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Performance of Earthquake-resistant RCC Frame Structures under Blast Explosions

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Abstract

Over the years, due to rapid development and urbanization, coupled with relatively high average household income, cities like Abu Dhabi have transformed to a larger and advanced metropolis. Most of the medium to high-rise structures in these cities in the middle-east are designed to be earthquake resistant. Due to increase in accidental and intentional explosions, high-rise buildings can be exposed to those types of blast pressures. It is a real matter of concern for the designers to know how these earthquake resistant structures would perform when exposed to accidental blast loads. This research is aimed at exploring the structural behavior and performance of earthquake resistant reinforced concrete (RCC) frame structures under blast loading. For this study, typical reinforced concrete frame structures designed to be earthquake resistant according to International Building Code (IBC 2009) and ACI 318-11 provisions applicable for Abu Dhabi city were studied. Vulnerability of these structures were investigated under different realistic blast scenarios obtained by varying scaled distances and explosion charge-weights to study the structural response. Relative performance of RCC structures designed with and without consideration of earthquake load in load combinations is also presented. A major focus of this research was to establish specific distances beyond which a given blast would have minimal impact on a typical earthquake resistant concrete structure which can assist designers in choosing a safe standoff distance for a given load. Investigations on variation in performance by changing material properties and structural configurations were also included in this study.

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Keywords: Earthquake-resistant; RCC frame; Blast loading; Standoff distance

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1. Introduction

The possibility of a reinforced concrete (RCC) structure getting exposed to blast loading due intentional or accidental explosion has notably increased in recent years. The prospect of structural failure due to progressive collapse as result of blast damage of critical elements has become a realistic possibility to consider for designers. In-depth analysis to explore the performance and vulnerability of typical reinforced structures has become necessary. The inclusion of earthquake loading in design codes has facilitate the design engineer to consider the effects of earthquake loading on structures during the design phase. Most of the high-rise structures in cities in the middle-east are designed to be earthquake resistant. The governing load combination for design of frame RCC structures in cities like Abu Dhabi is often found to be the combination with seismic loading. Due to increase in accidental and intentional explosions, medium to high-rise buildings can be exposed to those types of blast pressures. The provisions to consider for blast loading for structures are not yet well established as the blast event are often extreme events and it is challenging to quantify design parameters to be included in design for blast loading. The effect of blast load is significantly different from other typical dynamic loads due to its large magnitude and short duration. The speed with which a blast load is applied exceeds the loading rate of an earthquake by several orders of magnitude. Blast pressure may exceed hundreds and even thousands of kilo Newtons per square meter, but may last only a hundredth or even a thousandth of a second. There are many similarities between the effects of blasts on structures and the effects of earthquakes. Designs for both blast resistance and seismic resistance usually anticipate that the structure will undergo substantial non-linear response under design loading and that some structural elements will be damaged, perhaps to the point of failure. In this research, the performance of reinforced concrete structure that is designed to resist earthquakes according to the standards and codes of Abu Dhabi city would be monitored when exposed to blast loads. It remains to be seen whether or not; earthquake resistant structures have the ability to resist blast loads which can happen near the vicinity of the structure.

A significant amount of experimental and research work can be found on the response and behavior of reinforced concrete under blast loading at element level. Yusof et al. [1] conducted a series of experiments on a reinforced concrete wall to investigate its performance under various blast loading scenarios. Investigations on the behavior of concrete slabs under blast loading can be found in details in literature [2-3]. Procedure to estimate damage from certain blast load scenarios was established by Silva et al. [3] based on a series of experiments on RC slabs. Recent research has extended the study from reinforced concrete panels to fibre-reinforced panels [4-5]. Pandey et al. [6] studied the effects of an external explosion on the outer reinforced concrete shell of a typical nuclear containment structure using appropriate non-linear material models and the analysis was conducted till the ultimate stages. Due to computational limitations and nature of blast effect on structures, not much research can be found on the response analysis of a complete concrete structure exposed to blast loading. Although, some earlier studies concentrated on the blast effect on structures [7] and some recent [8] investigation on the effect of blast pressure on faces of a reinforced concrete building is available, the need for more in-depth study in these areas is important. To address some concerns, this present research focus on the study the performance and behavior of reinforced concrete structures designed as earthquake resistant structures under blast loading. Additional parametric studies were also conducted to investigate the effect of structure height, concrete strength and location of blast on the performance of a typical reinforced frame structure.

2. Design and FE modelling of RC Structure

A 14-story reinforced concrete frame structure with typical floor plan was selected for the first part of the study. For the structure under study, all structural members were designed in accordance of ACI 318-11 [9] building code. The seismic parameters and load criteria was chosen based on ASCE 7-10 code [10] for the site parameters of Abu Dhabi city as specified by the International Building Code (IBC) [11]. The reinforced concrete structure was designed to be earthquake resistant according to the National Earthquake Hazards Reduction Program (NEHRP) guidelines [12]. The parameters for the blast loading were chosen in accordance with the Unified Facilities Criteria-UFC 3-340-02 [13].

2.1. Seismic Design

For the seismic parameters, the building was classified as Occupancy Category II. According to the provision of ASCE 7-10, the structure was assigned to Seismic Design Category C. The seismic force-resisting system for the structure consists of intermediate moment resisting frames in the N-S direction. E-W loading is resisted by a dual frame-wall system. Torsional irregularity is verified by comparing the story drifts at each end of the building in accordance with standard table of ASCE 7-10. Story drifts were computed in accordance code provision and then checked against criteria given in the code. P-delta effects were considered in accordance with standard Section 12.8.7 of ASCE 7-10. For the location of the building, the short period and one-second period spectral response acceleration parameters S_S and S_1 are 0.58 and 0.18, respectively. For the very dense soil conditions, Site Class C is appropriate as described in Standard Section 20.3 of ASCE 7-10. All the structural members were designed in accordance to ACI 318-11 building code provisions.

2.2. Selected Structure

The selected reinforced-frame structure was 58 m in height. This regular shape building had a length of 63 m in the N-S direction, and had a width of 30 m in the E-W direction. The following are the dimensions of the structural components:

- Slab thickness = 100 mm
- Beams (moment frames) = 580 mm x 800 mm
- Columns = 750 mm x 750 mm
- Joists dimensions: 150 mm x 500 mm
- Shear wall: 300 mm - two symmetric near center of gravity.
- Concrete cover: 40 mm (clear)
- N-S bay: 9 meters / E-W bay: 6 meters

The structure would be tested under the impact of blasts having the following combination:
1.0 Dead Load + 0.25 Live Load + 1.0 Blast Load

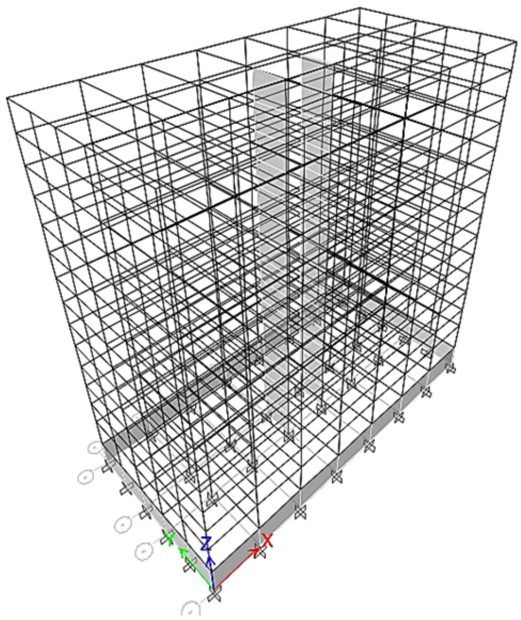

Fig. 1. 3D view of the modelled structure

2.3. Finite Element Model

The modelled three-dimensional structure was analyzed using commercial finite element package ETABS 2013 [14]. For realistic modelling and analysis of a concrete building, appropriate representation of stiffness properties of cracked sections is important. Often reduced moment of inertias for the beams, columns and walls based on the expected level of cracking are used. In this study, for the selected structure, the effective moment of inertia for beams were taken as 30% of the gross moment of inertia. For columns and walls, 50% off the gross was taken as the effective inertia. The effective stiffness of a moment frame element is based on the recommendations in Moehle el al. [15] and ASCE 41-13 [16] and to account for the expected axial loads and reinforcement levels in the members. The value for the shear walls is based on the recommendations in ASCE 41 for cracked concrete shear walls. All floor diaphragms are modeled as infinitely rigid in-plane and infinitely flexible out-of-plane, consistent with common practice for a regular-shaped concrete diaphragm. Beams, columns and structural wall boundary members are represented by two-dimensional frame elements. The beams are modeled as T-beams using the effective slab width per ACI 318. Beam-column joints are modeled in accordance with reference to the procedure in ASCE 41. Both the beams and columns are modeled with end offsets based on the geometry, but the beam offset is modeled as zero percent rigid, while the column offset is modeled as 100 percent rigid. For the structure, normal-weight concrete of 50 MPa strength was used for the entire structure. ASTM A615 420 MPa steel was used in the reinforcing bars. As required by ACI 318 Section 21.1.5.2, the longitudinal reinforcement in the moment frames and shear walls either must conform to ASTM A706 or be ASTM A615 reinforcement [17]. Time dependent properties such as compressive strength, modulus of elasticity, creep and shrinkage of concrete are based on CEB-FIP 1990 model [18]. Dynamic increase factors were used to amplify the measured static material strengths to account for high strain rates present in blast loading [13].

2.4. Application of Blast Load

Blast load was defined using time history function and was applied on dummy walls to reflect the effect of blast pressure. For different amount of TNT charge-weights, peak pressure values were calculated using UFC 3-340-2 [13] manual charts for the positive phase parameters for surface burst TNT explosions. The modified Friedlander equation [19] was used to obtain the time history function of the blast to be applied on the structure. The pressure generated due to the blast is applied on the structural members close to the blast. The explosive charge is detonated almost at ground surface, the blast waves immediately interact locally with the ground and they next propagate hemi-spherically outwards and impinge onto the structure. The intensity of the pressure waves generated due to the blast load are maximum in the center region. Areas away from the center experience lesser peak pressure values. Depending on the scale distance, blast pressure was distributed with different factors with the maximum factor of 1 for the area under the maximum pressure. The value of the peak pressure is entered as scale factor in the time history function.

3. Analysis Results and Discussion

The modelled reinforced concrete structure was analyzed for blast pressure loads derived for different realistic amount of TNT-blast charge weights that a typical city structure can be exposed. Structural response analyses were conducted for blast loads generated from different charge weights from 50kg to 500kg TNT-equivalent placed at the middle of both short and long direction of the building under study. The charge weights were placed at different distances from the mid-column location for both directions. Due to the selection of the location of the explosions, for every analysis the nearest column was at the shortest distance from the center of explosion and was exposed to the highest level of blast pressure. These columns located at the closest distances from the blast were designated as the critical elements. For each selected charge weight, the scale distance was increased until the critical structural element fails by crossing the design capacity of that element. Failure of structural elements due to concrete spalling are not considered in this study.

The variation in shear force and moment on the critical column due to different charge weights placed at the mid distance along the short span at different standoff distances are shown in Figure 2 and 3. A column is considered to fail when the shear force applied by the blast loading has exceeded the shear capacity of the column section. This simplified assumption was to identify standoff distances beyond which if blast is applied will not cause the column to fail. The instigation of progressive collapse due to the removal of a column was not studied in this research.

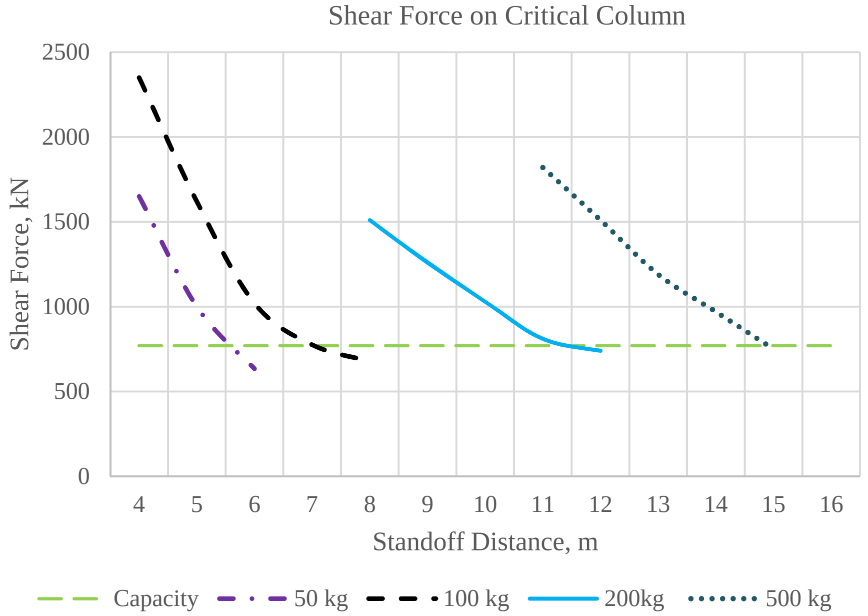

Fig. 2. Shear force on nearest column for various TNT blasts at different standoff distances

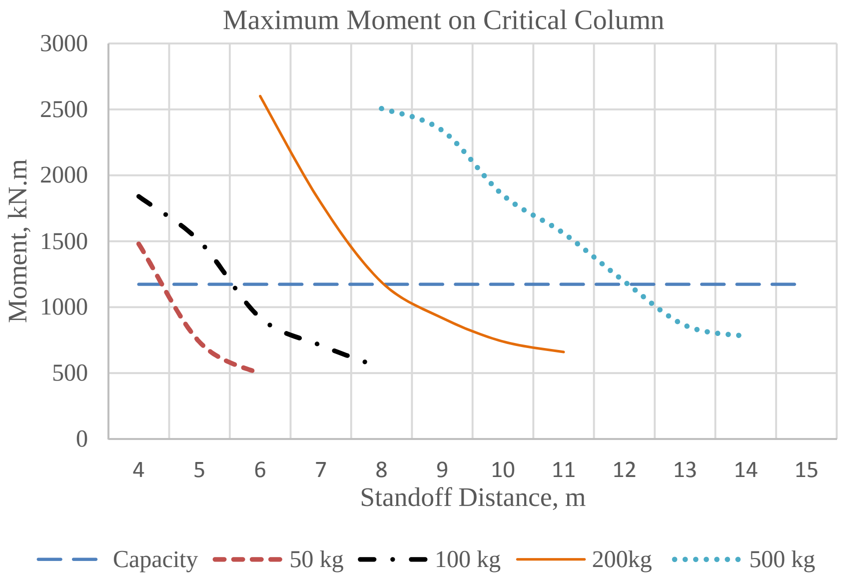

Fig. 2. Maximum moment in the nearest column for various TNT blasts at different standoff distances

3.1. Earthquake Resistant vs Non-Earthquake Resistant Structure

Similar analysis was performed on an identical structure that was designed without considering the code provisions for earthquake. The model of the non-earthquake resistant structure had same gridlines, material properties, floors heights, beam spans, panels as those of the earthquake-resistant structure previously analyzed. The load combination involving wind was the governing combination for beam, and gravity load combination governed the design for columns. As the non-earthquake resistant structure was designed without the seismic loading, the dimensions of the structural members were changed. Sizes of beams and columns were reduced to the extent required by the governed load combination. The minimum standoff distances required to avoid the failure were increased for the non-earthquake resistant structure. Fig. 4 shows a comparison between the minimum safe standoff distances that are needed for an Earthquake resistant and a Non-earthquake resistant structure for same TNT explosives.

Structural members of earthquake resistant structure had better reinforcement owing to the seismic load combination that governed the design. As a result, structural members of earthquake resistant structure performed better than those of the non-earthquake resistant structure and were required less standoff distance to resist the same blast load compared to non-resistant structure as indicated in Fig. 4.

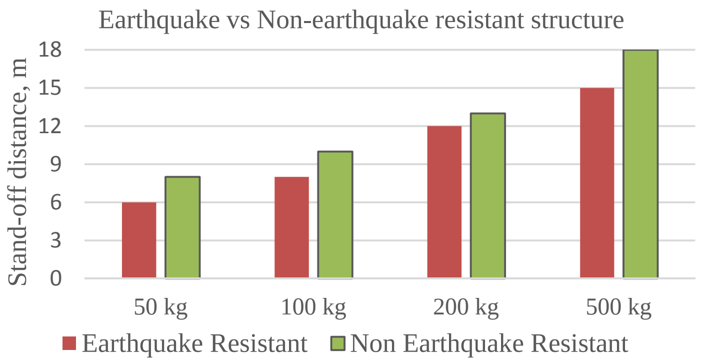

Fig. 4. Comparison of minimum standoff distances between Earthquake resistant and Non-earthquake resistant structures

3.2. Effect of Location of Blast- Short vs Long Span

Identical blast loading cases were applied on the earthquake resistant structure in both short and longer span of the structure. The minimum standoff distances required not to exceed the design capacity have found to increase when the blast is placed in the mid distance along long span instead of short span. The comparison between the minimum safe standoff distances for explosive location along short span and long span is shown in Fig. 5.

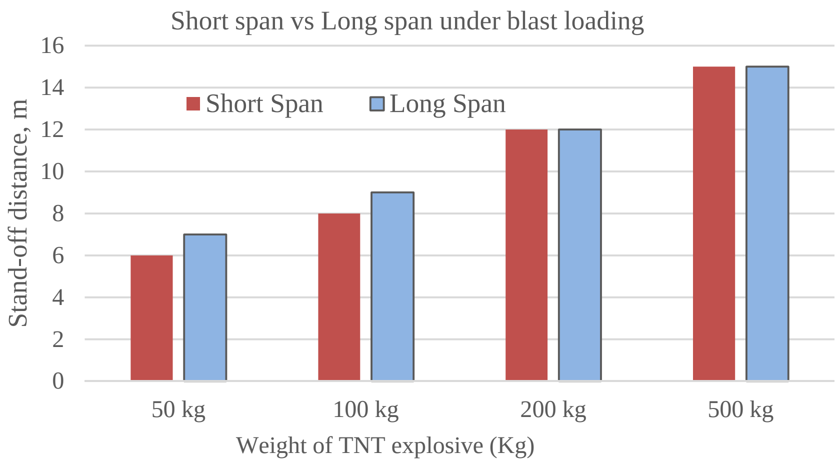

Fig. 5. Comparison of minimum stand-off distances when blast is acting on Short span vs Long span

The forces developed in the critical members of the shorter span were slightly lesser than those developed on the critical members of the longer span for the same standoff distances. This variation is due to the fact that critical column and beam of the shorter span carried slightly less gravity loads as compared to their counterparts in the longer span. Hence, under the blast load combination, they developed higher shear and moment.

3.3. Effect of Concrete Strength

The earthquake resistant structure that was initially being investigated had a concrete compressive strength of 50 MPa. For the same modelled structure, the concrete strength was increased up to 90 MPa and identical blast load cases were applied on these structures. When concrete strength was increased, the shear and moment capacities of those columns were also increased. For concrete strength of 70 MPa the safe standoff distance was almost similar to that when the concrete strength was 50 MPa. Safe standoff distance was reduced by 16% when concrete strength was increased to 90 MPa.

3.4. Effect of Height of the Structure

The reinforced concrete structure that was analyzed and designed to be earthquake resistant was 14 stories in height. Six more structures with different number of floors were analyzed under identical blast loading cases. The new structures were exactly similar to the 14 story structure in terms of gridlines, material property, loads acting and member sizes. With the addition of more stories, the net load acting on the columns and beams were increased. In the blast design combination, the dead load accounts for a factor of 1.0 and live load has a factor of 0.25. Hence, the net shear and moment forces of the column would increase. Table 1 shows the variation in shear force of the critical column if the blast weights are applied at the minimum safe standoff distance which were obtained for 14-story structure on the other structures which have more stories. Thus, it can be verified if the same minimum safe standoff distances that were needed for a 14-story structure would also remain same for structures having more stories.

The shear capacity of the column remains the same since member sizes were not altered. If the shear force developed due to the blast load exceeds the shear capacity of the column which is 770 kN, then the column would fail under shear. Fig. 6 displays the variation in shear force for different structures due to a 100 kg blast located at 8 m standoff as 8 m was previously determined as the safe minimum standoff for a 14-story building against a 100 kg blast. Fig. 6 shows that structures having stories 15 and 16 also required similar minimum safe stand-off distances. However, the critical column of the 17, 18, 19 and 20 story structure failed in shear for 8 m standoff. Therefore this minimum safe standoff distance has to be increased for these structures.

Table 1. Shear forces on critical column for different story heights

Weight of TNT blast (kg)	**Shear force on critical column, kN**						
	14-story	15-story	16-story	17-story	18-story	19-story	20-story
50 kg at 6 m	634	658	678	713	743	775	800
100 kg at 8 m	705	735	760	788	818	832	860
200 kg at 12 m	763	788	810	836	866	901	930
500 kg at 15 m	750	780	806	840	869	892	915

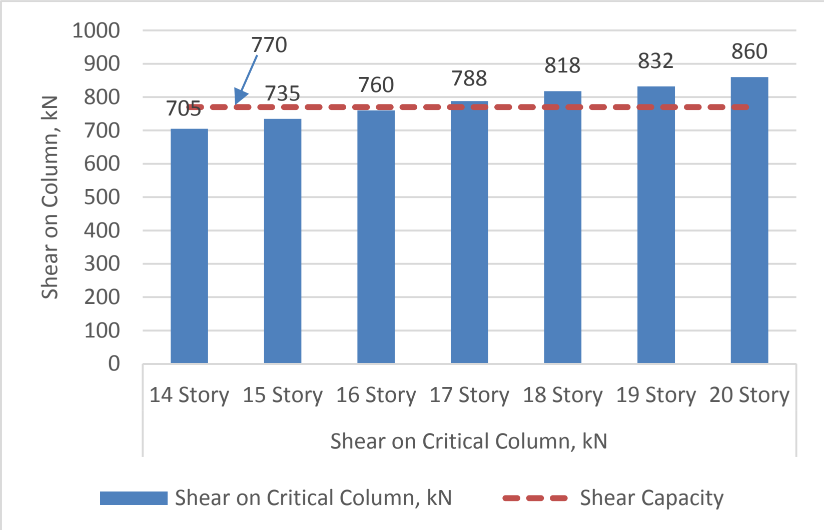

Fig. 6. Variation in shear force of selected column due to 100 kg TNT blast for structures with different stories.

A standoff distance increase of 1 to 2 meters from the distance required for the 14 story structure were found to be sufficient for a 20 story structure. However, the minimum safe standoff distances don’t increase drastically if the number of stories are increased. Thus, with increase in the number of stories, there is a slight increase in the minimum safe standoff distance. This can be attributed to the fact that having more stories results in additional gravity loads on the critical columns.

4. Conclusion

The results based on simplified analyses were presented in this research to identify structural response and a safe standoff distance required for an earthquake resistant building to avoid failure of a column exposed to a blast loading. For each of the separate blast weights that were considered in this research, a minimum safe standoff distance was found out beyond which none of the structural members would fail due to the impact of the blast. The results from the parametric study shows that standoff distances of 6 to 12 m are required to avoid a column loss due to a typical explosion on an earthquake-resistant structure. It was also found that structural members of an earthquake resistant structure had better blast resisting capabilities. Non-earthquake resistant structure needed a greater standoff distance to resist the same blast load as compared to the earthquake resistant structure. It was also showed that if the blast load is acting on the longer span, the structure is slightly more susceptible than the case if the blast load is acting on the shorter span. Using high strength concrete improves the shear and moment capacities of the columns and beams, but they have very little impact on the minimum safe standoff distances. Also, if the number of stories are increased, the minimum safe standoff distance also increases slightly because of the additional gravity loads that are acting on the critical column. This paper can provide a guide lines for possible require standoff distances for a give blast required to avoid any possible failure of a structural member.

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