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CONTACT EXPLOSION RESPONSE OF REINFORCED CONCRETE COLUMNS: EXPERIMENTAL AND VALIDATION OF NUMERICAL MODEL

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Abstract: Protective design of critical infrastructure and iconic buildings and monuments against terrorist attacks requires the incorporation of blast-resistant design to ensure adequate safety against explosive threats in today's environment. Consequently, the response analysis of structures subjected to blast loading has gained importance with structural engineers in the recent years. Past research efforts have mostly focussed on the far-field blast response of structural components with limited emphasis on the near-field and contact explosion response. Thus, there is a lack of knowledge on the response of structural components to the effects of near-field and contact explosion. The behavior of reinforced concrete components have been studied numerically however there is limited experimental data for validation of these numerical models. The experimental data is scarcest in case of concrete columns. Columns are the most vulnerable and critical member in any structure and are prone to contact explosion attacks using small quantities of explosives. This paper presents a benchmark study for the response of full scale reinforced concrete columns with pad footing when subjected to contact explosions of varying charge mass. The quantitative and qualitative assessments of damage to concrete columns, including spalling and scabbing are presented. The experimental data was used to validate a set of numerical models in LS-DYNA. These models were used in further parametric studies to establish the effects of various design parameters on the response of concrete columns to contact explosions. Preliminary results of the parametric studies show that the response of the concrete columns subject to contact explosion can be reliably predicted using the validated numerical models.

1 INTRODUCTION

Critical infrastructures such as major bridges, petrochemical refineries, thermal or nuclear power plants, stock exchanges, military or political headquarters and iconic monuments have been the targets for terrorist attacks in the past. The past attacks show that the terrorist threats to critical infrastructure are evolving and need an equally evolved and developed protective design capability. There is an ever more stringent control over energetic materials required for large scale bombings. The scenario of critical reinforced concrete (RC) columns being subjected to contact explosion of small charge weights is a credible threat perception. A strategically planned contact explosion on a critical RC column can severely compromise the axial load carrying capacity leading to partial or a complete collapse of the building. Currently, studies on response of RC members subjected to contact explosions are limited to numerical analyses and data from experimental work is scarce. Access to experimental facilities to conduct blast tests is restricted to a select few government organizations and research institutions. Additionally, the data acquisition systems for contact explosion events are not well established in the literature. It is difficult to acquire experimental data such as pressure and shock wave properties due to very high temperature and pressure in the vicinity of the fireball of contact explosion. The lack of quantitative experimental data for validation of numerical models impedes the research on response of RC members subjected to contact explosion. Response of RC slab subjected to contact explosion can be approximated as a 1-D wave propagation phenomenon influenced by limited parameters like charge mass to slab thickness ratio and compressive strength of concrete and yield strength reinforcement. On the other hand response of RC columns subjected to contact explosion can be approximated as a 2-D wave propagation phenomenon influenced by additional parameters like aspect ratio of the column cross-section, axial load level, transverse reinforcement spacing, infill boundary condition etc (Dua & Braimah, 2016). The response of RC columns to contact explosions is hence difficult to predict and requires further investigation.

2 LITERATURE REVIEW

The blast loading behavior on structural elements differs considerably for contact and far-field explosion events (Dua & Braimah, 2016). Contact explosions yield a spatially and temporally non-uniform loading causing predominantly local shear response, while far-field explosions yield spatially uniform loading on the structure causing global flexural response. The material response to contact explosion is highly non-linear and often leads to inelastic deformations in the material. As a result, the empirical methods applicable to far-field blast response analysis are not valid for contact explosion response.

Prior to NCHRP Report No. 645 (2009), no experimental data existed in the public domain documenting the response of RC concrete columns subjected to near-field and contact explosions. The report documented response of RC bridge columns of different cross-sections due to explosions at far-field and near-field scaled distances and also in contact. Numerical modelling guidelines for LS-DYNA were presented and code-ready blast load on RC bridge columns were predicted which correlated well with the experimental results (Williams, 2009).

Experimentally validated empirical relations for residual axial compression capacity of localized blast-damaged RC columns and steel composite RC columns were reported by Wu et al. (2011a) and Wu et al. (2011b). A term ‘explosive mass ratio’ was defined as the ratio of explosive charge mass to the mass of 1-m high column and used in parametric analysis to study the effect of contact explosions. It was reported that for an explosive mass ratio of 0.04, 60% residual capacity remained due to contact explosion at the bottom of the RC column as compared to 90% residual capacity due to contact explosion at a height of 1.5 m from the bottom of the RC column. Parametric analysis for effect of column height was presented and it was concluded that column height does not affect the residual capacity of blast-damaged columns. An element size of 50-mm was used to model the column as well as the Arbitrary Lagrangian-Eulerian (ALE) domains.

Close-in explosion yields flexural response associated with cover spalling as in most cases the shear capacity exceeds the shear demand from the loading (Cui et al., 2015). Cui et al. (2015) implemented a damage criteria defined as the ratio of the depth of column and relative residual deflection to perform parametric analysis. It was reported that a larger cross-section with higher transverse reinforcement ratio and thinner cover improved the blast response of the columns by reducing the spall depth. Recently Yuan et al. (2017) presented a study on response of RC bridge columns to contact explosion. Experimental tests were conducted on square and circular cross-section columns subjected to contact explosion of 1 kg of TNT. The columns were tested without axial loads. LS-DYNA numerical models captured the experimental behavior appropriately except for the back-face damage. The comparative damage profiles of experimental and numerical results were reported for qualitative validation and comparative accelerometer readings were reported for quantitative validation (Yuan et al., 2017).

In design practice, it is often assumed that the column failure is caused due to transverse loading rather than the axial load. All the studies reviewed in the literature ignored axial load effects citing reasons like high cost prohibitions for inclusion in experimental tests and negligible effect as compared to transverse load. Krauthammer et al. (2013) however reported that axial load can have significant effect on the overall response of RC columns subjected to blast loading. The authors conducted a single degree of freedom (SDOF) analysis and reported that both the quasi-static and impulsive regime response of RC columns subjected to blast loading are affected by the axial load. The flexural strength of the column improved with higher axial load up to the balanced eccentricity. Beyond the balanced eccentricity of the column, the flexural strength started to reduce when subjected to blast loads as the failure mode shifted from ductile tension failure to brittle compression failure. On the other hand, even an axial load of less than 50% of the balanced axial load significantly reduced the ability to withstand impulsive loading. Contrarily to this, Wu et al. (2011a) reported improvement in shear strength to resist localized damage at higher axial load.

Researchers in the past have used multi-material ALE (MMALE) numerical formulation, which is an appropriate method for blast wave generation however its main disadvantage is its mesh dependency (Hanssen et al., 2004; Børvik et al., 2009; Kakogiannis et al., 2010). The accuracy of numerical results is highly sensitive to the mesh properties and can lead to large differences in the results. Zukas and Scheffler (2000) reported that numerical results of a same problem as analysed by different LS-DYNA users can vary by up to 80% due to different mesh properties (Trajkovski et al., 2014). In particular, the mesh dependency is directly related to the computational requirement for simulating a near-field or contact explosion. Hence, mesh sensitivity analysis is important for such studies in order to produce accurate results from a computationally cost effective model.

The literature review presented in the preceding section suggests scarcity of experimental data pertaining to contact explosion on RC columns. Experimental tests reviewed above were conducted on reduced scale columns without realistic boundary conditions. The NCHRP Report No. 645 (2009) presented experimental tests on full scale columns however the specific details of charge mass, cross-sectional details and reinforcement percentage were not made available in the public domain. Numerical studies have concluded that contact explosion induces local response but the effect of boundary conditions at the column's top and bottom for a given location of explosive are yet to be experimentally studied. No experimental data could be found on the effect of service axial loads on response of RC columns subjected to contact explosion placed at the bottom of the column which is a credible threat scenario. The numerical models in the literature reviewed above implemented the detonation process and fluid structure interaction (FSI) with element size of 5 – 50 mm. Thus the empirical expression for residual capacity of columns obtained using these numerical models might not be accurate due to the coarse mesh sizes.

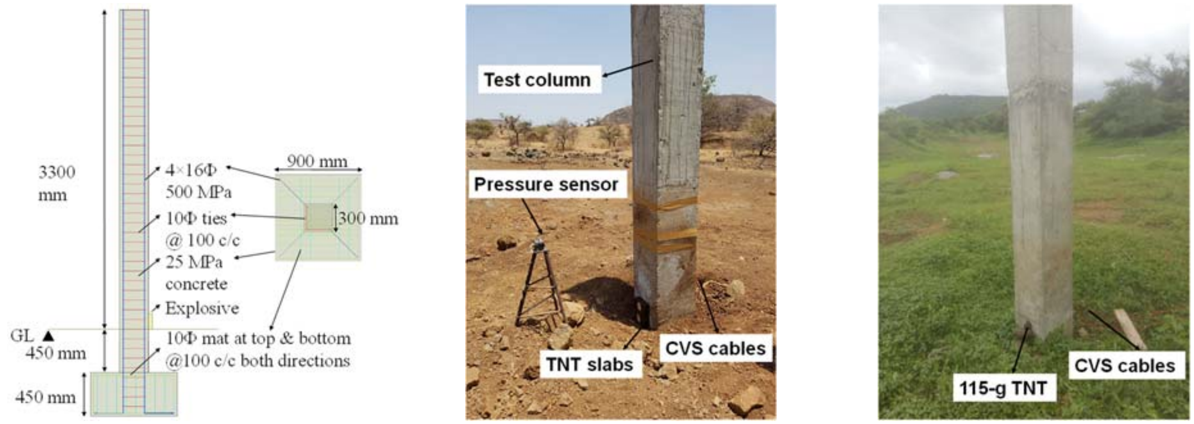
This paper presents a benchmark study for the response of full scale reinforced concrete columns subjected to contact explosions of varying charge mass. The quantitative and qualitative assessments of damage to concrete columns, including spalling and scabbing are presented. The experimental data was used to validate a set of numerical models in LS-DYNA. These models were used in further parametric studies to establish the effects of various design parameters on the response of concrete columns to contact explosions. Preliminary results of the parametric studies show that the response of the concrete columns subject to contact explosion can be reliably predicted using the validated numerical models.

3 EXPERIMENTAL TESTS

3.1 Experimental Setup

Three RC columns were studied for the experimental phase. The material properties, cross-sectional details and reinforcement percentage were same for the three columns (Figure 1(a)) and each column was subjected to contact explosion of different charge mass. Boundary conditions and gravity loads were not provided for the column top for simplification purpose. The effect of axial load and boundary condition at the top of the concrete column will be investigated as part of a future research program. The compressive strength of the concrete was attained through compressive testing of 150-mm cubes. The average compressive strength and density of three 75-mm diameter cores extracted from the test column were determined as 25 MPa and 2635 kg/m^3 respectively. Mat_CSCM concrete constitutive model in LS-DYNA was implemented with 25 MPa unconfined compressive strength. The concrete was poured in two lifts and no splicing was provided in the longitudinal reinforcements. The columns were cured by covering them with wet burlap blankets for 14 days and the testing was carried out after 28 days of casting. The backfill in the foundation pit was allowed to consolidate naturally during this period after initial manual compaction.

The pre-blast experimental setup for 1000-g and 115-g TNT charge are presented as Figure 1(b) and (c). The explosive was placed on the ground in contact with the column face emulating an explosive device placed in a possible terrorist threat scenario.



(a) (b) (c)

Figure 1: Experimental setup (a) Column detailing; Setup for (b) 1000-g TNT (c) 115-g TNT equivalent

Standard demolition explosives were used for the tests and the quality controlled chemical and material properties reported by the factory are presented in Table 1. In case of the 115-g explosive charge mass, plastic explosive (PEK) was used because smaller TNT slabs were not available.

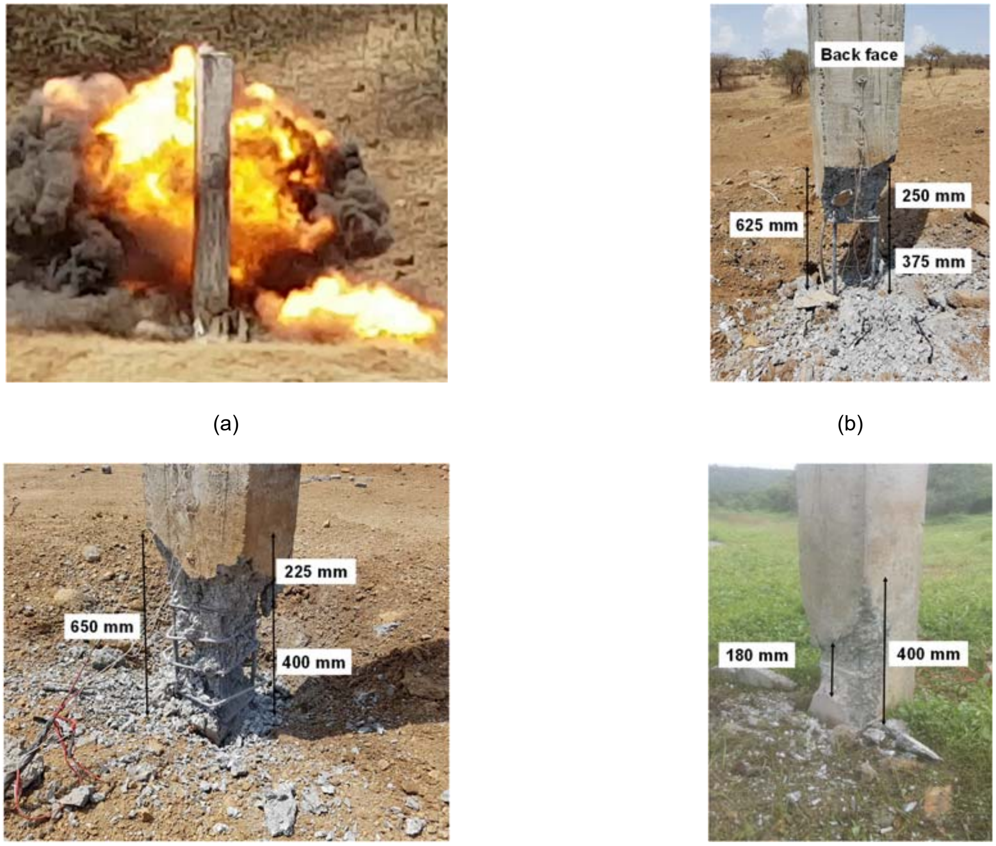
Table 1: Chemical Properties for TNT and PEK

Property	Detonation Velocity, m/s	Density, kg/m^3	Mass of one unit, kg	TNT equivalent	Means of Initiation
Plastic Explosive (PEK1)	8750	1549	0.1	1.15	Lead Azide electric detonator
TNT Slab	6930	1550	0.5	1	Lead Azide electric detonator

3.2 Results and Discussion

The damage profiles of RC columns (300mmx300mm) due to contact explosion of different charge mass are presented in Figure 2. For the column subjected to 1000-g of TNT explosive, the concrete core was completely damaged with zero residual axial strength as evident from Figure 2(b). The 500-g TNT explosive also resulted in complete damage to the cover and the concrete core with zero residual capacity (Figure 2(c)). On the other hand, the 115-g TNT equivalent charge caused full-width front face spalling in the concrete cover zone with a height of 180-mm at the center and 400 mm at the edges(Figure 2(d)).

From the experimental observations, the breaching charge for the presented RC column is between the range of 115 g - 500 g. Moreover, the experimentally determined range is consistent with the explosive factor reported by Fujikake and Aemlaor (2013). The columns failed due to local shear and the concrete core was completely crushed during the contact explosion of the 1000-g TNT and 500-g TNT explosive charge masses. The phenomenon leading to this failure mode is discussed later in this paper. The impulse generated due to a contact explosion is transferred to the RC column inducing a compressive shock wave that propagates outwards from the contact point (Puryear et al., 2012). The shock wave attenuates as it propagates through the concrete core towards the side and back faces compressing the material along its path. In case the compressive force generated by the shock wave exceeds the compressive strength of the concrete, it leads to crushing of the material. On arriving at the side and back faces the compressive wave is reflected or transmitted depending on impedance values of the concrete and air surrounding it. The reflected wave is a tensile wave that propagates back into the core of the concrete element. The scabbing on the side and back faces is caused when the tensile strength of concrete is less than the tensile stress caused due to the reflected tensile shock wave. The reinforcement ties confines the concrete core of the column providing enhanced compressive and tensile strengths. This damage mechanism resulted in spalling of the side face corners whereas due to the attenuation and confinement effects, there was no back face scabbing observed in the RC column subjected to 115-g TNT equivalent explosive. The amount of concrete spalling and scabbing has a direct bearing on the residual axial load carrying capacity of the RC columns.



(a) (b)

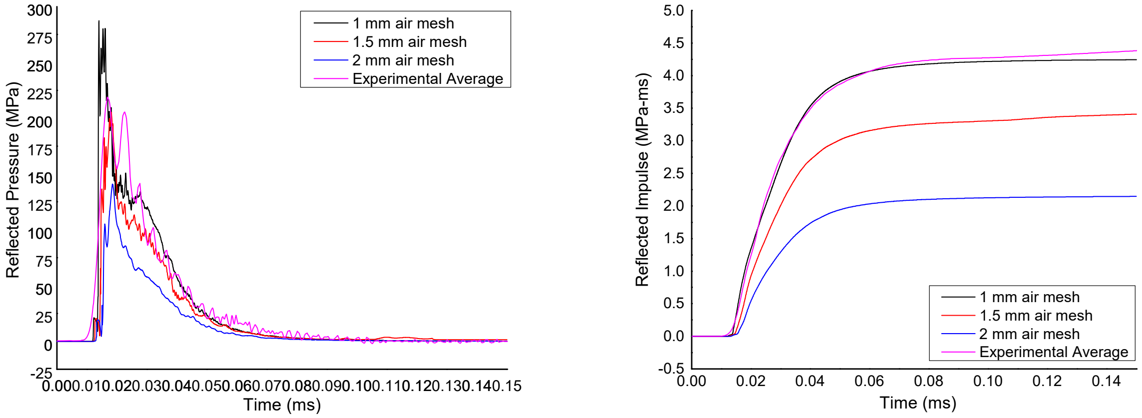
(c) (d)

Figure 2: Experimental results (a) Fireball after detonation; Post blast damage profiles for (b) 1000-g TNT (c) 500-g TNT and (d) 115-g TNT equivalent

4 NUMERICAL SIMULATIONS

4.1 Mesh Sensitivity Analysis

A mesh sensitivity analysis was performed prior to the numerical simulation of the experimental tests. The mesh sensitivity simulations were compared with experimental results presented by Rigby et al. (2015).



(a) (b)

Figure 3: Mesh sensitivity analysis (a) Reflected pressure time-histories for varying element size (b) Reflected impulse time-histories for varying element size

The normal and radial reflected blast parameters acquired via split Hopkinson's pressure bars (SHPB) were reported by Rigby et al. (2015) at a close-in scaled distance of 0.15 m/kg$^{1/3}$. A quarter symmetric model of the experimental setup was implemented with varying element sizes for the air domain. The reflected pressure and impulse histories at 0.15 m/kg$^{1/3}$ scaled distance were plotted with the average of six tests reported by Rigby et al. (2015) and are presented as Figure 3(a) and 3(b), respectively.

In near-field or contact explosions, the duration of blast loading is shorter than the time to maximum response of the member. In such cases the structural members are analyzed for impulse loading and not the blast pressure loading, (Dua & Braimah, 2016). As presented in Table 2, the peak impulse is highly sensitive to the air domain element size. 1-mm element size yielded least error for peak reflected impulse and the error increased to 51% with an element size of 2-mm. This is in agreement with the results reported by Trajkovski et al. (2014) and Cormie et al. (2014). It can be concluded from the forgoing results that 1-mm element size is appropriate to generate accurate peak impulse value which is critical for modelling near-field or contact explosion events. The modeling complexities and computational challenges associated with simulating response of concrete columns subject to contact explosion are discussed in the following section.

Table 2: Mesh Sensitivity Analysis for Reflected Pressure and Impulse

	Experimental average	1 mm air mesh	Error %	1.5 mm air mesh	Error %	2 mm air mesh	Error %
Reflected peak pressure (MPa)	220	287.4	30	204.2	7.2	140.4	36.2
Reflected peak impulse (MPa.ms)	4.45	4.25	4.5	3.41	23.4	2.15	51.7

4.2 Modelling Technique

There are three prevalent techniques used for blast analysis of structures: (a) Simplified analytical methods such as Pressure-Impulse (PI) charts, single degree of freedom (SDOF) or multi degree of freedom (MDOF) dynamic analysis using blast load parameters generated from empirical charts provided by UFC-3-340-02 (2008), Kingery and Bulmash (1984), TM5-855-1 (1987) or other such codes, (b) non-linear finite element analysis using blast load obtained from underlying empirical equations and charts by Kingery and Bulmash (1984), UFC-3-340-02 (2008), TM5-855-1 (1987) and (c) high fidelity finite element analysis programs which use explicit modelling of the detonation process, blast wave propagation and FSI. While the first two methods are appropriate to predict far-field blast response, MMALE formulation is better suited to model contact explosion as it provides a complete description of the blast wave parameters (Børvik et al., 2009). The technique involves modelling the chemical reaction during detonation and consequent blast wave propagation. However, the primary disadvantage of modelling detonation and propagation is mesh sensitivity (Kakogiannis et al., 2010) and hence a higher computational cost due to a fine mesh requirement. Kalra et al. (2014) presented a 2D to 3D MMALE mapping technique in LS-DYNA for reducing the computational cost. The explosive detonation and blast wave propagation was simulated in 2D domain and then mapped to a 3D domain to simulate the FSI between the generated blast wave and the Lagrangian entity. This technique however cannot be implemented for modelling contact explosions as the explosive detonation and FSI occurs simultaneously. Hence, a 3D domain with a fine mesh is required from the beginning (*t = 0*) of the contact explosion simulation. Lately, massive parallel processing (MPP) abilities have been introduced by LS-DYNA that allows parallel processing and availability of large memory resources. Albeit these resources are difficult to access and demands additional skills for setup.

In this paper chained mapping technique were implemented on a single system to accurately predict the impulse generated due to the contact explosion and couple the load with the Lagrangian entity. It involved initially modelling the detonation in a 3D fine mesh while FSI was implemented during the detonation process. The chained simulations were started with a smaller ALE domain of 1-mm element size to ensure accurate prediction of the pressure and impulse values as deduced from the mesh sensitivity analysis. The first simulation was terminated just before the blast wave arrived at the boundaries of the air domain to avoid reflection. Although LS-DYNA provides a keyword BOUNDARY_NON_REFLECTING, this keyword is applicable to Lagrangian entities and not to the ALE domains. Hence each simulation has to be terminated prior to the reflection. A 3D-3D ALE mapping was implemented in the next simulation wherein the underlying algorithm initializes the current ALE domain from the state at the end of the previous simulation. The Lagrangian column and the soil were initialized with the stress at the end of the previous run. These steps were performed with a full deck restart that enables addition or deletion of Lagrangian entities. The ALE domain was increased for subsequent simulations until the generated blast wave cleared away from the column. The material parameters for concrete, reinforcing bars, air and TNT entities were implemented from the data presented by Dua and Braimah (2017); Dua et al. (2017).

4.3 Numerical Results

The multistage simulations presented in this section represent the simulation for 500-g TNT explosive. The final response due to 115-g TNT equivalent explosion are presented subsequently.

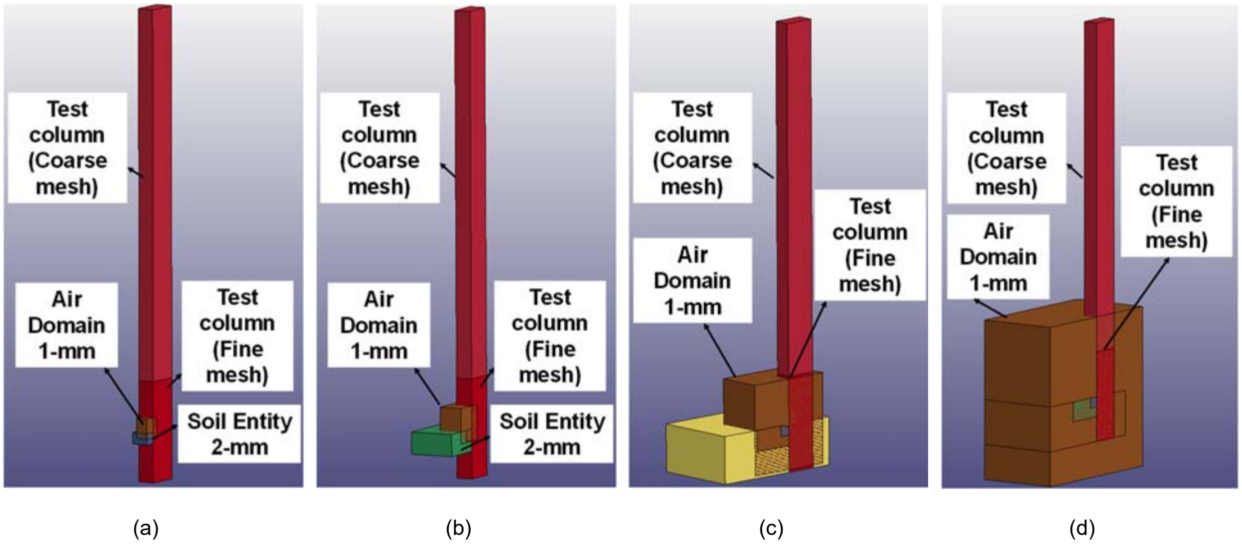
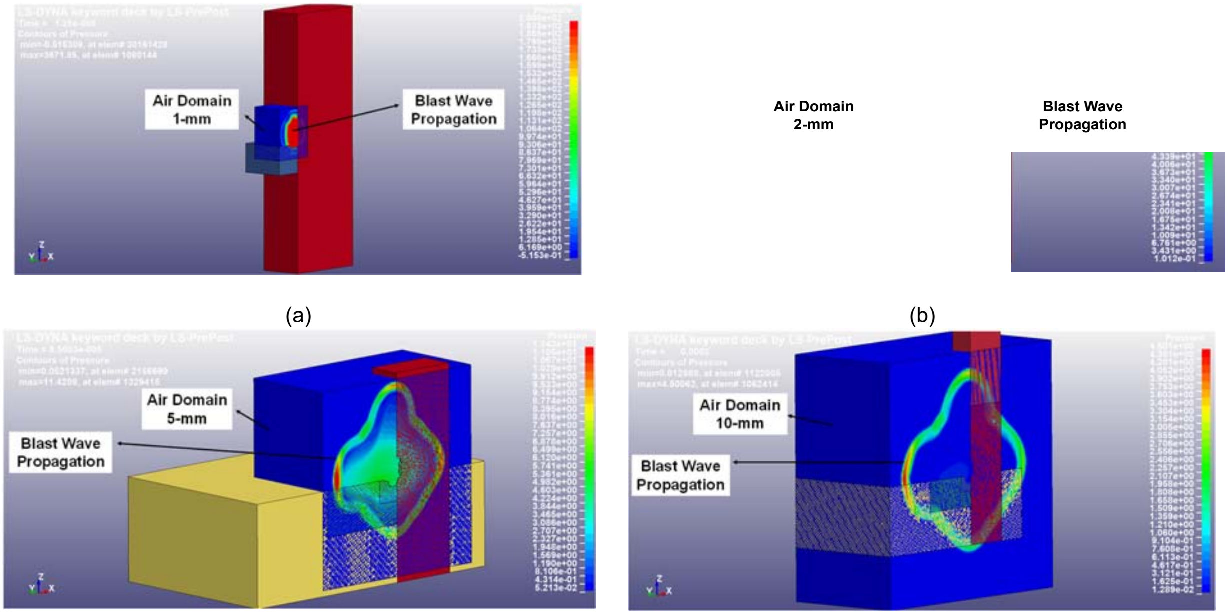


Figure 4: Geometrical models of the chained simulations (a) 1-mm (b) 2-mm (c) 5-mm (d) 10-mm

The first chained simulation was initialized with 1-mm element size air domain and 2-mm element size for the Lagrangian entities of concrete column and soil. The FSI between the detonation products and Lagrangian entities was implemented by the constrained Lagrange in solid (CLIS) keyword with coupling type (CTYPE) equals to 5. L.S.T.C (2015) recommends a smaller element size for the Lagrangian entities being coupled in a FSI problem as compared to the element size of the ALE domain. Alternatively a larger NQUAD (number of coupling points distributed per Lagrangian surface segment) value is recommended that implies longer computational time. Consequently the value for NQUAD parameter was adopted as 2 in the first simulation and subsequently reduced to 1 for subsequent simulations wherein the element size of air domain was larger than the Lagrangian entities (Figure 4).



(a) (b)

(c) (d)

Figure 5: Multistage pressure fringe plots (a) last cycle for 1-mm element size (b) last cycle for 2-mm element size (c) last cycle for 5-mm element size (d) last cycle for 10-mm element size

The first simulation was terminated at 0.0125 ms and the pressure fringe plots at the last cycle of each phase is presented in Figure 5. The range of pressure fringe plot is customized to highlight the extent of blast wave. The pressure during the last cycle of this simulation was mapped to a larger ALE domain with 2-mm element size during the second simulation. The stress time histories of the Lagrangian entities were initialized from the previous run and the simulation was run to 0.0275 ms.

The chained simulations were implemented four times during which the blast wave cleared the column and the blast pressure near the point of detonation reduced to zero. The concrete column takes longer to respond than the impulse uptake from the contact explosion and hence the last simulation was continued up to 30-ms without the ALE domain to capture the response of the column. The concrete part was checked to have near-zero velocity at the end of the simulation to ensure that peak response is captured.

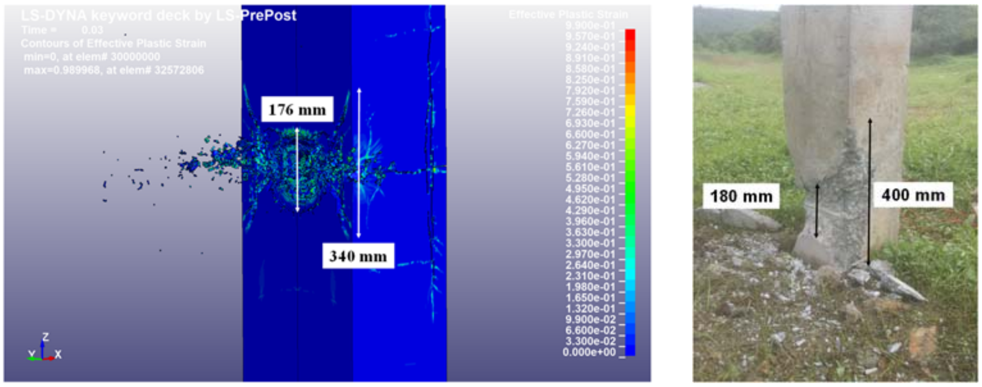


Figure 6: Comparison of Numerical and Experimental results-Front and side face damage profiles

The damage profile of the test column subjected to 115-g TNT equivalent explosive charge mass at the last cycle of the multistage simulation sequence is presented in Figure 6(a). Material erosion criteria was adopted for the Lagrangian entities to address numerical instabilities due to severe distortion of the elements during high strain-rate response in the non-linear regime. The MAT_159 concrete constitutive model allows erosion at accumulated damage of 0.99 which represents elements with no residual strength hence the erosion is linked to material failure. The damage profile presented in Figure 6 was determined from the erosion extent which represents the failed elements in the Lagrangian entities.

5 CONCLUSIONS

Three RC columns of same cross-section and reinforcements percentage were subjected to 1000-g, 500-g and 115-g of TNT equivalent explosion in contact at ground level. The boundary condition are the cottom of the column were provided with a pad footing. No restraint was provided at the top of the column for simplification of the experimental setup and the same is being considered for future experimental programs. The charge mass that could render the RC column with zero axial load carrying was determined to be in the range of 115-500 g which is in agreement with the range reported in the literature. An appropriate mesh size for the numerical model was selected using mesh sensitivity analysis performed at a scaled distance of 0.15 m/kg$^{1/3}$ and validated with experimental results. An element size of 1-mm for the ALE domain predicted the reflected impulse with least error. Furthermore, a multistage simulation technique was presented in the paper to reduce computation demand due to fine mesh requirement for the ALE domain to accurately predict the generated impulse. The column damage predicted with the multistage simulation were qualitatively compared to the experimental results. The damage profile of RC column subjected to 115-g TNT equivalent explosion in contact correlated well with the experimental observations establishing the qualitative efficacy of the numerical technique. The numerical parameters and multistage technique reported in the paper can be reliably implemented for further parametric studies. For further studies, the residual axial load carrying capacities of blast damaged columns will be numerically investigated and used in developing an empirical equation incorporating the concrete compressive strength, reinforcement percentage and the charge mass.

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