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Analysis on formulas of concrete plate under contact explosion

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Abstract. Based on many test data of concrete plates of several thicknesses, this paper presents some new simple engineering formulas for computing critical thickness of scabbing and perforation, the front explosion diameter and the rear scabbing diameter of reinforced concrete plates under contact explosion. For the damage problem of a 20 cm thick concrete target under contact explosion of 1.25 kg TNT charge, the paper gives the numerical simulation results of LS-DYNA software for comparison. The damage zone of concrete plate in numerical simulation is determined by analysis of tension pressure resulted from shock wave reflection on the free boundary. And the numerical simulation results are in basic agreement on the results of these engineering formulas.

1. Introduction

Explosion damage for structures is an important problem and focuses the attention of everyone. For concrete plates under explosion, the front impact crater damage and the rear scabbing damage may occur. For a certain charge of contact explosion, it is called as critical scabbing when the rear scabbing cracks occur. It is called as critical perforation when the front impact crater is collected through out to the rear scabbing hole.

Based on the experimental data, the engineering formula for computing critical thickness of scabbing and perforation of concrete plates under explosion has been studied for many years. In literature [1,2], Quanping Zheng etc. have reported much experimental results and had detailed analysis on early engineering formula. They reviewed that PCDM equation and the amended PCDM equation which shown in Eqs. (1) and Eq. (2) are used mostly.

$$h_s = 0.048\left(\frac{d}{W^{1/3}}\right)^{-0.3}\left(\frac{W}{W+C}\right)^{-0.3} W^{1/3} \quad (1)$$

$$h_s = 0.0115\left(\frac{d}{W^{1/3}}\right)^{-0.7}\left(\frac{W}{W+C}\right)^{-1.31} W^{1/3}. \quad (2)$$

In which, h_s is the critical scabbing thickness, h_p is critical perforation thickness, d is the distance from the charge to the plate, W is the charge mass and C is the confined case mass. But as shown in Eq. (1) and Eq. (2), d is too sensitive for small value, so PCDM equations can not be used to analysis problems under contact explosion.

In the first part of the paper, some new engineering formula for analysis on damage of reinforced concrete plates under contact explosion are presented based on conclusion of tests data in literature [1]. Then some numerical simulation results of LS-DYNA software are given for comparison.

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2. Fitting formulas

The research is based on the experimental data in literature [1].

Five kinds of thickness of reinforced concrete plate are used in experiments shown in Table 1. The compression strength of concrete are 37.5–118.6 MPa, and the charge mass are 0.064–16kg equivalent TNT.

Table 1 is the analysis and conclusion on critical scabbing and perforation thickness of the reinforced concrete under contact explosion, and the experimental data are quoted from the literature [1].

For the reinforced concrete plate under contact explosion, fitting experimental data (see Fig. 1) in Table 1, h_s and h_p can be received as Eq. (3) and Eq. (4):

$$h_s = -0.06114 + 0.38682\ W^{1/3} \quad (3)$$

$$h_p = 0.000876713 + 0.18345\ W^{1/3} \approx 0.18345\ W^{1/3}. \quad (4)$$

Figure 1 shows that linearity fitting as relation of $W^{1/3}$ has good results.

Figure 2 is the comparison of fitting results with data reported in literature [2]. Figure 2 shows that the scabbing thickness curve computed by Eq. (3) is consist with results in literature [2]. The curve for 0.5h$_s$ is also shown in Fig. 2. It is reported by BRL Lab in the United state that h_p equals 0.5h$_s$ for high velocity impact condition. The perforation thickness curve computed by Eq. (4) is different from results in literature [2] but it is consist with the curve for 0.5h$_s$. As analysis on experimental data in Table 1, there are much tests data for perforation condition, and the damage either from explosion or high velocity impact are all rooted from shock wave propagation and reflection in the target, so Eq. (4) should be credible.

Using the similar approach, the front explosion diameter d_e and the rear scabbing diameter d_s can be received as Eq. (5) and Eq. (6) and the comparison of

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Table 1. Experimental data from literature [1] (h is the thickness of the reinforced concrete, W_s and W_p are charge mass for critical scabbing and perforation.)

h (m)	W_s (kg)	W_p (kg)	Comment
0.1	≤ 0.064	0.2	For 0.064 kg charge, scabbing height is 1.1cm. 5 tests for 0.2–0.25 kg charge, plates are perforated or critical perforated.
0.2	/	1.2	1 test for 1.2 kg charge, the plate is perforated, 2 tests for charge mass of 1.4 kg, one plate is perforated and the other which has 2% reinforced fibers is critical perforated.
0.25	≤ 0.6	/	For 0.2 kg charge, no scabbing. For 0.6 kg and 1.0 kg charge, scabbing height are 12 cm and 14 cm.
0.3	≥ 0.6	3.8	For 0.6 kg charge, scabbing occur; For 3.8 kg charge, and the one plate is perforated other is critical perforated.
0.4	1.6	11	3 tests 1.6 kg charge, scabbing block occur;1 test for 10 kg charge and 2 tests for 12 kg charge, plates are critical perforated.

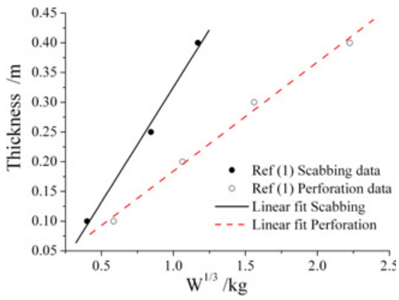

Figure 1. Fitting critical scabbing and perforation thickness.

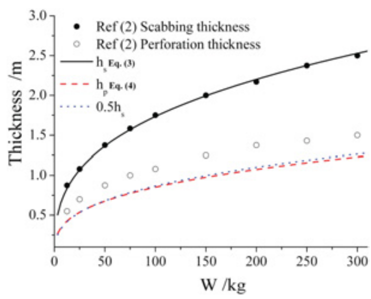

Figure 2. Comparison with data in literature [2].

fitting results with experimental data are shown in Fig. 3 and Fig. 4.

$$d_e = 0.32\ W^{1/3} \tag{5}$$

$$d_s = -0.1 + 0.58\ W^{1/3}. \tag{6}$$

In Fig. 3 and Fig. 4, there are much experimental data which are quoted from the literature [1]. It shows that data in Fig. 3 and Fig. 4 are more widely dispersed, so there is a certain deviation by using the fitting formula as Eq. (5) and Eq. (6). And it is noted that these data include 5 kinds of thickness for concrete plate, but the thickness have little effect on the front explosion diameter d_e or the rear scabbing diameter d_s.

These results of above simple fitting formula can be extended to large charge mass such as 300 kg which is shown in Fig. 5 and in Fig. 6. It shows that the rear scabbing diameter d_s is larger than the front explosion diameter d_e in Fig. 5 and $h_p = 0.5h_s$ is approximately right in Fig. 6.

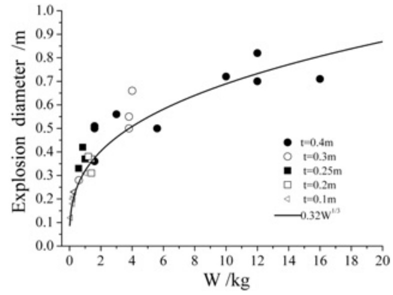

Figure 3. Fitting front explosion diameter d_e.

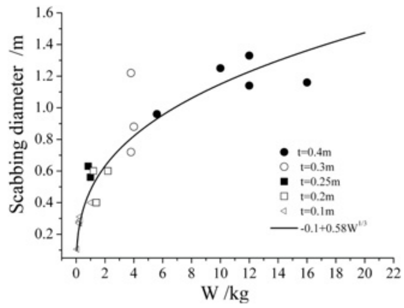

Figure 4. Fitting rear scabbing diameter d_s.

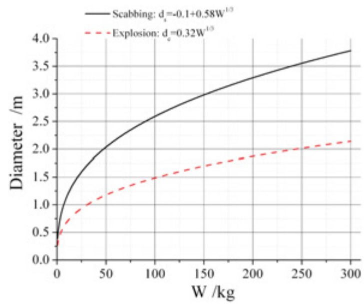

Figure 5. Extended results of de and d_s.

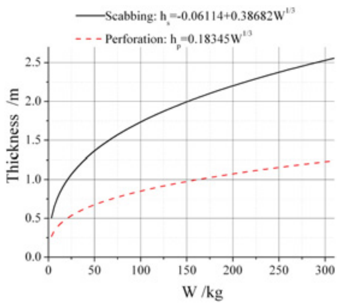

Figure 6. Extended results of hs and h_p.

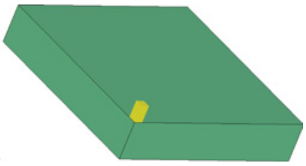

Figure 7. 1/4 model of numerical simulation.

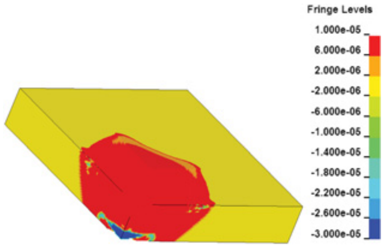

Figure 8. Pressure distribution at 100 μs.

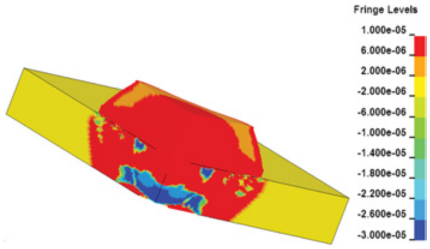

Figure 9. Pressure distribution at 120 μs.

3. Numerical simulation

According to above analysis, for 0.2 m thick concrete plate under contact explosion of 1.25 kg TNT charge, through out perforation will occur. The paper gives the numerical simulation results of LS-DYNA software for comparison. Figure 7 is the 1/4 model of simulation. ALE method is used. The yellow part in Fig. 7 is explosive and computed using fluid model, the concrete is simulated using solid elements.

The equation of state for detonation products is Jones-Wilkins-Lee (JWL) as

$$P = \mathrm{A}\left(1-\frac{\omega}{\mathrm{R}_1\bar{v}}\right)\exp\left(-\mathrm{R}_1\bar{v}\right) + \mathrm{B}\left(1-\frac{\omega}{\mathrm{R}_2\bar{v}}\right)\exp\left(-\mathrm{R}_2\bar{v}\right)+\omega\frac{E}{\bar{v}} \tag{7}$$

where $\bar{v} = v/v_0$ is relative volume, E is internal energy per unit reference volume. The others are parameters such as $\mathrm{A} = 373.77$ GPa, $\mathrm{B} = 3.7471$ GPa, $\mathrm{R}_1 = 4.5$, $\mathrm{R}_2 = 0.9$, $\omega = 0.35$. And the density of explisive is 1.63 g/cm^3, the detonation speed is $D_{\mathrm{CJ}} = 6.93$ km/s, the detonation pressure is $p_{\mathrm{CJ}} = 21.0$ GPa, and the initial internal energy per unit reference volume is 6.08 GPa.

The HJC model and the corresponding parameters from the literature [3] are used only setting the compression strength as 35 MPa and the tension strength as 3.5 MPa for concrete plate.

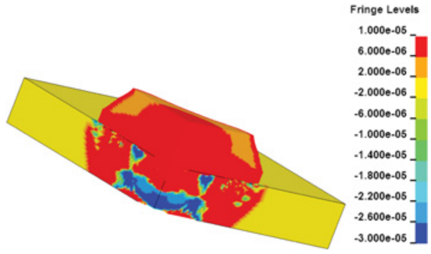

Figure 10. Pressure distribution at 125 μs.

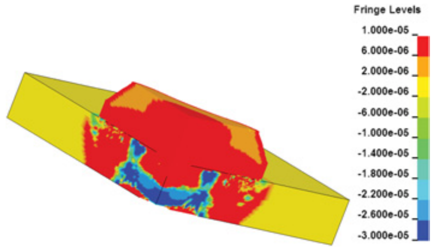

Figure 11. Pressure distribution at 130 μs.

Figures 8–11 show the pressure distribution results of the explosive production and the concrete plate for different times. The units in these figures are 100 GPa. The blue sign means the tension pressure is below the tension strength of concrete. For lack of accuracy damage model of concrete under explosion loading, the damage zone of concrete plate in numerical simulation is determined by the value of tension pressure resulted from shock wave reflection on the free boundary. According to analysis on tension pressure distribution, as shown in Fig. 11, the through out perforation will occur in the concrete plate. The front explosion diameter d_e is about 0.52 m, and the rear scabbing diameter d_s is about 0.74 m. These results are in consistent to the results of Eq. (5) and Eq. (6).

4. Conclusions

Based on analysis on experimental data, the paper presents new simple engineering formula for computing critical thickness of scabbing and perforation, the front explosion diameter and the rear scabbing diameter of reinforced concrete plates under contact explosion. And the numerical simulation results are in basic agreement on the results of these formulas.

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