Analysis of the synergetic effects of blast wave and fragment on concrete bridges

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Abstract: The complicated loading caused by explosions is not well understood, so the effect is often simplified when calculated. In order to increase the bridge protective level, a penetrating study of the mechanism of the synergetic effect of blast wave and fragment is necessary. Numerical simulation is used to analyse the dynamic response characteristics and the damage performances of the reinforced concrete bridge. Three conditions were designed to research the synergetic effect of the blast wave and fragment on the bridge. The research indicates that the synergetic effect is larger than the arithmetic sum of the effect of blast wave and fragment separately, which should be taken into account in the protection of bridge.

Keywords: Blast wave, Fragment, Synergetic effect, Dynamic response

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1. Introduction

Several decades has witnessed that destroying bridges is the best efficient way to restrict the enemy for cutting off the transportation line and blocking supply in the local conflict. Moreover in many developing areas, infrastructure construction is blooming, blast is the fastest way to demolish the old un-qualified bridges. When bomb or missile exploding, blast wave and fragment are produced and both them impacted on the bridges. In recent years, either blast destroy bridges or fragment penetrate concrete is studied very well. But the complicated combined loading caused by synergetic blast wave and fragment is not well known. However design a blast test to research the synergetic effect is insecure and expensive. Numerical analysis using AUTODYN is the appropriate mean to study the mechanism before material test.

2. Loading characteristics

2.1 Blast wave characteristics

When explosions occur, the energy released at a lighting speed, which produce gas mixture with high temperature (3.5×10^3—4×10^3℃) and high pressure (1×10^4—3×10^4MPa). Since the air initial pressure and density is low, explosive product diffused at a high speed will compress the air nearby, increasing the air pressure, density and temperature drastically, which will develop into blast wave. The blast wave spread rapidly, during the energy spread and deplete, the speed of the blast wave will decay rapidly. When the volume of the explosive product expands big enough, the pressure in it will drop to the original level P_0 of the air nearby. However the product volume will keep expanding to a maximum because of the inertia effect. Then the negative pressure area will occur because the average pressure of the product is lower than the original pressure P_0, and the air nearby will compress the product conversely, which will increase the product pressure. For the air, the first expansion—compression impulse is worthy of study. Classical blast wave spread in air is shown as figure 1.

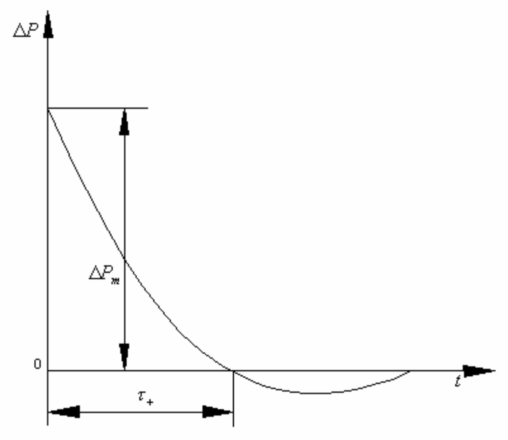


Figure.1 Pressure maximum of the blast wave

The expansion law of the explosive product can be simplified to the polytropic index equation of state [1].

$$PV^{\gamma} = const \tag{1}$$

P is the pressure of the explosive product; V is the volume of the unit quality; γ is the polytropic index, related to the component and density of the explosive product, γ enlarges when the density value increase.

AUTODYN is precise in explosions analysis for its BLAST boundary conditions. In this research, 2kg TNT exploding 2m above the bridge is simulated by AUTODYN [4].

2.2 Fragment characteristics

A large amount fragments are produced when explosion take place, these fragments with high speed will penetrate the bridges.

Mott formula is the most widely used to calculate the fragments' quality [1].

$$\mu^{0.5} = Kt_0(t_0 + d_i)^{1.5}(1+\frac{M_0}{2m_t})^{0.5} \Big/ d_i \tag{2}$$

$$m_p = 2\mu \tag{3}$$

m_t is the payload quality(kg); m_p is the fragment average quality(kg); t_0 is the thickness of the cartridge case(m); d_i is the internal diameter of the cartridge case(m); K is the explosive material factor($\mathrm{kg}^{1/2}/\mathrm{m}^{3/2}$).

Gurney formula considering cylindrical payload is used to calculate the fragments' initial speed [1].

$$v_0 = \sqrt{2E}\sqrt{\frac{C/m_t}{1+0.5C/m_t}} \tag{4}$$

v_0 is the initial speed of the fragments(mgs^{-1}); C is the quality of the explosive materials ($kggm^{-3}$);

$\sqrt{2E}$ is the Gurney factor(or Gurney specific energy), Gurney found the linear relation between the Gurney factor and explosive speed D_e through many tests.

$$\sqrt{2E}=520+0.28D_e \tag{5}$$

In order to simplify the research, this paper chooses spherical fragments with diameter 0.05m and initial speed $1700\,mgs^{-1}$.

3. Models and material parameters

3.1 Bridge model

In order to explain the mechanism clearly, a simple square section with 1m length of each side is used. The superior border has 3 longitudinal steels with diameter 6mm and inferior border has 3 longitudinal steels with diameter 12mm, shown as figure 2.

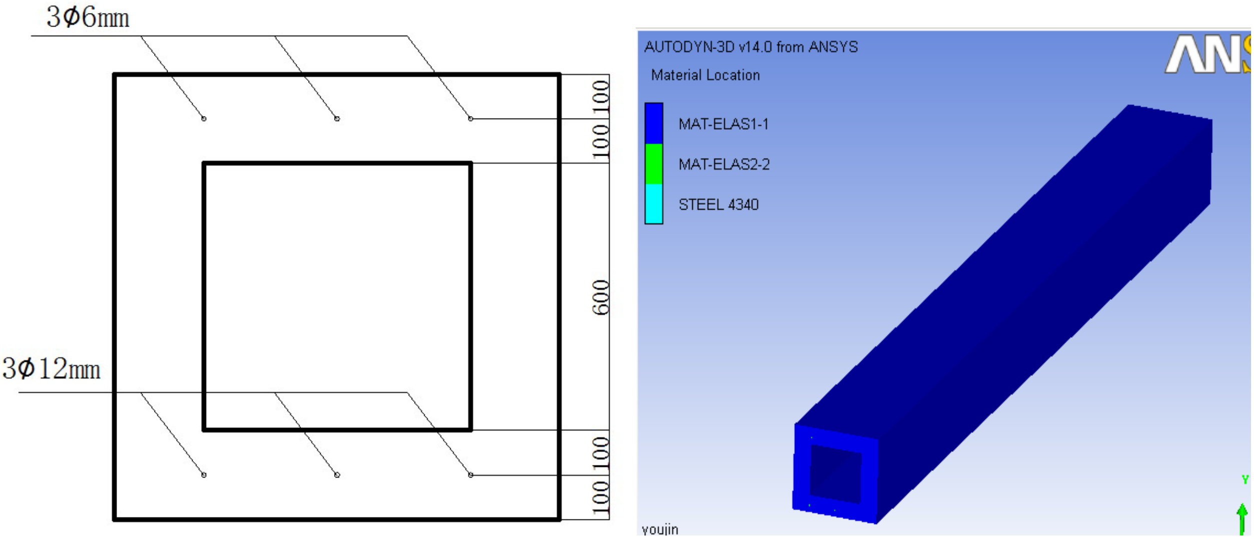


Figure.2 Beam section and 3-D model

3.2 Constitutive relation of the concrete

RHT model [2] was built by Riedel, Hiermaier and Thoma in 1999. The premise of the model formula is that the internal energy of the porous-material and compact-material under the same pressure and temperature are equal. The thermo-motive performances of the concrete under high pressure and the compression behaviors under low pressure will be described clearly by RHT. When the concrete is compacted enough, its state equation is shown as figure 3.

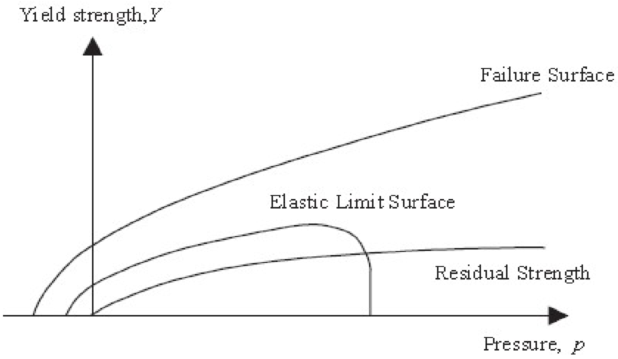


Figure.3 RHT constitutive relation of concrete

3.3 Dynamic constitutive relation of the fragment and steel

In order to describe the structure response to the explosive impact load, several conditions should be taken into account: the strain strengthening phenomenon of the material, the material behaviors under large strain, high strain rate and high temperature, even the material behaviors under the influence of the strain state change and the load history change.

Johnson-cook (JC) strength model [3] is widely used in commercial nonlinear finite-element because of its simple form, distinct concept and precise veracity. JC model is a kind of empirical viscoplasticity constitutive relation, it can describe the hardening effect, strain rate effect and softening temperature effect of metal materials very well.

$$\sigma = (A + B\varepsilon^n)(1 + C\ln\dot{\varepsilon}^*)(1 - T^{*m}) \tag{6}$$

$$T^* = (T - T_r)/(T_m - T_r) \tag{7}$$

σ is equivalent stress(N), ε is equivalent strain, $\dot{\varepsilon}^* = \dot{\varepsilon}/\dot{\varepsilon}_0$ is dimensionless plastic strain rate, $\dot{\varepsilon}_0$ is static experiment strain,， T is the sample surrounding temperature, T_r is room temperature, T_m is fusion point.

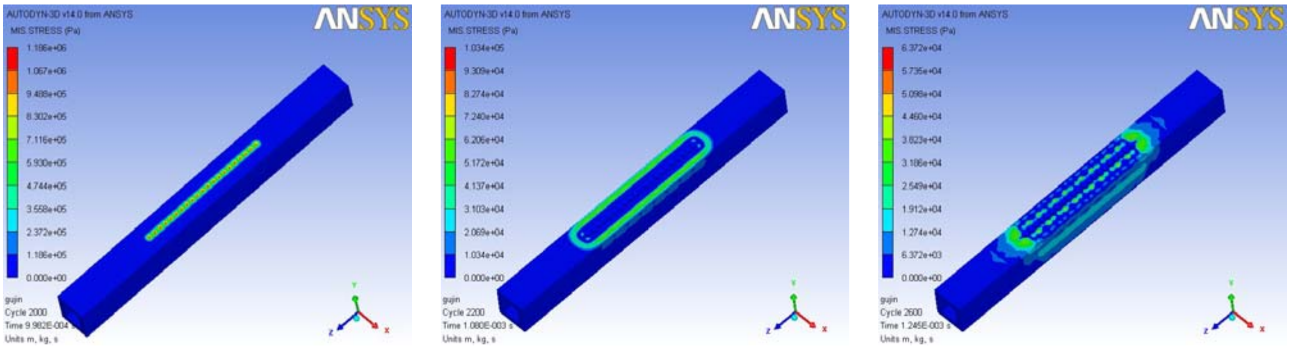
$(A + B\varepsilon^n)$ describes strain strengthening effect; $(1 + \ln\dot{\varepsilon}^*)$ describes strain rate strengthening effect; $(1 - (T^*)^m)$ describes softening temperature effect. Parameter value shown as follows.

Table1 JC constitutive relation parameters of 4340steel

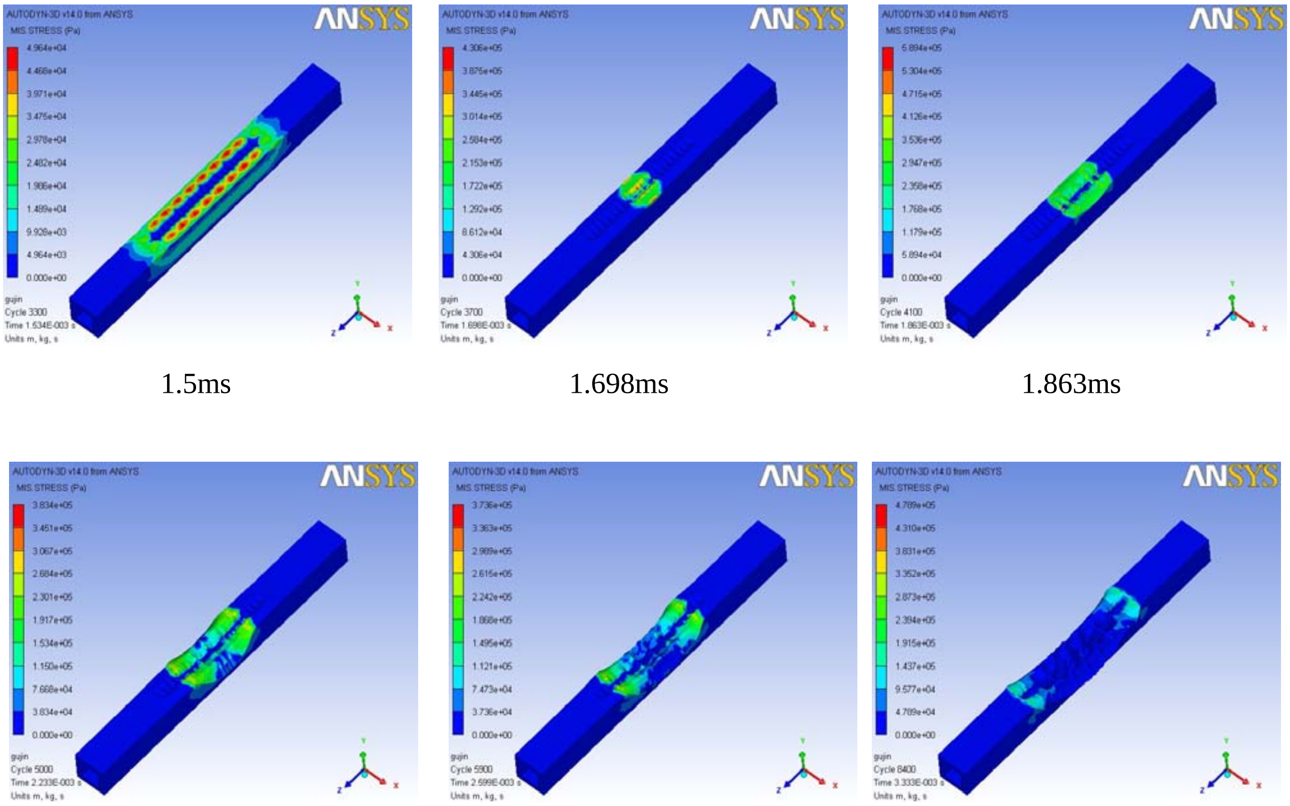
A(MPa)	B(MPa)	n	C	m	$\dot{\varepsilon}$	T_m (K)
791	510	0.26	0.014	1.03	1	1793

4. Results and analysis

4.1 Damage process of the synergetic effect



0.998ms 1ms 1.245ms


1.5ms 1.698ms 1.863ms

2.233ms 2.599ms 3.33ms

Fig.4 Damage process of the synergetic effect

Because the blast wave and fragments arrive at the bridge at different time, the failure mechanism of the bridge will change at different moment. The failure process of the bridge is divided into 4 stages in AUTODYN.

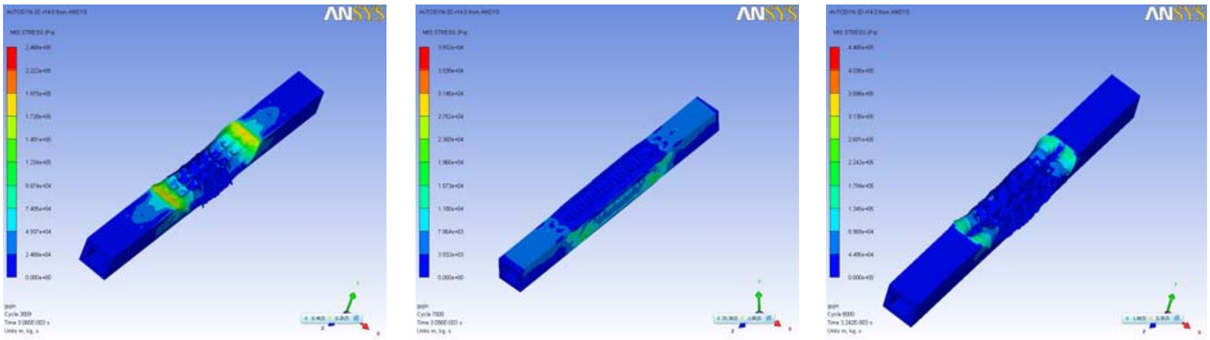
1st stage(0.998ms-1.245ms): The fragments arrive at the bridge upper surface, the stress wave begin to spread from the upper surface to the lower border in the beam. The fragments with high speed begin to smash the beam to pieces.

2nd stage(1.245ms-1.698ms): The fragments penetrate the beam further, reaching the longitudinal steels, leading a obvious deformation to the longitudinal steels. And the stress wave spread along the longitudinal steels and stirrups, the stress in the corner of the stirrups become larger.

3rd stage(1.698ms-3.33ms): The crest of the blast wave arrive the bridge surface, encountering with the fragments and effect the beam together. Some local deformations begin to occur in the concrete, and expand towards the lower border of the beam. The mid-span of the beam begin damaged.

4th stage(3.33ms- last): Because the fragments are crushed in pieces and its speed decreased, the vibrating beam will became static under the remainder blast wave and its own inertia gradually.

4.2 Failure modes contrast



(a)blast loading (b)fragment loading (c)combined loading

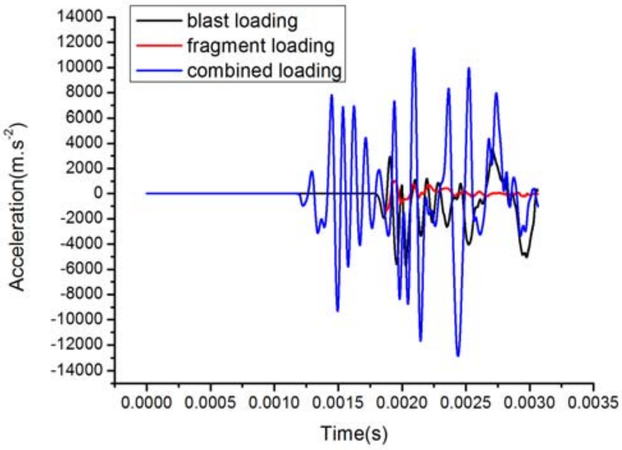
Fig.5 failure modes of the concrete beam

Fig.5 (a) when blast loading effect on the bridge separately, the largest deformation occurs in mid-span, steels restrict the beam became more damaged. Some beam border became damaged.

Fig.5 (b) when fragment loading effect on the bridge separately, some pits and holes occur on the beam surface, the longitudinal steels become curved and stressed the main pressure. Fragments pieces splash nearby during the penetrating process.

Fig.5 (b) when combined loading effect on the bridge, the beam damaged seriously. The longitudinal steels yield under the fragments effect and then expand the deformation because of the blast impact wave. The biggest displacement occurs in mid-span, many pits and holes occur on the beam surface, and seriously damage the beam border.

4.3 Dynamic response of the bottom midpoint



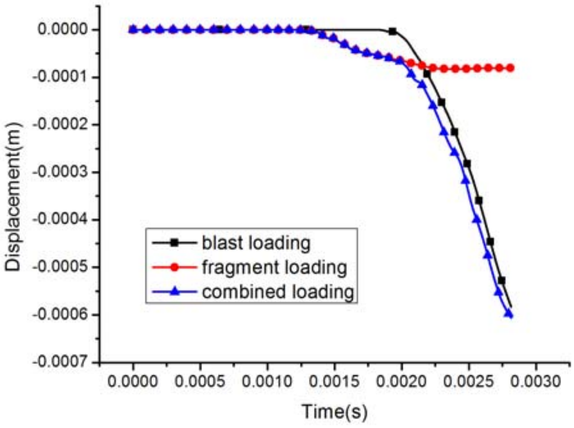


Fig.6 acceleration of the bottom midpoint

Fig.7 displacement of the bottom midpoint

Figure 6 and 7 indicate that the acceleration response under synergetic effect is larger than the response under fragment or blast wave effect separately, further more larger than the sum of the separate responses. And the displacement response under the synergetic effect is larger than the separate responses.

5. Conclusions

(1)The concrete bridges will be damaged seriously by the synergetic effect of blast wave and fragment.
(2)The synergetic effect to damage the bridge embodied in two ways: impact on the global bridge and destroy the local beam, which will decrease the loading capacity of the bridge.
(3)The acceleration changed seriously under the synergetic effect which should be taken into account in antiknock design.

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