Numerical Simulation of RC Beams Subjected to Continuous Explosive Loading

Guanjun Cao1*, Jinhuo Yu1

1 School of Highway, Chang'an University, Xi'an 710064, China;

Author's brief introduction: Guanjun Cao (1995-), Male, Master, E-mail address: 2019121017@chd.edu.cn;

*Corresponding author’s E-mail address: 2019121017@chd.edu.cn; caogunjun95@163.com

Abstract. In order to study the performance of reinforced concrete (RC) beams Subjected to continuous explosive load, the numerical model of RC beam is established by LS-DYNA finite element program. And the numerical model experiences two explosive cases continuously. The reliability of the numerical model is verified by comparing with the field test results of a RC beam under the same explosive cases. It provides a reference for the future numerical simulation and experimental research of Building components under continuous explosive load.

1. Introduction

In the new century, with the rapid development of national economy, people's demand for energy is increasing. This also makes the fire and explosion of various energy transportation vehicles and gas pipelines inevitable. This kind of accidents often lead to continuous explosions, which cause great damage to bridges and other engineering structures. RC beams is a common stressed component in bridge engineering. Studying its performance under continuous explosion load is the basis of anti-explosion design of engineering structures.

Many scholars have carried out a lot of research on the anti-explosion of RC beams. Wang et al.[1] conducted contact explosion tests of RC beams with the same size under different charge quantities. The results show that under the contact explosion load, RC beams have local failure modes such as front cratering, side collapse, back collapse and section punching. The depth of blasting pit, collapse thickness, surface damage area and longitudinal reinforcement deformation in the compression area all increase linearly with the cubic root of charge. Zhang et al.[2] studied the damage state of RC beam under close range explosion through field test. The results show that the macroscopic damage and fracture of the material are similar under all test conditions; Compared with large-size beams, the local damage of small-size beams is reduced. Lin et al.[3] conducted field explosion tests and a series of numerical simulations on 9 scale beam models to study the dynamic response and local damage of the specimens under explosion. The results show that the damage of RC beam decreases gradually with the movement of explosive from the middle of the span to the end of the beam. Ganchai et al.[4] conducted one, two and three independent explosion tests on FRP Reinforced RC slab (single-sided FRP, single-layer FRP and double-layer FRP). The results show that the RC slab with FRP interlayer can withstand the secondary explosion better. Kumar and Petroski [5] established...
an ideal rigid plastic model to study the plastic response of beams with central cracks under transverse impact load. The results show that the initial defects have a great influence on the failure mode and failure behavior of the beam. Hu et al. [6] studied the mechanical response of RC bridge under explosion by combining simulation and test. The results show that when the car bomb explodes above the bridge deck, the car steel plate can effectively block the propagation of shock wave.

In conclusion, scholars at home and abroad have made rich achievements in the research of RC beams under one explosion, but there is almost no research on RC beams under continuous explosion. In addition, the field explosion test is not only expensive, but also difficult to collect complete test data. So it is necessary to explore the finite element method to study the performance of RC beams under continuous explosion. In this paper, the numerical model of RC beam is established by LS-DYNA. The reliability of the numerical model is verified by comparing the damage and acceleration of a field test and numerical simulation. It lays a foundation for the numerical simulation and experimental research of RC beams under continuous explosion.

2. finite element model
In this paper, the numerical model is established by the nonlinear finite element program LS-DYNA, which is based on explicit integration and has been widely used in the simulation analysis of structural anti-explosion. The numerical model adopts ALE (Arbitrary-Lagrangian-Eulerian) method. The explosive and air are simulated by Euler element, and the structure is simulated by Lagrange element. Although ALE method will spend more calculation time, it can well simulate the formation and propagation of explosion shock wave and the interaction between shock wave and structure.

The finite element model includes five parts: reinforcement, concrete, explosive, air and boundary conditions, as shown in Figure 1. Air, concrete and explosive use SOLID element and reinforcement use BEAM element. The element size of the air model is 4cm, totaling 63100 elements. The element size of RC beam model is 2cm, totaling 52000 elements. These element sizes are determined after convergence analysis. Further reduction of the mesh size will not significantly improve the accuracy of the calculation results, but will cause the number of element to multiply and require higher computer performance and computing time. For a limited air area, in order to avoid the influence of wave reflection at the boundary on the solution area, it is necessary to impose non-reflective boundary conditions on each surface to simulate infinite space. The non-reflective boundary passes through the keyword *BOUNDARY_NON_REFLECTING. The Lagrange element (RC beam) and the Euler element (air and explosive) are via *CONSTRAINED_LAGRANGE_IN_SOLID is embedded together. The RC beam in the model is articulated at both ends.

3. Material Model
Select *MAT_HIGH_EXPLOSIVE_BURN and EOS_JWL simulates the detonation of explosives. The P-V relation of explosive material model and state equation is as follows.

Figure 1. Numerical Model for RC Beams
\[ p = A \left(1 - \frac{\omega}{RV}\right)e^{-Rv} + B \left(1 - \frac{\omega}{R_2V}\right)e^{-R_2v} + \frac{\omega E}{V} \]  

(1)

In equation: \( P \) is the detonation pressure; \( V \) is the relative volume; \( E \) is the initial unit volume energy; \( \omega, A, B, R_1 \) and \( R_2 \) are material constants determined by experiments. The values of parameters in the model are given in Table 1.

Table 1. Material Parameters of Explosive Model

| Parameter | Value |
|-----------|-------|
| \( A \) (GPa) | 3.74e11 |
| \( B \) (GPa) | 3.747 |
| \( R_1 \) | 4.15 |
| \( R_2 \) | 0.95 |
| \( \omega \) | 0.35 |
| \( V \) (kJ m\(^{-3}\)) | 1.0 |
| \( E \) (kJ m\(^{-3}\)) | 7.0e9 |
| \( \rho \) (kg m\(^{-3}\)) | 1.695e3 \(a\) |
| \( \rho D \) (m s\(^{-1}\)) | 8.2e3 \(b\) |
| \( P_{CJ} \) (GPa) | 21 \(c\) |

\(a\) Notes are explosive density.
\(b\) explosive velocity.
\(c\) explosive pressure.

Select *MAT_NULL simulates air and its linear polynomial equation of state is:

\[ p = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + \left(C_4 + C_5\mu + C_6\mu^2\right)E \]  

(2)

\[ \mu = \frac{\rho}{\rho_0} - 1 \]  

(3)

In equation: \( E \) is the ratio of gas density to initial gas density.\(C_0, C_1, C_2, C_3 \) and \( C_6 \) are all 0, \( C_4 \) and \( C_5 \) are 0.4.

Concrete model use *MAT_CONCRETE_DAMAGE_REL3, which can effectively simulate the mechanical behavior of concrete under high strain rate and large deformation, refers to Table 2 for detailed parameters.

Table 2. Material Parameters of Concrete Model

| Parameter | Value |
|-----------|-------|
| \( \rho \) (kg m\(^{-3}\)) | 2400 |
| \( PR \) | 0.25 |
| \( FT \) (MPa) | 2.93e6 |
| \( A_0 \) (MPa) | -4.076e7 |
| \( RSIZE \) | 39.37 \(a\) |
| \( UCF \) | 1.45e-4 \(b\) |
| \( LCRATE \) | -- \(c\) |

\(a\) Notes are the length unit conversion factor.
\(b\) Stress unit conversion factor.
\(c\) Relationship curve between strain rate and strength of concrete.

Steel is a strain rate sensitive material, and use *MAT_PLASTIC_KINEMATIC describes the dynamic characteristics of reinforcement, and its detailed parameters are shown in Table 3.

Table 3. Material Parameters of Reinforcement Model

| Parameter | Value |
|-----------|-------|
| \( \rho \) (kg m\(^{-3}\)) | 7850 |
| \( E \) (GPa) | 200 |
| \( NU \) | 0.3 |
| \( SIGY \) (MPa) | 450 |
| \( ETAN \) (MPa) | 2000 \(a\) |
| \( BETA \) | 1.0 \(b\) |
| \( SRC \) | 40.0 \(c\) |
| \( SRP \) | 5.0 \(d\) |
| \( FS \) | 0.1 \(e\) |

\(a\) Notes are tangent modulus.
\(b\) BETA is the hardening parameter.
\(c\) SRC and \(d\) SRP are strain rate parameters.
\(e\) FS is the failure strain.

4. Erosion criteria and restart

The Lagrange element will produce large deformation under explosive load. In order to avoid excessive deformation of the element and accurately simulate crushing and flaking of concrete, erosion algorithm is used for concrete in the model. In this algorithm, there are many judgment that can be used to set material failure, such as pressure, maximum principal stress, equivalent stress, maximum principal strain and maximum shear strain. The model uses the maximum principal strain as
the erosion judgment and deletes the corresponding units when the criterion is met. Based on a lot of data, the range of maximum principal strain is determined, and it is found through a lot of trial calculations that the critical value of maximum principal strain is 0.04.

This paper divides the numerical simulation of RC beam under continuous explosion into two stages according to the actual test process by utilizing the complete restart function of LS-DYNA. The first stage is 0.5kg of explosive equivalent and the second stage is 1.0kg of explosive equivalent based on the first stage. By defining the keyword *SRTESS_INITIALIZATION inherits stress and deformation. The calculation time for both stages is 10ms.

5. Results and Verification
The accuracy of the numerical model is verified by the RC beam of an explosion test. The RC beam continues to experience case1 (0.5kg explosive equivalent) and case2 (1.0 explosive equivalent). See Table 4 for detailed parameters. The comparison between the test results and the simulation results of specimen B1 under case1 is shown in Figure 2.

| Test case | Specimen NO. | TNT equivalent (kg) | TNT location | Blast type          |
|-----------|--------------|---------------------|--------------|---------------------|
| Cases1    | B1           | 0.5                 | Mid span of RC beam | Contact explosion |
| Cases2    | B1           | 1.0                 | Mid span of RC beam | Contact explosion |

![Figure 2. Damage Comparison between Test and Simulation (Case 1)](image)

The comparison of test results and simulation results of specimen B1 under case2 is shown in Figure 3.

![Figure 3. Damage Comparison between Test and Simulation (Case 2)](image)

Test acceleration time history of specimen B1 at 0.5m mid-span under case1 compared with simulation results as shown in Figure 4. The simulated peak acceleration and vibration trend are in agreement with the test results. The maximum acceleration of the test and simulation is reached at 1.27ms, the maximum of the test is 51000m·s⁻², the maximum of the simulation is 45800 m·s⁻², and the error is 10.2%. The main fluctuation data are concentrated between 1.1m s and 3ms. In the field test, the acceleration sensor under case2 was completely destroyed, so its acceleration was not analyzed.
6. Conclusion
The numerical model of reinforced concrete beam under continuous explosive load is established by using finite element program, and the damage state and acceleration time history of numerical simulation and field test are compared. The results show that the numerical simulation results of reinforced concrete beam under explosion are in good agreement with the field test results. The damage error is within 3% and the acceleration error is within 10%. It shows that the finite element method can simulate test better. It can be used for more parameter analysis and provide guidance for the design of continuous explosion test project in the future.

Reference:
[1] Wang H M, Liu F and Yan L H. Local Damage Effect of Reinforced Concrete Beams under Contact Explosions J. Explosion and impact, 2020,40 (12):37-45.
[2] Zhang D, YAO S J and Lu F. Experimental Study on Scaling of RC Beams under Close-In Blast Loading J. Engineering Failure Analysis,2013,33:497-504.
[3] Lin S C, Li D and Yang B. Experimental Study and Numerical Simulation on Damage Assessment of Reinforced Concrete Beams J. International Journal of Impact Engineering, 2019, 132(OCT.):103323.1-103323.15.
[4] Ganchai T, Nicholas H and Priyan M. Behavior of FRP-RC Slabs under Multiple Independent Air Blasts J. Journal of Performance of Constructed Facilities, 2011, 25(5): 433-440.
[5] Kumar S, Petroski H J. Plastic Response to Impact of a Simply Supported Beam with a Stable Crack J. International Journal of Impact Engineering, 1985, 3(1): 27-40.
[6] Hu Z J, Tang X H, and Fang J Q. Analysis of Pressure Field and Response for Concrete Bridge under Close Blast Loading J. Chinese Journal of Highway, 2014, 27 (05):141-147+157.