response is very complicated, and it is difficult to accurately describe it through analytical methods. Research is often carried out through experiments or numerical simulations.

Scholars have carried out a large number of simulations on reinforced concrete beams under explosions, but the simulation results are affected by material models and erosion. Under the condition of similar reinforcement ratio, material and size, 1.63kg TNT equivalent caused severe punching shear failure of the beam [1] while 4kg TNT equivalent caused slight damage [2], so numerical simulation needs to be established on the basis of experiments. Zhou [3] used DYNA to verify the experiment conducted by Wang [4]. The simulation obtained the beam deflection and the damage length of the mid-span area to be in good agreement with the experiment, and they used numerical simulation to study the damage of the beam by the span-to-height ratio. Gholipour [5] simulated the failure of reinforced concrete beams under the combination of close-in explosion and impact load by finite element, and studied the changing trend of the failure characteristics of the beams under different loading modes. Wang [2] found that the length of the beam concrete failure zone and the degree of deformation of the steel bar are approximately scaled to the 1/3 power of the explosive amount using numerical simulation. Wang [4] divided the beam damage criterion based on the scaled distance.
According to experiments, Wang [6] proposed that the local damage parameter and the charge amount are approximately linear. Yao [7] fitted the relationship between the flex-thickness ratio and scaled distance and stirrup ratio, reinforcement ratio[8], concrete strength, and explosive size all affect the failure mode of beams, but most of them were qualitative analysis. Related studies had analysed the influence of these parameters on the failure mode of beams, but no quantitative conclusions have been given.

Fluid-solid interaction is a common method for numerical simulation, but the solution has strict requirements on the grid size. In order to avoid leakage of explosive fluid into the concrete, the structural grid should be smaller than the fluid grid size or increase the coupling point, which will increase the calculation time. The keyword LOAD BLAST in DYNA is only applicable to where the scaled distance is greater than 0.2 m/kg$^{1/3}$. When the scaled distance or the standoff distance is small, the pressure curve calculated by CONVEP has a large error with the actual situation. In order to improve the solution speed and accuracy of the simulation results, Yu [9] and Yan[10] used the principle of equal impulse to simplify the explosion load into a uniformly distributed load applied to the reinforced concrete column. This method avoided modelling the air domain. Modelling had greatly improved the calculation efficiency. However, due to over-simplification [10], the simulated concrete column produced compressive failure at the support. This failure did not occur in the test, but this provides a way to calculate the reflection overpressure on the beam surface and solve the response of the beam separately, the key lies in the accurate description of the overpressure and the reasonable selection of the material model of the beam. In terms of overpressure, Wang [11] compared the time history curve of the target point reflection overpressure obtained by AUTODYN simulation and experiment. The peak size and arrival time of the reflection overpressure of the two are in good agreement, and AUTODYN has been used to obtain Overpressure of various explosives [12]. As a typical material, reinforced concrete has a material model suitable for explosive conditions in DYNA.

To sum up, in order to obtain the damage law when the beam is severely damaged and improve the efficiency of numerical simulation, this article uses a method to analyse the damage of the beam under close-in explosion. The method mainly includes the following two aspects: I Calculating the explosion load by AUTODYN; II simulating the response of the beam in DYNA; then verifies the validity of the numerical simulation according to the experiment; Uses dimensional analysis to deduce the relationship between the size of the damage area of the front and back explosion surface of the beam and standoff explosion. On the basis of numerical simulation, the damage area and standoff distance are fitted, and the empirical equation of the fitting is verified according to the experiments in other documents.

2. Numerical Simulation of Reinforced Concrete Beams

2.1. Calculation of Beam Surface Pressure Load
AUTODYN is used to simulate the spherical explosion of a 1kg TNT charge. The material parameters used are all taken from the material model library that comes with AUTODYN. The initial internal energy of air is 2.068*10$^2$kJ/g, explosive is TNT, central detonation of spherical charge, and the density is 1.63g/cm$^3$. Symmetrical modelling is adopted, air and explosives are Euler grids, and unit length is 1mm. The reflection of the shock wave on the beam surface and the symmetrical boundary are simulated through total reflection boundary, and the other two sides are the outflow boundary conditions. The gauges are used to obtain the reflection overpressure time history curve of the beam surface under different standoff distances. Since the shock wave distribution on the beam is approximately exponential, the distance between gauges gradually increases. The numerical model and the distribution of gauges are shown in figure 1.

Figure 2 shows the calculated time history curve of reflected overpressure at the mid-span position of the standoff distance of 0.2m. When the shock wave reaches the surface of the beam, the reflected pressure rises to the peak instantaneously, then the pressure drops, attenuates to the ambient pressure and forms a negative pressure section, and gradually return to atmospheric pressure (Solid line). In
order to verify the simulation method, it is agreed in the calculation: Ignore the rise time of the shock wave, that is, when the shock wave reaches the surface of the beam, it reaches the peak value, and the time when the reflected overpressure begins to change is taken as the time \( t_a \) when the shock wave reaches the surface of the beam; The time history curve is simplified to linear according to the principle of equal impulse and the negative pressure section is ignored (Dotted line);

![Computational model of reflection overpressure](image1)

**Figure 1.** Computational model of reflection overpressure.

![Overpressure time history curve of mid-span reflection](image2)

**Figure 2.** Overpressure time history curve of mid-span reflection.

Using MATLAB to obtain the specific impulse \( i_j \) of gauges, the method is \( i_j = \sum P_i dt \), reflected overpressure peak \( P_{\text{max}} \), overpressure arrival time \( t_a \), in which environmental pressure is reduced when calculating the specific impulse and reflected overpressure peak.

Write the standoff distance, specific impulse, and shock wave arrival time of each gauge into DYNA, and obtain the peak reflected overpressure, shock wave arrival time and specific impulse of each position on the beam through linear interpolation (1), and then use the principle of equal impulse to calculate the positive pressure action time \( t_d \), see equation (2):

\[
\varphi = \left( \varphi_{n+1} - \varphi_n \right) \left( Z - Z_n \right) \left( S_{n+1} - S_n \right)^{-1} + \varphi_n \quad (1)
\]

\[
t_d = 2i / P_{\text{max}} \quad (2)
\]

Where \( \varphi \) is the parameters \( (P_{\text{max}}, i_j, t_a, t_d) \), \( S \) is the standoff distance, \( Z \) is the scaled distance. The reflected pressure \( P \) at any time is calculated by the following equation:

\[
\begin{cases}
P = \left[ P_m - P_m \left( t - t_a \right) \left( t_d - t_a \right)^{-1} \right], & t_a < t < t_d \\ P = 0, & \text{others} \end{cases} \quad (3)
\]

### 2.2. Numerical Simulation of Beam Response

Using DYNA to study the local failure characteristics of reinforced concrete beams under close-in explosions, using a separate modelling method. Due to the load and beam symmetry, a 1/2 model was established along the beam axis. According to the dimension and boundary condition of the beam in the experiment, the model is built. Concrete and fixing devices use SOLID165 elements, and steel bars use BEAM161 elements. The keyword BEAM IN SOLID is used to couple those. Defining the contact between the fixed devices and beam, and the symmetry boundary conditions are imposed on the symmetry plane. Since there is no air domain, the number of grids has dropped significantly, so a more
refined grid is used to solve the response of reinforced concrete beams, and the unit is 2.5mm, a total of 880,816 units. The simulation model is shown in figure 3.

![Figure 3. Simulation model of reinforced concrete beams.](image)

The concrete adopts the K&C model, the steel bar adopts bilinear elastoplastic model, and fixing device adopts elastoplastic model. Relevant material parameters are shown in table 1.

| Material | Density ρ (g/cm³) | Poisson’s ratio P | Yield strength Fc (MPa) | Elastic modulus E (MPa) |
|----------|-----------------|-----------------|----------------------|----------------------|
| concrete | 2.4             | 0.2             | 41.7                 | 200                  |
| reinforced | 7.8             | 0.26            | 435                  | 200                  |
| support  | 7.8             | 0.26            | 700                  | 200                  |

The fracture and failure of concrete are simulated by erosion. Due to erosion effect on local failure characteristics, this paper adopts a relatively conservative erosion criterion [13] with a principal strain of 0.5; the concrete strain rate magnification factor is calculated according to equation 4 and 5[14, 15], magnification factor of concrete $r_{fc}$ under compression is:

$$r_{fc} = \begin{cases} \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_s} \right)^{1/3}, & \dot{\varepsilon} \leq 30 / s \\ \frac{\gamma \dot{\varepsilon}}{\dot{\varepsilon}_s}, & \dot{\varepsilon} > 30 / s \end{cases}$$

(4)

Where $\dot{\varepsilon}$ is the strain rate; $\dot{\varepsilon}_s$ is the reference strain rate, $\dot{\varepsilon}_s = 3 \times 10^{-5} \text{s}^{-1}$, $\log \gamma = 6.156 \alpha - 2$, $f'_{C}$ is compressive strength of concrete.

Magnification factor of concrete $r_{ft}$ under tension is:

$$r_{ft} = \begin{cases} \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_s} \right)^{1/3}, & \dot{\varepsilon} \leq 1.0 / s \\ \beta \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_s} \right)^{1/3}, & \dot{\varepsilon} > 1.0 / s \end{cases}$$

(5)

Where $\dot{\varepsilon}$ is the strain rate; $\dot{\varepsilon}_s$ is the reference strain rate, $\dot{\varepsilon}_s = 3 \times 10^{-5} \text{s}^{-1}$, $\log \beta = 6\delta - 2$, $\delta = 1/(1 + 0.8f'_{C})$, $f'_{C}$ is compressive strength of concrete.

3. Validation of the Partial Method

3.1. Calculation Time of Different Simulation Methods

In order to show the improvement of the solution efficiency of this method, a reinforced concrete beam fluid-solid interaction model is established. As shown in figure 4, the 1/2 model is adopted, the air mesh element size is 10mm, the beam element mesh size is 5mm, and the total number of element is 154768, the material parameter setting of reinforced concrete beam is invariable. Explosives and air
use multi-material ALE algorithm, explosives use JWL equation of state, and air use linear polynomial equation of state.

![Figure 4. Fluid-solid interaction model.](image)

The number of elements in the fluid-structure coupling model is 1/6 of the previous one, but the time required to solve the model is equivalent.

### 3.2. Comparison of Results Between Numerical Simulation and Experiment

In order to verify the validity of the numerical simulation results, a close-in explosion test of reinforced concrete beam 1# is carried out. The reinforced concrete beam is a rectangular section beam with a length of 160 cm, a width of 13 cm, and a height of 13 cm. The simply supported boundary is simulated by spacers and sticks, as shown in figure 5.

![Figure 5. Explosion test.](image)

The thickness of the protective layer is 2 cm, and the uniaxial test is carried out with prefabricated cement blocks. The measured strength is 41.7 MPa, the longitudinal reinforcement is 4Φ10 mm, the symmetrical reinforcement, the stirrup is Φ6 mm, and the spacing is 100 mm. The longitudinal steel bars and stirrups ultimate strength are about 625 MPa, and the yield strength is about 435 MPa. The test conditions are shown in table 2.

| Scaled distance Z (m/kg$^{1/3}$) | TNT equivalent W (kg) | Standoff distance S (m) |
|----------------------------------|-----------------------|------------------------|
| 0.1                              | 1                     | 0.1                    |

Table 2. Test condition.

The whole response of the beam lags behind the local failure of the beam, so the deflection is not chosen as the damage parameter when verifying the damage characteristics of the numerical model. In this paper, the width of blasting area on the front and back face is selected as the damage parameter. Due to the irregular rectangle shape of the fracture zone, the fracture zone is calculated as the length of the beam $L$ minus the length of the undamaged zone $D$ as shown in figure 6.
According to the numerical calculation results, the local damage of the beam has been completed within 1-2ms, so 3ms is selected as the time when the local damage parameter is measured. The damage result of the beam is shown in figure 7. The beam has severe punching and shear failure, forming a trapezoidal hollow area in the middle of the span.

![Image](image_url)

**Figure 6.** Calculation method of fracture zone.

![Image](image_url)

**Figure 7.** Local failure mode.

According to the measurement, the test and simulation results are shown in table 3

|        | Front face $L_1$ (cm) | Back face $L_2$ (cm) |
|--------|-----------------------|----------------------|
| test   | 36.5                  | 52                   |
| simulation | 37.8                  | 51.7                 |
| error/\% | 3.5                  | 0.6                  |

The error between the two results is less than 5%, so the simulation method and model used in this paper can simulate the damage of the beam under the close-in explosion.

4. Punching Shear Failure Model Under Close-In Explosion

4.1. Dimensional Analysis

The damage law of the blast wave to the reinforced concrete beam involves various physical parameters, and the relationship between the various parameters can be found through dimensional analysis. The destruction width of the front and back explosion surface is the main parameter to measure the punching-shear failure of beams. Therefore, this paper mainly conducts dimensional analysis on the damage size of the punching-shear failure of reinforced concrete beams. Figure 8 shows a schematic diagram of a reinforced concrete beam under a spherical charge.
Figure 8. Schematic diagram of punching shear failure.

Among them, $L_1$ and $L_2$ are the broken widths of the front and back explosion surfaces. Through analysis, the main influencing factors that affect the beam damage parameters are:

1) TNT: charge radius $r_0(L)$, density $\rho_T(L \cdot M)$, standoff distance $S(L)$, detonation velocity $V_T(LT^{-1})$, energy density $e_T(L^2T^{-3}M)$, product expansion coefficient $\gamma(1)$;

2) Rebar: strength $\sigma_S(L \cdot M)$, elastic modulus $E_S(L \cdot M)$, shear modulus $G_S(L \cdot M)$;

3) Concrete: thickness $d(L)$, width $b(L)$, strength $\sigma_c(L \cdot M)$, elastic modulus $E_c(L \cdot M)$, shear modulus $G_c(L \cdot M)$, reinforcement ratio $\eta(1)$.

The basic dimensions of the above physical quantities are $L, M, T$, so take the charge radius $r_0(L)$, density $\rho_T(L \cdot M)$, detonation velocity $V_T(LT^{-1})$ as the basic parameters, and the size of the failure zone must satisfy a certain dimensionless function relationship:

$$
\left( \frac{L_1}{r_0}, \frac{L_2}{r_0} \right) = f \left( \frac{R}{r_0}, \frac{d}{r_0}, \frac{b}{r_0}, \frac{e_T}{V_T^2}, \frac{\sigma_S}{\rho_T V_T^2}, \frac{E_S}{\rho_T V_T^2}, \frac{G_S}{\rho_T V_T^2}, \frac{\sigma_c}{\rho_T V_T^2}, \frac{E_c}{\rho_T V_T^2}, \frac{G_c}{\rho_T V_T^2}, \gamma, \eta \right)
$$

Dimensionless parameters can be approximated by power exponents within a certain range. The damage effect of beams is studied by changing the burst center distance, so the parameters of reinforced concrete beams and explosives can be regarded as invariants. The relevant quantities in equation (6) are all constants, so:

$$
(r_0, d, b, e_T, V_T, \sigma_S, E_S, G_S, \sigma_c, E_c, G_c, \gamma, \eta) = \text{const}
$$

equation (6) can be expressed as:

$$
\begin{align*}
L_1 &= A' r_0 \left( \frac{S}{r_0} \right)^{a_0} \quad S \geq r_0 \\
L_2 &= B' r_0 \left( \frac{S}{r_0} \right)^{b_0} \quad S \geq r_0
\end{align*}
$$

4.2. Similarity Rate of Beam Broken Area

Because this article considers that the charge is spherical, there is

$$
r_0 = \left( \frac{3m}{4 \rho} \right)^{1/3}
$$

Substitution equation (8):

$$
\begin{align*}
L_1 / m^{1/3} &= A' \left( \frac{S}{m^{1/3}} \right)^{a_0} \quad S \geq r_0 \\
L_2 / m^{1/3} &= B' \left( \frac{S}{m^{1/3}} \right)^{b_0} \quad S \geq r_0
\end{align*}
$$

so the scaled crushing width ($L/m^{1/3}$) is related to the scaled distance.

When $S=r_0$, the standoff distance is equal to the charge radius, and contact explosion occurs at this time. When $S>r_1$, the failure mode of the beam changes, the equation (9) of the failure size remains unchanged, and the undetermined coefficient changes.

The following equation is obtained by comparing the two crushing widths in equation (10):
\[ \frac{L_1}{L_2} = C \left( \frac{S}{m^{1/3}} \right)^{\zeta_1} = CZ^{\zeta_1} \quad S \geq r_0 \]  

(11)

Where \( Z \) is the scaled distance, \( m \cdot kg^{-1/3} \).

For the same explosive, this ratio is only related to the scaled distance. If the broken size under different working conditions is compared, for the same explosive, the ratio of the broken size of the beam is

\[ \frac{L / m^{1/3}}{L' / m^{1/3}} = \frac{A \left( S / m^{1/3} \right)^{\alpha}}{A' \left( S / m^{1/3} \right)^{\alpha}} = D \left( \frac{Z}{Z'} \right)^{\alpha} \quad S \geq r_0 \]  

(12)

In a certain range, the size and the proportion distance of concrete failure zone have similarity ratio.

4.3. Fitting the Relationship Between Broken Area and Standoff Distance

In order to study the influence of the standoff distance on the damage characteristics of the beam, the following conditions are set up. The charges are all spherical charges. The simulation method is to calculate the response of the reinforced concrete beam in the second section. The size of the broken zone, as shown in table 4, is the numerical simulation working condition and the beam failure size at 3ms. The simulation results of the beam at 3ms under each working condition are shown in figure 9.

**Table 4. Simulation conditions and results.**

| Standoff distance \( S \) (mm) | Scaled distance \( Z/(m \cdot kg^{-1/3}) \) | Size of front surface \( L_1/(\text{mm}) \) | Size of back surface \( L_2/(\text{mm}) \) |
|-------------------|-----------------|------------------|------------------|
| 1                 | 100             | 0.1              | 378.21           | 517.34           |
| 2                 | 110             | 0.11             | 362.76           | 501.77           |
| 3                 | 120             | 0.12             | 332.32           | 489.69           |
| 4                 | 130             | 0.13             | 295.53           | 454.95           |
| 5                 | 140             | 0.14             | 284.83           | 434.83           |
| 6                 | 150             | 0.15             | 285.35           | 414.59           |
| 7                 | 160             | 0.16             | 279.26           | 411.84           |
| 8                 | 170             | 0.17             | 277.57           | 394.11           |
| 9                 | 180             | 0.18             | 272.28           | 336.43           |
| 10                | 190             | 0.19             | 261.19           | 346.74           |
| 11                | 200             | 0.20             | 254.94           | 329.32           |
| 12                | 210             | 0.21             | 247.26           |                 |

**Figure 9. Failure mode of different beams.**
According to the simulation results, it is found that under a small scaled distance, the punching shear failure of the beam occurs due to the local shear force exceeding the shear limit, forming a trapezoidal hollow area. When the scaled distance is greater than $0.16 \text{m} \cdot \text{kg}^{-1/3}$, the failure mode of the beam changes to collapse. When the scaled distance is greater than $0.2 \text{m} \cdot \text{kg}^{-1/3}$, the beam does not penetrate, but there is a loss of concrete on the front and back explosion surfaces. In order to reduce the error, the simulation result is no longer used when the scaled distance exceeds $0.2 \text{m} \cdot \text{kg}^{-1/3}$.

According to the simulation results, the relationship between the width of the concrete broken zone and the standoff distance can be obtained as:

$$L_1 / r_0 = 9.65 \left( \frac{S}{r_0} \right)^{-0.564} \quad S \geq r_0 \quad (13)$$

$$L_2 / r_0 = 14.85 \left( \frac{S}{r_0} \right)^{-0.654} \quad S \geq r_0 \quad (14)$$

Where $L_1$ is the size of the broken area on the front surface, mm; $L_2$ is the size of the broken area on the back surface, mm; $S$ is the standoff distance, mm; $r_0$ is the charge radius, mm;

**Figure 10.** Fitting of broken area and standoff distance in front blasting face. **Figure 11.** Fitting of broken area and standoff distance in back blasting face.

4.4. Empirical Equation Verification
Nagata [16] carried out 4 rounds of close-in explosion test, the charge is C4, the equivalent TNT mass is 470g, and the equivalent radius is 41.24mm. This article will combine its test with the test data carried out in this article to verify the crushing area fitting. The test conditions in reference [16] are shown in table 5.

| Standoff distance S/(mm) | Acaled diastance Z/(m·kg$^{-1/3}$) | Experimental results |
|--------------------------|---------------------------------|---------------------|
| n1 35                    | 0.045(contact)                 | ![Image](image1)    |
| n2 77                    | 0.1                            | ![Image](image2)    |
| n3 154                   | 0.2                            | ![Image](image3)    |

The results of test and equation (13) and (14) are shown in table 6.
Table 6. Comparison of test and calculation results.

|          | Test (mm) | Calculation (mm) | Error (%) |
|----------|-----------|------------------|-----------|
| 1# Front | 36.50     | 36.81            | 0.9       |
| n1 Front | 362.25    | 337.75           | 6.7       |
| n2 Front | 305.32    | 279.88           | 8.3       |
| n3 Front | 216.57    | 189.32           | 12.5      |
| 1# Back  | 52.00     | 53.50            | 2.9       |
| n1 Back  | 530.12    | 519.75           | 2.0       |
| n2 Back  | 449.75    | 407.17           | 9.5       |

The error is less than 15%, which may be due to the difference of charge shape and beam thickness as well as the change of failure mode.

5. Conclusion

(1) The method of using AUTODYN and DYNA to obtain the beam response is more accurate in the simulation of the local failure of the beam, which is suitable for the components with simple structure and easy to determine the explosion-bearing position. Compared with the fluid-structure coupling method, this method has higher efficiency and finer mesh.

(2) On the basis of numerical simulation and dimensional analysis, the relationship between the standoff distance and the beam damage parameters is proposed, and the calculation equation for the damage area of the front surface of the beam is obtained by fitting $L_1 / r_0 = 9.65 \left( S / r_0 \right)^{0.564}$; the calculation equation of the back surface damage area for: $L_2 / r_0 = 14.85 \left( S / r_0 \right)^{0.654}$.

(3) The empirical equation is used to calculate the broken area in the test, and the error is less than 15%. The modelling method, related equations and derivations used in this paper have reference value for the damage assessment of reinforced concrete beams.

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