Finite Element Method of Normal Reinforced Concrete Slab under Contact Explosion

Khanathip Prabuntrarik[1,*] Pornpen Limpaninlachat[2] and Withit Pansuk[3]

[1,2] Department of Civil and Environmental Engineering, Faculty of Engineering, Mahidol University, Nakhon Pathom, THAILAND

[3] Center of Excellence in Innovative Construction Materials, Department of Civil Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok, THAILAND

**Corresponding author; E-mail address: khanathip.prb@student.mahidol.ac.th*

Abstract

Blast load is a special and specific situation that rarely occurs in structural engineering, but it can cause severe damage to the structure and user due to the high energy dissipation in both tension and compression. The experiment under blast conditions is difficult to conduct because of safety and taken high cost. Therefore, the Finite Element Method (FEM) is the effective method to investigate the blast load behaviors. This research aims to study the FEM analysis to create a numerical simulation of Normal Reinforced Concrete (NRC) slabs under blast conditions. The experimental results from the previous study were employed to validate the numerical simulation model with FEM software. The NRC slabs in 2000mm x 1000mm x 75mm of dimension under 1 lb and 2 lbs of TNT at 500 mm of standoff distance were used as the validated specimens. To model the structure under blast loads, additional properties regarding high strain rate condition were required, such as erosion. The validation between results from models and experiments such as maximum deflection and overpressure regarding the blasting of normal RC slabs with different blast loads were examined. According to the numerical results, with increase of the explosive charge weight from 1 lb to 2 lbs resulted in the more damage on slab surface and higher maximum deflection.

Keywords: Finite Element Method, Normal Reinforced Concrete, Blast Load

1. Introduction

In Thailand, Reinforced concrete (RC) structure has been widely used for construction for decade years due to its high strength to cost effective ratio, but the design guideline hasn't served for the severe situations such as explosion yet. RC structures have been typically applied for almost structural elements especially in beam, column, slab, and foundation. When the slab is affected by explosive pressure, the damage and collapse of structural slab can happen. This subsequently causes the unrestrained span length of the column and finally leads to the failure of the building system [1-2]. However, studying the behavior of the concrete slab under the blasting condition needs to spend high cost and time to conduct the experiment. To make an efficient method for investigating the behavior of the concrete slab under the blasting condition, the Finite Element Method (FEM) was used in this research. The LS-DYNA Prepost standalone software is well-known as the software used to simulate the behavior under a high strain rate behavior. This software provides many built-in materials data which can be used to simulate the behavior of normal reinforced concrete. Li et al. [3] and Wu et al. [4] validate the numerical simulation model using the MAT_CONCRETE_DAMAGE_REL3. This concrete model can predict the normal reinforced concrete slab behavior under blast. In addition, the Arbitrary Lagrangian-Eulerian Multi Material (ALE-MM) technique is employed to simulate the blast propagation in previous studies [4 -5].

Consequently, the aim of this study is to utilize the finite element method to create a numerical simulation model that investigates the behavior of normal reinforced concrete slabs under blasting loads. To achieve this objective, the reinforced concrete (RC) slabs under real experiment under blasting [6] were employed to compare with the numerical results. Two normal RC slabs with the dimensions of 2000mm x 1000mm x 75mm were modeled to blasting loads of 1 lb and 2 lbs with the constant standoff distance at 0.5 m above the slabs.

The experimental results of maximum displacement, overpressure, and the failure pattern were used for comparing with the numerical results in this study to observe the severe damage according to higher blast condition.

2. Blast behavior

The blast load is the kind of impact load with specific behavior. When the detonation occurs, the blast wave will be propagated in the ambient medium. The high temperature and high pressure will occur and get impact to the structural members at high strain rate. This causes the softening behavior of concrete structure [7]. The blast wave can generate both compression and tension pressure, which can be presented by the typical pressure-time history curve as shown in Fig.1. The ambient pressure started at P_0 until the incident pressure occurred at ta When the explosion has occurred, the pressure will increase to the maximum overpressure known as peak overpressure (P_{so}) then the pressure decreasing to P_0 at $t_a + t_0$ and continuously decrease to negative peak overpressure (P_{so}-) and return to the normal ambient stage P_0 at $t_a + t_0 + t_0^-$. The area in the range of t_a to $t_a + t_0$ is known as the positive specific impulse (i_s), in which the pressure affects the structure as compression. Subsequently, the pressure decreases continuously in the negative phase, ranging from $t_a + t_0$ to $t_a + t_0 + t_0^-$, which is known as the negative specific impulse (i_s^-). During the negative specific impulse, the pressure affects the structure as tension.

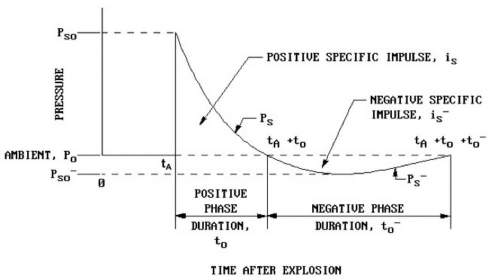


Fig. 1 Pressure-time history curve [8].

To calculate the blast property, there is the relationship between the standoff distance and explosive charge weight in term of the scaled distance as explained in Eq. 1 [8].

$$z = \frac{R}{W^{1/3}} \tag{1}$$

Where, Z stands for scaled distance, R is a standoff distance (m), and W is an explosive charge weight (kg). Accordingly, the peak overpressure can be investigated through the relationship with Z parameter as shown in Fig. 2.

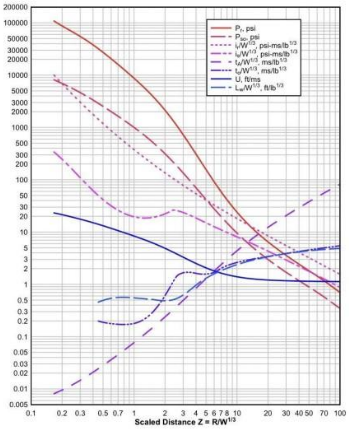


Fig. 2 Positive phase shock wave parameter for a Hemispherical TNT explosion on the surface [8].

3. Numerical simulation model in LS-DYNA

3.1 Experimental data used to validation

The experimental data were collected from S. Suwannarat's experimental [6]. The experimental setting is shown in Fig. 3. Slab specimens are 2000mm x 1000mm x 75mm in dimension with restrained in C-bar supports. These two slabs were subjected to the TNT explosive substance with standoff distance of 500 mm as shown in Fig. 3. Two different explosive charge weights used in the experiment were 1 lb and 2 lbs. The details of RC slabs and reinforcing rebars are shown in Table 1 and Fig. 4.

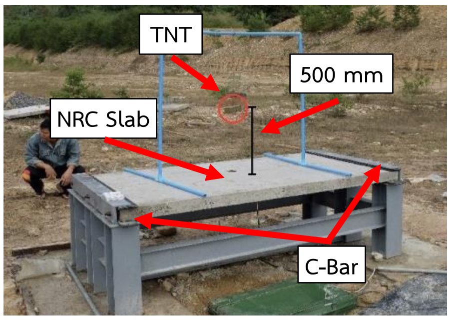


Fig. 3 Experimental setup for each testing [6].

Table 1 The specimen details [6]

Specimen name		NRC1LB	NRC2LB
concrete compressive strength		55 MPa	
steel reinforcement strength	grade	SR24	
	yield strength	305 MPa	
	Ultimate strength	440 MPa	
explosive charge weight		1 lb	2 lbs

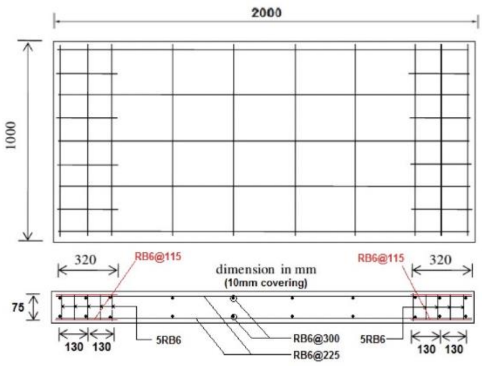


Fig. 4 The slab geometry and reinforcing detail [6].

3.2 Numerical implementation

To study the simulation of RC slabs against varied blast loading regarding the experiments. In this section, the methods used for numerical model of RC slab and blast condition will be described as follows.

3.2.1 Mesh and geometry

To reduce the computation time, a quarter part of RC slabs was generated as shown in Fig. 5. All restrained and blasting condition are same as the experiment. The numerical model was meshed with 10 mm for concrete element and 20 mm for components of air and TNT. The detonation point was set at the middle above the RC slab as shown in the Fig. 6.

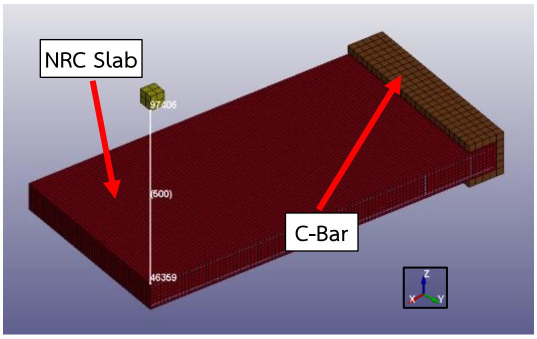


Fig. 5 A quarter part of RC slab with other component.

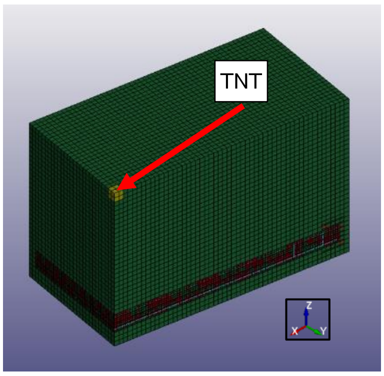


Fig. 6 The detonation point in numerical model.

3.2.2 Boundary condition

To simulate the symmetrical behavior, the boundary conditions were setup in the Y-Z plane and X-Z plane, which were the adjacent symmetrical surface. The Y-Z plane was assigned with fixed translation along x-axis and rotation about y- and z-axis. The X-Z plane was assigning the fixed translation along y-axis and rotation about x- and z-axis. The boundary condition of the planar is shown in Fig. 7. The non-reflective boundary condition was employed to avoid the reflection of the shock wave in the air domain. This boundary condition causes the blast wave to flow out from the air domain without reflection [5]. The C-bar support used in this study employed rigid materials that are restrained in all translations and rotations, causing the C-bar support to be unable to move in any direction. To create the bonding between the NRC slab and the C-bar, the AUTOMATIC_SURFACE_TO_SURFACE keyword was used.

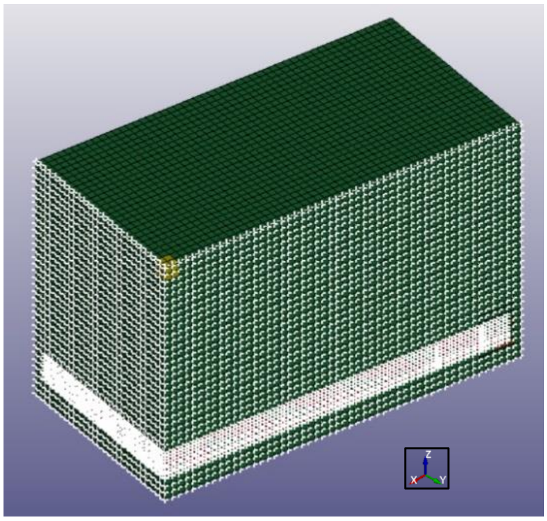


Fig. 7 Boundary condition of the numerical model

3.2.3 Materials in numerical model

1) Concrete material model

In the LS-DYNA Prepost, there are many concrete materials available in the materials libraries such as MAT_RHT, MAT_CSCM, MAT_JOHNSON_HOLMQUIST_CONCRETE and MAT_CONCRETE_DAMAGE_REL3. The concrete model based on Karagozian & Case (K&C) known as MAT_072R3 (MAT_CONCRETE_DAMAGE_REL3) can automatically generate various inelastic variables by just inputting compressive strength [7]. In the model under high strain rate, the erosion property is usually applied to shorten the computation time due to the concrete-element elimination after reaching the maximum principal strain [4-5].

This study applied the MAT_ADD_EROSION to facilitate erosion behavior. Table 2 shows the input parameters for concrete material. The concrete part uses constant stress solid element as the default element available in LS-DYNA Prepost and Flanagan-Belytschko viscous form with exact volume integration for solid elements for hourglass.

Table 2 The material details for concrete material.

Material model: MAT_072R3 (MAT_CONCRETE_DAMAGE_REL3)		
Description	Magnitude	Unit
Mass density	2.4e-06	kg/mm^3
Poison's ratio	0.2	-
Strength of concrete	-0.055	GPa
Unit conversion factor for length	0.03937	mm
Unit conversion factor for strength	1.45e+05	GPa

2) Steel Reinforcing bars

The MAT_PIECEWISE_LINEAR_PLASTICITY was employed to simulate the reinforced concrete behavior. This material contributes to isotropic and kinematic hardening plasticity properties. The input parameters in Table 3 were used to generate the arbitrary stress-strain curve [3]. The Hughes-Liu with cross section integration was employed as the element formulation option.

Table 3 The material details for steel reinforcing bars.

Material model: MAT_024 (MAT_PIECEWISE_LINEAR_PLASTICITY)		
Description	Magnitude	Unit
Mass Density	7.850e-06	kg/mm^3
Young's Modulus	210	GPa
Poisson's Ratio	0.3	-
Yield Stress	0.305	GPa

3) Arbitrary Lagrange-Euler Multi Materials method

The traditional technique to simulate the numerical analysis under blasting conditions is to apply pressure load directly with the LOAD_BLAST_ENHANCE keyword. However, to simulate the blast wave behavior more accurately. The Arbitrary Lagrangian-Eulerian Multi-Material (ALE-MM) technique was invented. The ALE-MM method needs to model the air between the explosive substance and the concrete structure. This is the reason why the ALE-MM method requires the material models and the equation of states (EoS) for both air and explosive substance as shown in Table 4 and 5, respectively. Nevertheless, the ALE-MM method has increased the computation time significantly [9]. The coupling between the Lagrangian approach and the Eulerian approach has formed by using the CONSTRAIN_LAGRANGE_IN_SOLID keyword. The hourglass employed a standard LS-DYNA viscous form and a single-point ALE multi-material element for the element formulation option. The explosive charge weight must be defined in terms of the TNT element volume, which should be based on the actual explosive charge weight used in the experimental setup.

The explosive charge weight can be determined by Eq.2.

$$\rho = \frac{m}{V} \tag{2}$$

The volume of the TNT for 1 lb and 2 lbs is 278,957.08 mm^3 and 557,035.47 mm^3, respectively, when the density of TNT equal to 1.630e-06 kg/mm^3.

Table 4 The material details for air and TNT [2].

Material model: MAT_008 (MAT_HIGH_EXPLOSIVE_BURN)		
Description	Magnitude	Unit
Mass Density	1.630e-06	kg/mm^3
Detonation velocity	6930	m/s^1
Chapman-Jouget pressure	21	GPa
Material model: MAT_009 (MAT_NULL)		
Mass Density	1.293e-09	kg/mm^3

Table 5 The EoS details for air and TNT [2].

Equation of State: JWL		
Description	Magnitude	Unit
A	373.78	GPa
B	3.74	GPa
R1	4.15	-
R2	0.90	-
Omega	0.35	-
Detonation energy per unit volume	6	J/mm^3
V0	1	-
Equation of State: LINEAR_POLYNOMIAL		
C4	0.4	-
C5	0.4	-
Initial internal energy	2.5	GPa

3.2.4 Constraint of the Lagrangian and Eulerian parts

The CONSTRAINT_LAGRANGE_IN_SOLID keyword is used to create the bonding between the Lagrangian parts group (master) such as concrete and reinforcement steel bar and the Eulerian parts group (slave) including air and TNT. The bonding between concrete and rebars set as master and slave parts, respectively, by using the ALE_COUPLING_NODAL_CONSTRAINT. The C-Bar uses the MAT_RIGID as the material to transfer load between RC slab and the support with restrained in all translations and rotations.

4. Result and discussion

According to the numerical simulation models, the normal reinforced concrete slab was subjected to the surface blasting conditions. By comparing the numerical and experimental results of the blast overpressure from 1 lb explosive charge in Fig. 8, the maximum overpressure from the model shows close value with the experiment as the peak overpressure (P_{so}) from the experimental and numerical result are 15.12 and 17.85 MPa, respectively. Moreover, only positive overpressure was presented in the model, which was different from the experimental result.

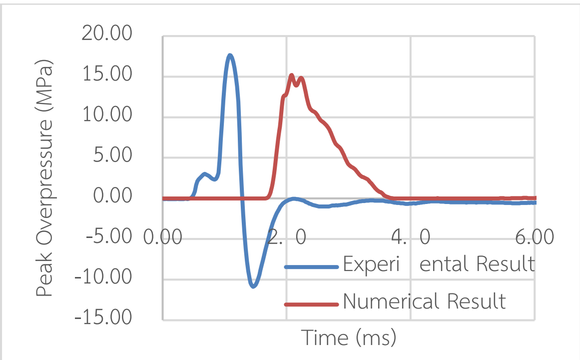
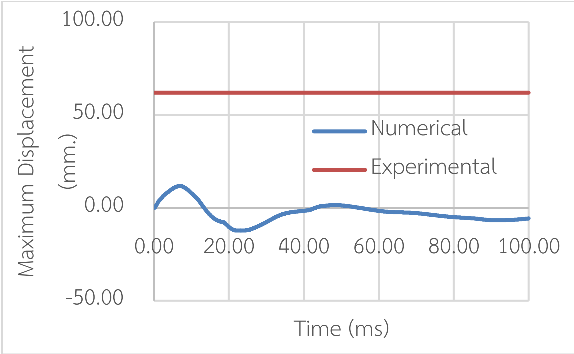
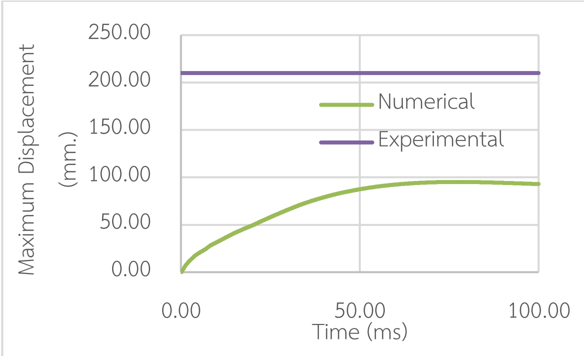


Fig. 8 The peak overpressure of the blast wave

By considering the maximum displacement from the model of RC slabs against 1 lb (NRC1LB) and 2 lbs (NRC2LB) compared with the experimental results in Fig. 9, there are the large gap between the experiment and numerical results. However, the severity of failure was observed in the RC slab resisting against higher blast load as shown in Fig. 10; the maximum displacement of RC slab under 2 lbs of blasting is 95.18 mm, meanwhile, the one in case of 1 lb blasting is much lower as 11.73 mm.



(a)



(b)

Fig. 9 The experimental result and numerical result of 1 lb (a) and 2 lbs (b).

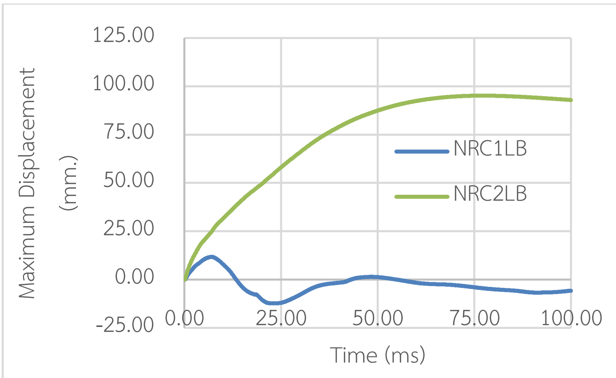
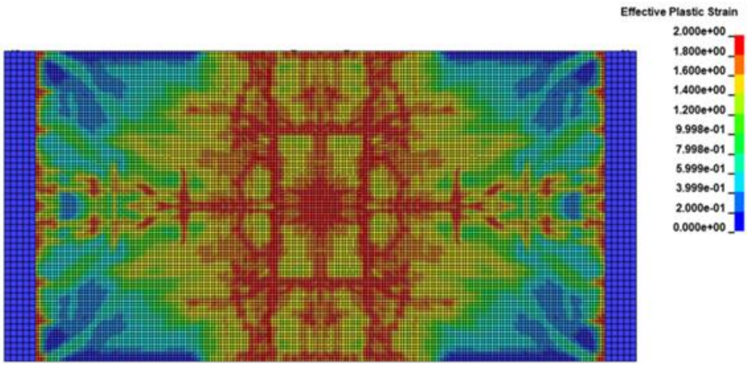


Fig. 10 The numerical result of 1 and 2 lbs.

In addition, the increasing of the explosive charge weight from 1 to 2 lbs also affected the different failure pattern on the RC slabs. Figures 11 and 12 show the damage of RC slabs for NRC1LB and NRC2LB, respectively. When the crack propagated through the middle of the slab, its behavior at that location was indicated by a red contour in Fig. 11(b), and Fig. 12(b). However, blue-green contours also appeared at the middle of the slab due to the erosion of surface elements, which revealed the subsequent layer shown in Fig. 12(b).

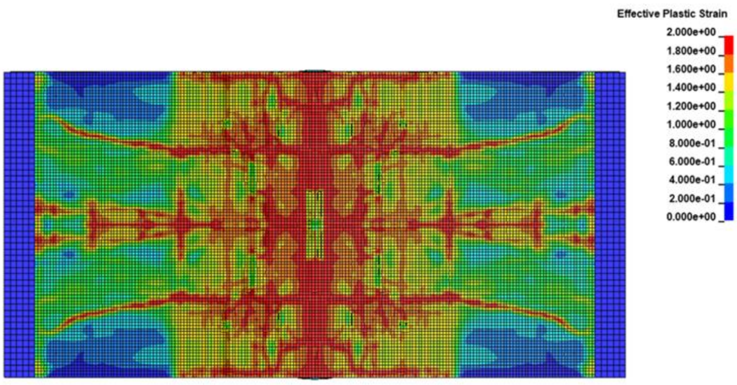
(a)



(b)

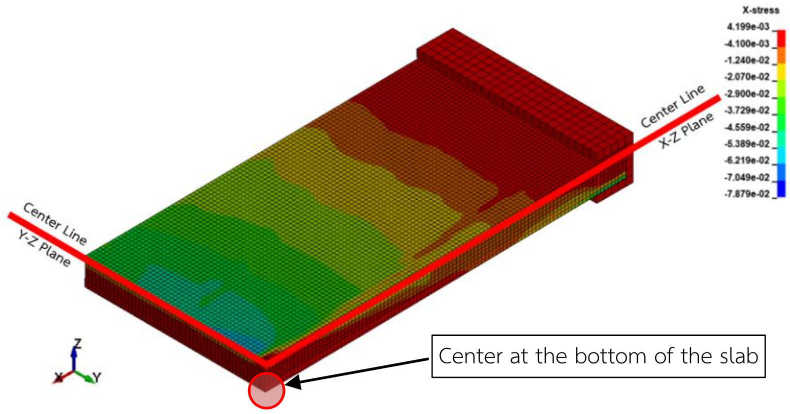
Fig. 11 The damaged normal reinforced concrete slab for NRC1LB from the experimental (bottom view) with a highlighted quarter of the slab [6] (a), and the crack propagation of the numerical result at the bottom surface of the slab (b).

(a)

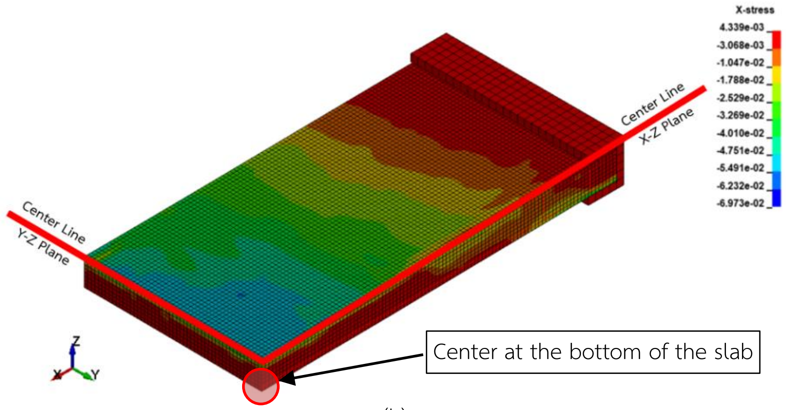


(b)

Fig. 12 The damaged normal reinforced concrete slab for NRC2LB from the experimental (bottom view) with a highlighted quarter of the slab [6] (a), and the crack propagation of the numerical result at the bottom surface of the slab (b).



(a)



(b)

Fig. 13 The quarter-scale numerical model (isometric view) with maximum stress contour for NRC1LB (a) and NRC2LB (b).

As shown in Fig. 9 (a), the numerical result from the NRC1LB model displays a rebound after deforming for 7 ms. However, before the slab rebounded, the stress intensity on the bottom slab can be observed at the center planes in both X-Z and Y-Z planes. The maximum stress is 4.20 MPa and 4.34 MPa for 1 lb and 2 lbs respectively, as shown in Fig. 13. The red contour (highest tensile stress) occurred intensively throughout Y-Z planes. From the results of maximum stress shows that the red contour along the middle of the bottom slabs has located at the same alignment of failure crack in the experimental slabs for both 1 lb and 2 lbs. The contour distribution of the red region in NRC2LB (shown in Fig. 13(b)) is greater than that in NRC1LB (shown in Fig. 13(a))

The damage caused by the 2 lbs explosive charge was more severe than that caused by the 1 lb charge, as seen in the more distributed area of red contour in model of 2 lbs charge. Moreover, more spalling occurs in the model of higher explosive charge weight as shown in Fig. 14 and Fig. 15.

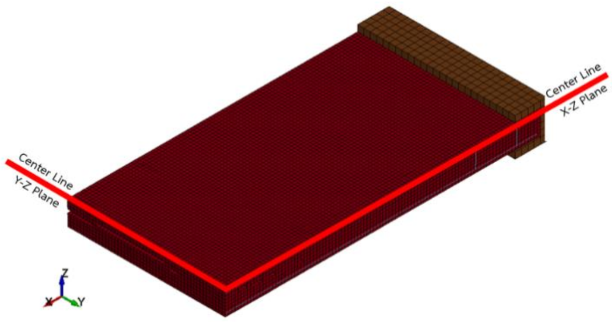
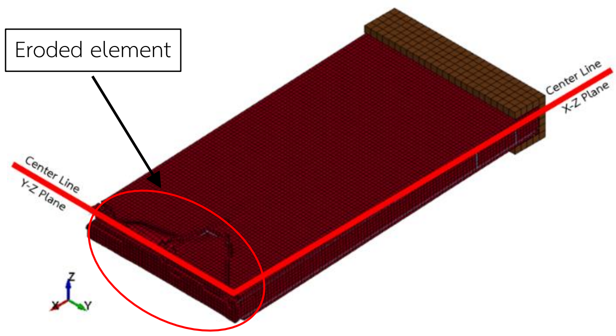


Fig. 14 the spalling and cracking damage along the middle of the slab for 1 lb.



(b)

Fig. 15 the spalling and cracking damage along the middle of the slab for 2 lbs.

However, the inaccuracy of the numerical results obtained from the MAT_072R3 simulation model is due to the use of auto-generated variables for the material model. Although these variables were generated based on experimental data from normal strength concrete, the material used in this simulation has a compressive strength that is classified as high strength concrete [7]. Further investigation of the material model comparison is needed.

5. Conclusion

This research aims to investigate the numerical simulation of the normal reinforced concrete (NRC) slab against a blasting load. The experimental result from previous research was employed to study the numerical analysis. The experimental setup was 2000mm x 1000mm x 75mm in dimension against 1 lb and 2 lbs at 0.50 m standoff distance. The conclusions of the study are as follows.

1. To simulate the numerical model of the NRC slab against blasting load. The materials related to the high strain rate property is required to simulate the RC slab under blasting behavior such as erosion property, equation of state, and inelastic parameter. To reduce the computation time, the numerical model is conducted on a quarter scale of the actual testing with added erosion to eliminate the eroded element.
2. Although the numerical simulation result has not accurately predicted the maximum displacement, it could show the trend according to the increasing explosive charge weight. The numerical simulation results demonstrated the maximum displacement is 11.13 mm and 95.18 mm for 1 lb and 2 lbs, respectively. In addition, the large area of high effective plastic strain level at the bottom of mid-slab under 2 lbs blasting presented the corresponding result to the more severe damage in the experimental RC slab under the same condition.

Acknowledgement

This research received funding support from the NSRF via the Program Management Unit for Human Resources & Institutional Development, Research, and Innovation [Grant number B16F640102].

References

[1] Luccioni, B.M., Ambrosini, R.D., and Danesi, R.F. (2004). Analysis of building collapse under blast loads. *Engineering Structures*, 26(1), pp. 63-71.

[2] ACI. (2004). *Facts for Steel Buildings – Blast and Progressive Collapse (ACI 239R-18)*. Michigan, Farmington Hills, American Concrete Institute.

[3] Li, J., Wu, C., and Hao, H. (2015). Investigation of ultra-high performance concrete slab and normal strength concrete slab under contact explosion. *Engineering Structures*, 102, pp. 395-408.

[4] Wu, C., Oehlers, D.J., Rebentrost, M., Leach, J., and Whittaker, A.S. (2009). Blast testing of ultra-high performance fibre and FRP-retrofitted concrete slabs. *Engineering Structures*, 31(9), pp. 2060-2069.

[5] Tai, Y.S., Chu, T.L., Hu, H.T., and Wu, J.Y. (2011). Dynamic response of a reinforced concrete slab subjected to air blast load. *Theoretical and Applied Fracture Mechanics*, 56(3), pp. 140-147.

[6] Suwarnarat, S. (2015). *Behavior of steel fiber reinforced concrete under blast load*. M.Eng. Thesis. Chulalongkorn University, Thailand.

[7] Mao, L., Barnett, S., Begg, D., Schleyer, G., and Wight, G. (2014). Numerical simulation of ultra high performance fibre reinforced concrete panel subjected to blast loading. *International Journal of Impact Engineering*, 64, pp. 91-100.

[8] Department of Defence Explosives Safety Board (2008). *Structures to Resist the Effects of Accidental Explosions (UFC 3-340-02)*, Unified Facilities Criteria.

[9] Shuaib, M., and Daoud, O. (2016). *Numerical Analysis of RC Slab under Blast Loads Using the Coupling of LBE and ALE Method in LS-DYNA*.