Reinforced Concrete Slab Subjected to Close-in Explosion

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Summary:

The present study tests and uses the LS-DYNA explicit solver to replicate explosive tests of reinforced concrete slabs subjected to various charge weights of TNT close-in explosions. The numerical model includes slab (with rebar), immediate ambient air, supporting timbers, and TNT. Reinforced concrete slab was modeled with Lagrange mesh, while the TNT and air were modeled with Arbitrary Lagrange-Euler (ALE) mesh. Release III of the Karagozian & Case (K&C) concrete damage material model (*Mat_72R3) with strain-rate enhancement of strength profile was used for concrete; kinematic hardening material model was used for steel reinforcement; equation of state for air was defined as linear polynomial; JWL equation of state was adopted for explosive TNT.

The concrete slab was subjected to explosions of 1kg, 2kg, and 3kg TNT equivalent explosive. Simulation results were compared with experimental data. The sizes of the central primary damage region (diameters for crater, through hole, and spallation) from the simulation displayed excellent correlation in the 2kg TNT and the 1kg TNT cases. However, the numerical predictions for the 3kg TNT case showed discrepancies with test results, which may be due to the different positioning of TNT in the simulation as compared to that in the experimental test.

Different boundary conditions were also considered: simply supported edge, free edge, four edge timber support, four equally spaced parallel timber support. All the support conditions gave very similar simulation results for primary damage; very slight difference was detected from the four parallel timber support with the other support conditions in secondary damage or crack pattern.

Keywords:

reinforced concrete slab, close-in explosion, strain-rate strength enhancement, ALE, fluid-structural interaction.

1 Introduction

In today's uncertain world, terrorism is a big concern. More and more attention has been drawn to design and retrofit of critical military or civil infrastructure against explosive attack. Dynamic response of critical structural elements and overall structures under high-rate blast or shock loads from close-in explosion is of particular interest. Since concrete is the fundamental construction material used worldwide, it is important to understand the material behavior and structural response of concrete members under extreme loading. Extensive research efforts, including field testing, theoretical analysis, and numerical modeling, have been devoted to serve this purpose. However, field tests are very expensive and time-consuming; and analytical models, such as single-degree-of-freedom models (SDOF), are often over-simplified and over-conserved to cover the structural complexity and high-nonlinearity involved. On the other hand, with the advancement of powerful computational tools, numerical simulation with sophisticated finite element (FE) codes, once verified against test data, has shown to be a very promising solution for determining the overall robustness of a structure under blast loading. This study is part of the comprehensive programme by Defense Science & Technology Agency (DSTA), Singapore to validate numerical simulation methodology against explosive test data. The focus for this study is on the response of the reinforced concrete slab subjected to close-in explosions with different charge weights. Parametric studies were performed to understand the sensitivity of the model to different boundary conditions.

In numerical simulation of reinforced concrete (RC) elements or structures under extreme load, the key point is an efficient material constitutive model and implementation methodology for concrete. Elemental tests, physics-based analyses, and numerical simulations from many researchers dating back to 1900 have brought insight to understanding concrete strength and deformation behaviors under different loading types. A state-of-the-art material constitutive model under high-rate loading should include all the features and the relevant numerical implementation methods of material behavior: pressure hardening, Lode angle dependency, strain hardening, strain softening, strain-rate dependency, and tension cut-off, etc. Many sophisticated material constitutive models have been developed and applied widely in numerical simulation [1-4]. Amongst these, the K&C concrete damage model, an adaptation and improvement of the plasticity concrete material model in Lagrangian finite code DYNA3D, has taken into account all of these features. This model has been shown by many researchers (and evidenced with test data) to be very efficient in simulating rate effects, overloading and large deformation under high-rate blast, shock, high-velocity impact, penetration, and perforation. Thus, this concrete material constitutive model was adopted in the high-fidelity physics based simulations in this study to capture fluid-structural interaction and strain-rate dependency of the reinforced concrete slab under TNT explosion. Comparisons of slab primary damage with test result demonstrate satisfactory agreement.

2 Test set up and results

The dimension of the reinforced concrete slab was the same in all test cases: 3,000mm×3,000mm×300mm. The layout of the reinforcement steel was T13@200mm two-way at the top and bottom with 460MPa steel as shown in Fig. 1. In total, three tests were carried out for the slabs with different charge weights. 1kg, 2kg TNT equivalent explosive were placed at the centre of the top surface of the slab, while the 3kg TNT equivalent explosive was placed 50mm above the centre of the slab. Two supporting timber supports were positioned at the edges as shown in Fig. 2.

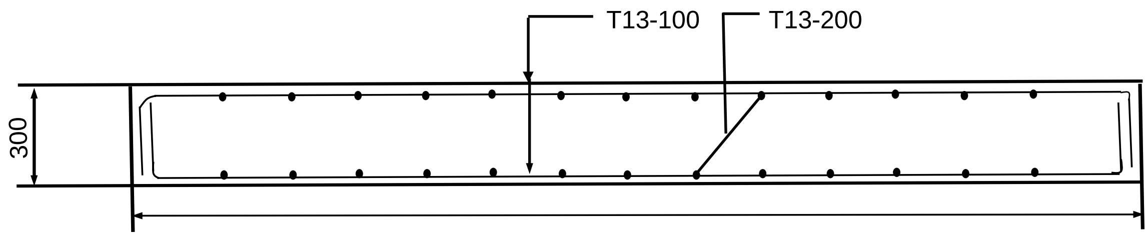

Fig. 1: Reinforcement layout

Fig. 2: Test set up

Figs. 3, 4, and 5 show the failure patterns of the slabs under different TNT charge weights after the detonations. The equivalent diameters of crater, the spallation, and the through hole are listed in Table 1. It was found that the 1kg TNT explosive did not produce a through hole, while the 2kg and 3kg TNT explosive did. No rupture of reinforcement occurred in all three test cases.

Table 1 Equivalent diameter of primary damage

Experimental results (mm)				*Simulation results (mm)*		
Charge	*Crater*	*Hole*	*Spallation*	*Crater*	*Hole*	*Spallation*
1 Kg	*500*	*0*	*750*	*500*	*30*	*650*
2 Kg	*600*	*250*	*700*	*600*	*266.0*	*700*
3 Kg	*650*	*225*	*850*	*740*	*150*	*650*

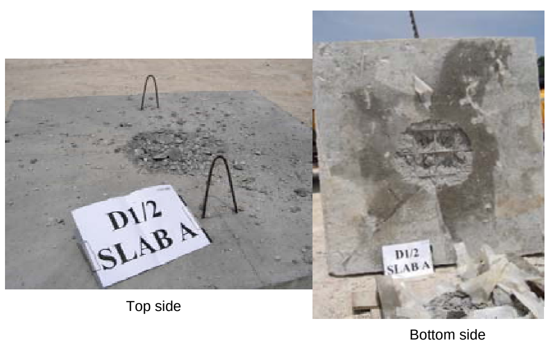

Fig. 3: Damage pattern for 1Kg TNT from test

Fig. 4: Damage pattern for 2Kg TNT from test

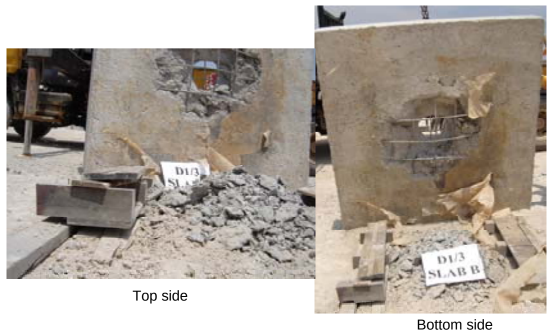

Fig. 5: Damage pattern for 3Kg TNT from test

3 Finite element model

One quarter of the slab with TNT on top surface was modeled with symmetrical boundary at the mid-surfaces. A thin layer of air surrounding the top surface and the four edges of slab was included in the model to take care of the much slower transmission speed of pressure in air than in slab. Supporting timbers were assumed to be rigid bodies with the bottom surface fixed. Surface-to-surface contact was assigned between the bottom surface of the slab and the top surfaces of the timber with a friction coefficient of 0.2. In total, 320,930 hex and beam elements and 334,850 nodes were included in the model with average element size of 20mm. Typical FE mesh is seen in Fig. 6.

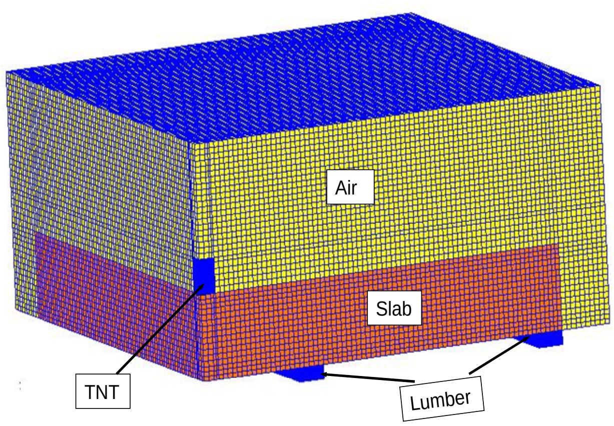

Fig. 6: Typical finite element mesh

The metric units adopted in the study is self-consistent with the unit of length in mm, force in N, mass in g, pressure in MPa, and time in ms. All the data presented in this study follow this unit system except explicitly stated otherwise.

The timbers were assigned rigid material properties with Young's modulus of 8,695MPa, mass density of 4,918Kg/m3, and the Poisson's ratio of 0.4, which was averaged from five types woods in Taiwan [5].
Hex element with single integration point was adopted for concrete. Release III of the K&C damage model for concrete provides the automatic generation of the default data. The only requirements were the concrete compressive strength or the grade of concrete (32MPa in the current study), rate of the pressure unit to the default unit of kips/sq.inch (145.00 is assigned for MPa/kips for the current study), and rate of the adopted length unit to the default unit of inch (0.03937 for the rate of mm/inch). All the other values were specified as zero and over-ridden by data calculated in subroutines linked to this material model automatically. The strain-rate enhancement of the strength profile is listed in Table 2. Detailed description and implementation of this concrete constitutive model is found in Malvar, et al. [2,3].

Table 2 Concrete strain rate dependant strength enhancement parameter

Strain rate	*Enhancement*	*Strain rate*	*Enhancement*	*Strain rate*	*Enhancement*
-30000	10.85	-0.01	1.38	0.01	1.18
-300	10.85	-0.001	1.273	0.1	1.26
-100	7.526	-0.0001	1.175	1	1.345
-30	5.038	-0.00001	1.084	3	1.388
-10	3.493	0	1	10	1.436
-3	2.338	0.00003	1	30	1.482
-1	1.621	0.0001	1.035	100	2.214
-0.1	1.496	0.001	1.105		

Steel reinforcement was modeled with beam elements with circular cross-section of 13mm in diameter. The concrete hex element and the steel beam element share common nodes to assume fully bonded interfaces. The stress-strain relationship of reinforcement steel is assumed to be piecewise-linear plasticity with strain rate-dependant Cowper-Symonds kinematic hardening formulation [6]. The kinematic hardening parameters at different strain rates are listed in Table 3.

Table 3 Strain rate dependant kinematic hardening parameter for rebar

Strain	*Yield strength at respective strain rate*							
	0.0	0.001	0.01	0.1	1.0	10	100	1000
0.0	4.77E+02	5.10E+02	5.44E+02	5.77E+02	6.15E+02	6.58E+02	7.01E+02	7.49E+02
7.97E-03	4.80E+02	5.13E+02	5.47E+02	5.80E+02	6.19E+02	6.62E+02	7.05E+02	7.53E+02
1.98E-02	5.63E+02	5.97E+02	6.30E+02	6.58E+02	7.03E+02	7.34E+02	7.65E+02	8.10E+02
3.44E-02	6.57E+02	6.90E+02	7.16E+02	7.42E+02	7.81E+02	8.14E+02	8.47E+02	8.73E+02
4.88E-02	7.10E+02	7.38E+02	7.59E+02	7.88E+02	8.23E+02	8.52E+02	8.80E+02	9.08E+02
7.70E-02	7.82E+02	8.06E+02	8.21E+02	8.45E+02	8.68E+02	8.99E+02	9.31E+02	9.54E+02
1.13E-01	8.42E+02	8.59E+02	8.76E+02	8.92E+02	9.09E+02	9.26E+02	9.51E+02	9.68E+02
3.50E-01	8.87E+02	9.04E+02	9.22E+02	9.40E+02	9.58E+02	9.75E+02	1.00E+03	1.02E+03
1.00E+00	9.65E+02	9.84E+02	1.00E+03	1.02E+03	1.04E+03	1.06E+03	1.09E+03	1.11E+03

The air is modeled with hex arbitrary Lagrange-Euler element with the material type of *mat_009 (*mat_null). Equation of state for air was defined as linear polynomial

$$P = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + \left(C_4 + C_5\mu + C_6\mu^2\right)E \tag{1}$$

with the parameters C0=C1=C2=C3=C6=0, C4=C5=0.4, the initial internal energy is 0.214, and the initial relative volume is 1 (LS-DYNA, 2006).

TNT explosive is also modeled with the hex arbitrary Lagrange-Euler elements. JWL equation of state was adopted for explosive TNT. The relevant material data adopted in this study was mass density of 1.63e-03g/mm3 and Chapman-Jouget pressure of 6930.0MPa. The JWL equation of state defines the pressure as the relative volume

$$p = A\left(1 - \frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1 - \frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E}{V} \quad (2)$$

where the five constants, the initial internal energy, and the initial relative volume are sequentially 371.2e3, 3750, 4.15, 0.95, 0.30, 6000, 1.

4 Simulation results

In total, 12 simulation cases were implemented to evaluate the effect of different boundary conditions. Nine of the simulation cases were variations of edge contact support, simple supports, and free edge, while the other three cases were supported with four parallel timbers equally spaced with two of them placed at the edge. It was found that all the cases with edge free or edge constraints had very similar failure patterns for similar TNT charge weight. Results for no lateral restraint of the edges is shown in Fig. 7. Very minimal difference was seen for the only edge support cases and the four timber support cases for the primary damage of the slabs (Figure 8). The difference was in the secondary cracking zones which was more orthogonal in the four timber support cases, but rather radial in the edge support only cases.

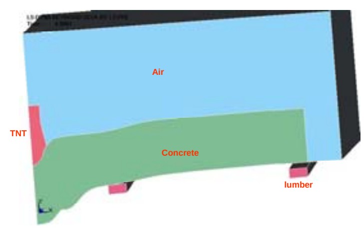

Fig. 7: Simulated deformation mechanism

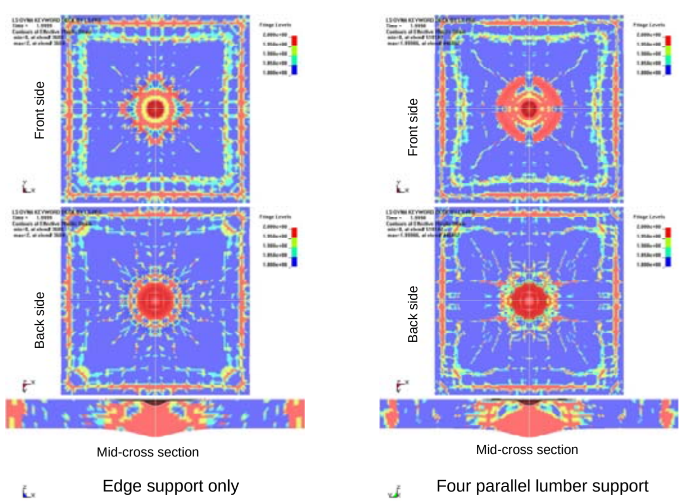

Fig. 8: Comparison of different supporting conditions

The simulated damage patterns are shown in Figs. 9, 10, and 11 for the respective 1kg, 2kg, and 3kg TNT equivalent cases. The sizes of primary damage at the centre part of the slabs were measured and summarized in Table 1 to be compared with test results. It was found that the sizes of the central primary damage were in excellent agreement with the test data for the 1kg and 2kg TNT equivalent explosives. For the 3kg TNT case, the damage zone from the simulation showed discrepancy when compared with test results. This may be due to the different positioning of the 3kg TNT equivalent explosive. In the simulation, it was modeled as a contact explosion, while in the test it was lifted up 50mm up the centre of the top surface of the slab. From the authors' test experiences, lifting up the TNT will reduce the crater size and increase the spallation and through hole sizes.

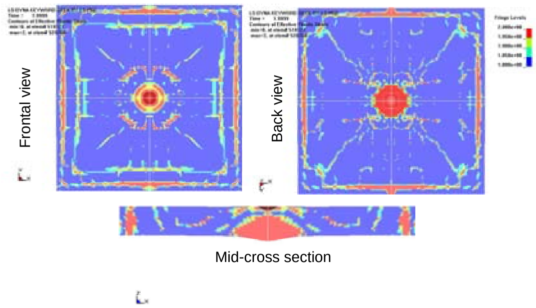

Fig. 9: Damage pattern for the 1Kg TNT explosion from simulation

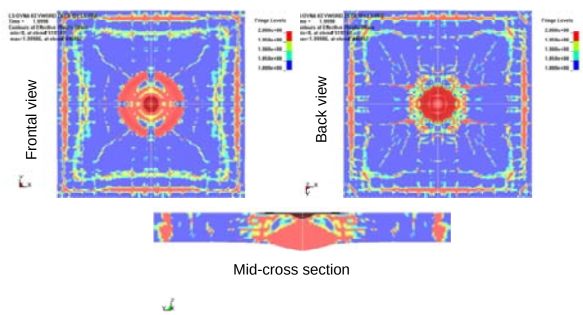

Fig. 10: Damage pattern for the 2Kg TNT explosion from simulation

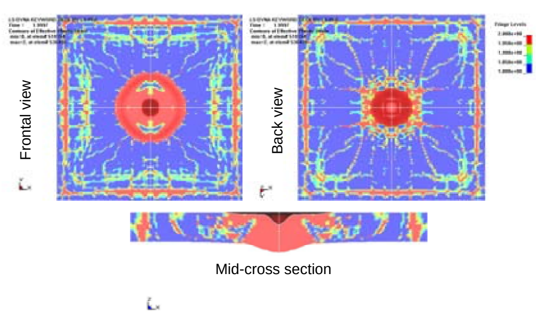

Fig. 11: Damage pattern for the 3Kg TNT explosion from simulation

It should be mentioned that the central primary damage area is defined in the current study as having effective plastic strain higher than 1.95. Secondary damage is considered to be 1.8 to 1.95 according to Malvar, et al. [2,3].
It is worth pointing out that the damage zone near the edge for all the simulation cases was not detected in the real tests. This is probably because in the simulation the anchorage of the reinforcement is not included and the artificial pressure wave propagation is not attenuated by damping unlike actual physical conditions.

5 Conclusion

From the analysis of the simulation results and verification against test data, it can be concluded that the current K&C concrete damage model in the hydrocode LS-DYNA is very efficient in predicting concrete material behavior under close-in high-rate explosive shock loading. Different boundary or supporting conditions make insignificant differences to the primary damage of the slabs under close in blast effects.

6 Literature

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