Experimental Research and Finite Element Analysis on Blast Damage of Unreinforced Steel Fiber Concrete T-beam Structures

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Abstract. To reveal the dynamic behavior and damage mechanism of unreinforced concrete T-beam bridge under blast loads, three specimens were designed. Dynamic strain, acceleration and acoustic velocity pro- and post-blast of three specimens were measured respectively, and the generation, development process and distribution condition of cracks were investigated. The results indicated that ribbed slab fracture failure was a key to the unstable failure of the whole T-beam bridge specimen. Adding steel fiber evenly to the T-beam bridge deck can change the degree of blast damage from “severe damage” to “moderate damage”, which improves the explosion anti performance of the bridge structures. The damage evaluation results provide the basis for damage repair and reinforcement treatment after explosion.

1. Introduction
Bridge structures were the link of ground traffic, and it is vulnerable to irreversible disasters attacks, such as terrorism attacks, earthquakes [1], tornadoes, etc. Under the action of various sudden and strong blasts, bridge structure was prone to local failure or overall instability and collapse, and had become an urgent problem in scientific research region.

Fujikura et al. [2] studied the anti blast performance of concrete beams and columns. Jiang et al. [3] carried on the numerical simulation to the bridge explosion phenomenon. Kasumassa et al. [4] carried out explosive tests on SFRC slab, and obtained typical failure mode and failure parameter index. Sahoo et al. [5] conducted two-point static load bending tests on 12 RC T-beams. Zhu et al. [6] used the finite element software LS-DYNA to study the damage behavior of city numerical bridge under blast loads. However, there are few researches on anti blast performance and damage mechanism of unreinforced steel fiber concrete T-beam bridge.

The dynamic response behavior and damage mechanism of unreinforced steel fiber concrete T-beam bridge under the action of the blast load were analyzed in combination with explosive failure phenomenon, acceleration, strain and acoustic velocity pro- and post-blast.

2. Experimental Methods
2.1. Test Specimens
Based on the specification [7], three concrete T-beam bridges, with different volume content of steel
fiber evenly on bridge deck, were designed for the tests, and numbered for C-1 to C-3.

The data shown in table 1 indicate that specimens C-1, C-2, C-3 were under the same concrete strength grade, and have the same support category and load category. Besides, the concrete T-beam bridges was a short bridge, and steel fibers were added only into the deck section. To ensure the same quality of concrete the C20 commercial concrete was used, pouring from the same batch, with 28 days of maintenance. Configurations of a specimen cross-section are shown in figure 1.

![Figure 1. Specimen dimension and loading details (Note: dimensions are in mm).](image)

### Table 1. Parameters of specimens.

| Specimen | Volume ratio of steel fiber | Concrete strength grade | Support category | Load category |
|----------|-----------------------------|-------------------------|------------------|--------------|
| C-1      | 0                           | C20                     | Simple support   | Blast load   |
| C-2      | 40kg/m³                     | C20                     | Simple support   | Blast load   |
| C-3      | 60kg/m³                     | C20                     | Simple support   | Blast load   |

2.2. Material Properties

The properties of the materials were controlled by the material categories and material specifications given in table 2.

### Table 2. Materials properties.

| Material          | Specification         | Elastic modulus $E_s$ (MPa) | Compressive strength $f_d$ (MPa) | Yield strength $f_y$ (MPa) | Ultimate strength $f_u$ (MPa) |
|-------------------|-----------------------|----------------------------|---------------------------------|---------------------------|-------------------------------|
| Concrete          | 150 mm length cube    | 0.21×10^5                  | 27.5                            | -                         | -                             |
| Steel fiber       | 380 level             | 0.52×10^5                  | -                               | 424.5                     | 747.2                         |

2.3. Test Device and Loading Method

The bridges were tested after being cured for 28 days. Specimen was simply supported on the batten, and the explosive was special no.2 rock emulsion explosive as showed in figure 1. The water-cement ratio of concrete equals to 1:0.5.

2.4. Measurement Contents

Dynamic strain, acceleration and acoustic velocity of ribbed slab pro- and post-blast were measured in the experiment. Acoustic velocity in concrete was measured by 5217A acoustic velocity meter. The
specific layout of measuring points was shown in figures 1 and 2.

![Figure 2. Measure point layout (Note: dimensions are in mm).](image)

3. Experimental Results and Analysis

3.1. Test Program and Failure Mode
When 60g TNT and 80g TNT and the blast end distance is 100mm, there was no obvious phenomenon in the three specimens, as showed in figure 3a. When 80g TNT and the blast end distance is 50 mm, the flange plate of the ordinary concrete T-beam bridge deck breaks, and the whole specimen basically loses its bearing capacity, as shown in figure 3b. There are no obvious cracks in the flange plate of unreinforced steel fiber reinforced concrete T-beam bridge deck, the cracks are narrow, and only occur at the explosion side, as showed in figure 3c. The whole bridge structure still has a certain bearing capacity and stability, as showed in figure 3d. The crack distribution and failure mode of the three specimens are shown in figure 3.

![Figure 3. Model fracture condition.](image)

3.2. Dynamic Response Analysis
From figure 4, by 60g of TNT, the strain values of the three specimens are basically the same. When 80g TNT and the blast end distance is 100mm, the longitudinal strain obviously changes when the distance between the explosion source and the bridge deck was 50 mm.
3.3. Acoustic Test Analysis

Because the properties of C20 concrete are similar to those of rock, the relationship between the damage index, \( D \), of rock and the reduction rate, \( \eta \), of acoustic velocity can be used to obtain the damage value of the bridge structure under the action of blast loads. Its expression is:

\[
D = 1 - \frac{V^2_i}{V^2_0}
\]  

(1)

where \( D \) is the damage index of bridge structures under blast loads; \( \eta \) is the acoustic reduction ratio, and \( \eta = \frac{V^2_0}{V^2_i} \); \( V_0 \) is the initial values of acoustic velocity; \( V_i \) is the acoustic velocity measurements after the \( i \)-th blast. Substitute the acoustic velocity measured into equation (1).

![Strain peak curves of S1-X](image1)

(a) Strain peak curves of S1-X

![Strain peak curves of S2-X](image2)

(b) Strain peak curves of S2-X

![Strain peak curves of S1-Y](image3)

(c) Strain peak curves of S1-Y

![Strain peak curves of S2-Y](image4)

(d) Strain peak curves of S2-Y

Figure 4. Model strain measurement result curves.

From figure 5, the damage index of the ribbed slab was larger than that of the flange plate. Adding steel fiber evenly to the T-beam bridge deck can change the degree of blast damage from “severe damage” to “moderate damage”. According to equation (1), the damage index range is -0.2 to 1.0 [8].

3.4. Acceleration Test Analysis

From figure 6, the acceleration of unreinforced steel fiber reinforced concrete T-beam bridge was less than that of the ordinary concrete T-beam bridge. When the motion was transmitted from the flange plate to the ribbed slab, the blast wave was relatively hysteretic, resulting in the phenomenon of “first increased and then decreased” in the acceleration of the ribbed slab. According to Eq. (1), the damage index range of the test piece is -0.2 to 1.0, which indicates that in the early stage of blast, and the criteria for the blast damage evaluation of unreinforced steel fiber reinforced concrete T-beam bridge structure are obtained [8], as shown in table 3.
Figure 5. Evolution law and quantitative evaluation of blast damage.

Figure 6. Model acceleration measurement result curves.
Table 3. Damage quantification of experimental results.

| Damage degree       | Damage index range | Damage state      | Experimental phenomena                                      |
|---------------------|--------------------|-------------------|-----------------------------------------------------------|
| Basically intact    | -0.2~0.1           | Undamaged         | Reduction in the width and number of existing cracks.     |
| Slight damage       | 0.1~0.3            | Mild injury       | New cracks are produced and existing cracks are widened.  |
| Moderate damage     | 0.3~0.55           | Repairable        | The number and width of new and old cracks continue to increase. |
| Severe damage       | 0.55~0.8           | Non repairable    | The number and width of new and old cracks are further increased. |
| Collapse            | 0.8~1.0            | Complete failure  | New and old cracks penetration, concrete is basically broken, bridge structure is unstable and collapsed. |

4. Conclusions

(1) With the increase of the steel fiber volume ratio of the bridge deck, the damage index of the flange plate position decreases gradually, and the degree of blast damage changes from “severe damage” to “moderate damage”.

(2) The evaluation criteria for blast damage of unreinforced steel fiber reinforced concrete T-beam bridge structure was obtained, which was to be used to evaluate the blast damage of bridge structure after blast loading. The damage evaluation results provide the basis for damage repair and reinforcement treatment after explosion.

Acknowledgments

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