Numerical study of RC slabs under two-point contact explosion load

Xinjing Yuan1*, Jian Song1

1 School of Highway, Chang’an University, Xi’an 710064, China;

Author’s brief introduction: Xinjing Yuan (1997-), Male, Master, E-mail address: 2019121031@chd.edu.cn;

*Corresponding author’s E-mail address: 2019121031@chd.edu.cn; yuanxinjing315@163.com.

Abstract. As an important bearing component of bridge, bridge deck is the key to bridge passage. In this paper, a solid model of reinforced concrete slab is established in LS-DYNA software, and the parameters are designed as the amount of explosive and the distance between explosives. The numerical simulation of two-point explosion test is carried out, and the damage mechanism and dynamic response of reinforced concrete slab under two-point explosion load are proposed. The results show that there is a phenomenon of energy accumulation in two-point contact explosion. At the same charge, the failure characteristics and dynamic response of RC slabs are related to the distance between the blast points. When the distance is small (30cm), the stress wave encounters and superposition strengthens between the blast points. When the spacing is large (60cm), the stress waves do not meet between the burst points, but reach the back burst surface and the side of the plate at the same time, and the damage is serious near the side of the plate, and the peak acceleration is small.

1. Introduction

As a key and controlling part of transportation, bridges are a guarantee for smooth road traffic. Occasional explosion of flammable and explosive materials during transportation will cause obstacles to transportation and major economic losses. In particular, on bridges with heavy traffic, once an explosion occurs, it is very likely that two or more vehicles will detonate together on the bridge deck. In the explosion incident on the bridge, the bridge deck is the most vulnerable component. Therefore, studying the damage mechanism and dynamic response of reinforced concrete slabs under two-point contact explosion provides a theoretical basis for the anti-blast design of the bridge deck and the safety assessment of the bridge, which has very important academic and engineering significance.

At present, with the development of computer technology and finite element software, the use of numerical simulation methods to study the dynamic response and damage mode of reinforced concrete slabs under explosive loads can shorten the scientific research cycle and reduce the test risk. Yao et al. [1] numerically simulated the blast resistance of reinforced concrete slabs with different reinforcement ratios, and the results showed that with the increase of the reinforcement ratio, the damage degree, deflection and spall radius of RC slabs all decrease. Casted et al. [2] improved its anti-blast performance by placing steel plates on reinforced concrete slabs and arranging steel fibers in the tension zone. Numerical simulation results show that reinforced concrete slabs containing steel fibers or polypropylene fibers in the tensile stress zone have better blast resistance than ordinary reinforced
concrete slabs. Li et al. [3] studied the dynamic response and anti-explosion performance of reinforced concrete slabs under explosion load by means of theoretical analysis and numerical simulation, and analyzed the influence of concrete strength, steel yield strength, plate thickness and boundary on the dynamic response and anti-explosion performance of slabs. In addition, many scholars [4-6] have proposed different material models to study and calculate the dynamic response and damage mode of reinforced concrete slabs, and the research methods have been relatively mature. Scholars [7-10] have carried out relevant tests and numerical simulation and studied the theory of two-point and multi-point explosion. It is found that the energy accumulation phenomenon exists in the multi-point explosion shock wave, which will produce high overpressure. In the case of simultaneous initiation of multiple points, the aggregation effect among multiple shock waves will produce strong damage to the structure.

To sum up, there have been some achievements in the research on the explosion load of reinforced concrete slabs, but all of them focus on non-contact explosion or one-point explosion. There are few studies on contact explosion, especially on two-point contact explosion. In this paper, the 3D finite element model of RC slabs are established by using LS-DYNA software, and a numerical model is proposed to simulate the two-point contact explosion process of RC slab based on multi-substance fluid-solid coupling method. The failure characteristics and dynamic response of RC slabs under two-point contact explosion are studied by numerical simulation results.

2. Explosion test simulation

2.1. Experimental descriptions
The size of rectangular reinforced concrete slab is 3000mm×1000mm×300mm. The fixed mode is hinged at both ends, and its net span is 2.6m. The design parameters of the test are explosive charge and blast point spacing. The explosion load condition is shown in Table 1.

| Specimen number | Number of explosive points | Explosive spacing /cm | Test dosage /kg |
|-----------------|---------------------------|-----------------------|-----------------|
| RCP1            | 2                         | 30                    | 0.5×2           |
| RCP2            | 2                         | 60                    | 0.5×2           |
| RCP3            | 2                         | 30                    | 0.25×2          |
| RCP4            | 2                         | 60                    | 0.25×2          |

2.2. Basic model
Figure 1 is the basic model of two-point contact explosion simulation, including five parts: steel bar, concrete, air, explosive and rigid body. The reinforcement and concrete are described by Lagrange algorithm. Explosive and air are described by Euler algorithm, which can well simulate the formation and propagation of blast wave and the interaction between shock wave and structure. In the numerical model, concrete and fixed rigid body use SOLID164 element with a grid size of 20mm, steel bar use BEAM161 element with a grid size of 20mm, air and explosive use SOLID164 element with a grid size of 40mm and 20mm respectively. The constraint coupling is set between the reinforcement and the concrete. Fluid-structure interaction is set among air, explosive and reinforced concrete structure. Rigid bodies are in contact with concrete definitions and are used to define articulated boundary conditions. Each explosive shall be detonated independently, and each explosive entity shall have a detonation point with the same detonation time. If the detonation interval is required, different initiation times can be defined.
2.3. Material model and parameter settings

2.3.1. Detonation products. The explosive material in the model is JH-2. The JWL equation of state, the explosive material model and the P-V relationship of the equation of state are used for the calculation of the detonation product action process as follows:

\[
P = A(1 - \frac{\omega}{R^2V}) \exp(-R^2V) + B(1 - \frac{\omega}{R^1V}) \exp(-R^1V) + \frac{\omega E_0}{V}
\]

(1)

Where \(P\) is the detonation pressure; \(V\) is the relative volume; \(E_0\) is the initial internal energy per unit volume; \(\omega\), \(A\), \(B\), \(R_1\), and \(R_2\) are the material constants; the value of the parameter in the model is \(A=3.74\times10^{11}; B=3.23\times10^9; R_1=4.150001; R_2=0.95; E_0=7.0\times10^9; V=1, \omega=0.3\).

2.3.2. Air. Simplify air as an inviscid ideal gas, assuming that the expansion of the shock wave is an isentropic adiabatic process air material model and linear polynomial equation of state:

\[
P = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu + C_6\mu^2)E_0
\]

\[
\mu = \frac{1}{V}-1
\]

(2)

(3)

Where \(E\) is the initial specific internal energy of the explosive, that is, the internal energy per unit volume; \(V\) is the relative volume; \(\mu\) is the ratio of the volume of the detonation product to the initial volume of the explosive, and \(\rho_0\), \(\rho\), and \(\lambda\) are the initial density, density and adiabaticity of the gas, respectively index. When the linear polynomial equation of state is used for air, the parameter values are \(C_0=C_4=C_5=C_6=0, C_1=C_2=C_3=0.4\).

2.3.3. Rebar. Since the steel bar is an isotropic material, considering kinematic hardening, the plastic bilinear kinematic hardening model is adopted, and the influence of the material strength on the strain rate is considered. The strain rate effect of the steel bar is calculated using the Cowper-Symonds model, that is, when calculating the yield stress of the steel bar, multiply the following coefficient:

\[
1 + \left(\frac{\dot{\varepsilon}}{C}\right) \exp\left(\frac{1}{P}\right)
\]

(4)

Where \(\dot{\varepsilon}\) is the strain rate, and \(C\) and \(P\) are the strain rate parameters of the Cowper-Symonds model. When the value of \(C\) and \(P\) is zero, the strain rate effect of the material is not considered. For steel bars, the values of these two parameters are: \(C=40, P=5\).

2.3.4. Concrete. During the explosion, the structure was in a state of high strain, and the concrete material used the CONCRETE_DAMAGE_REL3 model. The model considers the strain rate effect of the material through the dynamic improvement factor DIF, which is the ratio of the dynamic strength of the material to its static strength at a certain strain rate. The dynamic increase coefficient of concrete strength adopts the C&K model, which is improved on the basis of the calculation method recommended by the European standard CEB. The model does not automatically consider material failures, and additional erosion criteria need to be defined to consider the maximum normal strain and shear strain. When any failure criterion is met, these concrete elements can be deleted from the calculation.
2.4. Validation of finite element model

In order to verify the applicability of finite element, 1.5kg single point contact explosion of RC slab was simulated, and the numerical simulation results were compared with the actual explosion test results of the research group. Figure 2 is the damage comparison results. The measured longitudinal damage length of the bursting surface of RC slab is 56cm, the transverse damage length is 64cm, and the maximum depth is 14.2cm. The longitudinal damage length of the back bursting surface is 99cm and the transverse damage length is 60cm. In the numerical simulation, the longitudinal damage length of the bursting surface of RC plate is 58cm, the transverse damage length is 62cm, the maximum depth is 13.8cm, the longitudinal damage length of the back bursting surface is 98cm, the transverse damage length is 56cm. Figure 3 is the actual value and the simulation value of the 1/4 cross section of the RC slab. The peak acceleration value of the actual value is 24176.6m·s⁻², and that of the measured value is 25229.20m·s⁻². The error is about 4%. The comparison of damage results and acceleration results shows that the numerical simulation is in line with the reality.

![Figure 2](image1.png)

(a) Top damage
(b) Bottom damage

Figure 2 concrete damage obtained by numerical calculation with actual test results

![Figure 3](image2.png)

Figure 3 Acceleration time-history curves of 1/4 cross section of RC slab

3. Simulation result

3.1. Result damage

Table 2 shows the damage results of RC slabs under different explosion conditions. Under the condition of large charge (the total charge is 1kg), the entire mid-span section is damaged and the damage is serious. Two blast points on the burst face of RCP1 (spacing 30cm) form a connected oval pit, and the damage on the back burst face is a regular oval pit. The damage in the middle of the two explosive points is the most serious, but also can be seen that the concrete on both sides of the board has cracking; Two interconnected pits were also formed at the two explosive points on the bursting face and back bursting face of RCP2 (spacing 60cm). The concrete on both sides of the slab suffered the most serious damage and the penetrating damage occurred. Under the working condition of small charge (the total charge is 0.5kg), the damage of the slab is light and does not cover the whole mid-span section. The two blast points on the bursting face and back bursting face of RCP3 (spacing 30cm) form an oval pit connected as a whole, and the concrete on both sides of the slab does not crack. Two separate circular pits were formed at the two explosive points on the bursting face and the back bursting face of RCP4 (spacing 60cm), and the concrete on both sides of the slab cracked and spaled.
Table 2 Damage results of RC plates under different explosion conditions

| specimen | Top surface | Bottom surface |
|----------|-------------|----------------|
| RCP1     |             |                |
| RCP2     |             |                |
| RCP3     |             |                |
| RCP4     |             |                |

3.2. Dynamic response

3.2.1. Vertical stress wave. Table 3 shows the vertical stress waves of the plate during the period of 0-0.09 ms after the explosion. It can be seen from the vertical stress waves of the two-point contact explosion that when the explosive spacing is 30 cm, the two stress waves meet and superimpose each other in the plate, maintaining a high stress state in a farther range. When the spacing is 60 cm, the superposition effect is not obvious. According to the failure characteristics of the RC plate, the damage caused by explosion is that the compressive stress wave is generated on the bursting surface and causes the damage on the bursting surface of RC plate. Then the compressive stress wave propagates from the bursting point to the plate. When it meets other surfaces of the plate, it will reflect and generate strong tensile wave to cause damage. Under the condition of large charge, the stress wave in the plate reaches the back burst surface first when the contact explosion is 0.5 kg×2 and the blast point spacing is 30 cm. The strong tensile wave will lead to the spalling and collapse of the concrete on the back burst surface and form the pit. However, because the blast point is far away from the side of the slab, the tensile wave generated by the stress wave reflecting on the side of the slab is not enough to cause great damage to the concrete on the side of the slab. When the blast point spacing is 60 cm, the stress wave almost simultaneously reaches the side and back burst surface of the plate, and the strong tensile wave generated here causes damage to the side and back burst surface at the same time, and the penetrating failure occurs on both sides of the plate. Under the condition of small charge, the stress waves at two points of 0.25 kg×2 contact explosion are just intersecting when the distance between the two points of blast is 30 cm, so the damage range of the two points can be connected superimposed, but the damage range caused is small. When the explosive spacing is 60 cm, the stress waves of the two blast points do not intersect, the damage range of the two blast points is small, the destructive power is small, and two separate pits are formed, and no penetrating failure occurs on both sides of the plate.

Table 3 RC slab mid-span cross section vertical stress waves

| specimen | 0.03ms | 0.06ms | 0.09ms |
|----------|--------|--------|--------|
3.2.2. Dynamic response. The Figure 4 shows the acceleration time history curve of RC slabs. As can be seen from the figure, 0.5m away from the explosion center, the peak acceleration of RCP1–RCP4 are 54804.75m·s$^{-2}$, 48522.92m·s$^{-2}$, 26132.05·s$^{-2}$ and 18675.72m·s$^{-2}$, respectively. Among them, the peak acceleration of high charge condition is 2-3 times of that of small charge condition. Under the condition of large charge, the peak acceleration with the blast point spacing of 30cm is 1.13 times that of the peak acceleration with the blast point spacing of 60cm. Under the condition of small charge, the peak acceleration with the blast point spacing of 30cm is only 1.40 times that of the peak acceleration with the blast point spacing of 60cm. From the perspective of the peak acceleration size, the peak acceleration with the blast point spacing of 30cm is larger than that with the blast point spacing of 60cm. Combined with the analysis of the propagation phenomenon of stress wave, the superposition of blast wave is obvious and the peak acceleration is larger when the distance between two explosive points is 30cm. When the distance is 60cm, the phase separation shock waves generated by the two blast points are separated, and the peak acceleration is small.

Figure 4 Acceleration time history curve of RC slabs

4. conclusion
Under the two-point contact explosion load, the damage mechanism of RC slabs are as follows: the explosion generates stress waves and thus leads to the damage of the blasting surface of RC slab, and then the stress waves propagate and diffuse from the blasting point to the slab, and when they encounter other surfaces of the slab, they will reflect and generate strong tensile waves to cause damage. Two-point contact explosion energy gathered phenomenon, spacing is small, the explosive stress wave in the encounter between superposition, at this time between the explosive destruction: the worst spacing and larger near the side slab, the blast stress wave at the same time reach the slab back and side, creates strong tensile wave in reflection and back surfaces and side layer crack and collapse, near the location of the slab profile has been disrupted. The dynamic response of RC slabs are as follows: when the blast point spacing is small, the energy accumulation generated by the explosion is obvious, which makes the dynamic response of RC slab more obvious. When the spacing is 30cm, the peak acceleration of RC slab is larger than that of 60cm.
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