Experimental research on failure mode of reinforced concrete beams under contact explosion

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Abstract. In order to research the failure mode of reinforced concrete (RC) beams under contact explosion, experiments were carried out to explore the damage of RC prototype beams fixed at both ends under four TNT charge masses, the damage failure model and damage effect of RC beams under different charge masses were analyzed. The results show that the beam presents three local failure modes: crater damage, collapse, spall failure and punching failure. The degree of local damage has a serious impact on the overall bending deformation of the beam. Besides, reasonable reinforcement could effectively improve the anti-explosion performance of the beam. The research results could provide a theoretical basis for the design of the anti-blast structures and the damage analysis on the structure subjected to explosive action.

1. Introduction
The improvement of modern weapons' strike capability has put forward higher requirements on the anti-explosive performance of protective engineering structures. In addition, explosion disasters caused by terrorist attack or industrial life accidents continue to occur. High shock pressure and strong destructive force could easily cause serious impact damage directly leads to the destruction and collapse of buildings. Therefore, study on anti-explosion protection technology of buildings has become an important research topic in the field of civil engineering [1].

In recent years, there have been many studies at home and abroad concentrate focus on the damage characteristics and dynamic response of RC beams under the close-in explosion. Kuang [2] and Wang [3] et al. conducted a scaled beam explosion test research to study the failure mode and destruction characteristics of RC beams under different explosion distances and charges. Yan et al. [4] studied the failure mechanism of RC beams under blast explosion, and simulated the detailed process of concrete cracks to collapse and spalling at the bottom through numerical analysis. Lin [5] and Rao [6] analyzed the influence of the charge masses, the location of the explosion and the longitudinal reinforcement ratio on the dynamic response of the model beam through parameterized discussion. For contact
In explosion research, Wang et al. [7] conducted a simple support of RC model beam contact explosion test, studied the damage effects and characteristics of the beam under three charges, and found that with the increase of the charge, the damage mode of beam gradually change from bending failure to partial punching failure. Based on the test results, Li et al. [8] proposed the damage area ratio to evaluate the crater and collapse damage of the RC beam under contact explosion. It can be seen that although there have been some studies focus on the contact explosion of RC beam members, most of them are based on scale model tests or numerical analysis, and there are few studies focus on the local failure mode and anti-explosion performance of RC beams under contact explosion. Due to the complexity of the problem, the failure mode of the beam under contact explosion load is not fully studied. Therefore, it is of great significance to carry out RC beam contact explosion test research for the improvement of the blast damage theory and the damage assessment and anti-explosion design of RC structural beams.

2. Experimental program
A total of 4 reinforced concrete rectangular cross-section beams with the same material and size were designed, with a size of 6600mm × 350mm × 500mm (length × width × height). The concrete strength grade is C30, and the material composition and blending are shown in Table 1. The longitudinal steel bars are HRB400 ribbed steel bars and the concrete cover thickness is 15mm. In order to suppress the shear failure at both ends of the beam, the stirrups (limb hoop) are encrypted within 1140mm at both ends of the beam. The test beam is supplemented with waist bars and a double-layer cloth reinforcement method is used in the tension zone.

| Concrete strength grade | $f_{cu}$ (N/mm²) | Coarse aggregate maximum diameter/mm | Cement strength grade /MPa | Mix ratio (W:C:S:G) | Slump/mm |
|------------------------|-----------------|------------------------------------|--------------------------|-------------------|---------|
| C30                    | 38.22           | A15                                | 42.5                     | 0.44:1:1.21:2.25   | 10~30   |

The RC beam was fixed to a plain concrete support platform by 380mm wide legs at both ends of the beam. TNT explosives were used in the test, and the design charge was 4Kg, 6Kg, 8Kg, 16Kg (corresponding to the 1# ~ 4# test respectively), which was placed in the center of the upper surface of the beam and was detonated by the electric detonator.

Figure 1: Dimension and bar arrangement of RC beams (unit: mm)

Figure 2: Test device of RC beams under contact explosion
3. Test Results and analysis

3.1. Analysis of test results
The typical failure form of the RC beam in the 1\textsuperscript{st} ~ 4\textsuperscript{th} test under contact explosion is shown in Figure 3 ~ Figure 6. The description of the damage and destruction of the RC beam is listed in Table 2.

| Test Number | Local damage features | Overall damage features |
|-------------|-----------------------|------------------------|
| 1\textsuperscript{st} | The front concrete was broken, crater depth was 155mm, 6 longitudinal bars were exposed and 4 stirrups were broken apart; The concrete on the side spalled and the waist tendon were exposed; The concrete on both sides of the back surface flakes off, resulting in two seismic collapse cracks, with a distance of 1000mm, without concrete falling. | The displacement of beam center was 70mm, except for the local damage area at the explosion point, the rest of the beam remains intact. |
The crater depth was 210mm, the length of the exposed area of the longitudinal bars was 1150mm, four stirrups were scattered, and the middle of two were broken; Side face concrete peeled off and the diameter of the concrete fragment above the waist bar reached 230mm; Multiple fragments collapsed on the back explosion surface, the collapsed length was 1200mm, and there were 4 lateral cracks on both sides.

The beam deformation increases, and the center displacement was 330mm, and the deformation mainly concentrated in the local area at the burst point, other parts were complete.

The front crater depth was 255mm, 6 stirrups were broken, and the waist bars and the second layer 2C22 longitudinal bars at the bottom were slanted downwards; A large number of concrete fragments collapsed on the side, and cracks in the concrete were visible. The concrete collapse length of the back explosion surface was 1450 mm.

The beam was severely deformed, with a center displacement of 900mm. Except for the local damage area of the explosion, there were visible micro-cracks at the ends of the beam ends.

The full penetration area of the front explosion surface concrete was 1150mm, side surface of concrete was severely spalled, the longitudinal and waist bars of the front and back explosion surfaces were severely twisted and deformed, and the back collapse surface was 1670mm long.

The beam collapsed. Except for the damage of the entire section at the explosion point, there was a 2mm wide transverse crack at the end of the beam end, and the left concrete support moved 100mm to the right.

3.2. Analysis of local damage
The test results show that the RC beam exhibits three local failure modes under the action of the group charge contact explosion load: (1) Front crater, the concrete on the explosion surface was broken under the compression of the explosion shock wave, and the longitudinal reinforcement bent outward or downward, resulting in explosion craters; (2) Tensile seismic collapse damage, the tensile waves generated by the reflection of the explosion shock wave on the back explosion surface and the side cause cracking and spalling of the concrete layer; (3) Section breach failure, The high-strength explosion shock wave pressure makes the concrete in the explosion area completely broken, the longitudinal steel bars on the front and back explosion surfaces were cut off, and the cross section was completely penetrated.

The three local failure modes may occur in a single form or a composite form, which is related to the amount of charge. When the charge mass is small, it is mainly compressed into a combination of pits and side collapses, such as the 1# test; the charge mass continues to increase, compression would occur into a combination of crater and back explosion surface and side collapse, such as 2# and 3# test; when the charge mass is very large, it shows a single punching failure mode, such as the 4# test.

![Figure 7: Depth of explosive crater](image)

![Figure 8: Length of back collapse](image)
The crater depth \( h \) on the front blast surface and the collapse length \( L_z \) on the back blast surface were the main characteristic parameters of the local failure of the RC beam. According to the test results as shown in Figure 7 to Figure 8, it indicates that the local damage parameters were approximately linearly related to the cube root of the charge.

### 3.3. Analysis of overall damage

The overall failure mode of the beam was the bending mode, and the mid-span displacement could be used as the control parameter, and the bearing rotation angle could be used as the damage index [9] to analyze the overall anti-blast performance of the beam. Figure 9 shows the change of beam support angle (ratio of beam midpoint displacement to half-span length) of \( 1^\# \sim 3^\# \) test (\( 4^\# \) test beam collapsed) with the amount of charge.

The results show that the relationship between angle of the beam support and the charge were in a power function, and the overall bending deformation increases with the increase of the charge, which was greater than the increase of the local damage parameters, indicating that the local damage has a serious impact on the overall bending performance of the beam. Thus, the increased charge not only increases the overall load on the beam, but also increases the local damage, which greatly weakens the beam's bending resistance. When the charge mass is small, only the cracking of the concrete at the blasting surface occurs, which basically maintains the bending resistance of the section at the burst point; as the charge increases, the longitudinal bars in the compression area bend, the broken concrete falls off, and the bending moment of the section continues to weaken. When the steel bars were deformed or even broken at the cross section of the burst point, a large amount of concrete falls or the whole section breaks and falls, the section would lose its bending resistance, and the beam would be greatly deformed until it collapses.

The test results also show that the overall deformation of the beam is related to both the local failure mode (or charge) and the form of structural reinforcement. Although test \( 1^\# \) has obviously compressed into a crater on the front blast surface, the beam's overall bearing rotation angle was only 1.2 °. According to the damage criterion of reference[9], it was only a slight damage; the crater depth of \( 2^\# \) has exceeded 1/3 of the beam height, according to the theoretical criterion of reference[10], the cross section should be penetrated, but the test only occurred local rupture and collapse, and the bearing rotation angle was 5.7 °, that is, the overall beam damage was only weak and severe damage. The main reason is that the test beams were reinforced with waist bars and double-layer longitudinal bars in the tensile zone, which controls the collapse of the layered fragments and weakens the bending resistance of the beam section reduced due to local damage. It shows that waist bars and side bottom bars could improve the resistance to contact explosion of RC beams.

![Figure 9 Rotation angle of beam](image)

**Figure 9 Rotation angle of beam**

### 4. Conclusions

In this paper, the RC prototype beam contact explosion test was carried out to investigate the influence of the amount of charge on the beam's damage mode and damage effect. Studies have shown that there are two parts of failure mode of the RC beam under the action of contact explosion: local damage and...
overall deformation. Local damage includes three modes: front crater, Tensile seismic collapse damage and section breach failure, which may be presented in a single mode or a composite mode. The damage effect was linearly related to charge, the overall failure was mainly the bending failure mode, and the local failure has a serious impact on the overall flexural performance; the structural reinforcement method has a significant effect on the beam blast resistance local damage and the overall blast resistance performance. The research in this paper lays a foundation for further damage effect analysis and damage grade evaluation of RC beams under contact explosion.

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