NUMERICAL SIMULATION FOR RESPONSE OF REINFORCED CONCRETE SLABS WITH SPRINGS SUPPORTED UNDER BLAST LOADS

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Abstract. The blast doors with springs supported are reinforced using flexible supporting principle. The addition of spring support is the new technique for blast doors reinforcement. In order to study response of RC slabs with two edges fixed and RC slabs with springs supported, RC slabs are simulated using finite element software LS-DYNA. The numerical simulation results are in accordance with experimental results, ensuring the accuracy of the numerical simulation. Numerical results show that the addition of spring support significantly improve the anti-blasting ability of RC slabs. The results have a great reference value for research of blast doors with springs supported and provide the basis for designing the blast doors with springs supported.

1 Introduction

The entrance of protection engineering is the weakest part of protection engineering, and also threaten by enemy weapons. As the most important protective equipment of protection engineering entrance, blast door is directly attacked by blast loads [1, 2]. With the development of accuracy and lethality of weapons, increasing attention of protection engineering has turned to the research and manufacture of the highly resistant blast doors. Blast doors with springs supported as new blast doors are attracted widespread attention in recent years. Unlike the rigid protection, the adoption of traditional protection principle, blast doors with springs supported are reinforced using flexible supporting principle. On the one hand, it takes advantage of the flexible buffering support to increase the deformation time and decrease the peak pressure. On the other hand, Flexible support is compressed to absorb energy under blast loads, reducing deformation of the blast doors subjected to blast loads. Therefore, blast doors with springs supported as new blast doors have certain research value [3, 4, 5]. Because of the size of the blast door and the complexity explosion, there are a series of difficulties to do the prototype tests. Therefore, the experiments of blast doors are always simplified. Xiudi Li [6] and Dong Guo [7] have simplified the structure of blast door in the experiments and numerical simulation. They studied the dynamic response of reinforced concrete slabs in the place of blast doors under blast loads. Li W L [8, 9] and Henry Khov [10] have established the flexible restrained plate calculation model. It is concluded that the vertical elastic support can effectively reduce the deformation of the plate under blast loads according to the theoretical analysis. Therefore, the research in dynamic response of RC slabs with springs supported under blast loads has a reference value and significance for the design of blast door with springs supported.

In this paper, corresponding finite element simulations of RC slabs with two edges fixed are conducted using LS-DYNA software based on the experiments. In the simulation, the Finite Element model of RC slabs with springs supported were employed to simulate the dynamic response of RC slabs with spring end-supported, contrast to the response of RC slabs with two edges fixed. This paper analyzes spring support affecting the anti-blasting ability of RC slabs and then the dynamic response of RC slabs with different stiffness coefficient of the springs are compared. The study lay the foundation for the design and research of blast doors with springs supported.

2 Experimental procedure and results

To date, the research on the performance of blast door under blast loads is still limited. A series of experiments with the RC slabs have been conducted, to predict the response of the blast door subjected to blast loads. The anti-blasting performance of blast doors is analyzed through the dynamics response of RC slabs. Experimental study on the explosion of RC slabs with two edges fixed is conducted in the literature [11, 12]. We select one of the most representative set of RC-plate tests for numerical simulation. The 1100mm×1000mm×40mm slabs were cast with 40.2MPa concrete and reinforced with bottom Longitudinal and transverse steel mesh of designation HPB235 spacing 75mm, which had bar cross-sectional diameter 6mm. The concrete has a cylinder compressive strength of 40Mpa and tensile strength of 4Mpa. The Reinforcement has a yield strength of 395Mpa and ultimate strength of 501Mpa. These Experiments were carried out in Changsha County TiaoMa outfield. The TNT charges suspended above the center of the slabs were used to generate the blast environment. The TNT charges were 40cm away from RC slabs shown in Fig. 1. The maximum center deflections of the tests are summarized in Table 1.

Fig. 1 RC slab explosion test

Table 1 The results of RC slab explosion test

Test no	TNT(g)	Collapse distance(mm)	Central displacement(mm)
1	200	400	10.1
2	310	400	14.8
3	460	400	35.2

3 Numerical simulation of RC slabs with two edges fixed

3.1 Finite element Models and divided meshes

Assuming the uniformity of the blast load, a quarter of the geometrical model is adopted in the modeling because of the symmetrical character as shown in Fig. 2. The calculational time is saved. Constraints are applied to the plane of symmetry and no reflection boundary condition is applied in the air boundary. The distance between the explosive and concrete is 40cm. The finite element model is shown in Fig. 3.

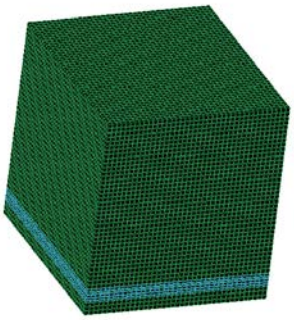


Fig. 2 a quarter of finite element model

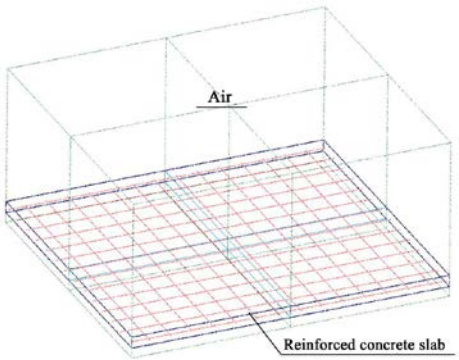


Fig. 3 Finite element model

There are four parts: concrete, steel bar, air and explosive. SOLID164 elements that are the most effective and stable elements, are adopted with concrete and air, BEAM161 elements are adopted with steel bar considering the transverse shear strain. The multi-material Eulerian and Lagrangian coupling algorithm were adopted using key words *constrained_lagrange_in_solid, an explicit finite element code for general fluid-structure interaction problems. A fluid-structure coupling finite element model was established which consists of Lagrange element for RC slabs, multiple ALE element for simulating air and TNT charge material. The explosive is added using key words *initial_volume_geometry. LS-DYNA provides an effective tool for analyzing the progressive collapse mechanism of RC slabs under blast loads. The element size has some influence on the numerical simulation results. The suitable size below 20cm will not only decrease the simulation time but also give an accurate modelling and failure modes. In this paper, the used mesh size for the finite element model is 0.8cm-1.25cm, which can ensure the accuracy and efficiency of numerical simulation.

3.2 Material models

The precision of numerical simulation depends on the validity and precision of the substance described. In this study, the Plastic-Kinematic model is adopted to model the response of steel material shown in Tab 2. The response of the concrete under blast loads is a complex non-1inear and rate-dependent process [13]. A variety of constitutive models for the dynamic and static responses of concrete have been proposed over the years. Among many constitutive models for concrete in LS-DYNA, the Johnson_Holmquist model can be used for concrete subjected to larger strains, high strain rates and high pressures, which in this study is shown in Tab 3. The High_Explosive_Burn model and JWL parameters for the explosive in the present study are shown in Tab 4. Null model for air in the present study is shown in Tab 5.

Tab 2 Parameters used in Plastic-Kinematic model for reinforcement

Density ρ(g/cm^3)	Elastic modulus(Mpa)	ν	σ_y (Mpa)	SRC	SRP	FS
7.8	2×10^5	0.33	395	4×10^{-3}	5	0.12

Tab 3 Material parameters used in HJC model for concrete

ρ(g/cm^3)	Shear modulus(Mpa)	A	B	C	N	Fc(Mpa)
2.44	1.23×10^5	0.79	1.6	0.07	0.61	40
T(Mpa)	EPSO	EFMIN	SFMAX	PC	UC	PL
4	E-6	0.01	7	1.33	0.001	0.008
UL	D1	D2	K1(Gpa)	K2(Gpa)	K3(Gpa)	FS
0.1	0.004	1	85	171	208	0.1

Tab 4 JWL parameters used for modeling TNT

ρ(g/cm^3)	D(m/s)	A(Mpa)	B(Mpa)	R_1	R_2	ω	E_0(Mpa)	V_0
1.654	6930	3.74×10^5	3.23×10^3	4.15	0.95	0.3	700	1

Tab 5 Material parameters for modeling air

ρ(g/cm^3)	C_0(Mpa)	C_1	C_2	C_3	C_4	C_5	C_6	E_0(Mpa)	V_0
0.00129	-0.1	0	0	0	0.4	0.4	0	0.25	1

3.3 Simulation results and discussion of RC slabs with two edges fixed

The dynamic response of reinforced concrete slabs under blast loads of different TNT equivalent are simulated by modifying the key words *initial_volume_fraction_geometry and *initial_detonation. Fig. 4-7 illustrate the simulation results with the minimum error (460g TNT equivalent) Fig. 4 illustrates a typical process of charge explosion which spreads with spherical explosions. The deformed configuration and stress nephogram of the slabs under blast load are shown in Fig. 6-7. The compress stress in the center of slabs was maximum. As shown in Fig. 5 and Fig. 7, there is the stress concentration on both sides due to the constraint of the steel frame.

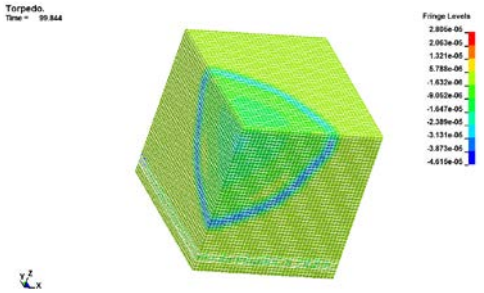


Fig. 4 Process of charge explosion

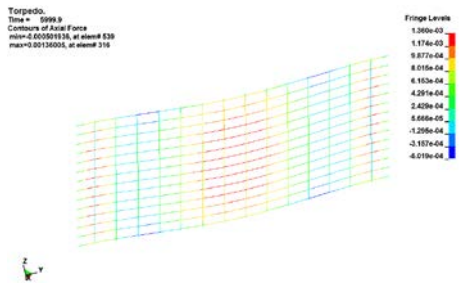


Fig. 5 Axial stress of steel bar

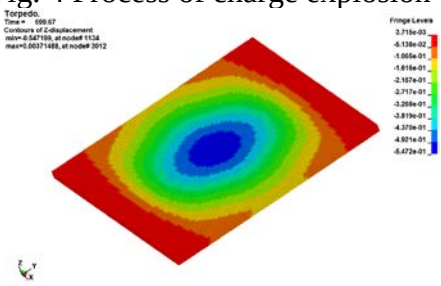


Fig. 6 Z-displacement of RC slab

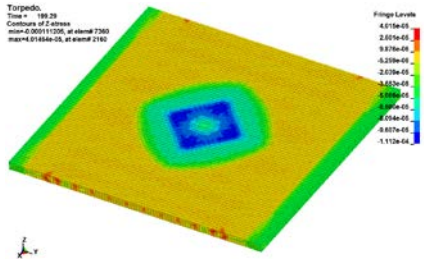


Fig. 7 Z-stress of RC slab

The central deformation of the slabs is maximum under blast loads, so this paper utilizes central displacement to represent the deformation of slabs. Fig. 8 shows the central vertical displacement-time history curve of RC slabs under different TNT equivalent explosion. The central displacement of RC slabs increase along with the increase of TNT equivalent, and the time for arrival of the peak displacement prolonged. The comparison between three curves shows that the RC slabs will first quickly deform to a certain position, then deform slowly until the maximum displacement is reached. Finally the RC slabs will rebound. The central displacement of RC slabs under rebound effect can be positive sometime when the TNT equivalent is 200g and 310g. Therefore, the rebound effect of RC slabs under blast load can not be ignored. With the numerical simulation results, it is found that the RC slabs will vibrate and reach the final deformation under the blast loads.

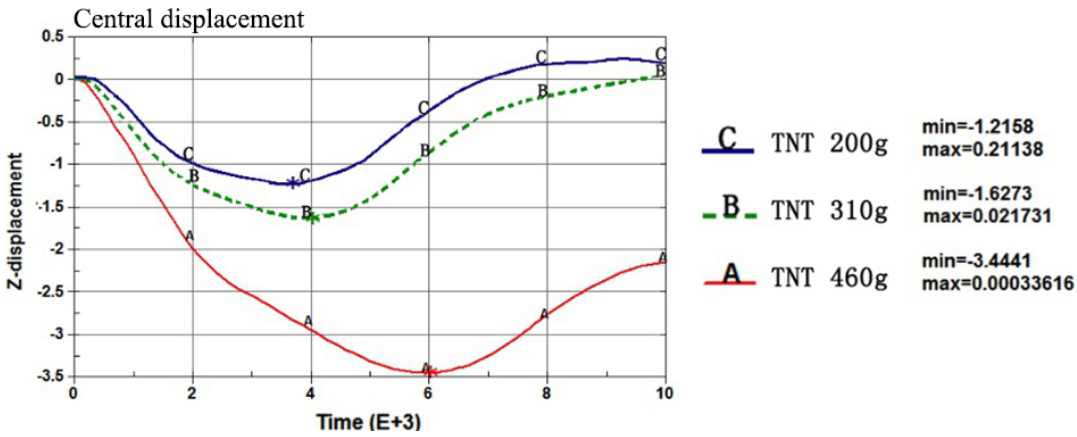


Fig. 8 the central vertical displacement-time history curve of RC slabs under different three TNT equivalent explosion

The results of numerical simulation on the central displacement of three groups of RC slabs are compared with the results of the experimental results, as shown in table 6. The simulation results are agreed well with the results of experiment and the error ranges from 2.16% to 20.40%.

Tab 6 Numerical simulation and experimental results on the central displacement of three groups of RC slabs

Test no	TNT equivalent(kg)	Collapse distance(mm)	Experimental result(mm)	Numerical simulation(mm)	error
1	0.2	400	10.1	12.16	20.40%
2	0.31	400	14.8	16.27	9.93%
3	0.46	400	35.2	34.44	2.16%

4 Numerical simulation of RC slabs with springs supported

4.1 RC slabs with springs supported subjected to blast load

The numerical simulation is adopted to study the dynamic response of RC slabs with springs supported under blast loads. 6 springs are set on each side of RC slabs (3 springs in a quarter model). The spring stiffness of the spring support is 10^7N/m. Combin14 elements is adopted with springs. The lateral constraints on the both sides of RC slabs will guarantee vertical movement of RC slabs. One end of spring support is connected to RC slabs, and the other end is fixed on the ground. Due to the addition of the spring, the total displacement of the RC slabs is increased. Considering the displacement of springs, the displacement of RC slabs enhances. The size of air model has increased. Fig. 9-10 illustrate the model of RC slabs with springs supported.

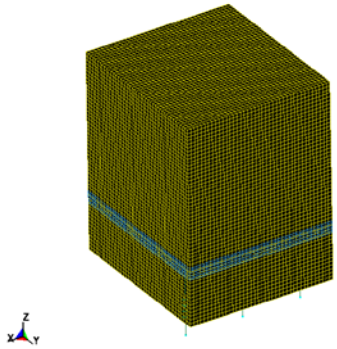


Fig. 9 A quarter of FE model

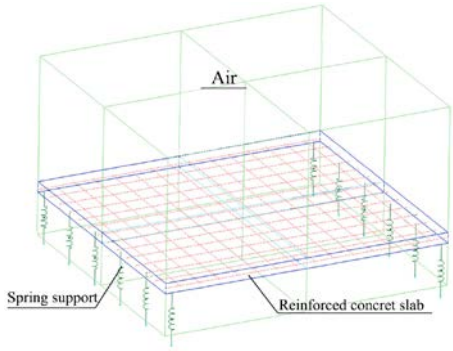


Fig. 10 RC slab with springs supported model

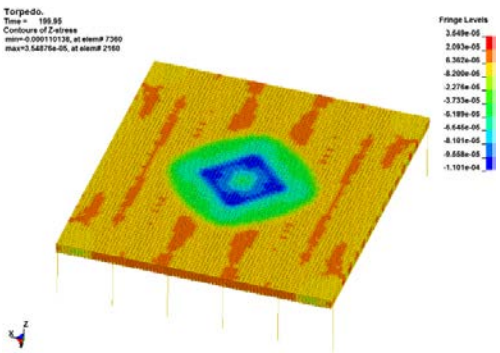


Fig. 11 vertical stress of RC slab

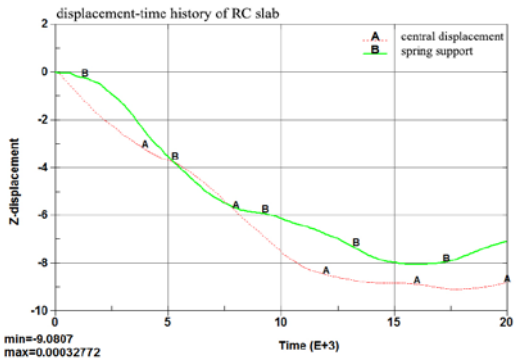


Fig. 12 displacement-time history curve

The RC slab will move down under blast loads and spring support are compressed. Fig. 11 illustrates stress cloud chart of RC slab with springs supported which is similar to the stress cloud chart of RC slab with two edges fixed (Fig. 7). Since spring support is set in place of clamped support, compared RC slab with two edges fixed. But there is no stress concentration phenomenon in the RC slab with springs supported. Under the horizontal restraint and spring support, RC slab is in vertical periodical motion. Fig. 12 shows displacement-time history of spring support and central displacement-time history curve of RC slabs. Because of the elastic buffer ability of spring support, the overall vertical displacement is greatly increased. The RC slab is deformed and the spring is compressed firstly. The central displacement of RC slab is larger than displacement of spring supports. The spring support is the first one to rebound as plastic deformation of reinforced concrete happens.

Fig. 12 shows the displacement of RC slab with springs supported and the displacement of spring supports. The difference (the central deflection of RC slab) between the central displacement of the RC slab (A) and the displacement of spring support is the deformation of the RC slab (B). Fig. 13 clearly shows the deflection of RC slab with two edges fixed and RC slab with springs supported.

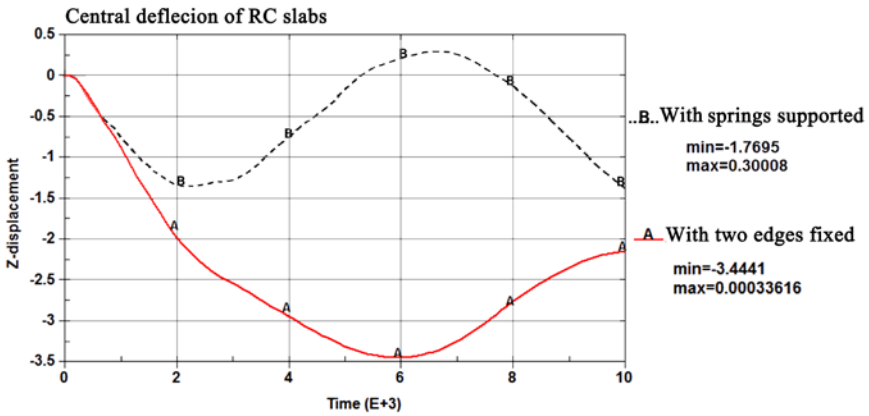
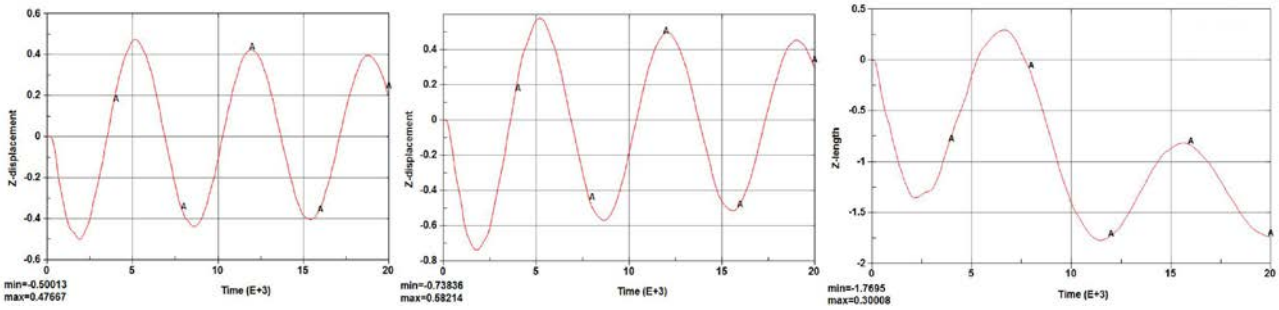


Fig. 13 Central deflection of RC slab

The deformation of RC slab under different TNT equivalent blast loads is shown in Fig. 14. The central deflection of RC slab increases with the increase of the TNT equivalent. With the addition of Spring support, RC slabs have longer deformation time before the maximum deflection is reached. From the numerical results in Fig. 13, the maximum of central defection of RC slab are 0.47667cm, 0.58214cm and 1.7695cm. Compared with RC slab with two edges fixed, the maximum deflection of the slab is reduced. When the TNT equivalent are 200g and 310g, the RC slab significantly rebound. It is due to the fact that the structure was in elastic phase with the addition of the elastic buffer ability of spring support.



(a) 200g TNT (b) 310g TNT (c) 460g TNT

Fig. 14 Central deflection of RC slab under 200g TNT, 310g TNT and s460g TNT

When TNT equivalent increase to 460g, the maximum displacement of the RC slab will not be reached in the first springback. After several times of rebounding, The maximum deflection of the RC slab is gradually reached. As a result, the damping effect of will be larger, the destruction RC slabs subjected to will be smaller. The deformation of RC slab is small because of the addition of the spring supports.

Tab 7 Deflection of two kind of RC slabs under 460g TNT

Test no	TNT equivalent(kg)	Deflection of RC slab with two edges fixed(mm)	Deflection of RC slab with springs supported(mm)	Percentage of reduction
1	0.46	10.1	4.77	52.77%
2	0.46	14.8	5.82	60.68%
3	0.46	35.2	17.70	49.72%

The central deflection of RC slab with two edges fixed and RC slab with springs supported under different TNT equivalent explosion are shown in Tab 7. With the addition of spring support, whose stiffness coefficient is 10^7N/m, The maximum deflection of RC slab decrease by half. It illustrates that spring support can contribute to enhancement of its anti-explosion ability. Therefore, the addition of spring support is a effective safeguard, can decrease plastic deformation, keep stability and improve the anti-explosion ability of the blast doors.

4.2 RC slabs with springs supported subjected to blast load

According to the study by Qin Fang [3, 4] on the blast doors with springs supported, spring support has a great influence on the dynamic response of the door. There are $K_1=10^6$N/m, $K_2=10^7$N/m and

$K_3=10^8$N/m three kinds of stiffness coefficients of spring supports. The deflection-time history curves of RC slab with three different springs supported under 460g TNT equivalent explosion are shown in Fig. 14 and Fig. 15-16. The maximum deflection of RC slab are 13.10mm, 17.70mm and 51.73mm. The results showed that with the increase of stiffness coefficient of spring support, the frequencies of springback diminish, the time before RC slab Reaching the maximum displacement increases, and the center deflection increases. So the addition of spring support of smaller stiffness coefficient, can effectively reduce the deformation of a RC slab, improve the anti-explosion ability of RC slabs. Meanwhile it increases the rebound effect of RC slabs. The maximum deflections of RC slab with three different spring supports are shown in Tab 8.

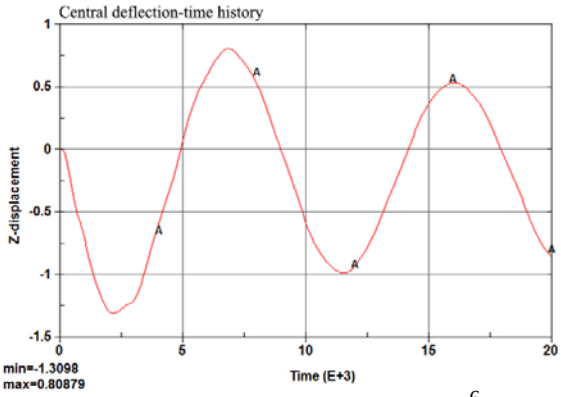


Fig. 15 Deflection-time history ($K_1=10^6$N/m)

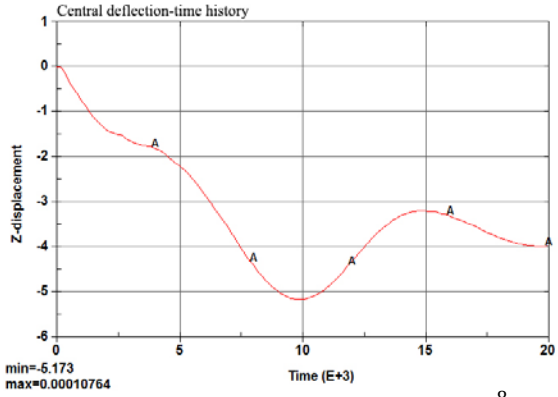


Fig. 16 Deflection-time history ($K_3=10^8$N/m)

Tab 8 Central deflection of RC slab with different spring supports

Test no	TNT equivalent (kg)	stiffness coefficients (N/m)	Central deflection(mm)
1	0.2	10^6	13.10
2	0.31	10^7	17.70
3	0.46	10^8	51.73

5 Conclusion

This paper performs numerical simulations in RC slabs with springs supported, with reference to RC slab with two edges fixed, as the subject research on blast doors with springs supported. The dynamic response of RC slabs with two edges fixed and RC slabs with springs supported has been discussed based on the numerical simulation results

(1)According to simulation, results of experiment of RC slabs with two edges fixed are agreed well with the results of numerical simulation. The simulation results can reflect the dynamic response of RC slab under blast loads.

(2)Based on finite element software LS-DYNA, RC slabs with springs supported ($K=10^7$K/m) under different blast loads were simulated numerically. The whole displacement of RC slabs increase, but the deflection of blast door decrease by half. As a result, the addition of spring support is a effective safeguard, can decrease plastic deformation, keep stability and improve the anti-blast ability of the blast doors

(3)The RC slabs with three different springs supported under 460g TNT equivalent explosion were simulated by finite element software LS-DYNA. The addition of spring support of smaller stiffness coefficient, can effectively reduce the deformation of a RC slab, improve the anti-explosion ability of RC slabs. Meanwhile it increases the rebound effect of RC slabs. The research of the RC slab with spring supported has scientific meaning and reference value to blast doors with springs supported, and provides provide the basis for the design of blast doors with springs supported.

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