Numerical Study on Dynamic Response of RC Slabs Subjected to Cyclic Blast Loading

Xinyu Wang

Henan Polytechnic University

Bin Dong (✉ bdong2125@163.com)

Henan Polytechnic University

Xicai Gao

State Key Laboratory of Coal Resources in Western China

Bin Hu

China Ordnance Test Center

Yaozhe Liang

Hebei Academy of Building Research Co., Ltd

Junbo Wang

Henan Polytechnic University

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Abstract

Finite element (FE) model which can be used to investigate accumulated damage of the reinforced concrete (RC) slabs under cyclic blast loading is proposed. Firstly, accuracy of the FE model is verified through an experiment. Secondly, effects of the explosive inclination angle, standoff distance, and the explosive mass on the dynamic response of RC slabs are studied. At last, accumulated damage of the reinforced concrete (RC) slabs under cyclic blast loading is presented using the FE model. It is indicated that parameters of the explosive inclination angle, the scale distance, and the explosive mass have strong influences on the dynamic behavior of RC slabs. Under cyclic blast loading with small explosive charge, damage of the RC slab mainly appears in the first blast cycle. Displacement of the RC slab, axial force and strain of the rebars increase remarkably, which could be the mainly reason that damage evolution of the RC slab is not obvious, in the second blast cycle.

1. Introduction

Reinforced concrete is widely used in civil and military buildings because of its good blast resistance and integrity, and its safety under blast load is always one of the most concerned issues. In recent years, there has seen a significant rise in explosions caused by terrorist attacks and accidental explosions globally¹⁻³. These explosions have a huge impact on RC structures, resulting in tremendous casualties and economic losses^{4,5}. However, due to the randomness of explosion events, it is hard to predict the location and number of the explosions and the blast wave intensity. Thus, it is of great urgency and importance to study dynamic response of RC structures or members under single and cyclic blast loads.

At present, the following methods are primarily adopted to investigate dynamic behaviours of RC structures under blast load: theoretical analysis, field test and numerical simulation. The more commonly used theoretical analysis mainly includes single-degree-of-freedom (SDOF) methods⁶⁻⁸, modal approximation⁹ and lumped mass model¹⁰. However, owing to complexity of the structure and its actual boundary conditions, the simplified theoretical method cannot fully reflect the actual state of the structure, nor it can be easily used to study the damage characteristics of concrete structural members under blast load.

Field blast test is the most effective method to understand the dynamic behaviour of concrete members subjected to near-field blast load^{11,12} presented details of a large-scale test program on composite structural panels under the action of explosive loading. Luccioni *et al.*¹³ presented behaviour of concrete slab lying on the ground due to blast loads. Ngo *et al.*¹⁴ investigated the blast-resistance of prestressed super high strength concrete panels subjected to blast load. Ohkubo *et al.*¹⁵ evaluated the effect of fiber reinforcement on improving the performance of explosive-resistant of concrete slabs, experimentally. Lu and Silva^{16,17} presented a procedure which could estimate the damage level of RC slabs, by considering the effect of the charge weights and standoff distances. Wang *et al.*¹⁸ made experimental studies on the dynamic behaviour of small-size RC slabs under close-in blast loads. Yao *et al.*¹⁹ analyzed through blast

experiments the explosion-proof performance and damage behavior of reinforced concrete slabs at various reinforcement ratios. In order to better simulate real in-situ conditions, field tests of real scale bridge decks were performed by Foglar *et al.*²⁰. Shi *et al.*¹¹ examined fragmentation characteristic and local damage of the RC slabs under close-in explosions through full-scale field tests. Wu *et al.*²¹ investigated the fragments size distributions of two RC slabs due to airblast loads in a blast chamber. Contact explosion tests were carried out by Li *et al.*²² to observe crater and spall damage of ultra-high performance concrete slabs. Failure patterns and dynamic response of the small-scale slabs under contact detonation were obtained by Zhao *et al.*²³, experimentally. Ichino *et al.*²⁴ investigated effect of parameters such as TSC strength, type and diameter of coarse aggregate on the local failure of two-stage concrete plate under contact explosion.

As a useful supplement to the blast impact test, numerical simulation has been used by many scholars to simulate the blast resistance and dynamic response of structural components under blast load. Among the great deal of numerical analysis software^{25–29}, LS-DYNA is the most widely used. Tai *et al.*³⁰ studied the dynamic response of RC slabs under the action of the blast wave. Using the ConWep code proposed by Kingery and Bulmash³¹, Yao *et al.*¹⁹ investigated the damage characteristics and blast resistance of RC slabs with different reinforcement ratios. Strain-rate effects on the compressive and tensile strength of concrete are investigated numerically by Lin *et al.*³². Li and Hao³³ studied spall damage of RC columns subjected to blast loads. Using the ConWep air blast function, Zhao *et al.*^{34,35} made a numerical investigation on the dynamic behaviours of concrete slabs under close-in blast load. Kong *et al.*³⁶ studied effect of AFRP on the blast resistance of RC slab. Using Arbitrary Lagrangian-Eulerian (ALE) coupling method, Yang *et al.*³⁷ and Feng *et al.*³⁸ investigated dynamic response of rubber concrete slabs under close-in blast loading. Wu *et al.*³⁹ studied dynamic failure process of RC slab under internal blast load.

In this paper, a numerical analysis is proposed to investigate dynamic behaviours and damage of RC slabs subjected to close-in blast loading, by using the ALE method. FE model is verified firstly by simulation of a previous test reported by Zhao *et al.*²³. Then, parameters of explosive inclination angle, scale distance, and explosive mass on the dynamic behaviour of RC slabs are studied systematically. Finally, cumulative damage of the RC slab under the cyclic blast load is investigated, and damage evolution of the RC slab during cyclic blast load is quantitatively evaluated.

2. Previous Tests

Zhao *et al.*²³ conducted three groups of blasting tests on C30 RC slabs, and studied the effects of reinforcement ratio and explosive mass on the blast resistance of RC slabs. One of the RC slabs measured 100cm×100cm×4cm (length×width×height). A single-mesh layer HRB335 reinforcement bars was applied, with a diameter of 8mm and a perpendicular spacing of 100mm. Dimensions of the specimen are shown in Fig. 1.

The specimen was fixed at two opposite sides on the steel frame by U-shape loop clamps. The cylindrical emulsion explosive was hung 40cm over the concrete slab (Fig. 2). The blast-induced vertical acceleration and vertical displacements were measured by 3 acceleration sensors (ASs) and 3 linear voltage differential transducers (LVDTs), respectively.

3. Numerical Model Calibration

The three-dimensional numerical model of the RC slab in literature Zhao *et al.*²³ was established using the software of ANSYS/LS-DYNA, and dynamic response of the RC slab subjected to blast load was studied. The results were compared with the test results in the literature to verify rationality of the numerical model.

3.1. Material models

3.1.1. Concrete

*MAT_CONCRETE_DAMAGE_REL3 is used to model concrete⁴⁰. This model defines the plastic properties of concrete through three yield failure surfaces, as shown in Fig. 3.

The initial yield surface, ultimate strength surface and softened strength surface are expressed as follows:

$$\Delta \sigma_y = a_y + \frac{p}{a_{y1} + a_{y2}p}$$

1

$$\Delta \sigma_m = a_m + \frac{p}{a_{m1} + a_{m2}p}$$

2

$$\Delta \sigma_r = \frac{p}{a_{r1} + a_{r2}p}$$

3

Where $\Delta \sigma = \sqrt{3J_2}$ and J_2 is the second invariant of deviatoric stress; p is the hydrostatic pressure; and a_y , a_{y1} , a_{y2} , a_m , a_{m1} , a_{m2} , a_{r1} and a_{r2} are strength parameters of the material.

With the linear interpolation method, the yield surface of concrete under the current stress state can be obtained and expressed as:

$$\Delta \sigma_f = \eta \left(\Delta \sigma_m - \Delta \sigma_y \right) + \Delta \sigma_y \left(\lambda \leq \lambda_m \right)$$

4

$$\Delta \sigma_f = \eta \left(\Delta \sigma_m - \Delta \sigma_r \right) + \Delta \sigma_r \left(\lambda > \lambda_m \right)$$

5

Where the value of η is determined by the damage variable λ . When λ increases from 0 to λ_m , η increases from 0 to 1, representing the strengthening stage; when λ increases from λ_m to infinity, η decreases from 1 to 0, representing the softening stage.

In the LS-DYNA finite element software, this model is coupled with the state equation *EOS_TABULATED_COMPACTON to define the functional relationship between the concrete pressure and volumetric strain. The pressure is defined as:

$$P = C(\varepsilon_v) + \gamma T(\varepsilon_v) E_1$$

6

Where the volumetric strain ε_v is defined as the natural logarithm of the relative volume, and are the functions of the volumetric strain, E_1 is the initial internal energy and γ is the heat capacity ratio.

The relationship of concrete pressure and volumetric strain is shown in Fig. 4. It is indicated that while the tensile stress is greater than the threshold value of the hydrostatic pressure, tensile failure occurs. Once the volumetric strain goes over the elastic limit, the concrete is compacted and then becomes a granular material. The material input parameters for the concrete in this paper are shown in Table 1.

Table 1
The material parameters for the concrete model.

Density (kg/m ³)	Passion's ratio	Uniaxial tensile strength (MPa)	Maximum shear failure surface parameter (MPa)	Unit conversion factor for length	Unit conversion factor for stress
2450	0.21	1.76	-30	38.9	0.00014

The dynamic tensile strength of RC changes significantly under the action of blast loading, indicating its high strain rate sensitivity. For this reason, the strain rate effect should be considered in the selection of material model for blast-resistance analysis. This is achieved in this paper by adopting the dynamic increase factor (DIF) recommended in the European concrete specification CEB⁴¹.

For concrete in compression:

$$CDIF = \frac{f_{cd}}{f_{cs}} = \begin{cases} \left(\gamma_1 \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_s} \right)^{1.026\alpha} \right)^{1/3} & \dot{\varepsilon}_s < \dot{\varepsilon} \leq 30s^{-1} \\ \left(\gamma_1 \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_s} \right)^{1.026\alpha} \right)^{1/3} & 30s^{-1} < \dot{\varepsilon} < 300s^{-1} \end{cases}$$

7

Where f_{cd} is the dynamic compressive strength of concrete under the dynamic strain rate $\dot{\varepsilon}$; and f_{cs} is the compressive strength of concrete under the static strain rate $\dot{\varepsilon}_s$. In this study, $\dot{\varepsilon}_s = 30 \times 10^{-6} s^{-1}$, $\log \gamma_1 = 6.156\alpha - 2$ and $\alpha = (5 + 9f_{cs}/10)^{-1}$.

For concrete in tension:

$$TDIF = \frac{f_{td}}{f_{ts}} = \begin{cases} \left(\beta \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_s} \right)^{1.016\alpha} \right)^{1/3} & \dot{\varepsilon}_s < \dot{\varepsilon} \leq 30s^{-1} \\ \left(\beta \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_s} \right)^{1.016\alpha} \right)^{1/3} & 30s^{-1} < \dot{\varepsilon} < 300s^{-1} \end{cases}$$

8

Where f_{td} is the dynamic tensile strength of concrete under the dynamic strain rate $\dot{\varepsilon}$; f_{ts} is the tensile strength of concrete under the static strain rate $\dot{\varepsilon}_s$. In this study, $\dot{\varepsilon}_s = 3 \times 10^{-6} s^{-1}$, $\log \beta = 7.112\delta - 2.33$ and $\delta = 1/(10 + 6f_{cs}/10)^{-1}$.

3.1.2. Reinforcement bar

The reinforcement bar was modelled using the *MAT_PLASTIC_KINEMATIC. This model can simulate isotropic and kinematic hardening plasticity. The isotropic and kinematic hardening can be determined by seamlessly changing the hardening parameter between 0 and 1. The constitutive model of the reinforcement bar is shown in Fig. 5.

The Cowper–Symonds model³² is adopted to incorporate the strain-rate effect under blast loading. The yield stress after hardening is defined by Eq. (9).

$$\sigma_y = \left(1 + \frac{\dot{\varepsilon}}{C_s} \right)^{1/P_s} (\sigma_0 + \chi E_p \varepsilon_p^{eff})$$

9

$$E_p = \frac{E_t E}{E - E_t}$$

10

Where σ_0 is the initial yield stress and $\dot{\varepsilon}$ is the strain rate, C_s and P_s are the strain rate parameters for Cowper–Symonds model, ε_p^{eff} is the effective plastic strain, χ is the hardening parameter, E_p is the plastic hardening modulus, E_t is the tangent modulus, and E is the modulus of elasticity.

Parameters for reinforcement material are shown in Table 2.

Table 2
The material parameters for the reinforcement bar²³.

Density (kg/m ³)	Young's modulus (GPa)	Passion's ratio	Yield stress (MPa)	Tangent modulus (GPa)	Strain rate parameter, C_s	Strain rate parameter, P_s	Effective plastic strain for eroding elements
7900	200	0.3	335	1	40	5.0	0.12

3.1.3. Equation of state

The emulsion explosive is described by the *MAT_HIGH_EXPLOSIVE_BURN material model and JWLV state equation⁴², which is

$$P = A_1 \left(1 - \frac{\omega}{R_1 V} \right) e^{-R_1 V} + B_1 \left(1 - \frac{\omega}{R_2 V} \right) e^{-R_2 V} + \frac{\omega E_{e0}}{V}$$

11

Where P is the pressure, A_1 , B_1 , R_1 , R_2 and ω are constants, and E_{e0} are the relative volume and the internal energy per unit volume, respectively. Parameters of the model are shown in Table 3.

Table 3
The material parameters for the explosive

Density (kg/m ³)	Detonation velocity (m/s)	Chapman-Jouget pressure (GPa)	E_{e0} (GPa)	Test constants				
				A_1 (GPa)	B_1 (GPa)	R_1	R_2	ω
1150	4480	7.60	2.67	325.29	5.75	5.82	1.53	0.62

*MAT_NULL (MAT_9) is used to model air. The pressure of EOS is given in Eq. (12).

$$P = C_1 + C_2 \mu + C_3 \mu^2 + C_4 \mu^3 + (C_5 + C_6 \mu + C_7 \mu^2) E_{a0}$$

12

Where $\mu = \rho / \rho_0 - 1$ (ρ is the air density and ρ_0 is the initial air density); E_{a0} is the internal energy per unit volume, and $C_1, C_2, C_3, C_4, C_5, C_6$ and C_7 are the state equation parameters. Parameters of the model are shown in Table 4.

Table 4
The material parameters for the air.

Density (kg/m ³)	C_1	C_2	C_3	C_4	C_5	C_6	C_7	E_{a0} (MPa)
1.29	0.00	0.00	0.00	0.00	0.40	0.40	0.00	0.25

3.1.4. Erosion criteria

For simulate the failure mode of RC slab after explosion accurately, the erosion algorithm is used to define the failure criteria of material through the *MAT_ADD_EROSION keywords⁴³. Once the dynamic response of a material element reaches a threshold value, that element will be removed immediately. Here, the maximum principal strain is selected to define the failure criteria of material. The threshold of the maximum principal strain determined by simulation trial is 0.015, which means that the maximum principal strain of the element will be deleted immediately if it reaches or exceeds this value.

3.2. Finite element model

The FE model is composed of concrete, reinforcement bars, air and explosive, as illustrated in Fig. 6. In this model, concrete, air and explosive were simulated by SOLID164 element, and reinforcement bars were simulated by BEAM161 element. Reinforcement bars and concrete were modeled separately, and it was assumed that the concrete and reinforcement bars bond well within a very short time without any slip under high blast pressure. The interaction between the reinforcement bars and concrete was simulated by constraining and coupling the reinforcement bars into the concrete using the keyword *CONSTRAINED_BEAM_IN_SOLID. Fixed boundary condition was applied on two sides of the concrete slab and non-reflection boundary condition (NRBC) was applied on the six surfaces of the finite element model to simulate the infinite air domain.

3.3. Comparison of numerical and experimental results

The experimental data from specimen P1-2 in literature²³ was selected to verify the applicability of the numerical model established in this paper. In the literature, the standoff distance was 40cm, the mass of the emulsion explosive was 0.2kg, and the scale distance was $0.684 \text{ m/kg}^{1/3}$. In this paper, the angle was defined as θ , which changed clockwise at an interval of 15° between 0° and 90° , as shown in Fig. 7(a). Moreover, the same points in the literature were selected for displacement measurement in this numerical model, as shown in Fig. 7(b).

Figures 8(a)-(g) show the damage of RC slab on the top surface with different values of θ . Under the action of blast load, obvious damage can be found at the fixed boundaries of the RC slab when θ takes different values, and there is also a strip damage zone perpendicular to the length direction of the strip

explosive on the top surface. Fig. 8(h) shows the damage test results for the top surface in the literature²³. It can be seen that a longitudinal crack parallel to the fixed boundary appears in the middle of the slab, concrete spalling is observed at the four corners of the slab, and no penetration damage across the slab is detected. By comparison, it is found that the calculation results when $\theta = 90^\circ$ are consistent with the damage situation of the RC slab tested.

The displacement comparison of the measuring points is shown in Fig. 9. When $\theta = 0^\circ$, the displacement values of points D_1 , D_2 and D_3 obtained by numerical simulation at 4ms are -1.28cm, -0.80cm, -0.95cm, respectively, which are well consistent with the experimental results of -1.15cm, -0.89cm and -1.0cm, and thus lead to reasonable evaluation of the RC slabs response subjected to blast loads.

4. Results Analysis

With the above numerical model verified, the effect of different factors such as standoff distance, explosive mass and cyclic blast load on the dynamic behaviour and cumulative damage of the RC slab is studied, when $\theta = 60^\circ$.

4.1. The effect of standoff distance

The dynamic response of the RC slab subjected to blast load was studied when the standoff distance was 40cm, 60cm, 80cm and 100cm, respectively. The explosive mass was 0.2kg.

Figure 10 shows the damage contours of the slab at different standoff distances. With the change of the standoff distance, the slab shows no penetration or spalling damage, and fixed boundaries of the top surface are found with serious damage. As the standoff distance increases, the damage zone of the slab gradually decreases and the distribution range of cracks on the bottom surface gets smaller and shrinks toward the center of the slab. The slab shows obvious bending deformation, but the bending degree decreases with the increase of the standoff distance.

Figure 11 shows the displacement vs time history of the RC slab at different standoff distances. As demonstrated in the figure, for the same measuring point, the peak displacement decreases non-linearly with the increase of the standoff distance. Compared with measuring points D_2 and D_3 , the peak vertical displacement of D_1 is the largest at the same standoff distance. The reason might be that D_1 is less affected by the boundary conditions.

Figure 12 shows the axial stress contours of the rebars in the RC slab at $t=5\text{ms}$. Under the action of blast load, stress of the rebars in the middle area of the slab parallel to the fixed boundary is larger, because this area is less affected by the boundary in the blasting process. With increase of the standoff distance, bending deformation of the slab decreases, and the number of rebars under tension also decreases. When the standoff distance grows from 40cm to 100cm, the peak axial stress of the rebars decreases gradually. Especially when the standoff distance increases from 80cm to 100cm, the peak axial stress of

the rebars decreases most significantly, from 422.3MPa to 234.8MPa. During this period, the detonation wave weakens dramatically.

4.2. The effect of explosive mass

The standoff distance is set to 100cm. In this section, dynamic behaviour of the RC slab is studied when the explosive mass is 0.2kg, 0.1kg, 0.05kg and 0.025kg, respectively.

Damage of the RC slab with different explosive masses is shown in Fig. 13. As shown in Fig. 13, due to the large distance of the detonation wave from of the slab surface (the standoff distance-span ratio is 1), damage pattern of the RC slab is characterized by serious damage at the fixed boundary of the top surface, and damage of the bottom surface concentrated in the middle area of the slab parallel to the fixed boundary direction, accompanied by a small number of cracks. With decrease of the explosive mass, damage zone of the bottom surface decreases, and the bending deformation of the RC slab reduces as well. When the explosive mass is 0.025kg, the damage zone of the bottom surface is approximately bilaterally symmetrical.

Figure 14 shows the relationship between displacement and time history of the measuring points under different explosive mass. As can be seen from the figure, with the explosive mass decreasing, the scale distance increases, energy of the detonation wave and the peak displacement of the same measuring point decrease. Under the same explosive mass, the peak displacement of D_1 is the largest, and those of D_2 and D_3 are close to each other. The smaller the explosive mass, the longer the flat section of the displacement-time history curves.

Figure 15 shows the axial stress contours of the rebars at $t=5\text{ms}$. With the decrease of explosive mass, the peak axial stress of the rebars in both the tensile and compressive zones of the slab decreases gradually. Particularly, when the explosive mass decreases from 0.2kg to 0.1kg, the peak value of the axial tensile stress of the rebars changes most significantly, from 234.8MPa to 95.4MPa. Under the same explosive mass, the peak axial tensile stress is greater than the peak axial compressive stress of the rebars. Affected by the fixed boundary, the maximum axial tensile stress appears in the middle of the rebars perpendicular to the fixed boundary direction on the top and bottom sides of the slab.

4.3. Dynamic response of RC slab under cyclic blast load

The standoff distance is set to 100cm and the explosive mass 0.025kg, so as to investigate the dynamic response of the slab subjected to cyclic blast load. The cumulative damage of the slab under cyclic blast load is studied by adopting the complete restart technology of the finite element analysis software ANSYS/LS-DYNA. After trial calculations, the calculation time of a single cycle is set to 45ms, which ensures that the RC slab reaches a stable state before the next blast load is applied.

4.3.1. Damage evolution

In the concrete material models selected in this paper, the damage variables defined are different, depending on whether the concrete is under compression or tension, and the expressions are⁴⁴:

$$\lambda = \int \bar{\epsilon}^p \frac{d\bar{\epsilon}^p}{r_f \left(1 + p / r_f f_t\right)^{b_1}}, \text{ for } p \geq 0 \quad (13)$$

$$\lambda = \int \bar{\epsilon}^p \frac{d\bar{\epsilon}^p}{r_f \left(1 + p / r_f f_t\right)^{b_2}}, \text{ for } p < 0 \quad (14)$$

Where $d\bar{\epsilon}^p = \sqrt{\left(\frac{2}{3}\right) d\epsilon_{ij}^p d\epsilon_{ij}^p}$ is the increment of effective plastic strain, and ϵ_{ij}^p is the plastic strain of the concrete material; f_t is the quasi-static tensile strength of the concrete material; r_f is the strain enhancement factor; b_1 and b_2 are the parameters that control the softening section of the compressive and tensile stress-strain curves, respectively; and p is the hydrostatic pressure. This model describes the damage of concrete through scaled damage factor (SDF), which is expressed as follows:

$$\text{SDF} = \frac{2\lambda}{\lambda + \lambda_m}$$

15

SDF is a positive value of monotonic increase between 0 and 2. $0 < \text{SDF} < 1$ shows that the concrete material enters the strengthening section without damage, $\text{SDF} \geq 1$ shows that the concrete material enters the softening section and begins to damage, and $\text{SDF} = 2$ indicates that the material is completely destroyed.

Through the SDF that comes with the model above, the damage and failure of the RC slab can be analyzed through the damage contours. Fig. 16 shows the damage evolution contours of the slab after the first explosion. After the explosion, obvious damage first appears on the fixed boundaries and bottom surface of the slab. When $t = 7\text{ms}$, part of the concrete on the bottom surface undergoes tensile failure and cracks begin to propagate. When $t = 9\text{ms}$, longitudinal cracks parallel to the fixed boundary direction appear on the slab top surface, accompanied by symmetrically distributed damage zones. As the blast wave continues to release energy, more cracks appear and damage of the RC slab gradually intensifies. When $t = 15\text{ms}$, visible cracks appear in the middle of the top surface of the RC slab along the fixed boundary direction. When $t = 45\text{ms}$, the RC slab tends to stay stable, and the cracks become visible on the bottom surface of the slab.

Figure 16. Damage evolution of RC slab during the first explosion

Figure 17 shows the damage evolution of the slab after the second explosion. Within a short time after the second explosion, the damage area on the slab surfaces does not change significantly. When $t = 52\text{ms}$,

new cracks are generated near the upper left boundary of the bottom surface of the RC slab, while few obvious cracks are generated on the top surface, as shown in Figure 17. Then, with the further action of the blast load, the top surface undergoes no significant change in the number of new cracks and damage area. When $t=90\text{ms}$, a strip damage zone parallel to the crack direction appears on the bottom surface.

Figure 17. Damage evolution of RC slab during the second explosion

Figure 18 compares the failure elements of the RC slab after two explosions. After the calculation for the first explosion cycle was completed, some elements at the fixed boundaries of the RC slab were deleted due to failure, but the concrete slab was still fixed on the support below it. After the calculation for the second cycle was completed, all the elements at the fixed boundaries of the RC slab were deleted, which led to failure of the constraint. The RC slab fell as a whole, making the calculation for the third cycle impossible.

In order to dig deeper into the RC slab damage subjected to cyclic blast load, the elements with the same plane coordinates on the surfaces of the slab were selected and their damage evolution process was calculated. The position and number of the selected elements are shown in Fig. 19.

Figure 20(a) shows the damage evolution of the elements on path 1 at the top surface of the slab. During the first explosion, the damage value of elements H303901, H303921 and H303941 had two sharp increases. The second increase was particularly obvious (at around $t=9\text{ms}$). The damage value of elements H303961 and H303981 had only one increase at around $t=9.5\text{ms}$. After the calculation for the first cycle was completed, the damage value of element H303901 at the center of the slab was the largest, and that of element H303981 near the boundary was the smallest. During the second explosion, no change was found in the damage value of the elements on path 1 at the top surface of the slab.

Figure 20(b) shows the damage evolution of the elements on path 2 at the top surface of the RC slab. During the first explosion, the damage value of elements H311901, H307901, H319901 and H315901 had two sharp rises. The second increase was particularly obvious (at around $t=9\text{ms}$). Element H307901 failed at around $t=9.5\text{ms}$. During the second explosion, the damage value of element H319901 showed a third rise at $t=46.5\text{ms}$, and reached the maximum ($\text{SDF}=1.48$) until $t=49\text{ms}$. After the calculation for the second cycle was completed, the damage values of elements H319901 and H315901 are close, and the damage value of element H311901 is the smallest.

In general, the damage value of the elements at the center of the top surface is larger, while that near the boundary is smaller. The damage value of each element at the top surface increases sharply at around $t=9\text{ms}$. This is because the RC slab rebounds at this time, causing the top surface to be under tension and the damage value of each unit at the top surface to increase.

Figure 21(a) shows the damage evolution of the elements on path 3 at the bottom surface. During the first explosion, the damage value of element H23901 had two sharp rises. The first increase was particularly obvious (at around $t=2\text{ms}$). The damage value of elements H23921 and H23941 had one

sharp rise and elements H23961 and H23981 showed no damage. After the calculation for the first cycle was completed, the damage value of element H23901 at the center of the slab was the largest, with its SDF being 1.88. During the second explosion, the damage value of elements H23901 and H23921 demonstrated no change, that of elements H23941 and H23981 had one slight increase and that of element H23961 had two slight increases.

Figure 21(b) shows the damage evolution of the elements on path 4 at the bottom surface. The damage value of elements H27901, H35901 and H39901 had a sharp increase at around $t=2\text{ms}$, and then the elements failed. The damage value of element H31901 had a sharp increase at around $t=1.5\text{ms}$, with its SDF reaching 1.57, and remained unchanged during the second explosion.

Compared with the top surface, the bottom surface of the slab is subject to tension earlier during the explosions, and the elements on the bottom surface are also damaged earlier.

Through the analysis of the damage evolution pattern of the selected elements, it can be seen that the damage of the elements on the concrete slab shows an irreversible increase. The damage value of the elements near the center of the slab is usually larger. Under cyclic blast load, the damage of the bottom surface elements of the concrete slab appears earlier, and the damage evolution pattern of the top surface elements is greatly affected by the rebound of the slab. The damage of the elements in the concrete slab mostly occurs during the first explosion. The damage value of some elements increases during the second explosion, but with a relatively small increment.

4.3.2. Displacement

The vertical displacement-time history curves for the measuring points of the RC slab during the two explosions are shown in Fig. 22. During the first explosion, the concrete slab shows an obvious rebound ($t=8.5\text{ms}-24\text{ms}$), and then the displacement of the measuring points increases, but at a low rate. After the calculation for the first explosion cycle is completed, the vertical displacement of the measuring point D1 is 0.79cm, and the vertical displacements of the measuring points D2 and D3 are close to each other, about 0.38cm. The first blast load leads to local cracking of the slab, which destroys the integrity of the slab and subjects the rebars to yield deformation. After the second explosion, the rebars are subjected to a greater force and gradually enter the strengthening stage. The vertical displacements of the three measuring points on the RC slab increase rapidly. After the calculation for the second explosion cycle is completed, the vertical displacements of the measuring points D1, D2 and D3 are 4.62cm, 4.74cm and 4.70cm, respectively.

4.3.3. Axial force and strain of rebars

In order to analyze the force and deformation of the rebars in the concrete slab during the two explosions, the rebar elements near the center of the concrete slab, the fixed boundary and the free boundary were selected for analysis. The numbers and locations of the elements are shown in Fig. 23.

Figure 24 shows the relationships between axial stress and time history of the rebar elements in two explosions. During the two explosions, the axial stress of rebar element B1911 increases gradually, but at a very low rate. The axial stresses of rebar elements B2991 and B3711 follow basically the same change trend. During the first explosion, the peak axial stress of rebar element B2991 is 267.25MPa, which occurs at $t=15.5\text{ms}$, and that of rebar element B3711 is 294.23MPa, which occurs at $t=12.5\text{ms}$. After the second explosion, the axial stresses of rebar elements B2991 and B3711 increase sharply at around $t=47.5\text{ms}$, and keep going up until they reach the maximum value of 491.26MPa and 474.45MPa. Compared to the first blast load, after the calculation for the second blast load is completed, the axial stress of rebar elements B2991 and B3711 increases by 28.47Mpa and 212.78Mpa, respectively. In view of the cumulative damage evolution of the concrete slab, the increase in the axial force of the rebars is one of the important factors that prevent significant increase in the cumulative damage of the RC slab after the second explosion. In other words, rebars play a crucial part in reducing the structural damage and failure of RC slabs under cyclic blast load.

Figure 25 shows the axial strain-time history curves of the rebar elements in two explosions. As can be seen from the figure, axial strain of the rebar near the fixed boundary of the RC slab shows no evident change, while that of the rebar near the center of the slab and the free boundary increases greatly during the second explosion. Therefore, in case of cracking or overall damage of the RC simply supported slab under the action of cyclic blast load, re-application of the blast load leads to significant rise in axial deformation of the rebars, especially in the middle area and free boundaries of the slab.

5 Conclusions

Dynamic behaviors of RC slabs under blast load were numerically investigated by LS-DYNA in this paper. Validity of the numerical model is calibrated through a blasting test. The effect of the explosive inclination angle, scale distance, and explosive mass on the response of reinforced concrete slabs is explored by intensive numerical simulations. Damage evolution of the slabs under cyclic blast loading is studied using the numerical model. The conclusions are summarized as follows:

- (1) The parameters such as the explosive inclination angle, scale distance and explosive mass can significantly affect the dynamic behavior of RC slabs. When θ takes different values, obvious damage can be found at the fixed boundaries of the slab and there is also a strip damage zone perpendicular to the length direction of the strip explosive on the top surface of the slab.
- (2) With increase of the standoff distance, the damage zone of the slab gradually decreases and the distribution range of cracks on the bottom surface gets smaller and shrinks toward the center of the slab. The slab shows obvious bending deformation, and the bending deformation of the RC slab decreases with the standoff distance increases.
- (3) Damage zone of both surface of the RC slab decreases with decrease of the explosive mass, and the bending deformation of the RC slab reduces as well. When the explosive mass is 0.025kg, damage zone of the RC slab is approximately bilaterally symmetrical.

(4) Under cyclic blast loading with small explosive charge, damage of the RC slab mainly appears in the first blast cycle. In contrast to the first blast cycle, displacement of the RC slab, axial force and strain of the rebars increase remarkably, which could be the mainly reason that damage evolution of the RC slab is not obvious, in the second blast cycle.

Declarations

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Data Availability' statement

The datasets used and analysed during the current study available from the corresponding author on reasonable request.

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Figures

Figure 1

Dimensions of the specimen (cm)

Figure 2

Test device (Zhao *et al.*, 2019)

Figure 3

Strength model for concrete material

Figure 4

Pressure versus volumetric strain

Figure 5

Constitutive model of reinforcement material

Figure 6

Finite element model

Figure 7

Layout of explosive and measurement points (cm)

Figure 8

Comparison of the numerical and experimental results of the RC slab damage contours

Figure 9

Comparison of the numerical and experimental results of the displacement (a) point D₁; (b) point D₂; (c) point D₃.

Figure 10

Damage contours of RC slab with different standoff distances

Figure 11

Displacement time history at different distances (a) point D₁; (b) point D₂; (c) point D₃.

Figure 12

Axial stress contours of rebars with different distances (Pa).

Figure 13

Damage distribution of RC slab under different explosive masses

Figure 14

Displacement time history of measuring points under different explosive masses (a) point D_1 ; (b) point D_2 ; (c) point D_3 .

Figure 15

Axial stress contours of rebars under different explosive masses (Pa)

Figure 16

Damage evolution of RC slab during the first explosion

Figure 17

Damage evolution of RC slab during the second explosion

Figure 18

Comparison of failure elements (a) after the 1st explosion; (b) after the 2nd explosion.

Figure 19

Diagram of elements selected to be analyzed

Figure 20

Cumulative damage evolution of elements on top surface (a) Path 1; (b) Path 2.

Figure 21

Cumulative damage evolution of bottom surface elements (a) Path 3; (b) Path 4.

Figure 22

Displacement-time history curves of measuring points

Figure 23

Selection of rebar elements

Figure 24

Axial stress-time history curves of rebar elements

Figure 25

Axial strain-time history curves of rebar elements