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Analysis of RC Columns and Slabs Subjected to Blast Loadings

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Abstract. Linear and non-linear structural analyses can be solved using the finite element method (FEM) and other numerical techniques. A new applied element method (AEM) that can predict with a higher degree of accuracy the continuum and discrete behavior of structures has recently been developed. In AEM, elements sharing the same surface will have connectivity springs even if the shared surfaces are only a portion of the surface. The collapse phases of structures by using AEM can be tracked and monitored. In the current research, the application of AEM is demonstrated by a non-linear dynamic analysis for reinforced concrete (RC) columns and slabs subjected to blast loading. The available experimental works carried out by other researchers to study the impact of close-in blast loading on RC members are used for verification. A good correlation between the experimental and numerical results has been achieved.

1. INTRODUCTION

Progressive collapse has become a hot topic for research studies due to many accidents and crashes that have occurred since the beginning of the 20thcentury. For instance,thegas explosion occurred to the Ronan Point apartments tower in 1968, progressive collapse to the Murrah Federal Office buildingin 1995 and collapse of World Trade Center in 2001 (Refer to Figure 1).

Fig (1.a): Gas Explosions in Ronan Point Building
https://community.betfair.com/chit_chat/go/thread/view/94038/29212513/?pg=2&output_method=iframe

Fig (1.b): Failure of Murrah Federal Structure
https://www.bestonlineengineeringdegree.com/the-10-worst-high-rise-building-collapses-in-history/

Fig (1.c): World Trade Center Collapse
https://www.bestonlineengineeringdegree.com/the-10-worst-high-rise-building-collapses-in-history

As a result, many international structural codes have begun to give the design criteria for resistance of structures to failure, such as the U.S. General Services Administration (GSA) [1]published in 2003 and Unified Facilities Requirements (UFC)[2]published in 2005 and 2009 by the US Department of Defense (DoD). According to the DoDguidelines, two general techniques are used to minimize the risk of progressive collapse; direct and indirect design methods. Direct design method involves explicit analysis of the building for a design-level blast load. On the other hands, indirect method ensures protection against progressive collapse through the selection of appropriate structural system, layout of vertical loadbearing elements as well as designing and detailing individual members for strength, ductility and stability.

The simulation using computer programs simulation is an important key in determining the performance of structures in extreme loading conditions. However, it is not possible to foresee the behavior of collapse for structures using the FEM. Therefore continuum mechanics-based methods cannot be extended to simulate the collapse analysis.

A new method called AEMthat is capable of predicting to a higher degree of accuracy the continuum and discrete behavior of structures, has been developed. The obtained results using AEMare very precise with relatively short CPU running time. In this paper, AEM is used to conduct a numerical analysis to simulate the behavior of blast loading on RC columns and slabs.

The AEMhad been used by many some researchers.Krauthammer et al. [3],developed theoretical and numerical methods to study of the progressive collapse phenomenon. Also, they made laboratory tests to verify the developed procedure.Lupoae et al. [4], discussed the impact of infill walls on progressive collapse of perimeter frames with and without openings using ELS. Salem et al. [5], used the AEM to suggest an optimal and economical design solution to avoid the failure of multistory RC structure due to the removal of columns. Khalil [6], studied the progressive collapse of 4stories steel construction using AEM and the alternative load path method of the UFC guidelines and compared the results with FEM. Raparla et al. [7], used AEM method to study the collapse behavior of a building designed according to Indian standards.Kyei[8], developed a finite element code (LS-DYNA) for studying the behavior of seismically detailed RC columns subjected to blast loading. Ismail, [9]studied the effect of the spring element size, spring distribution and shear stiffness on the accuracy of the AEM in obtaining the buckling load of a rectangular plate with simply supports, and compared the results with the completed theoreticalsolution.Botez et al. [10],presented a numerical study of the structural response of RC slab subjected to blasting load.ConWEP (Conventional Weapon Effects Program) procedure was applied to simulate the air pressure wave propagation caused by deflagration, and an erosion algorithm was followed for removing the excessively distorted finite elements in tension.

2. OBJECTIVE

This paper aim is to verify the ability of AEM to simulate effect of blast load on RC structures. The experimental workscarried out by Siba, F. [11]and Zhao, C.F. and Chen, J.Y. [12]to study the effects of explosion on RC columns and slabs, are modeled using ELS program, and the obtained numerical results are compared with the experimental ones

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3. APPLIED ELEMENT METHOD OVERVIEW

The structure is modelled with as an assembly of small elements which are generated by practically dividing the structure, (see Figure 2-a). As shown in Figure 2-b, the two elements are assumed to be linked by one normal and two shear springs located at contact points, which are distributed around the element’s edges. The stresses and deformations are represented by each group of springs of a certain volume.

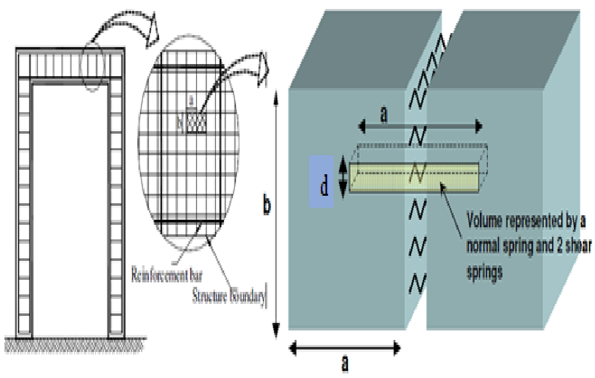


Fig 2: Applied Element Modeling[13]
(a) Element generation **(b)** Spring distribution and

for AEM	area of influence of each pair of springs

3.1 Element Formulation in the AEM

The stiffness of the springs in normal and tangential direction is provided by:

$$K_n = \frac{E \times d \times t}{a} K_s = \frac{G \times d \times t}{a} \qquad (3.1)$$

where, *E* and *G* are Young's Modulus and Shear modulus, respectively, '*d*' is the distance between springs, '*t*' is the thickness, and '*a*' is the length of the representative area. Equation 3.1 merely reflects spring axial stiffness. Each element has three degrees of freedom at its centroid representing the element's rigid body motion. Deformation in each set of springs on the surface of the elements may be geometrically connected to the degree of freedom at the centroid, thereby generating a stiffness matrix for that set of springs. Then the element stiffness matrix is generated by summing the stiffness matrices of each set of springs. The model can be analyzed using the following equation:

$$[F] = [K_G][\Delta] \qquad (3.2)$$

where, $[F]$ is the applied load vector, $[\Delta]$ is the displacement vector, and $[K_G]$ is the global stiffness matrix.

The AEM's benefit lies in the use of springs to attach adjacent elements.Stress and the resulting strain are measured during the loading process for each set of normal and shear springs. Considering material properties, the maximum force resisted by a spring can be determined. If the full force is achieved, the springs are cut or not taken into consideration in further analysis. This can occur within the model, so no preconceived position of cracks is needed. If all the springs which connect an element are cut, the element will be separated from the structure. The element has its assigned mass and produces inertial forces in the dynamic analysis. The ability to cover this broad variety of structural behavior in a single model is the crucial difference between the AEM and other numerical approaches.

3.2 Formulation of Stiffness Matrix of 2-D Element

Figure 3shows the overall position of the element. It is assumed that the two elements are bound by pairs of normal and shear springs at each point of contact spread along the faces of each element. The contact points coordinates (dx, dy) can be obtained with respect to the centroid of each element. Two transverse and one rotational degree of freedom are considered to be at the centroid of an element.

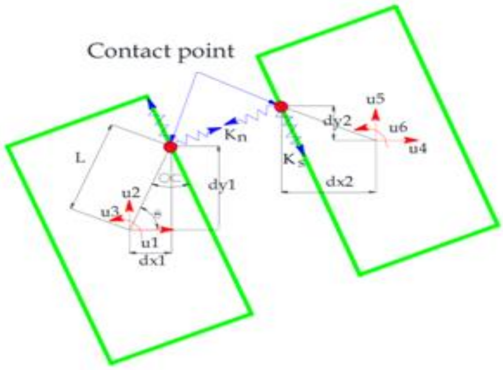


Fig 3: General Position of Deformed Element[13]

4.VALIDATION OF AEM USING *ELS*

The AEM is verified by comparing output response of structure to blast load results using ELS with literature experimental studies.Experimental tests conducted by Siba, F.[11]and Zhao, C.F. and Chen, J.Y. [12]are modelled using ELS (V. 2.3) to validate the AEM.

4.1 Validation Study for the Full-Scale Column Blast Load [11]

4.1.1 Experiment Description

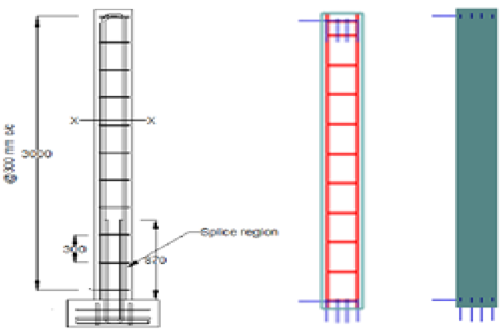
The experimental work was conducted in a near field to investigate the effects of explosions on RC columns, for scaled distances, z (m/kg$^{1/3}$). A total of twenty columns were constructed, sixteen of them were subjected to close-range explosion testing at the Canadian Forces Base (CFB), Petawawa. The other four columns were subjected to static testing at the structures laboratory of Carleton University, Canada.There were also two reaction structures constructed to support the columns during testing. The end conditions were designed to simulate fixed support conditions.

Table 1 gives the columns names, the stirrups spacing, concrete cover, the lap splice length and the axial load ratio (ALR). The columns have a dimension of 300 x 300 mm and reinforced with 4-25 M, giving a vertical reinforcement ratio of 0.02. The details of the two columns areshown in Figure 4(a).

Table 1: Columns Designation and Details

Column designation	Stirrups spacing(mm)	Concrete Cover (mm)	Lap splice (mm)	ALR
CONV-6	300	40	870	0.00
CONV-20	300	40	870	0.32

Column transverse reinforcement was detailed in compliance with CSA A23.3-04 clause7.6.5.2 (CSA 2004) for columns with prevailing resistance to gravity loads.The column vertical lap splices were found at the base of the column within the region of the plastic hinge. The columns had a height of 3200 mm.



(a) Conventional column detailing[11] **(b)**Modelling in ELS [This work]

Fig 4: Columns Details

4.1.1 Columns Modeling in ELS

The 300 x 300 x 3200 mm RC column has a meshing of 15 mm cube solid elements. In a mesh sensitivity analysis, this mesh size was developed to obtain accurate results with minimal computational effort. The nodes at the base and top of the column were all restrained in three Cartesian coordinates to avoid both translational and rotational movements as shown in Figure 4(b). Concrete has a compressive strength equal to 41.30 MPa. The yield strength for the transverse reinforcement of 10 M (11.3 mm diameter) is 465.20 MPa with a yield strain of 0.0022. The yield strength for the longtudinal steel reinforcement 25M (19.5 mm diameter) is 474.4 MPa with a yield strain of 0.0024.

4.1.2 Explosion Load

The charge weight is 123 kg of TNT, effective stand-off distance is2.60m, the reflected pressure at the middle-front is 24.50 MPa and arrival time and blast duration are 0.84 ms and 2.48 ms, respectively.

4.1.3 Test Results

Figure 5 shows a photo of the CONV-20 column before testing. The two columns tested in, were positionedequally from the centre of the blast; with a stand-off distance of 2.60 m and scaled distance of 0.52 m/kg$^{1/3}$.

Fig 5: Photographs of Column (CONV-20) Prior to Explosion[11]

Table 2showsthe summary of the obtined numerical and experimental results for column (CONV-20). Blast loading ranged across the front face of the column from 26,800 kN/m^2 at the bottom-front to 20,900 kN/m^2 at the top-front pressure gauge.

Table 2: Summary of (CONV-20) Results

(a) Blast Pressure Results							
Test	CONV-20						
Test Details	Charge Mass		Standoff		z (m/kg$^{1/3}$)		ALR
	150-kg ANFO		2.60 m		0.52		0
Gauge	Bottom-Front		Mid-Front		Top-Front		Mid-Back
	Exp.	ELS	Exp.	ELS	Exp.	ELS	Exp.

Location (mm)	210		1250		2200		1300
Range (mm)	2717.4		2612		2863.60		-
Incident Angle	16.9°		5.5°		24.8°		-
P_r (kPa)	35,555	26,800	26,531	24,000	2,598	20,900	Failed
T_a (ms)	1.00	15.90	1.10	15.90	1.48	15.90	-
T_d (ms)	0.41	1.20	0.26	1.50	0.82	1.50	-
(b) Displacement Results							
CONV-20	@ 1.00m		@ 1.50m		@ 2.00m		
Experimental	11.20 mm		14.30 mm		9.90 mm		
ELS	12.10 mm		17.20 mm		11.10 mm		

Table 3 shows the summary of the obtined numerical and experimental results for column (CONV-6). Blast loading ranged across the front face of the column from24,600 kN/m^2 at the bottom-front to 22,700 kN/m^2 at the top-front pressure gauge.

Table 3: Summary of (CONV-6) Results

(a) Blast Pressure Results							
Test	CONV-20						
Test Details	Charge Mass		Standoff		z (m/kg$^{1/3}$)		ALR
	150-kg ANFO		2.66 m		0.53		0.32
Gauge	Bottom-Front		Mid-Front		Top-Front		Mid-Back
	Exp.	ELS	Exp.	ELS	Exp.	ELS	Exp.
Location	250		1250		2200		1250
Range (mm)	2763.7		2671.7		2918.2		-
Incident	15.7°		5.4°		24.3°		-
P_r (kPa)	Failed	24,600	30,376	22,000	8,796	20,900	Failed
T_a (ms)	-	15.80	1.09	15.80	1.40	15.90	-
T_d (ms)	-	1.20	0.37	1.20	0.69	1.20	-
(b) Displacement Results							
CONV-6	@ 1.00m		@ 1.50m		@ 2.00m		
Experimental	Failed		17.20 mm		13.20 mm		
ELS	12.70 mm		17.80 mm		11.10 mm		

The displacement-time history for CONV-20 and CONV-6 are shown in Figures6 and 7, respectively. For CONV-20, the critical experimental displacement was 14.30 mm whilethe critical numerical displacement is 17.2 mm at mid-height. Similarly, for CONV-6 the critical experimental displacement was 17.20 mm while the critical displacement value at mid height is 17.8 mm.From Figures 6 and 7, there are a good matching between the numerical and experimental results.

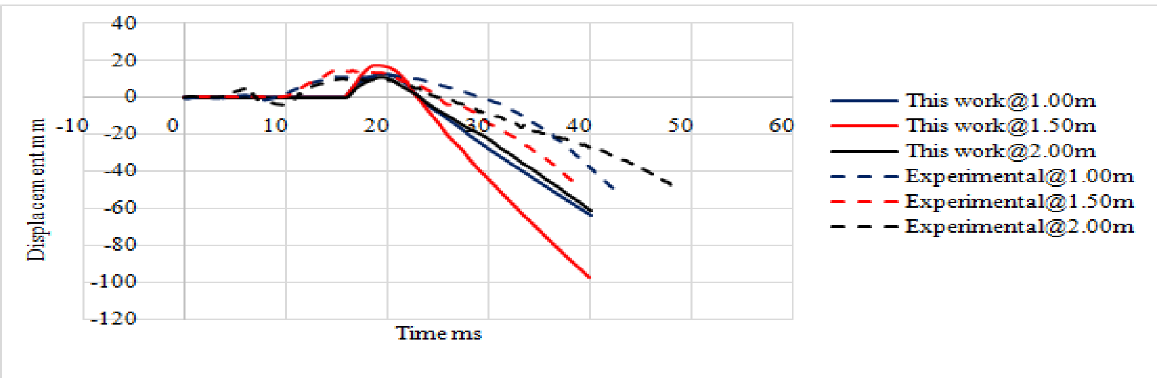


Fig 6: Displacement-time history for column CONV-20

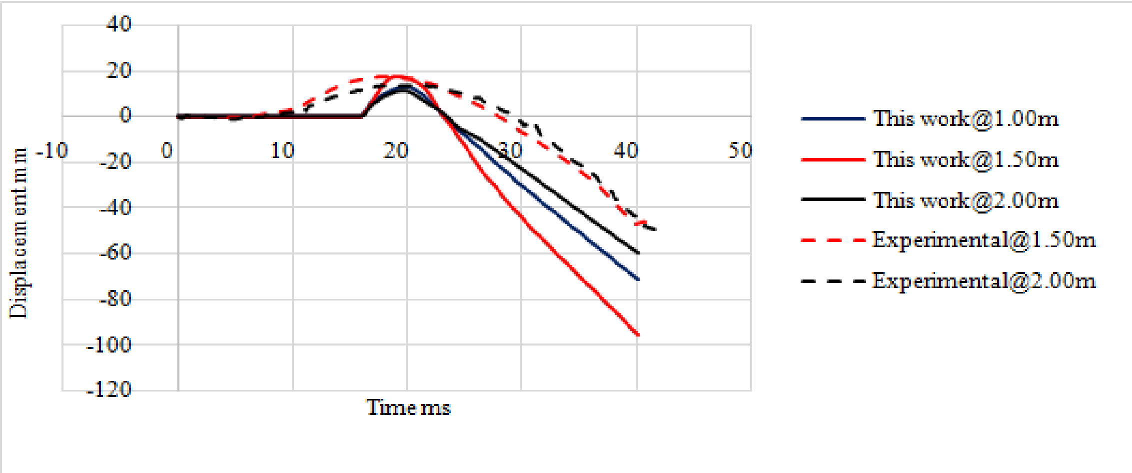


Fig 7: Displacement-Time history for Column CONV-6

Figures (8) and (9) show the comparison of the collapse shapes for the two studied columns obtained from ELS model and the real experiments performed by Siba, F [11]. From these figures, there are a good matching between the numerical and experimental results. Furthermorem there are a considerable lateral deflection in the column at mid-height, the lower half of the column consists of many concrete deteriorated parts.

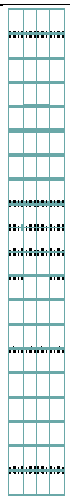
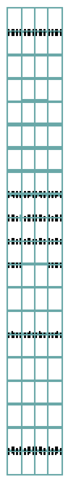
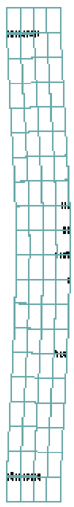
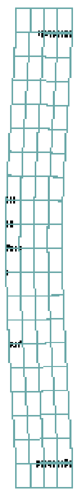
Face	AEM Model (This work)	Experimental [11]	Face	AEM Model (This work)	Experimental [11]
Front			Back		
Right			Left		

Fig 8: Analytical and Experimental Deformed Shapes for the CONV-20

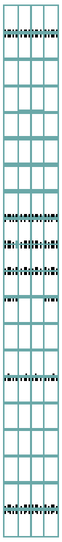
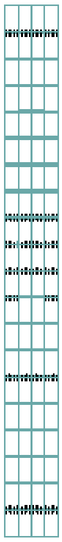
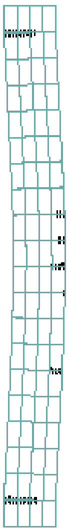
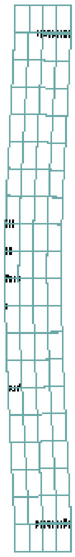
Face	AEM Model (This work)	Experimental [11]	Face	AEM Model (This work)	Experimental [11]
Front			Back		
Right			Left		

Fig 9: Analytical and Experimental Deformed Shapes for the CONV-6

4.2 Validation Study for the Full-Scale Slab Blast Load [12]

4.2.1 Experiment Description

This experimental work was done by Zhao, C.F. and Chen, J.Y.[12]. In their work, RC slabs were built with 6 mm diameter meshing bar spaced at a distance of 75 mm. The reinforcement ratio and the concrete cover were 1.43% and 20 mm, respectively. Figure 10 shows the dimensions and a sectionaldetail of the tested specimens. All slab specimens have a dimension of 1000 x 1000 mm and 40 mm in vertical thickness. Figure 11 shows the slab modeling in ELS.

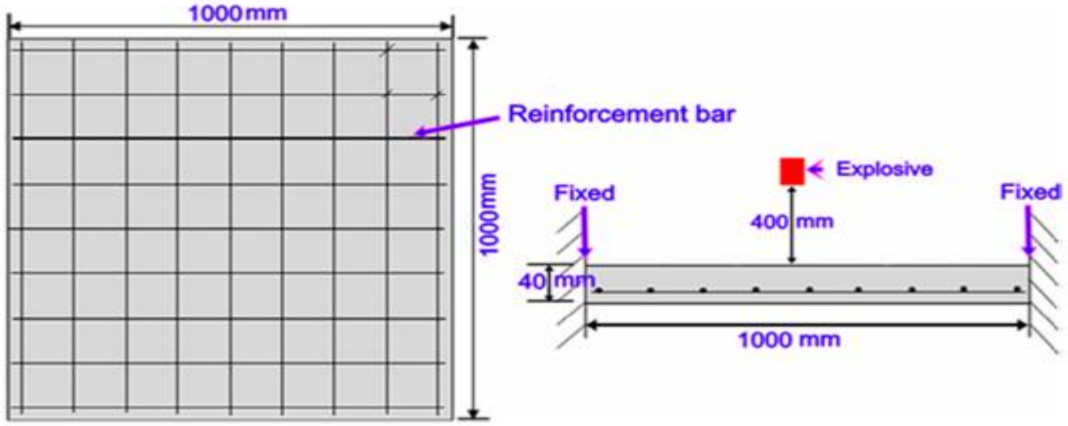


Fig 10: Geometry of the Reinforced Concrete Slab[12]

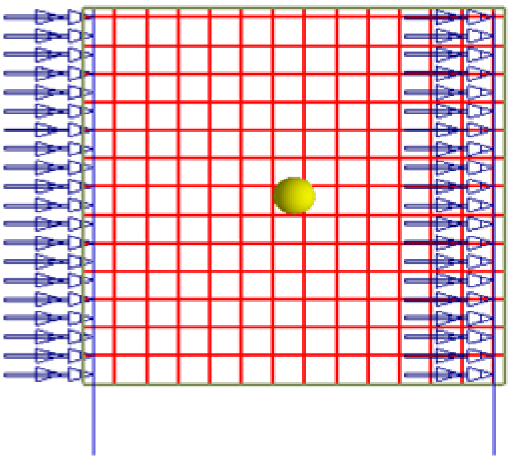


Fig 11: SlabModeling in ELS [This work]

4.2.2 Material Properties

The cylinder compressive strength, tensile strength and Young's modulus of concrete are 39.5 MPa, 4.2 MPa and 28.3 GPa, respectively. The yield strength of reinforcement was of 600 MPa and Young's modulus of 200 GPa.

4.2.3 Explosion Load

The TNT explosive is used in the experiment as it is a high standard explosion and the explosive mass is 0.2–0.46 kg. The TNT explosive was placed over the test specimens at height of 400 mm. The description of the experiment are shown in Table 4. The peak pressure for the TNT explosion case can be measured at 20.75 MPa from TM5-1300.

Table 4: Experimental Details

Test	Slab	Dimension (mm)	Explosive Charge (kg)	Scale Distance ($m/kg^{1/3}$)	Damage Level
T1	S1	1000 x 1000 x 40	0.20	0.684	Low damage
T2	S2	1000 x 1000 x 40	0.31	0.591	Moderate damage
T3	S3	1000 x 1000 x 40	0.46	0.518	Moderate damage

4.2.4 Test Results

The maximum displacement values corresponding to the TNT charges of 0.20kg, 0.31kg and 0.46kg, the obtained numerical results by the authors using ELS and by Zhao, C.F. and Chen, J.Y. [12] using LSDYNAare summarized in Table 5 along with the error percentage with respect to the experimental test results.

Table 5: Comparison Results between Numerical Simulation and Experimental Results

Slab	TNTcharge(kg)	Maximum displacement values(mm)			% Error
		Experimental[12]	This work	Numerical [12]	
S1	0.20	10	9.92	8.80	-0.80
S2	0.31	15	14.85	12.70	-1.00
S3	0.46	35	33.00	31.10	-5.71

The numerical results for each of the three TNT charges analysed provide the concrete tension degradation patterns. This type of results is a way of quantifying the damage caused by each of TNT charge applied. Figure 12compare theresults from the numerical and experimental results for RC slabs. Again, it can be concluded that the numerical obtined results using ELS are in good agrrement with thoes from experimental works.

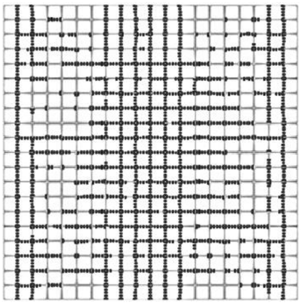
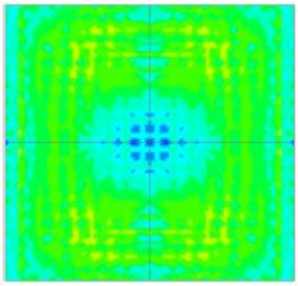
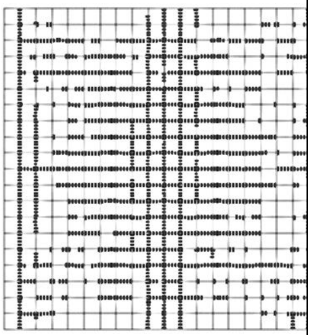
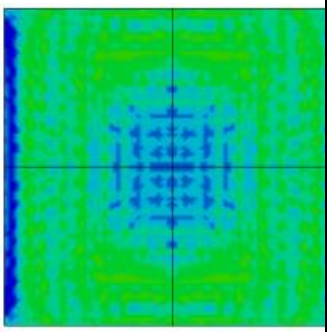
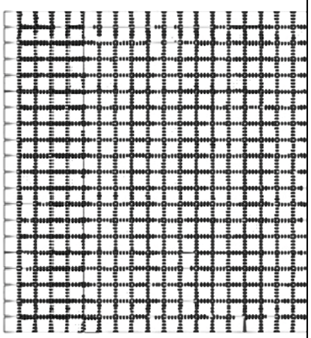
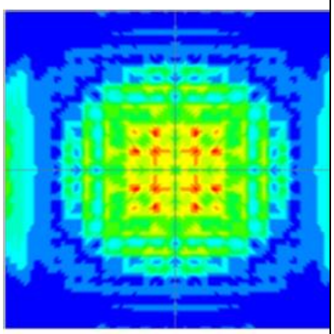
Time	Experimental[12]	AEM Model [This work]	LS DYNA [12]
S1			
S2			
S3			

Fig 12: Experimental and Analytical Deformed Shapes for the slabs

CONCLUSION

In this study, a numerical investigations of blast-loaded RC columns and slabs are performed using ELS computer program based on the AEM.The numerical results obtained are compared with the experimental works conducted bySiba, F[11] and Zhao, C.F. and Chen, J.Y. [12]. The main results of the present study can be summarised as follows:

1. For progressive collapse analysis, the AEM proven that it is a good tool for simulating the RC columns and slabs subject to blast loads. The experimental and numerical results for the studied RC columns and slabs are well matched.
2. The developed models considered as an alterntaive economical tool for analysis of RC columns and slabs behavior in blast loadings conditions. The time-consuming and highly expensive full-scale blast loading experimental tests canbe minimised.
3. For the studied RC columns subjected to the effects of close-in blasting load, there are a considerable lateral deflection in the column at mid-height, the lower half of the column consists of many concrete deteriorated parts, and the concrete is almost crushed near both the upper and lower supports.

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