Analysis of deformation characteristics of high-strength reinforced concrete beams under explosion load

Z Liao¹, D G Tang¹, L Z Shao¹, Z Z Li¹ and D P Yang¹,²,³

¹State Key Laboratory for Disaster Prevention & Mitigation of Explosion & Impact, The Army Engineering University of PLA, Nanjing 210000, Jiangsu, China
²Research Institute for National Defense Engineering of Academy of Military Science PLA, Luoyang 471000, Henan, China

E-mail: ydpheixiami@sina.com

Abstract. The dynamic response and failure characteristics of reinforced concrete beams under explosion loads are affected by various factors. To study the effect of reinforcement strength on the deformation properties of RC beams and to analyze the deformation differences of high-strength RC beams under different explosion loads, comparative explosion tests on two kinds of simply supported RC beams with longitudinal reinforcement yield strength of 400 MPa and 700 MPa were carried out respectively in this paper. The test results show that the deformation of the mid-span section concrete of the high-strength RC beam is basically the same as that of the ordinary RC beam when the peak overpressure value is small, and the strength advantage of the high-strength reinforcement has not been fully exerted. With the increase of explosion load, the maximum tensile strain and compressive strain of concrete at the mid-span section of high-strength RC beams are 46.6% and 43.5% of ordinary RC beams respectively. Under the action of high overpressure explosion load, the deformation of RC beams can be significantly reduced by high-strength reinforcement, which limits the development of cracks.

1. Introduction

The anti-explosion performance of reinforced concrete beams under explosion load has always been a research hotspot in the field of protective engineering [1-3]. To obtain structures with better anti-explosion performance, researchers at home and abroad have carried out a lot of research on a series of new materials and structural forms [4-6], such as ultra-high performance concrete [7,8], steel fiber reinforced concrete [9,10] and new reinforced concrete composite structure [11,12], and have made a lot of achievements. The reinforcement plays a skeleton role in the RC structure. Therefore, the strength index of the reinforcement is of great significance to the deformation and failure of the structure. At present, the use of high-strength reinforcement is an important development direction in the field of both military and civil construction engineering. In the field of civil architecture, some high-rise buildings have made extensive use of high-strength and high-performance reinforcement with yield strength above 600 MPa [13,14].

With the continuous development of RC structure to high resistance, it is difficult for low-strength reinforcement to meet the practical needs. High-strength reinforcement can not only improve the bearing capacity of the structure, but also reduce the consumption of steel and save resources. However, there are few studies on the anti-explosion performance of RC structures with high strength reinforcement under explosion load. Therefore, it is necessary to carry out further research on this issue. In this paper,
explosion tests on RC beams with two kinds of strength reinforcement are conducted. The deformation characteristics of high-strength RC beams under different explosion loads are also studied so as to provide reference for the application of high-strength reinforcement in engineering anti-explosion field.

2. Explosion tests

2.1. Specimen design
Specimens of the two types have the same size, both of which are 1700 mm ×150 mm ×300 mm (length ×width ×height), as shown in figure 1. The compressive strength of the concrete is 40 MPa and the thickness of the protective layer of the specimen is 25 mm. The standard strength of stirrup is 400 MPa and the stirrup rate is 0.38%. The standard strength of longitudinal reinforcement of the two types of specimens are different, namely 400 MPa and 700 MPa respectively, but the reinforcement ratio is identical. Before the test, the flexural capacity of the RC beams under uniformly distributed explosive load was estimated, and the peak overpressure of the applied load was determined to be 0.25 MPa and 0.35 MPa. The test conditions are shown in table 1.

![Figure 1. Diagram of specimen and reinforcement layout.](image)

| Test | Specimen | Reinforcement strength (MPa) | Peak overpressure (MPa) |
|------|----------|-------------------------------|------------------------|
| 1    | B400-1   | 400                           | 0.25                   |
|      | B700-1   | 700                           |                        |
| 2    | B400-2   | 400                           | 0.35                   |
|      | B700-2   | 700                           |                        |

2.2. Test principle and sensor layout
The tests were carried out in a cylindrical explosion pressure simulator with an internal diameter of 1900 mm, as shown in figure 2(a). The explosion pressure simulator consists of explosion section, transition section, test section and control system, as shown in figure 2(b). The detonating cord is detonated in the explosion section to produce a large amount of detonation products. The detonation product acts on the surface of the specimens through a grid system arranged in the transition section to form a uniformly distributed blast wave. Due to the natural cooling and the leakage action of the reserved vaporous hole, the explosion overpressure in the simulator decreases, and finally forms a long positive duration blast wave. The pressure sensors are symmetrically arranged at both ends of the specimens. The collection and analysis of test data are completed by the DH5922N dynamic signal testing system, as shown in figure 3. It is composed of a variety of front-end measurement systems with different sampling rates, a unified post-processing and operation interface. The system also has good software interface and powerful data processing and analysis function, which provides great convenience for the analysis of test results.
Figure 2. The diagram of test device. (a) Test setup and (b) Schematic diagram of test.

Figure 3. DH5922N dynamic signal testing system.

Figure 4. KH1122-PC12B pressure sensor.

The KH1122-PC12B pressure sensor manufactured by Nanjing Wotian Technology Co., Ltd. was used to measure the shock wave load on the specimen, as shown in figure 4. Two pressure sensors of this type were placed in each test and placed at the ends of the specimen. The sensitivity of the pressure sensor was 28.038 mV/MPa.

To study the effect of reinforcement strength on deformation parameters of RC beams under different explosive loads, the strain of concrete was measured with BX120-20AA strain gage, as shown in figure 5. There are altogether 7 strain gauges on the upper surface, side and bottom of the mid-span section of the specimen, which are numbered ε1~ε7. The detailed layout of the strain gauges is shown in figure 6.
3. Test results and analysis

3.1. Explosion load
To get more accurate explosion load, the measured values of the two pressure sensors are averaged. The overpressure time-history curves of test 1 and test 2 are shown in figure 7. As shown in figure 7, the explosive loads acting on RC beams reaches the peak overpressure in an instant, and then decreases exponentially. The positive duration time of explosive loads is almost not affected by the peak overpressure value, and the peak overpressure corresponding to test 1 and 2 is 0.245 MPa and 0.372 MPa, respectively.

3.2. Concrete strain
The RC beam is deformed under uniformly distributed explosive load, and the concrete strain value at the mid-span section directly reflects the deformation degree of the RC beam. Figures 8 and 9 show the strain time-history curves of RC beams at mid-span section with the peak overpressure values of 0.245 MPa and 0.372 MPa respectively. The corresponding maximum strain of the concrete is shown in table 2.
It can be seen from Table 2 that when the peak overpressure of explosion load is 0.245 MPa, the deformation of the mid-span section concrete of high-strength RC beam is basically the same as that of ordinary RC beam. This is because the deformation of the two RC beams is relatively small. Both the high strength reinforcement and ordinary reinforcement are in the elastic deformation at this time. When the peak overpressure increases to 0.372 MPa, the maximum concrete strain in the tensile zone on the bottom surface of high-strength RC beam is 3921 με, which is only 46.6% of ordinary RC beam (8409 με); The maximum concrete strain in the compressive zone on the top surface of high-strength RC beam is 786 με, which is only 43.5% of ordinary RC beam. The deformation of RC beam increases with the increase of explosive load. When the ordinary RC beams enter the yield stage and produce large deformation, the high-strength RC beams are still in the elastic stage due to the high yield strength of its longitudinal reinforcement. Therefore, high-strength reinforcement can effectively reduce the deformation of RC beams and improve the anti-explosion performance of the component.

**Table 2. Maximum strain of concrete.**

| Measuring point | Specimen | B400-1 | B700-1 | B400-2 | B700-2 |
|-----------------|----------|--------|--------|--------|--------|
| ε1/10^6         | -202^a   | -147   | -1806  | -786   |
| ε3/10^6         | -126     | -121   | -881   | -520   |
| ε6/10^6         | 610^b    | 594    | 8409   | 3921   |

^a^ "-^a^" denotes the compressive strain.

^b^ "^b^" denotes the tensile strain.

**Figure 8.** Strain time-history curves of concrete (0.245 MPa). (a) B400-1 and (b) B700-1.

**Figure 9.** Strain time-history curves of concrete (0.372MPa). (a) B400-2 and (b) B700-2.
4. Summary
In this paper, two kinds of simply supported RC beams with longitudinal reinforcement yield strength of 400 MPa and 700 MPa are tested and analyzed under different uniform explosion loads. The main conclusions are as follows:

- when the peak overpressure of explosion load is less than 0.245 MPa, the strength of longitudinal reinforcement has little influence on the deformation of RC beams, and the deformation characteristics of high-strength RC beam and ordinary RC beam are basically the same.
- when the peak overpressure of explosion load increases to 0.372 MPa, the maximum strain of concrete in tension zone and compression zone of high-strength RC beams is only 46.6% and 43.5% of that of ordinary RC beams, respectively. The concrete deformation of high-strength RC beam is significantly less than that of ordinary RC beam.

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