Dynamic response of RC beams subjected to short-range lateral blast load

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Abstract—In this paper, the finite element software ABAQUS is used to simulate the RC beams under the short distance lateral blast load, consider the constraint effect of the plate, and analyze the influence of proportional distance, strength of concrete, strength of reinforcement, ratio of longitudinal reinforcement and other influencing factors on the dynamic response of RC beam. The results show that the CONWEP loading blast is reliable. The proportional distance is less than 0.200, and the lateral blast load has a great influence on the maximum lateral displacement of reinforced concrete beam with plate constraint. The influence of the strength grade of concrete and steel on the dynamic response of RC beams with slab constraints is limited. There is a negative correlation between the ratio of longitudinal reinforcement and the lateral displacement of RC beams with slab constraints. When longitudinal reinforcement ratio is more than 2.11%, RC beams with slab constraint can well resist lateral explosion load, but the lifting amplitude is not obvious.

1. INTRODUCTION
The current national conditions of China determine that the structure adopted by most of our buildings is still the reinforced concrete structure, in which beams play a very important role as one of the main load-bearing structures. In recent years, the explosion accidents due to human factors have attracted more attention. Many experts and scholars have used numerical simulation methods to conduct a lot of research on the dynamic response of reinforced concrete beams under blast loads. Fang and Wu [1] studied the failure modes of RC beams under blast loads and explored the main factors affecting the failure modes. Fang, Liu, and Zhang [2] conducted steel analysis under the blast load, which makes the study of material fracture under different stresses more universally applicable. It is particularly suitable for studying the issue of ductile fracture with large-scale deformation of components without obvious initial defects, such as progressive-collapse resistance of building structures. Tang, Liao, Xue, and Zheng [3] studied the resistance to bending failure of high-strength reinforced concrete beams under blast loads, pointing out that high-strength reinforced concrete beams have good bending resistance and better deformation recovery capabilities than ordinary concrete beams. Zhang [4]used ANSYS/LS-DYNA, a finite element software, to create a reinforced concrete beam model, and analyzed the effects of different reinforcement ratios on the dynamic response of these beams under explosive loads, thereby obtaining the factors that have a greater impact on the dynamic response of these beams. Sheng [5]used ANSYS/LS-DYNA to establish an analysis model of reinforced concrete beams under explosion, and numerically analyzed the dynamic response of the beams under explosive loads. The result shows that
with the increase of the longitudinal reinforcement ratio and the stirrup spacing or the decrease of the span-height ratio and the concrete strength, the failure mode of beams changed from bending failure to shear failure. Zhang [6] studied the impact of the combined loading schemes with different loading sequences, initial loading intervals, and moderate rate loading stresses on the explosion response of RC beams. Some important structural parameters concerning the vulnerability of different RC beams, including the beam height, span, and reinforcement configuration, are used to evaluate the bending resistance of the remaining RC beam under blast loads by proposing a damage index. Yan, Liu, Song, and Jiang [7] studied the understanding of the damage mechanism of reinforced concrete components under the action of explosion, and improved the damage evaluation of reinforced concrete structures under explosion. Zhang, Yao, Lu, Chen, and Lin [8] studied the failure forms and damage situations of reinforced concrete beams under blast loads. The results show that the damage of small-sized reinforced concrete beams is slightly lower than that of large-sized ones.

2. LOADING PRINCIPLE OF CONWEP

CONWEP was originally the software used by the U.S. military to calculate the explosive load of weapons. It was mainly based on a large number of explosion tests conducted by Kingery and Bulmash in the 20th century in Canada and the United States. CONWEP can be used to calculate the explosive over-pressure of the structure at the time of explosion. CONWEP helps to form the history curve of explosion load time by providing the empirical data including maximum over-pressure, arrival time, over-pressure time, and exponential attenuation factor, as shown in “Fig. 1”.

![Figure 1 Curve of explosion over-pressure in air](image)

In formula, $\theta$ is the incident angle of the incident wave, $P_{\text{incident}}$ is the pressure of the incident wave, $P_{\text{reflect}}$ is the pressure of the reflected wave, and $P(t)$ is the total pressure at any point on the target.

3. NUMERICAL SIMULATION AND VERIFICATION OF CONWEP PRINCIPLE

ABAQUS, the finite element software, is used to establish a reinforced concrete beam model. Both ends of the beam are hinged. The concrete adopts the plastic damage model while the steel bar is modified using John-Cook [9] and is embedded in the concrete. The data obtained through numerical simulation are as follows, and the comparison with experimental data in reference [8] is shown in Table 1.

| Beam size | Stirrup | Proportional distance | Experimental results (mm) | Simulation results (mm) | Error (%) |
|-----------|---------|-----------------------|----------------------------|-------------------------|-----------|
| 1100×100  | Φ6@60  | 0.40                  | 40                         | 38.27                   | 4.33      |
| 1350×125×125 | Φ6@60 | 0.44                  | 44                         | 55.75                   | 26.7      |
| 1350×125×125 | Φ6@120 | 0.44                  | 62                         | 58.98                   | 5.00      |
It can be seen from Table 1 that the error between explosive loads using CONWEP and experimental results is within a reasonable range; therefore, the reliability of numerical simulation results is ensured.

4. NUMERICAL SIMULATION OF RC BEAM UNDER SHORT-RANGE LATERAL BLAST LOADS

4.1. Plate constraints on reinforced concrete beams and numerical simulation

The end faces of the columns of the entire reinforced concrete frame are respectively constrained and hinged. The entire reinforced model is embedded in the concrete frame. The length, width, and height of the reinforced concrete beam are 100mm; the concrete thickness is 25mm, and the spacing between stirrups is 100mm. The CONWEP loading method in ABAQUS is used to determine the amount of TNT explosive as 8kg and the explosion distance as 0.4m. The concrete adopts the C3D8R unit, which is a three-dimensional solid eight-node hexahedron unit, and the steel bar adopts the T3D2 unit, which is a two-node linear three-dimensional truss unit. The entire frame structure is divided by different grid sizes. The 25mm grid is used for the reinforced concrete beams for the key research, and the 100mm grid is used for the non-researched reinforced concrete columns, thereby improving the calculation efficiency of the numerical simulation. The concrete adopts the plastic damage model while the reinforced materials use the improved John-Cook [9] model.

4.2. Dynamic response of reinforced concrete beams with plate constraints

When the TNT equivalent is 8kg, the vertical distance from the explosive center to the frontal surface of the beam is 0.4m, the strength level of the longitudinal reinforcement and stirrups is HRB335, and the strength level of the concrete is C40. When a short-range lateral explosion is applied by CONWEP and the over-pressure duration is given as $t = 35.0\text{ms}$ under load, the aberration nephogram of the reinforced concrete beam under the plate constraint is shown in “Fig. 2”.

![Figure 2 Stress nephogram of reinforced concrete beam at $t = 35.0\text{ms}$](image)

![Figure 3 Various time-history curves of reinforced concrete beams](image)
It can be seen from “Fig. 2” and “Fig. 3”, the reinforced concrete beam with the plate constraint will undergo torsional failure under a short-range lateral blast load; during this process, the plate constraining the beam will undergo the torsional deflection. The torsional stiffness of the plate will also have a certain restraint effect on the deformation of the beam, so that the internal force of the reinforced concrete beam will be redistributed. A stress band of about 1m will be respectively formed from the two ends of the beam to the central point, which is the delicate place that can be strengthened by the reinforcement stirrup. Most of the energy of a reinforced concrete beam with the plate restraint is converted into plastic dissipative energy, internal energy, damage loss energy, and strain energy under the action of a short-range lateral explosive load.

5. NUMERICAL SIMULATION OF RC BEAM UNDER SHORT-RANGE LATERAL BLAST LOADS

5.1. Effect of proportional distances
Change the TNT equivalent when the other parameters remain unchanged, and then we can obtain the proportional distances of 0.186, 0.192, 0.200, 0.220, 0.234, and 0.277, respectively. Extract the simulation data at node 1615, and we can obtain the time-history curve of the lateral displacement of the reinforced concrete beam after processing, as shown in “Figure 4”.

![Time history curve of lateral displacement of the beam](image)

(a) Time history curve of lateral displacement of the beam

![Maximum lateral displacement-proportional distance curve of the beam](image)

(b) Maximum lateral displacement-proportional distance curve of the beam

Figure 4. Curves of various lateral displacements of beams with plate constraints

In the case of the plate constraint, the overall stiffness of the reinforced concrete beam is enhanced, which can effectively improve the ability of the reinforced concrete beam to resist lateral explosion loads. When the proportional distance is less than 0.200, the lateral explosion load has a greater influence on the maximum lateral displacement of the reinforced concrete beam with the plate restraint.

5.2. Impact of strength of concrete and steel
Through ABAQUS numerical simulation, the simulation data of reinforced concrete beams at various strength grades of concrete and steel are obtained, as shown in “Fig. 5”.

![Simulation data of various lateral displacements](image)
Under the action of a short-range lateral explosive load, the time-history curve of the lateral displacement of the reinforced concrete beam shows a simple harmonic motion. Due to the economic factors and that the brittleness of the concrete material increases with the increase of the grade, it is feasible to select C40 concrete to resist lateral blast loads. The strength grade has a little impact on reinforced concrete beams with plate restraints.

5.3. Impact of longitudinal reinforcement ratio

Conduct numerical simulation using longitudinal reinforcement ratios of 1.13%, 1.44%, 1.71%, 1.79%, 2.11%, 2.19%, and 2.64%, and we can obtain “Fig. 6”. The lateral displacement of reinforced concrete beams with plate restraints will decrease with the increase of the reinforcement ratio. When the reinforcement ratio is greater than 2.11%, the reinforced concrete beam with plate restraints can well resist lateral explosion load, but not significantly.
6. CONCLUSION

Through ABAQUS numerical simulation, this paper explores the impacts of proportional distance, concrete strength, reinforcement strength, and longitudinal reinforcement ratio on the dynamic response of reinforced concrete beams with plate constraints. Based on data processing and analysis, the conclusion is as follows:

1) Reinforced concrete beams with plate constraints will undergo bending and torsional failure under the action of lateral explosions; a stress band of about 1m will be respectively formed at the two ends of the beam to the center, which is also relatively vulnerable parts that can be strengthened using stirrups.

2) Proportional distance has a greater impact on the dynamic response of reinforced concrete beams with plate restraints. When the proportional distance is less than 0.200, the lateral blast load has a greater effect on the maximum lateral displacement of reinforced concrete beams with plate restraints.

3) The influence of concrete strength and strength grade of steel bars on the dynamic response of reinforced concrete beams with plate restraints is not obvious. The C40 concrete and HRB335 steel bars can maintain good economic benefits while taking into account the anti-explosive performance.

4) There is a negative correlation between the longitudinal reinforcement ratio and the lateral displacement of the reinforced concrete beam with plate restraints. When the reinforcement ratio is greater than 2.11%, the beam with plate restraints can well resist lateral explosion loads, but not significantly.

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