Engineering Structures 205 (2020) 109891

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

# Experimental and numerical investigation of rectangular reinforced concrete columns under contact explosion effects

Alok Dua[a,*], Abass Braimah[a], Manish Kumar[b]

[a] Carleton University, Canada
[b] Indian Institute of Technology Bombay (IITB), India

ARTICLE INFO

*Keywords:*
Contact explosion
Aspect-ratio
RC column
Fluid-Structure-Interaction (FSI)
Blast
Rectangular RC column

ABSTRACT

The response of reinforced concrete (RC) members subjected to contact explosion effects is more severe than the response to non-contact explosions due to local material failure. The shock-wave reflection within the RC member causes severe local material damage. The resulting loss of concrete cross-section reduces the axial load and bending capacity of the RC member. It is hypothesized that the concrete loss from the sides can be prevented by increasing the aspect ratio of the cross-section. In a low aspect ratio RC column, the reflection is from three faces whereas in RC slabs and high aspect ratio columns the shock-wave reflection from the back-face only is significant. This study experimentally investigates the response of rectangular RC columns with varying widths of the cross-section, subjected to contact explosion effects. A range of aspect ratios was investigated to preclude the side face damage for a given depth of rectangular RC column. High fidelity numerical models were developed to predict the blast-response and the residual axial capacity of the blast-damaged rectangular columns. The numerical models were validated, and the results show a good correlation with the experimental results. Using a rectangular RC column aspect ratio with a width that precludes the side face spall significantly improves the residual axial capacity of the blast-damaged columns. Furthermore, parametric analyses were performed to numerically investigate the influence of the width on the residual axial load carrying capacity of rectangular RC columns subjected to contact explosion effects of breach-charge mass required for the provided depth. An increase in the width of the column improved the damage resistance even though the rectangular column was breached around the point of detonation. Hence, increasing the width of the rectangular RC columns can be effectively used to mitigate contact explosion effects.

## 1. Introduction

Reinforced concrete (RC) columns are critical load-bearing members in a framed structure and abrupt failure of non-redundant columns due to material loss can initiate a cascading failure [1]. In the past few decades, many terrorist attacks and accidental explosions have resulted in the complete or partial collapse of buildings causing high fatalities and loss of property. For example, the world trade center attack in 1993 caused failure of floor slabs however adequate redundancy of the columns prevented building collapse [2]; the Oklahoma City Bombing in 1995 led to partial collapse of the Alfred P. Murrah building and caused 268 deaths [3]; attack on five residential apartments in Russia in 1999 led to the building collapse and 293 deaths [4]. These are just a few examples that show the severity of damage and casualty levels that the inadequacy in blast-resistance of RC columns can cause. Moreover, the damage to RC columns is higher due to contact explosion effects which is a credible terrorist threat. The experimental results presented in this paper suggest that concealed explosives in the range of 5–25 kg can possibly render an RC column of up to 1000 × 1000 mm cross-section with zero residual axial load-carrying capacity that can be detrimental to the structural integrity of the structure. Therefore, it is imperative to design strategically important structures envisaged as a potential target for terrorist attacks by incorporating mitigation strategies that limit the damage caused by contact explosions.

Structural resiliency against far-field explosion events is well established in the literature [5–20]. However, experimental work on contact explosion effects is scarce [7,14,21–24]. The response of RC components to contact explosion effects is highly non-linear and is an ongoing field of study. Besides, mitigation of contact explosion effects is yet to be studied. The failure of square RC columns when subjected to contact explosion effects is due to local material damage on all three sides other than the incident face [25]. This study examines the

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[*] Corresponding author.
*E-mail address:* alok.dua@carleton.ca (A. Dua).

https://doi.org/10.1016/j.engstruct.2019.109891
Received 10 February 2019; Received in revised form 23 October 2019; Accepted 4 November 2019

possibility of reducing the local material damage in an RC column subjected to contact explosion effects. The width of RC columns was varied to preclude the side face damage and restricting the material loss in the concrete core. A numerical study was also performed to investigate the effects of varying width (aspect ratio) of the columns on its residual axial capacity.

## 2. Literature review

### 2.1. Contact explosion

The blast response analysis and protective design methodologies are presented in manuals like [26–28] and FEMA [29] that are appropriate for far-field detonations. DoD [27] and ASCE [30] defines the near-field range as a scaled distance smaller than 1.18 $m/kg^{1/3}$. Several other researchers (e.g., Cormie et al. [31]; Shin et al. [32] and Braimah et al. [10]) have reported that the blast parameters presented by Kingery and Bulmash [33] and ConWep [34] are not accurate in the near-field range and specifically for a scaled distance smaller than 0.4 $m/kg^{1/3}$. The numerical and experimental response of RC members subject to near-field explosion effects have been reported recently (e.g., Cui et al. [9]; Crawford et al. [12]; Shin et al. [32]; Enstock and Smith [35]; Hanssen et al. [36]; Naito et al. [37]; Wang et al. [38]; Wang et al. [39]; Zhang et al. [40]). However, these are limited to RC slabs and façade members. There is limited information available on the behavior of RC columns subject to contact explosion effects and its mitigation strategies [7–9,19,24,41]. The studies on behavior of RC columns subjected to contact explosion effects are focused on numerical simulations. Experimental validations, if any, are qualitative i.e. by comparing the damage profile. Quantitative validation of numerical results has not been found in the literature.

DoT [42] reported experimental data on the response of RC bridge columns subjected to near-field and contact explosions. The document also presented the numerical response of RC bridge columns subjected to far-field explosion effects that correlated well with the experimental observations [20]. The side face spalling in RC columns subjected to a contact explosion was attributed to the Poisson's effect. The compressive force due to a contact explosion causes expansion of the column core perpendicular to the direction of loading and it occurs early during the loading prior to the global response of the column.

Wu et al. [24] and Wu et al. [41] proposed empirical relationships using experimental and numerical data to calculate residual axial compression capacity of localized blast-damaged RC columns and steel composite RC columns. A parameter, explosive mass ratio, defined as the ratio of explosive charge mass to the mass of 1-m high column was utilized in the study to express the contact explosion effect on RC columns. The contact explosion due to the explosive mass ratio of 0.04 resulted in a 60% residual compression capacity when an explosive was detonated at the bottom of the column. On the other hand, 90% residual compression capacity was obtained when the explosive was detonated at a height of 1.5 m from the ground. The overall column height did not have any effect on the residual capacity of blast-damaged columns. The location of the contact explosion had a significant effect on the residual axial capacity. An explosion on the bottom of the column resulted in lower residual axial capacity when compared to an explosion at 1.5 m height. For the numerical simulations, an element size of 50-mm was used to model the column as well as the Arbitrary Lagrangian-Eulerian (ALE) domains. The effects of the service axial load on the columns were not considered in this study. Actual boundary conditions as in the case of real-life structures were not created for the experimental tests.

Recently, Yuan et al. [7] presented a study on the experimental and numerical response of square and circular RC bridge piers subjected to contact explosion of 1 kg of equivalent Trinitrotoluene (TNT) explosive. Axial load on the column was not considered for the experimental tests. The experimental and numerical damage profiles were compared for qualitative validation and accelerometer readings were compared for quantitative validation. The Lagrangian entities in the LS-DYNA model were meshed with an element size of 8 mm to 20 mm and the multi-material ALE (MMALE) domain was meshed with an element size of 20 mm. LS-DYNA numerical models reasonably captured the experimental results, except for the damage to the column face opposite to detonation.

### 2.2. Numerical modeling

There are three prevalent techniques used for blast analysis of structures: (a) Simplified analytical methods such as Pressure-Impulse (PI) diagrams, single degree of freedom (SDOF) or multi-degree of freedom (MDOF) dynamic analysis using blast load parameters generated from empirical charts provided by DoD [27], Kingery and Bulmash [33], DoD [26] or other such codes, (b) Non-linear finite element analysis implementing blast load parameters generated from underlying empirical equations and charts by Kingery and Bulmash [33], DoD [27], DoD [26] and (c) high fidelity finite element analysis programs with explicit modeling of the detonation process, blast wave propagation and fluid–structure interaction (FSI). While the first two methods have been reported to accurately predict far-field blast response [10,31], contact explosion effects can only be accurately modeled with MMALE formulation as it provides a complete description of the blast wave parameters [43]. The technique involves modeling the chemical reaction during detonation and consequent blast wave propagation. However, the primary disadvantage of modeling detonation and blast wave propagation is its mesh size dependence [44] and hence a higher computational cost due to a fine mesh requirement. Kalra et al. [45] 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 the 2D domain and mapped to a 3D domain to implement the FSI between the generated blast wave and the Lagrangian entity. This technique, however, cannot be implemented for modeling contact explosions as the explosive detonation and FSI occur simultaneously. Simulating detonation and FSI in 2D will not represent the true phenomenon as the blast wave is spatially and temporally nonlinear around the explosive. Moreover, the spatially non-linear Lagrangian response in 3D will not be captured with the 2D model. Hence, a finely meshed 3D domain is required to accurately model the detonation process and the Lagrangian response during a contact explosion event.

## 3. Research significance

The response of RC columns subjected to non-contact explosion effects is well established in the literature. Recently, the research focus has shifted to contact explosion events and some experimental results on the response of RC columns have been presented in the literature. The results are mostly restricted to the qualitative analysis of the damage profile in terms of spall diameter or area. Only a handful of studies have been found in the literature that has reported a quantitative analysis of the blast response in terms of residual axial capacity. These quantitative results are restricted to square and circular columns. The response of columns with rectangular cross-section subjected to contact explosion effects remain uninvestigated.

The research presented in this paper forms a part of a larger research program designed to investigate the effects of contact explosion effects on RC columns and mitigation strategies. This paper presents the response of the rectangular RC columns subjected to contact explosion effects. Three rectangular RC columns with varying widths and the same depth (different aspect ratios) were subjected to contact explosion effects of the same explosive mass. The blast-damaged columns were tested for residual axial load-carrying capacity and compared to the residual capacities of blast-damaged square columns with the same depth. The response was also modeled numerically to predict the