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Seismic Reinforcement Detailing Effects on Blast Resistance of Reinforced Concrete Columns

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Abstract: The study of blast resistance of reinforced concrete columns has dramatically increased since the attack on the Alfred P. Murrah Building in Oklahoma City. Most of the research has concentrated on the response of columns to far-field blast loading. In certain cases the research has neglected the effects of reinforcement detailing or axial loading on the columns.

This paper presents a numerical study to investigate the effects of axial loading on the response of reinforced concrete columns to blast loading from proximate explosions.

A high-fidelity physics based finite element analysis tool, LS-DYNA, was used to model the reinforced concrete columns. The columns are subjected to free-air blast loading to evaluate the effects of axial loads on the response of concrete columns detailed in accordance with seismic detailing provisions of CSA A23.3-04. The results show that increased axial loading on reinforced concrete columns reduces the lateral deflection and the support rotation. Thus, columns in lower stories of high-rise buildings, where axial loading from gravity loads could be significant, are capable of resisting higher blast loading in comparison with similar columns in the low-rise buildings.

1 Introduction

With terrorist attacks on the ascendancy worldwide, the vulnerability of conventionally designed buildings to blast loading has been brought to the fore. There is an increasing need for research into the behaviour of structural elements subjected to blast loads, especially critical load bearing elements such as columns. Most of the research works currently underway, and investigating the blast load effect on conventionally designed buildings, suggests that seismic design and detailing can enhance the performance of columns. In the design of buildings to resist earthquake loads, a seismic force resisting system (SFRS) has to be identified, designed, and detailed depending on the level of ductility expected for the building. Other columns which do not form part of this SFRS are also detailed to allow for adequate lateral drift and resistance to the P-Δ effects due to axial loading from gravity loads. The magnitude of the gravity loads carried by these columns are expressed by the axial load ratio (ALR), defined as ratio of the applied loading to the capacity of the column. This paper presents a numerical investigation designed to study the performance of seismically detailed reinforced concrete columns not forming part of the SFRS and in the lower stories of low-rise to high-rise buildings. The responses of reinforced concrete columns with ALRs varying from 0.2, for low-rise buildings, to up to 0.6, for mid-rise buildings, are presented in this paper.

A high-fidelity physics based finite element analysis tool, LS-DYNA, was used to model the reinforced concrete columns. The columns were subjected to free-air blast loading to evaluate the effects of the seismic reinforcement detailing and axial loads. The objectives of the study were to evaluate the behaviour of columns detailed for different levels of ductility. Also the failure modes of the columns and the effects of ALR on the lateral response of the columns were of interest.

2 Seismic Column Detailing Provisions

CSA A23.3-04[1], provide guidelines for the design and detailing of various seismic force resisting components depending on the level of ductility required of the components. The SFRS is typically designed to resist the entire lateral load from an earthquake imposed on a building. Damage to the structure from the earthquake is concentrated in the SFRS and within the plastic hinge regions. Other structural members that are not a part of the SFRS are designed to resist gravity loads as well as accommodate the lateral deformation of the SFRS. This is achieved by detailing rules that ensure the formation of plastic hinges and preclusion of shear or compression failure.

Reinforced concrete columns with a 300×300 mm cross-section and a height of 3000 mm were modelled and analysed. The columns were reinforced with 4-25M longitudinal steel reinforcements while the transverse steel reinforcement was detailed in accordance with clause 21 of CSA A23.3-04[1]. Figure 1 presents the reinforcement detailing of the reinforced concrete columns. The transverse reinforcement spacing was 75 mm in the 525-mm plastic hinges towards the supports and 150 mm between the plastic hinge regions. Plastic hinges are assumed to form at about 40% of the expected lateral displacement and thus the columns were detailed to incorporate large ductility demands with R_d of 4.0.

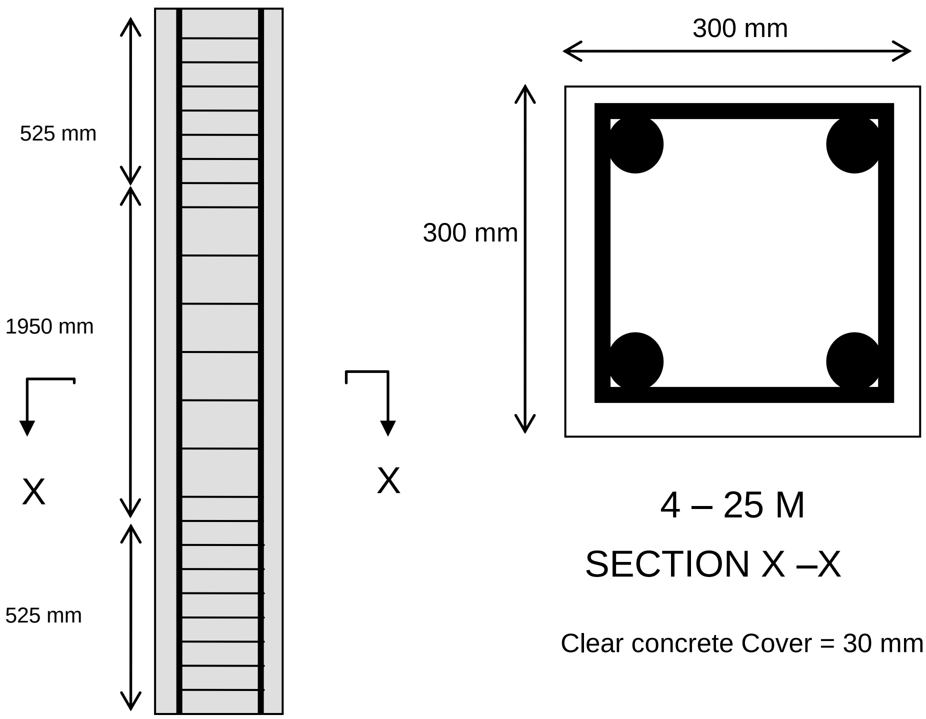


Figure 1: Reinforcement detailing of columns used in numerical simulations.

3 LS-DYNA analysis of Seismically Detailed Columns

3.1 Structural geometry

In the modelling of reinforced concrete, the constant stress solid element was used for the concrete while the steel reinforcement was modelled with the Hugh-Liu beam elements [3]. The constant stress solid element with hourglass stabilization enable to simulation of very severe deformations.

Prior to model development and analysis a mesh sensitivity analysis was conducted to minimise computer resource requirements while maintaining accuracy of the results. Various mesh sizes ranging from 5 mm to 30 mm were tested. The mesh sensitivity analysis showed that a mesh size of 15 mm was adequate and used for all final analysis. Beam elements were used to model the reinforcement. The interaction between the beam (reinforcement) and the solid (concrete) elements, assuming perfect bonding, was established by using the CONSTRAINED_LAGRANGE_IN_SOLID key card in LS-DYNA.

3.2 Constitutive Models

The Continuous Surface Cap Model (CSCM 159) was used to model the concrete. The CSCM 159 was primarily developed for simulating concrete behaviour in roadside applications[2]. It has isotropic properties with three stress invariant yield surfaces. The CSCM also predicts failure by incorporating an erosion paramter. The unconfined compressive strength of concrete as well as the average coarse aggregate size were used as default parameters in the model.The MAT_PIECEWISE_LINEAR_PLASTICITY model was used to model the steel reinforcement.

3.3 Axial Load Ratio

The effects of ALR on reinforced concrete columns have been investigated by many researchers. Wu et al. [4], in their study of the effects of explosives on the compressive capacities of contact blast damaged composite columns considered the effects of ALR. This was done by applying a linearly varying force up to service axial load before the simulated blast loads were applied to the column. The ALRs they considered ranged from 0.2 to 0.4. The authors determined that an increase in ALR significantly affected the residual shear and moment capacities.

According to CSA A.23.04 [1], axial load resistance of a concentrically loaded column can be computed by factoring in the contributions of concrete and steel reinforcement:

$$P_{ro} = P_{rco} + P_{rso}$$

Where:

$$P_{rco} = \alpha_1 \emptyset_c f_c'(A_g - A_{st})$$

$$P_{rso} = \emptyset_s A_{st} f_y$$

$$P_{ro} = \alpha_1 \emptyset_c f_c'(A_g - A_{st}) + \emptyset_s A_{st} f_y$$

Due to the possibility of accidental eccentricity CSA A.23.04 proposes a reduction factor of 0.8 to be applied to the computed P_{ro}, for tied columns, to obtain the maximum resistance, P_{rmax};

$$P_{rmax} = 0.8P_{ro}$$

$$P_{rmax} = 0.8(\alpha_1 \emptyset_c f_c'(A_g - A_{st}) + \emptyset_s A_{st} f_y)$$

The axial loads calculated from the chosen ALRs was applied to the columns to create pre-compression state and then the blast loading from a proximate explosion was applied.

3.4 Blast Loading

The LOAD_BLAST_ENHANCED (LBE) key in LS-DYNA was used to simulate the blast loading. The LBE key produces empirical pressure loads that are applied directly to the nodes of the lagrangian, concrete, column. The blast simulations produced by this key card is very similar to the results obtained from the semi-empirical blast load calculation program – Conventional Weapons Effects Program (CONWEP). The LBE is computationally less expensive when compared to the detailed Arbitrary Lagrangian Eulerian method and also requires fewer input parameters. The LBE key card has been reported to produce blast loading with acceptable accuracy for numerical simulations [5].

3.5 Numerical Simulations

In its reference manual on the mitigation to potential terrorist attacks against buildings, the Federal Emergency Management Agency (FEMA) [6] sought to predict various minimum standoff distances at which blast loading from various explosive charge masses caused damage to structural and non-structural components of the building façade.

Table 1 shows explosive charge masses by mode of transport and minimum standoff distances at which reinforced concrete components could experience failure.

Table 1: Charge masses and minimum corresponding stand-off distances for initiation of concrete failure for various modes of transportation of explosives (Adapted from FEMA-426 [6])

Mode of Transport	**Charge (kg)**	**Minimum Stand-off distance at which concrete failure is initiated (m)**
Luggage	24	4.6
Automobiles	90	7.3
Vans	500	12
Trucks	9100	21

For the purposes of this research a standoff distance of 3.6 m and a height of burst of 1.2 m was used to simulate an explosive charge detonated on a truck bed. The charge masses used were 18kg, 50kg, 100kg, 250kg, and 500kg.

4 Validation of LS-DYNA model

4.1 Description of Experiment

The LS-DYNA numerical models used for the concrete and steel reinforcement elements were validated against experimental test results reported by Carriere [7]. Carriere [7] tested 150×150 mm cross-section reinforced concrete columns. The columns were reinforced with 6-mm diameter longitudinal and transverse steel reinforcement. The columns were tested under live explosions for different C4 explosive charge masses at a standoff distance of 2 m

The concrete column from Carrier’s tests was modelled in LS-DYNA to validate the constitutive material models chosen, the support conditions, and blast load module. Figure 2 presents the damage sustained by the concrete column under blast loading from 20 kg C4 explosive compared with the results from the LS-DYNA simulation. The crack patterns, with cracking concentrated at the support and mid-span, show a very good agreement between experiment and simulation.

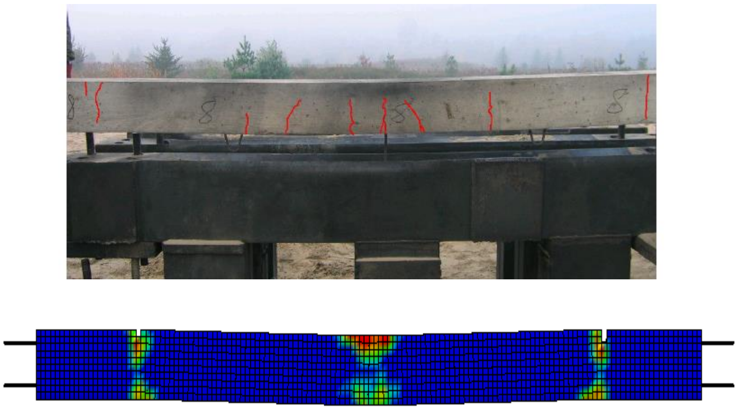


Figure 2: Validation of damage of reinforced concrete column

A mesh sensitivity analysis was carried out to optimize the accuracy of the results against computer resource requirements and run time. The reinforced concrete columns were modelled with mesh sizes ranging from 100 mm to 5 mm. Table 2 presents displacement and approximate run times to complete analysis for the 15 kg C4 charge mass. A 15 mm mesh size was observed to give adequate accuracy at reasonable run times and was chosen for all subsequent analysis.

Table 2: Mesh Sensitivity Analysis

Mesh Size	Maximum Displacement	Approximate Run Times
30 mm	9 mm	5 minutes
15 mm	12 mm	15 minutes
5 mm	12 mm	2 hours 30 minutes

Table 3 shows very good agreement between experimental and numerical midspan displacements for blast loading from 15 kg of C4 at 2 m standoff; however the numerical simulation underestimated the deflections at 20 kg of C4. At the close-in standoff distance of 2 m, the fireball from detonation totally engulfs the reinforced concrete column and creates a very turbulent environment. The effects of this turbulence is not modelled by LS-DYNA and could be contribute the to underestimation of displacements at the higher charge mass.

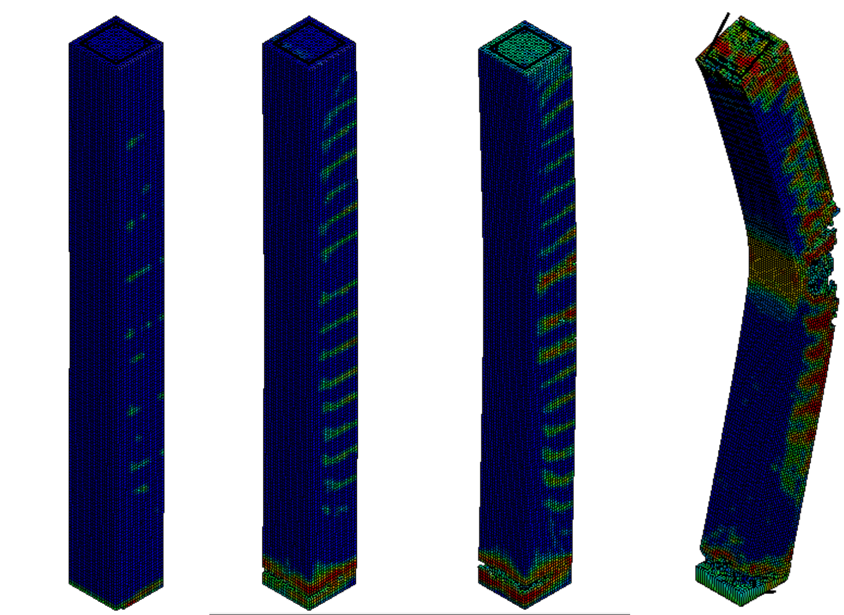
Table 3: Comparison of experimental displacements to numerical displacements

Charge Mass of C-4 (kg)	Experimental Displacement	Numerical Displacement (mm)
15	13 mm	12 mm
20	35 mm	24 mm

5. Results

Figure 3 presents the response of the reinforced concrete columns under blast loading from different explosive charge masses at a standoff distance of 3.6 m. Cracking and subsequent reinforcement yielding began at the fixed column support (bottom support) before commencing at the mid-height. At 500 kg, transverse reinforcement fracture is observed at the top support.

Figures 4 and 5 present the displacement time-history of the reinforced concrete column under blast loading from detonation of 50 kg and 100 kg explosive charge masses, respectively. The concrete columns were modelled with different ALRs. The displacement time-histories show that the effect of increased ALR is a reduction in lateral deflection of the column. This means that the ALR has the effect of increasing the stiffness of the column at lower charge masses. At higher charge masses, greater than 250 kg, the axial load applied quickly leads to secondary deflections due to the resulting eccentricity. At higher ALRs the columns lack the flexural capacity reserves to resist blast loading and suffer compression failure at relatively low blast loads. Additionally the effects of P-Δ is much pronounced.



18 kg 50 kg 100 kg 500 kg

Figure 3: Response of concrete columns to blast loading

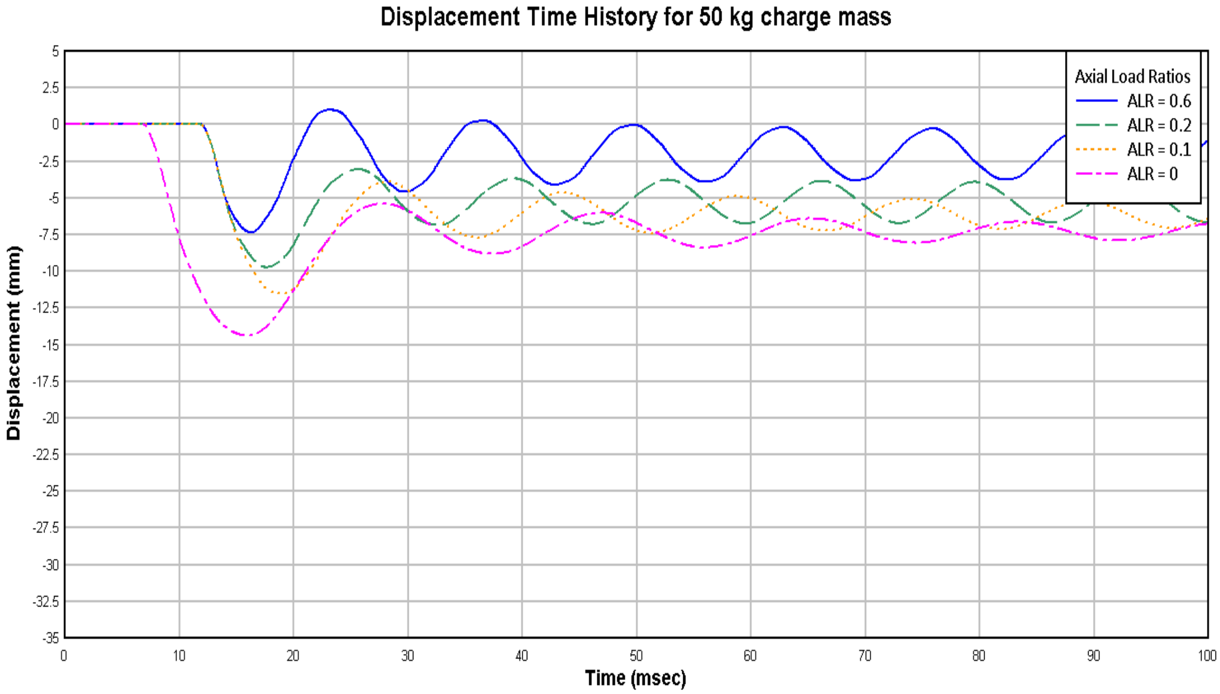


Figure 4: Displacement Time History for various axial load ratios using a charge mass of 50 kg at a 3.6 m stand-off distance.

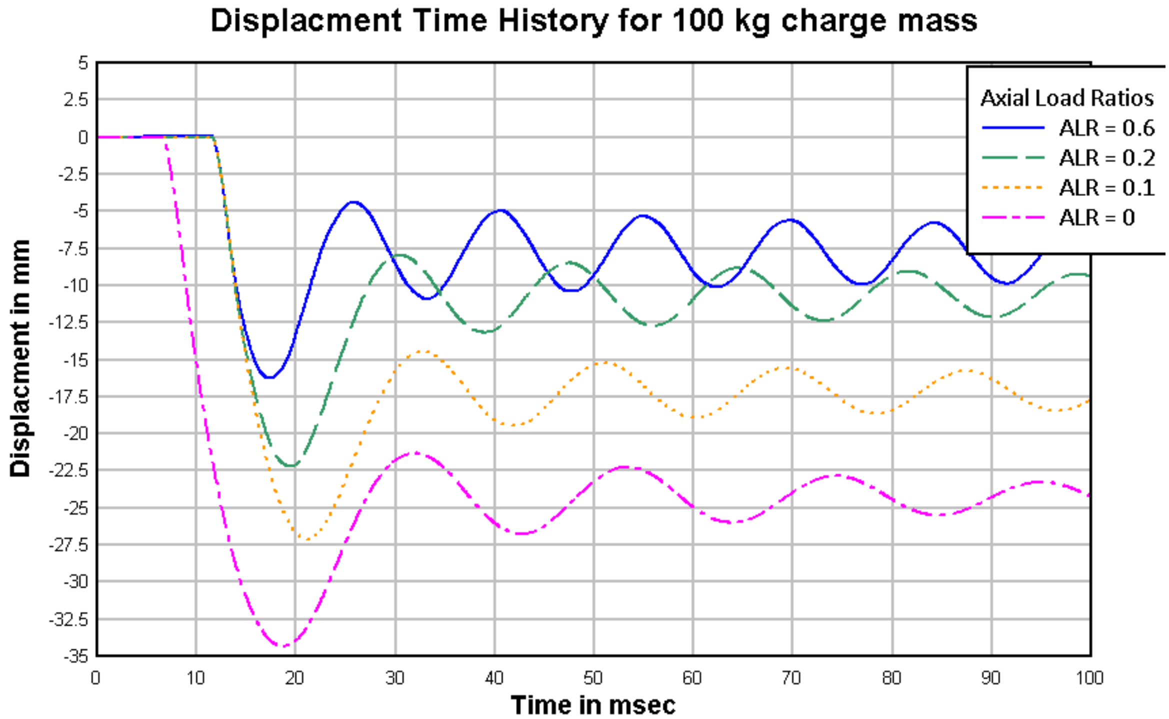


Figure 5: Displacement Time History for various axial load ratios using a charge mass of 100 kg at a 3.6 m stand-off distance.

With regards to displacements, it was evident that as the charge mass increased beyond 250 kg for the chosen standoff distance of 3.6 m, secondary deformations rapidly set in resulting in the total collapse of the column. This phenomenon was more evident for the high ALR of 0.6.

The reduced lateral deflection of the columns at higher ALRs indicate that reinforced concrete columns in the lower stories of high-rise buildings will have lower support rotations at the same blast load levels in comparison with columns in low-rise buildings. However, failure could be catastrophic at the higher ALR values as the effects of magnified moment due to the axial load from gravity loads is more pronounced.

5 CONCLUSION

The research reported in this paper is part of an on-going research program undertaken to study the effect of axial loads and transverse reinforcement detailing on the response of reinforced concrete columns under blast loading. The research reported in this paper has shown that the effect of ALR is an increase in the stiffness of the reinforced concrete columns and a reduction in the lateral deflection under blast loading. However, at higher axial load levels the columns could fail at much lower load levels due to lack of flexural capacity reserves and secondary effects instability.

6 REFERENCES

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