

Numerical Modelling of Reinforced Concrete Slabs under Blast Loads of Close-in Detonations Using the Lagrangian Approach

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Abstract. This paper includes an investigation for the deformations, including deflections and damage modes, which occur in reinforced concrete (RC) slabs when subjected to blast loads of explosions. The slab considered for the investigation is a one-way square RC slab with the dimensions of 1000 x 1000 x 40 mm, fixed supported at two opposite sides. It was subjected to close-in detonations of three different charge weights for a constant standoff distance. For the study, the slab was analysed using the numerical method by means of nonlinear finite element analysis. The slab was modelled as 3-D structural continuum using LS-DYNA software. For concrete modelling, two constitutive models were selected, namely the KCC and Winfrith concrete models. Blast loads were applied to the slab through the Lagrangian approach, and the blast command available in the software, namely `LOAD_BLAST_ENHANCED`, was selected for the application. The deflections and damage modes results obtained were compared to those from a previously published experiment. From the study, both the KCC and Winfrith concrete models effectively and satisfactorily estimated the actual slab maximum deflection. For damage modes, the KCC model appeared to be capable to capture satisfactorily the general damage mode including flexural cracks. However, the model could not capture the local shear mode at the middle of slab (spallation) because the Lagrangian approach does not simulate the interaction between the ambient air and the solid slab.

1. Introduction

Nowadays, the need for the protection against the effects of blast loads has increased as the number of explosion incidents that caused serious damages have greatly increased. Explosions can be caused either accidentally, as those occur by handling or storing explosives, or intentionally as in terrorist attacks. The principal material used for blast mitigation is reinforced concrete (RC) as it encompasses good characteristics in blast resistance. Among the RC structural elements, slabs are important elements and they are used widely for both structural and non-structural purposes.

Blast wave generated in an explosion imposes a short duration dynamic loads on structures. In general, materials including concrete and steel behave differently under dynamic loads. They



experience an increase in strength under rapidly applied loads. The deformations which occur in a structural member due to blast can be assessed by using either the experimental approach or the analytical approach which includes simplified empirical and advanced numerical techniques. The finite element (FE) method is an advanced technique which is used to solve complex structural analysis problems including blast problems. Many works such as those carried out by Hao and Zhongxian [1], Wang et al [2], Zhao and Chen [3], Tai et al [4] and others have proved that by using the FE method of analysis, the deformation which occurs in concrete due to blast loads can be effectively and satisfactorily assessed.

In the FE method, blast loads can be simulated using many approaches. The Lagrangian approach is one of them in which blast loads are applied directly in the form of load-time history on a designated surface. The use of this approach is advantageous as many software packages, such as the LS-DYNA, offer the automatic generation of blast loads by defining the basic parameters of the explosion. In addition, it does not require the modelling of air as in the Multi-Material Arbitrary Lagrangian Eulerian (MM-ALE) approach [5]. However, the Lagrangian does not take into account the interaction between air and structure [6].

RC elements possess different general behaviours depending on the intensity and standoff distance of the explosive. In the case of close-in detonations, the blast load produced is non-uniform with high intensity [7]. Thus, extremely high pressure detonations are developed which can produce local (punching) failure (including spalling and scabbing) of an element which is regarded to the brittle nature of concrete. The deformation is associated with considerable deflection values as well. The effect of close-in detonations on one-way concrete slabs was investigated by Wang et al [2] by using the experimental and numerical approaches. In this paper, this experiment was simulated numerically using the Lagrangian approach with nonlinear finite element analysis software, namely LS-DYNA. The obtained results were verified and compared with the experimental results.

2. Model Description

The model was for one-way RC slab supported at two opposite sides and subjected to close-in detonation of TNT explosives, and it similar to the slab in reference [2]. The charge weights considered for the detonations were 0.2, 0.31 and 0.46kg, and their configuration is as shown in Figure 1. The software used for modelling was LS-DYNA software, and the program library was used for the selection of element types and constitutive models for concrete and steel. The simulation of blast loading was carried out using the blast command available in the software.

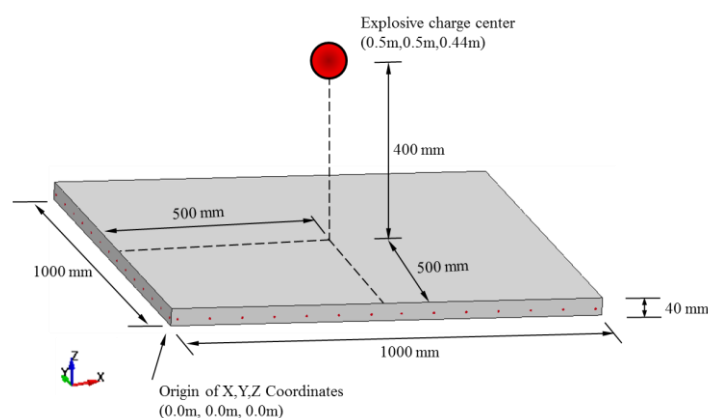


Figure 1. Configuration of the explosive charge

The slab dimensions were 1000 mm x 1000 mm x 40 mm. It was reinforced at its both directions by 6 mm steel bar reinforcement mesh with 75 mm spacing and 20 mm concrete cover. It was assumed to be fixed at the two supporting sides, although it was partially fixed in the experiment [2]. The dimensions of the slab in addition to the reinforcement detailing and supporting conditions are shown in Figure 2.

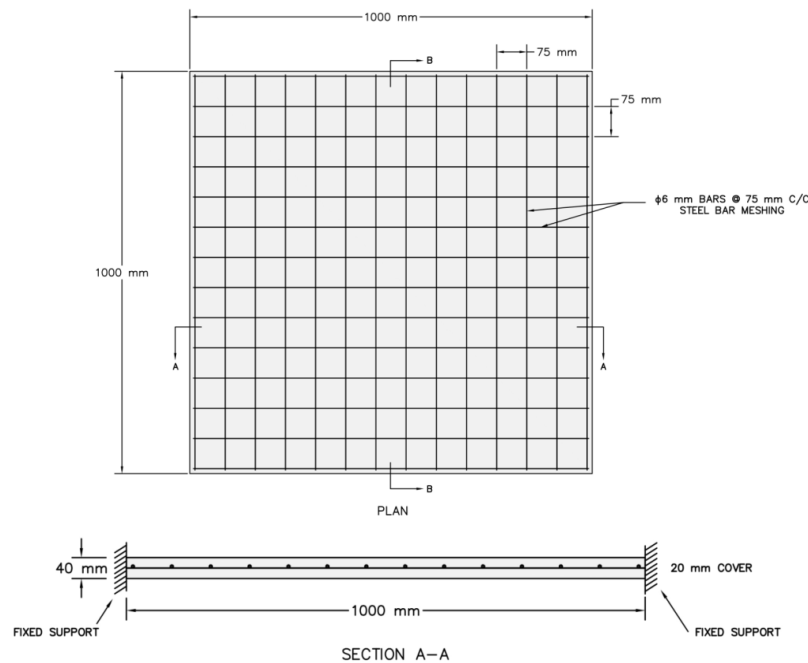


Figure 2. RC slab geometry and reinforcement details

The approach used for slab modelling was the three dimensional (3-D) approach in which the concrete was modelled as a 3-D block. This approach allows capturing the local deflections and damage. In the model, the concrete was discretized into solid elements, and the steel reinforcement into beam elements. Both meshed parts are connected using discrete technique which would insure the displacement compatibility of concrete and steel at the shared nodes. In addition, it would simulate the effect of links between steel bar mesh. The fixity at supports is applied by assigning fixed boundary conditions to support nodes. A schematic representation for slab finite element details is shown in Figure 3.

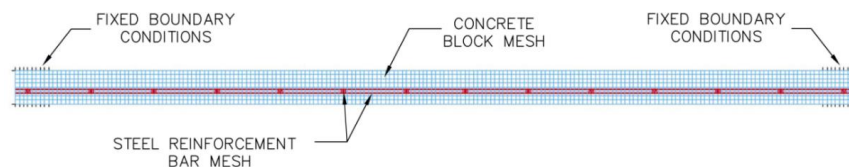


Figure 3. Schematic representation for finite element scheme details of RC slab

2.1. RC Slab Meshing

2.1.1. Concrete Meshing

The concrete of the RC slab was modelled as a solid box of dimensions 1000mm x 1000mm x 40mm which was composed of 8-node hexahedron solid elements with constant stress solid element formulation. The size of each element is 5mm x 5mm x 5mm which results in a number of 8 elements through the slab thickness. In the model, the total number of solid elements is 320,000 consisting of 363,639 nodes.

2.1.2. Steel Reinforcement Meshing

The steel reinforcement mesh was modelled as one layer of 6 mm diameter reinforcement bars and spaced at 75 mm. The type of element assigned to bars was Hughes-Liu beam element with mesh size of 5 mm, knowing that either truss or beam element can be used to model reinforcement bars. The total number of beam elements is 6,000 consisting of 5,835 nodes.

2.2. Material Constitutive Models

The RC used for slabs in the experiment had the properties of 39.5 MPa compressive strength (f_c), 4.2 MPa tensile strength (f_t), and 28.3 GPa Young's modulus (E_c). For concrete modelling, two constitutive models were selected. These models are namely Karagozian & Case Concrete (KCC) (MAT072R3) and the Winfrith concrete (MAT084) models. Both KCC and the Winfrith concrete models are invariant isotropic plasticity models, and they are suitable for blast problems, as they can capture the keys of concrete behaviours such as strain rate enhancement effect; however, the former proved to have better prediction for the localized shear. Both models take relatively simple input [8][9].

2.2.1. Concrete Constitutive Models

2.2.1.1 The KCC Concrete Model

The KCC (MAT072R3), is one of the material models that commonly used for concrete modelling. The main advantage offered by the KCC model that it allows the automatic generation of all the parameters by inputting only the unconfined compressive strength and the density of concrete [9]. For modelling, the default model parameter generation feature was used. This required the specification of the unconfined compression strength and density of concrete. For 39.5MPa concrete, the inputs in the model cards were as follows: concrete density (R0) 2400 kg/m³, negative of the unconfined compressive strength (A0) -39.5 MPa, conversion factors for length factors for length (inches-to-meters) and pressure (psi-to-MPa) (RSIZE & UCF) 39.72 and 145 for respectively. The remaining parameters were generated and determined automatically by the software.

2.2.1.2 The Winfrith Concrete Model

The Winfrith concrete model (MAT084) is a smeared crack model implemented in the 8-node single integration point continuum element. Similar to MAT072R3, it also allows the automatic generation of all the parameters by inputting certain parameters [10]. Those imported to the software were as follows: mass density of concrete (R0) 2400 kg/m³, initial tangent modulus of concrete (TM) 28.3 GPa, Poisson's ratio (PR) 0.29, uniaxial compressive strength (UCS) 39.5 MPa, uniaxial tensile strength (UTS) 4.2 MPa and aggregate size (ASIZE)16 mm (assumed). The remaining parameters were generated and determined automatically by the software.

2.2.2. Steel Constitutive Models

The steel material properties in the slab reinforcement used in the experiment were as follows: 600 MPa yield stress (f_y), 200 GPa Young's modulus (E_s) and 0.29 Poisson's ratio (ν). MAT003, which suited to model isotropic and kinematic hardening, was used for steel modelling.

2.3. Blast Modelling

The detonations considered in this study were for three different TNT charge weights of 0.2, 0.31 and 0.46 kg which had 40 cm standoff distance. For blast simulation, the Lagrangian approach was used for applying the blast loads on the RC slab surface. LOAD_BLAST_ENHANCED (LBE) keyword provided by LS-DYNA was selected. In LBE, the air blast pressure is computed empirically

with ConWep [10] data which is a collection of conventional weapons effects calculation from the equations and curves of TM 5-855-1 manual (similar to UFC 03-340-02 [7]) [11] [12].

3. Results and Discussions

3.1. Blast Pressure-Time History Results

The general blast wave characteristics provided by LBE were verified by observing the pressure-time histories which proved to follow the Friedlander curve as shown in Figure 4. The scaled distance Z for the 0.2, 0.31 and 0.46 kg TNT charge weights and 0.4 m standoff distance was 0.68, 0.59 and 0.52 $\text{m/kg}^{1/3}$ respectively. Since Z values are less than 0.71 $\text{m/kg}^{1/3}$, the detonation type for all charges is close-in [7]. The resulting pressures obtained from LBE for the TNT charge weights were relatively high, and their values in addition to other blast parameters, shown in Table 1, exhibited similar results as in UFC 03-340-02[7]. Pressure contours on slab for $W_{\text{TNT}}=0.2$ kg at different time steps Figure 5.

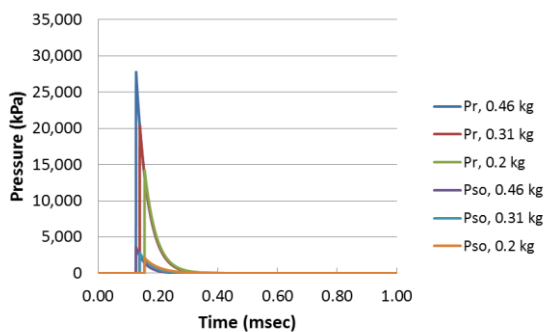


Figure 4. Pressure-time histories of reflected (P_r) and incident (P_{so}) pressures for 0.2, 0.31 and 0.46 kg TNT charge weights and 0.4 m standoff distance

Table 1. Positive phase blast parameters for different charge weights obtained from LBE

	Charge Weights (W_{TNT})		
	0.2 kg	0.31 kg	0.46 kg
Standoff distance, R (m)	0.40	0.40	0.40
Scaled distance, $Z=R/W^{1/3}$ ($\text{m/kg}^{1/3}$)	0.68	0.59	0.52
Overpressure, (reflected pressure), P_r (kPa)	14216.00	20406.00	27813.00
Incident pressure, P_{so} (kPa)	2108.87	2804.48	3595.09
P_r/P_{so} ratio	6.74	7.28	7.74
Reflected impulse, i_r (kPa.msec)	548.75	774.28	1065.95
Incident impulse, i_s (kPa.msec)	100.85	104.07	110.64
Arrival time, t_a (msec)	0.16	0.14	0.13
Positive phase duration, t_o (msec)	0.46	0.33	0.27

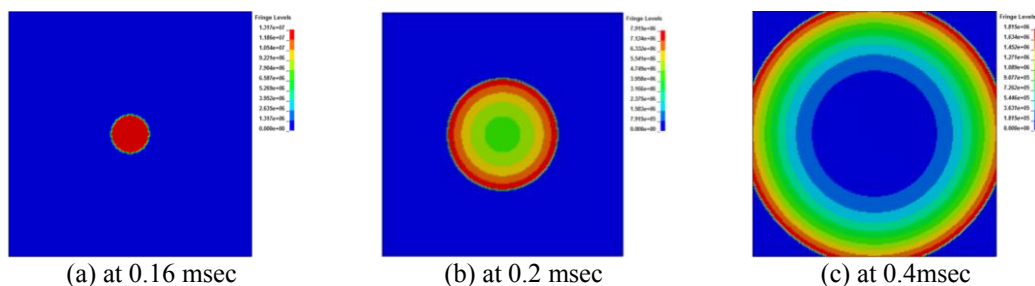


Figure 5. Pressure contours for the applied reflected pressure on slab surface. $W_{\text{TNT}} = 0.2$ kg and $R = 0.4$ m ($Z = 0.68 \text{ m/kg}^{1/3}$)

3.2. Deflection of Slab

The FE analysis indicated the pattern of deflection for the one-way square slab under blast loading through time. Before RC slab reached the one-way slab failure pattern, the square slab went through different stages. Since the blast loading was applied at the centre of slab and expanded circularly on the blast application surface, the slab correspondingly responded and started to deflect circularly when the load was applied. This deflection pattern continued until the unsupported edges started to respond. Then, the deflection was redistributed until the slab reached the one-way slab pattern. Both the KCC and Winfrith Concrete material models exhibited a similar behaviour. Graphical presentations for the slab deflection contours at different time instants for 0.2 kg TNT charge weight for the KCC material model is shown in Figure 6, and cross section of the slab at maximum deflection is shown in Figure 7.

Deflections were measured at the slab surface mid-point, and the displacement-time histories at this point for slabs with different concrete models are shown in Figure 8. In general, the maximum deflection, shown in Table 2, was noticed to be increased when the TNT charge weight was increased.

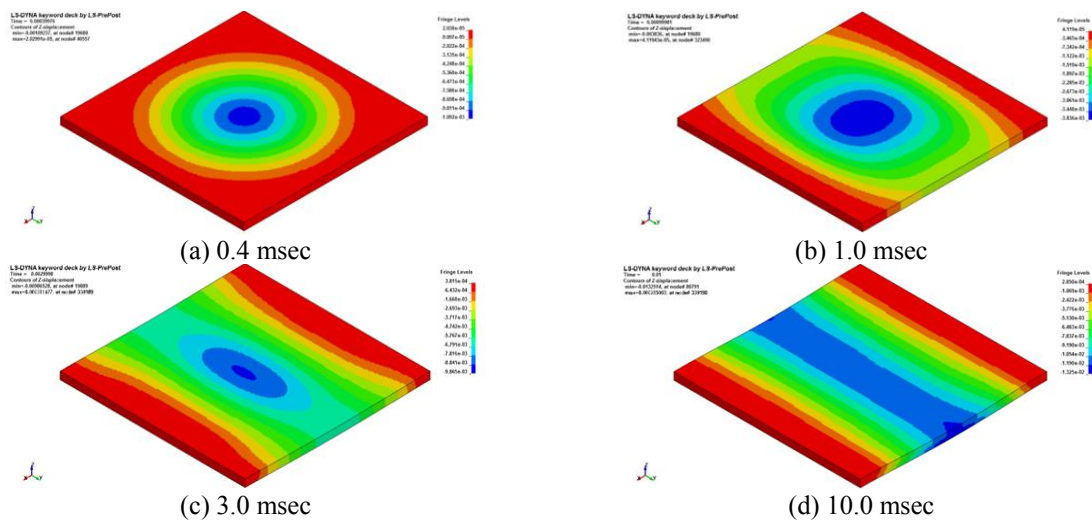


Figure 6. Pressure contours for the applied reflected pressure on slab surface. $W_{\text{TNT}} = 0.2 \text{ kg}$ and $R = 0.4 \text{ m}$ ($Z = 0.68 \text{ m/kg}^{1/3}$)

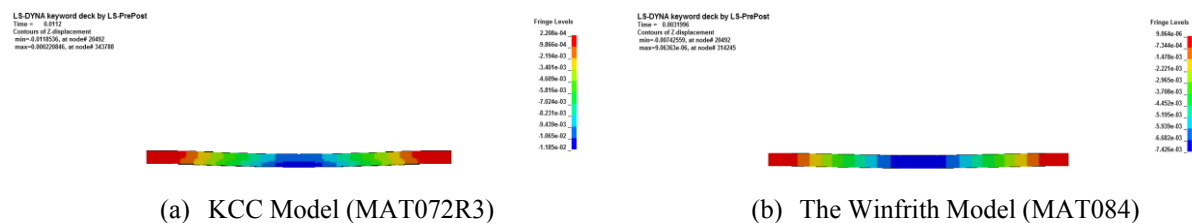


Figure 7. Cross sections at the middle of slab model in LS-DYNA along supports direction for maximum deflection. $W_{\text{TNT}} = 0.2 \text{ kg}$, $R = 0.4 \text{ m}$ ($Z = 0.68 \text{ m/kg}^{1/3}$)

Comparing results obtained from KCC and the Winfrith models with those from the experiment (as shown in Figure 9 and Table 2), it was noticed that both constitutive models estimated the maximum slab deflection effectively. While the former appeared to estimate it more accurately for 0.2 and 0.46 kg TNT charge weights.

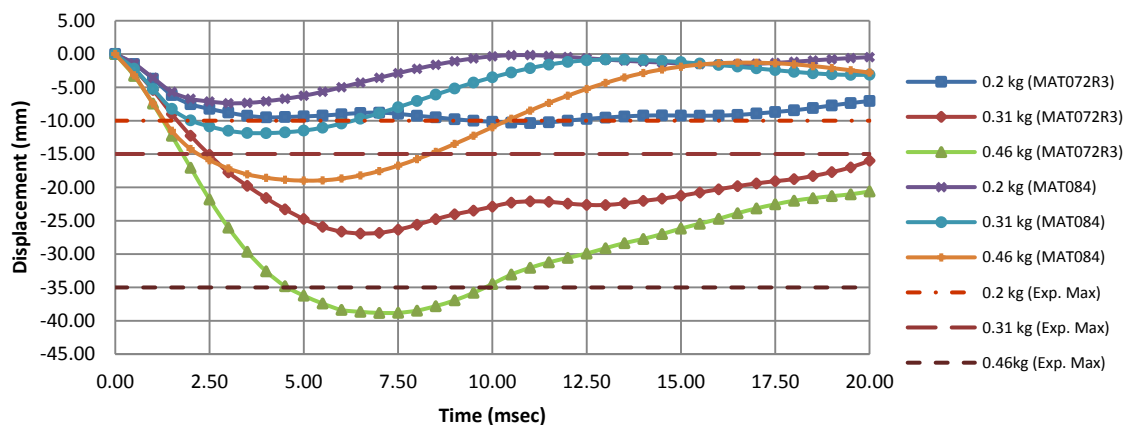


Figure 8. Displacement-time histories at middle of slab for the KCC (MAT072R3), the Winfrith concrete models (Exp. Max: maximum displacement in the experiment)

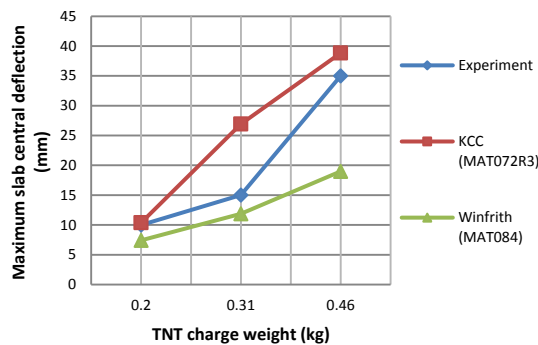


Figure 9. Variation in maximum slab central deflection

Table 2. Summary of slab maximum deflection for charge weights

Slab No.	W_{TNT} (kg)	R (m)	Z ($m/kg^{1/3}$)	Max. Deflection (mm)		
				Experiment	FEM (LS-DYNA)	
					KCC (MAT072R3)	Winfrith (MAT084)
1	0.2	0.40	0.68	10.00	10.36	7.41
2	0.31	0.40	0.59	15.00	26.92	11.87
3	0.46	0.40	0.52	35.00	38.84	18.99

3.3. Damage Modes

Damage modes obtained from models at maximum deflection were verified by observing the plastic strain in slabs. In the experiment [2], the actual slab damage modes were varied from low damage associated with cracks for $W_{TNT}=0.2$ kg ($0.68 m/kg^{1/3}$) and moderate damage associated with spallation, scabbing and cracks for $W_{TNT}=0.31$ and 0.46 kg (0.59 and $0.52 m/kg^{1/3}$). These modes were compared with those in the numerical models [13]. As example, the results for $W_{TNT}=0.31$ ($0.59 m/kg^{1/3}$) are as shown in Figure 10 and Figure 11.

For the KCC model, the captured damage at slab top was the yielding at the supports. The model could not assess the spallation effectively because the LBE command applies blast loading using the Lagrangian approach which does not consider interaction between the ambient air and solid slabs is not considered [6]. While at the slab bottom the flexural cracks in addition to localised shear regions were appeared at supports and middle of slab, and they agreed approximately with the actual damage. On the other hand, the Winfrith concrete model appeared to behave more rigidly as the damage mode obtained was composed of a damage strip that expanded along the middle of the slab at top, and support yielding at slab bottom.

Therefore, the damage modes can be better estimated using the KCC model, and the interaction between the air and solid slab can be included using the ALE approach which will consequently result in the effective estimation of spallation such as the obtained in reference [2].

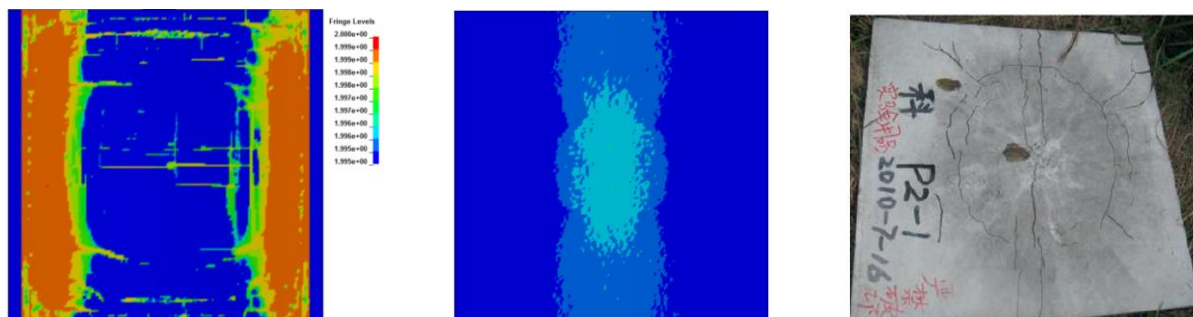


Figure 10. Damage mode of top of slab for 0.31 kg, and $R = 0.4$ m ($Z = 0.59 m/kg^{1/3}$). KCC (left), the Winfrith (middle) the experiment [2] (right)



Figure 11. Damage mode of bottom of slab for 0.31 kg, and $R = 0.4$ m ($Z = 0.59$ m/kg^{1/3}). KCC (left), the Winfrith (middle) the experiment [2] (right)

4. Conclusions and Recommendations

The numerical models of the one-way RC slab subjected to blast loads, which is applied using Lagrangian approach, for close-in detonations indicated that the slab deflection can be estimated satisfactorily. Both KCC and the Winfrith concrete models can indicate the slab deflection effectively, while the former demonstrated more accurate results. Also, the KCC appeared to be capable of capturing the flexural damage on slab and yielding at supports. While the spallation occur in the tension zone at the top of slab could not be captured. This effect can be achieved using the Arbitrary-Lagrangian Eulerian (ALE) approach which is capable to simulate the interaction between the ambient air and the solid slab.

References

- [1] D. Hao and L. Zhongxian, "Numerical analysis of dynamic behavior of RC slabs under blast loading," *Transactions of Tianjin University*, vol. 15, no. 1, pp. 61-64, February 2009.
- [2] W. Wang, D. Zhang, L. Fangyun, S.-C. Wang and F. Tang, "Experimental study and numerical simulation of the damage mode of a square reinforced concrete slab under close-in explosion," *Engineering Failure Analysis*, vol. 27, p. 41-51, 2013.
- [3] C. F. Zhao and J. Y. Chen, "Damage mechanism and mode of square reinforced concrete slab subjected to blast loading," *Theoretical and Applied Fracture Mechanics*, vol. 63-64, p. 54-62, (2013).
- [4] Y. S. Tai, T. L. Chu, H. T. Hu and J. Y. Wu, "Dynamic response of a reinforced concrete slab subjected to air blast load," *Theoretical and Applied Fracture Mechanics*, vol. 56, p. 140-147, 2011.
- [5] Z. S. Tabatabaei and J. S. Volz, "A Comparison between Three Different Blast Methods in LS-DYNA: LBE, MM-ALE, Coupling of LBE and MM-ALE," in *12th International LS-DYNA Users Conference*, Dearborn, Michigan, USA, 2007.
- [6] Y. Lin, G. Shunfeng and J. Weiliang, "Spallation Mechanism of RC Slabs Under Contact Detonation," *Trans. Tianjin Univ.*, vol. 14, pp. 464-469, 2008.
- [7] USA Department of Defence, "Structures to Resist The Effect of Accidental Explosions - Unified Facilities Criteria (UFC) 3-340-02", Department of Defence, 2008.
- [8] L. Schwer and L. Malvar, "Simplified Concrete Modeling with *MAT_CONCRETE_DAMAGE_REL3," in *JRI LS-DYNA User Week 2005*, Nagoya, Japan, 2005.
- [9] L. Schwer, "The Winfrith Concrete Model : Beauty or Beast ? Insights into the Winfrith Concrete Model," in *8th European LS-DYNA Users Conference*, Strasbourg, 2011.
- [10] D. W. Hyde, "User's Guide for Computer Programs CONWEP and FUNPRO. Applications of TM 5-855-1, "Fundamentals of Protective Design for Conventional Weapons", Washington, DC, 1988.
- [11] G. Randers-Pehrson and K. A. Bannister, "Airblast Loading Model for DYNA2D and DYNA3D," Adelphi, Maryland, 1997.
- [12] L.S.T.C., LS-DYNA Keyword User's Manual, Livermore: Livermore Software Technology Corporation (LSTC), 2007.
- [13] M. M. N. Shuaib, "Numerical Modeling of Reinforced Concrete Slab under Blast Loads", M.Sc. Thesis, University of Khartoum, Khartoum, Sudan, 2014.