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Technical Note

Probability Assessment and Risk Management of Progressive Collapse in Strategic Buildings Facing Blast Loads

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ABSTRACT: Nowadays, as a result of increased terrorist and bomb attacks throughout the globe in the vicinity of strategic buildings, designing these structures against impact loads, particularly the blast-related ones, has been taken into more consideration. The current procedure for designing the structure against an explosion is a design against the local failure of the current elements in the first step and then, in the next step, against local damage as well as tactful thinking to prevent this damage from spreading to other parts of the structure. The present research investigates the impacts of explosives, derived from probable terror–stricken scenarios inside and outside a strategic four-story steel building with a special moment frame system. Then, the resistive capacity of the damaged building (due to blast) has been evaluated against the progressive collapse, and finally, the rate of the collapse risk and the reliability of the structure have been obtained by presenting a probable method. Thus, the vulnerable parts inside and outside the building are identified and safety measures have been determined, so that in case of no safety or excessive collapse risk- access to dangerous parts of the building could be reinforced or limited. Results show that progressive collapse probability and reliability of the building are 57% and 43% respectively.

Keywords: Blast Load, Non-Linear Dynamic Analysis, Progressive Collapse, Risk Assessment, Strategic Building.

INTRODUCTION

Nowadays, lots of attention are given to evaluative techniques and risk management to decrease the vulnerability, derived from natural and artificial threats. One of the most important studies is the evaluation of the possible dangers derived from terrorist attacks in the guise of explosions in the infrastructures (Abdollahzadeh and Faghihmaleki, 2016a,b; Abdollahzadeh and Nemati, 2014). Stewart et al. (2006) have discussed the problems, related to risk evaluation such as the concept of danger

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transmission, also comparing it with natural disasters. Rong and Li (2007) undertook a probabilistic assessment of the influence of potential blast loadings and their resultant damage scale on building structures. Using Monte-Carlo simulation and Single-Degree-of-Freedom (SDOF) system, they examined the maximum displacement and displacement ductility factors of a reinforced concrete structure with flexural frames under blast loadings. Stewart and Netherton (2008) developed a procedure of Probabilistic Risk Assessment (PRA) to predict the risks of explosive blast damage to buildings' infrastructure. Cizelj et al. (2009) likewise, presented a vulnerability assessment of blast-loaded structures. Shi et al. (2010) also offered a method to assess progressive collapse in RC frame structures under blast loadings. Cullis et al. (2010) ventured into evaluating the effects of different explosions and blast loads on buildings. Asprone et al. (2010) presented a probabilistic model to evaluate hazardous risk along with the collapse limit state of a reinforced concrete building, exposed to explosive threat within a seismic area. Zahrai and Ezoddin (2014) investigated the progressive collapse in intermediate moment, resisting reinforced concrete frame due to column removal in numerical study. Also, Tavakoli and Kiakojouri (2015) studied the removal of threat-independent column and fire-induced progressive collapse in numerical method, comparing it also. Abdollahzadeh et al. (2015) presented a seismic fragility curve for Special Truss Moment Frames (STMF), using the capacity spectrum method.

Presenting a probabilistic approach, this study offers the relation to determine the collapse risk as well as building reliability. And as a case study in the present study, a four-story steel building with special moment frames was considered and probability of progressive collapse and the building reliability under probable blast scenarios inside and outside the building, have been investigated.

METHODOLOGY

Measuring of Explosion Power

The most common method to determine the explosion power is the Hapkinson–Cranz measure or the cube rule. This rule was introduced by Hapkinson in 1915 for the first time, later to be developed by Cranz in 1926 (Brode, 1959). It indicates that two similar explosive charges, blowing up with similar geometries but with different sizes, in the similar atmospheric conditions; create similar explosive waves when they have similar scaled distances (Bangash and Bangash, 2006). The scaled distance is a dimensional parameter determined by the Eq. (1):

$$z = \frac{R}{W^{1/3}} \qquad (1)$$

in which Z: is the scaled distance, R: is the standoff distance and W: is the explosives' weight of the equivalent TNT in kilogram. The Hapkinson-Cranz equation is only valid for explosions, resulted from TNT and the TNT unit is used as a reference to determine the explosion power. For other explosives, the equivalent TNT weight is obtained by Eq. (2) (UFC, 2008).

$$W = \left[\frac{\Delta H_{EXP}}{\Delta H_{TNT}}\right] W_{EXP} \qquad (2)$$

where ΔH_{EXP}: is the amount of heat resulted from the detonation of the given explosive, ΔH_{TNT}: is the heat from the explosion of equivalent TNT and W_{EXP}: is the weight of the given explosive.

Dynamic Characteristics of the Materials Exposed to the Blast

Blast loads typically produce very high strain rates, ranging from 10^2 to 10^4 s^{-1}. This high straining rate will alter the dynamic mechanical properties of target structures and, accordingly, the expected damaged mechanisms for various structural elements. To define the steel behavior under the blast load, real stress-strain curve of St37 steel should be used. Since it is possible that the steel column enters the plastic area under the blast loading, the steel behavior in the plastic area must be defined similar to Table 1. Plastic strain is the strain in the area of plastic minus elastic, strain related to the failure strain. The sensitivity of the strain rate is expressed by Eq. (3) (Dusenberry, 2010).

$$\acute{\sigma}_y = [1 + (\frac{\dot{\varepsilon^{pl}}}{\gamma})^m]\sigma_y \qquad (3)$$

where $\acute{\sigma}_y$: is the yield stress, considering the effect of the strain rate, $\dot{\varepsilon^{pl}}$: is the rate of the plastic stain, γ: is the viscosity parameter, m: is the strain hardening parameter and σ_y: is the static yielding stress. When $\dot{\varepsilon^{pl}}$ approaches zero in low rate loading, or when γ becomes infinite, the solution approaches the static solution (independent of the rate). The values suggested for the structural steel are $\gamma = 40\ s^{-1}$ and $m = 0.2$. To account for the increase in the materials' strength due to high strain-rate, the static strength of the steel is multiplied by dynamic amplification factors, given in Table 2.

Table 1. Characteristics of the steel in the plastic area

Plastic Strain (m/m)	True Stress (Mpa)
0	300
0.025	350
0.1	375
0.2	394
0.35	400

Table 2. Dynamic amplification factors to account for rapid strain rate (TMS-1300, 1990)

Component	σ_y	σ_u
Beam	1.29	1.1
Column	1.1	1.05

Probable Locations of the Blast Scenario

In order to investigate the effect of the blast inside or outside a building, at first, it is necessary to identify the probable points for terrorist explosive attacks. Since carrying heavy explosives into the building is not possible or highly risky, and terrorism attacks inside the building make a low effect, parked or moving cars near the building which are filled with explosives is almost the only method, used for terroristic aims. Weight of explosive mass depends on the carrying capacity of the car. The weight of explosives mass used in terrorist scenario is inspired by FEMA426 (FEMA-426, 2003), based on which the equivalent TNT weight in accordance to its carrying method in a terrorism blast event is as following:

a) Big trucks are equal to 4540 Kg TNT.
b) Small cars and vans are equal to 227 and 1816 Kg TNT respectively.
c) The suicidal attack by one who carries the explosive belt is equal to 4.5 to 18 Kg TNT.
d) Bombs, carried by individuals, equal to 2 to 4.5 Kg TNT.

On this basis, the explosion will happen with a probability of 30% inside the building with the same probability in each of the four floors (25% probability for each) by an individual carrying explosive belt or handbag, equal to 3.5, 5 and 7 Kg TNT, and also will happen with a probability of 70% outside the building by automobiles carrying bombs equal to 200, 400, and 600 Kg TNT.

Simulation of the Blast Load and Its Effect on Axial Load of the Column

Simulation of the blast effect is done by ABAQUS (2010). Considering that the columns experience significant damage under blast loads as well as their importance in load-carrying capability, stability, and progressive collapse of the building, it is assumed that the blast load is a decreasing triangular impact versus time, uniformly applied only to the columns of each floor, as shown in Figure 1. Here, impact means the area under the time-pressure curve in an explosive load. The columns are modeled by the S4R shell element which is a four-node shell element with reduced integration to prevent shear locking. In S4R element, the non-linear effects, resulting from the extra shear under the blast load, have been given more careful attention in comparison to other elements; this element shows high convergence rate in nonlinear analyses. The amount of the axial load in columns, exposed to the explosion, depends on the geometry, support conditions, and slenderness. Although according to the researches, the axial load can be ignored when analyzing the column, under explosion, with a slenderness coefficient lower than 38 (Godinho et al., 2007), but for the purpose of greater validity it has been considered in this paper.

Failure Criterion of the Column Exposed to the Blast

In order to determine the failure state of the columns due to the blast, the Von Mises yield criterion has been applied. The yield criterion determines the boundary between the elastic and plastic behavior, showing the stress level in which the plastic deformation initiates. According to this criterion, yielding of a column section occurs when the Von Mises stress reaches the yield stress. Here, failure does not necessarily mean fracture. The deformation, resulting from the material yielding, causes the member to lose the load tolerability and become unusable. For instance, for the column, the Von Mises stress has exceeded the yield stress (330 Mpa, by taking into account the effect of the strain rate) under the blast load and design axial force at the moment of 0.0025 second and the column has lost its load- carrying ability, becoming unusable.

Analyzing the Building after the Blast against Progressive Collapse

The progressive collapse is the spread of the local failure from one member to another which results in the collapse of the whole structure or its major parts. To reduce the possibility of progressive collapse in buildings, two general patterns have been proposed (UFC, 2009):

a) The direct design which includes two approaches, namely special local strength and alternative path;

b) The indirect design which includes suggestions for decreasing the progressive collapse of structures such as the suitable plan-design and the allied mortising in the structure (Tie forces) (UFC, 2009).

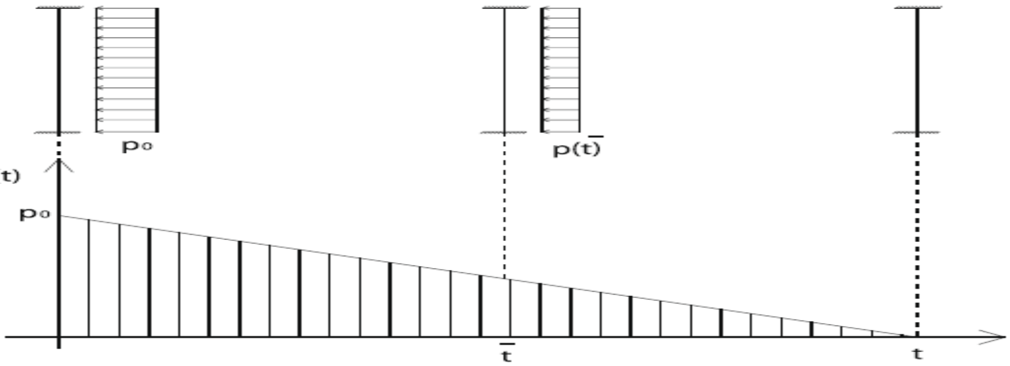

Fig. 1. The time-pressure curve of the blast load on the columns (Asprone et al., 2010)

To assess the progressive collapse for the columns, after analyzing the model of probable explosive-terroristic scenarios inside and outside the building, a dynamic nonlinear analysis is followed, based on the UFC (2009). To evaluate the members that experience inelastic deformation, one should determine the characteristics of plastic hinges in accordance to the FEMA356 (2000). In this way, the M3 moment hinge is assigned to both end-points and mid-span of the beams, with the P-M2-M3 interaction hinge assigned to both end-points of the columns. The progressive collapse analysis is carried out under the combination of 1.2DL+0.5LL gravity loads and the lateral load of 0.002ΣP are applied to the structure simultaneously, as shown in Figures 2 and 3. The lateral load is applied in four directions. DL is the dead load; LL, the live one; and ΣP is the sum of both. Exceeding CP performance point in plastic hinges of the beams and LS performance point in those of the columns indicate the incidence of a progressive collapse in the building. Figure 4 shows a case of progressive collapse event.

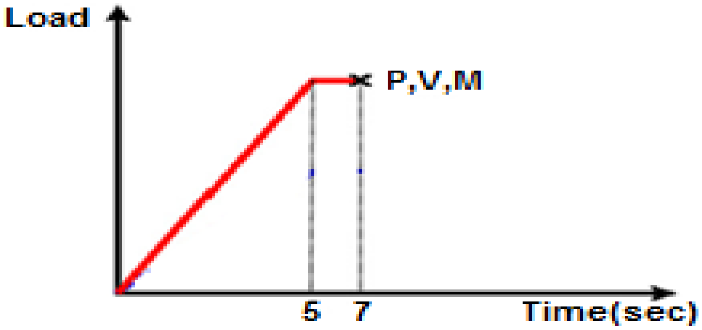

Fig. 2. Applied loads in nonlinear dynamic analysis

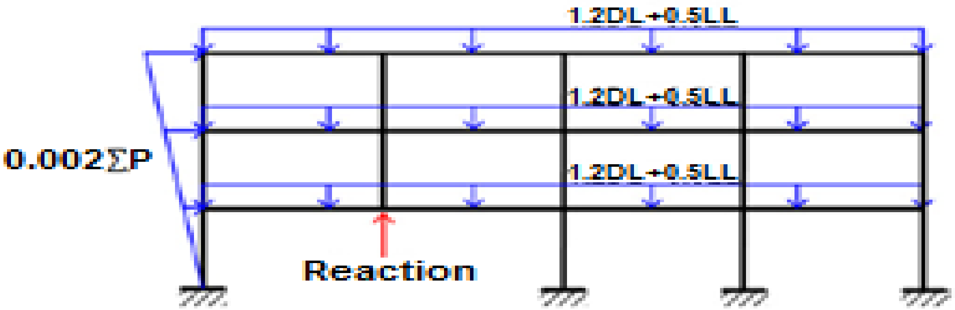

Fig. 3. Simulation of the dynamic effects due to sudden omission of the column

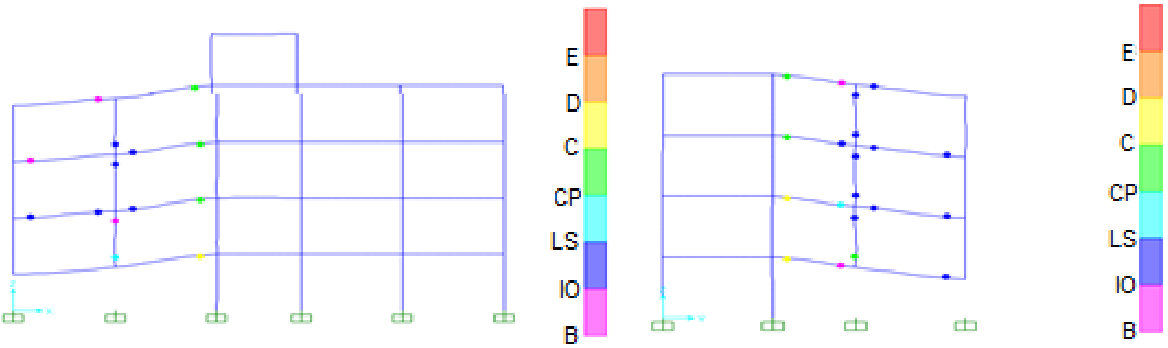

Fig. 4. The occurrence of failure in progressive collapse analysis

Risk Assessment and Reliability

Risk assessment is a logical method to determine, both qualitatively and quantitatively, the amount of the dangers and potential outcomes derived from the possible events on individuals, materials, equipment, and environment. Complex uncertainties of critical events, probable in the lifetime of strategic structures, make the probabilistic assessment of the structural performance inevitable. Collapse probability of the structure under critical events during its lifespan can be written in conditional probability form as Eq. (4) (Ellingwood, 2006):

$$P(C) = \Sigma P(C/A)P(A) \tag{4}$$

where *A*: stands for a critical event such as explosion, earthquake, storm, etc.; *P(C)*: is the collapse probability, *P(C/A)*: is the collapse probability, conditioned on the critical event A and *P(A)*: is the occurrence probability of the critical event A.

Eq. (4) is based on the total possibility theorem, assuming that critical events are mutually exclusive and exhaustive. One of the critical events a strategic structure may face in its lifespan is explosive–terrorist attacks where the blast fragility is considered as collapse probability with the assumption that the amount of the explosive mass and the location of the blast center inside or nearby the structure are given. Considering the blast as a critical event, the collapse probability can be written as Eq. (5).

$$P(C) = \Sigma P(C/Blast)P(Blast) \tag{5}$$

where *P(C/Blast)*: is the collapse probability, conditioned on the blast and *P(Blast)*: is the occurrence probability of the blast.

The concept of the reliability has been interpreted in several different ways and with different methods. The most common definition of reliability introduces it as the probability of a sample performing a given task in a given period and under specified operating conditions. Due to uncertainties, the reliability should be considered in a probabilistic framework. In analysis and design of the building, reliability has been defined as the probability of the structure's not exceeding any of the determined limits during its lifespan. The reliability (R_0) is defined in terms of the collapse probability, *P(C)*, as Eq. (6) (Nowak and Collins, 2000):

$$R_0 = 1 - P(C) \tag{6}$$

NUMERICAL EXAMPLE

A possible application of the methodology described in the previous section can refer to the calculation of collapse probability and building reliability of a generic four-story steel framed building. A numerical example has been presented below with the characteristic of the case study structure, outlined in the following.

Structural Model Description

The studied model is a four-story steel structure with special moment-resisting frame system in both X and Y direction. Being of enormous importance, it is located in a very high seismic zone. Columns to foundation connections are rigid. Floor slabs are one- way joist block and net height of each story is 2.8 m. The limit state or LRFD method has been used to design the structure against blast. AISC360-05/ LRFD (2005) Code has been utilized to analyze and design in SAP 2000. Figure 5 shows the typical plan of the stories. Box sections indicate the columns. The section is suitable for buildings with moment-resisting frames in both directions. IPE sections are also chosen for the beams. The design process is performed in several phases so that on one hand, selected sections are near the optimal sections, regarding the stresses and the lateral displacements of the structure, and on the other hand, the particles' design is simple, uniform, and applicable. Also, it is assumed that the connections are designed for final capacity of connected member and discussions about the connections were omitted. The results are summarized in Table 3 and the material parameters are outlined in Table 4.

Probable Locations of the Blast Scenario

As mentioned in the previous section, the location of explosive charges is determined so that all critical points are covered and are close to reality. Furthermore, carrying heavy explosive to the building is not possible or quite risky and a terrorist attack inside the building will have low effect, thus parked or moving cars, filled with explosives, located in the vicinity of the building have been used for the terrorist attack. Weight of explosive mass is dependent on the carrying capacity of the car. In order to reduce the destructive effects of the blast, as shown in Figure 6, a surrounding system is considered at the distance of 10 meters from the perimeter of the building in order not to allow bomb-carrying vehicles to get very close to the building. Regarding the building plan, probable locations of outside explosive charges have been taken into consideration as shown in Figure 6. They are the parking lots of the bomb-carrying cars, out and close to the fence. 32 points are considered which are in front of the building's columns and four sides of the fence in order to identify the most critical case for terrorist attack by the bomb-carrying car. For the inside-building blast, in accordance to Figure 6, in each floor 44 points have been considered, each being 1.5 m distant from related column axis in x and y directions.

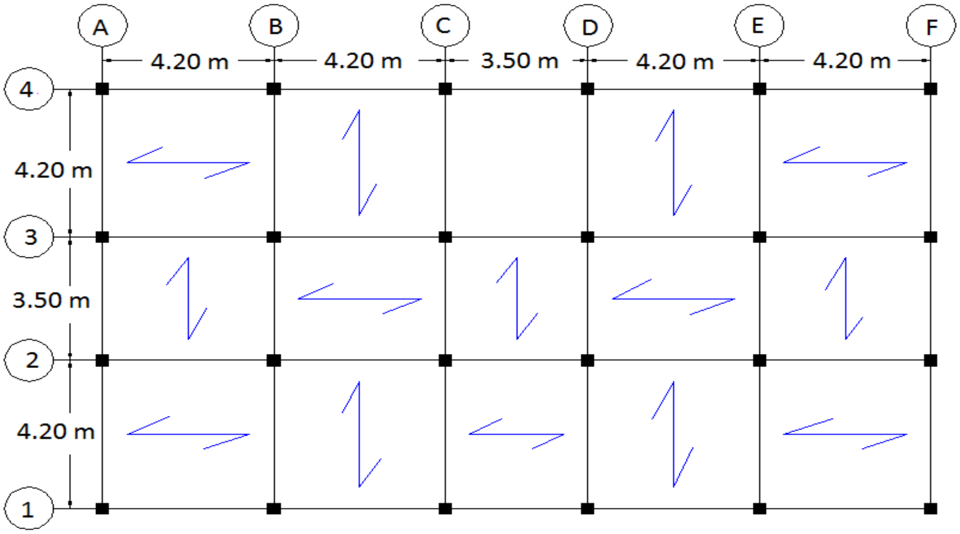

Fig. 5. Typical plan of the stories

Table 3. Designed sections of the members

Column	Beam	Floor Number
BOX22x22x1.25	IPE270	1st floor
BOX20x20x1.25	IPE270	2nd floor
BOX18x18x1	IPE240	3rd floor
BOX16x16x1	IPE180	4th floor
BOX14x14x0.8	IPE160	roof

Table 4. Material properties

Elastic Properties	Plastic Properties		Rate Dependent		Dynamic Amplification Factors			General Property
	Plastic Strain (m/m)	**True Stress (Mpa)**	**Hardening**	**Power Law**	**Component**	**σ_y**	**σ_u**	
$E = 210 \times 10^9$(Pa)	0	300	multiplier	40	Beam	1.29	1.1	$\rho = 7800\ {kg}/{m^3}$
$\upsilon = 0.3$	0.025	350	Exponent	5	Column	1.1	1.05	
	0.1	375						
	0.2	394						
	0.35	400						

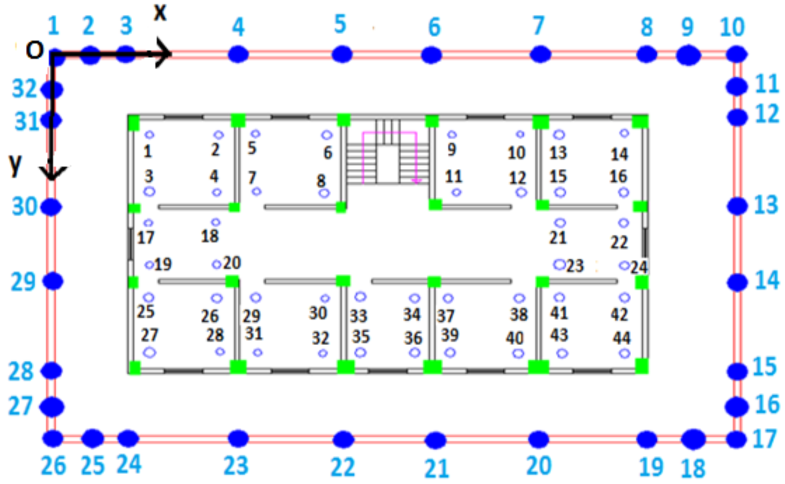

Fig. 6. Probable points of outside and inside blast scenario

It was mentioned that the explosion will happen with a probability of 30% inside the building with equal probability in each of the four floors (25% for each) by an individual, carrying an explosive belt or a handbag equal to 3.5, 5 and 7 Kg of TNT and also will happen with a probability of 70% outside the building by automobiles, carrying bombs equal to 200, 400, and 600 Kg of TNT.

Simulation of the Considered Scenarios

In the first step, for each of the columns, hit by the explosion at the distance R from the center of the charge, given the amount of explosive w, the reduced distance $Z = R/\sqrt[3]{w}$ is calculated. Then a triangular impulse loading is considered to act on the columns (Figure 1), whose parameters P_0 (maximum initial pressure) and t (duration of the impulse) were illustrated in pervious section. It is further assumed that the intensity of the impact loading is uniform across the column height. Furthermore, since such a load generally acts in a direction not parallel to local axes of the column, it is divided into two components, both acting on the column simultaneously, with each one used to verify whether the column fails or not. Simulation of the blast effect is done by ABAQUS. The columns are modeled by the S4R shell element; both ends of the columns were fixed in all degrees. The column was meshed sweep with hex-dominated elements. Moreover, the blast load was applied only on one face of the column that was affected by blast straightaway. Furthermore, this load was divided into two components in x and y directions, depending on the angle between gas explosion position and the column, and was calculated for each column.

With regards to the limitations in experimental studies within the field of explosions, in order to validate the modeling in ABAQUS, initially a plate under blast loading, in accordance to the work by Maleki and Rahmaniyan (2011), was modeled and the results were compared. The results were similar and hence the modeling was fine. Therefore, all samples were modeled in the same way. In the next step, a simulation technique was employed to generate all scenario realizations, assuming that the structure is subjected to 1.2DL + 0.5LL gravity loads as well as the 0.002ΣP lateral loads. Also, all the columns that failed in the blast scenario were removed and plastic hinges assigned to the rest of columns in two positions (start and end of the columns) along with all the beams in three positions (start, middle, and end of the beams). SAP2000 provides default hinge properties and recommends P-M2-M3 hinges for columns and M3 hinges for beams. Default hinges are assigned to the elements (P-M2-M3 for columns and M3 for beams). Exceeding CP performance point in plastic hinges of the beams and LS performance point in those of the columns indicate the incident of a progressive collapse in the building.

Reliability and Risk Assessment of the Building

After progressive collapse analysis for each probable explosive scenario inside and outside the building, from Eq. (4), the collapse probability of the building for the explosive-terrorist events have been determined. For the explosion outside the building, 32 probable location each with 3 weights of explosive mass (200, 400, and 600 Kg of TNT), in total a sum of 96 scenarios, have been considered. In 56 cases of the 96 scenarios, the building experienced progressive collapse. Among the 56 scenarios, causing progressive collapse, 28 scenarios occurred due to the explosion of an automobile with the weight of the explosive 400 Kg TNT and another 28 due to the explosion of an automobile with 600 Kg TNT. In the explosion of an automobile with 200 Kg TNT, no column became defective in the building, indicating that the building has kept its resistance (Table 5).

This study shows that buildings with even a surrounding fence at a 10 m distance is vulnerable to automobile-carried bombs with weights of explosive mass more than 400 Kg TNT, thus the strengths and distance of security fence or members of surrounding frames should be improved. Given the occurrence of the blast scenario outside the building with a probability of 70%, progressive collapse probability via Eq. (4) is 41% (20.5% by automobile-carried bomb explosion with 400 Kg TNT and the remaining 20.5% by automobile-carried bomb with 600 Kg TNT) (Eq. (7)). In this equation, $P(C_1)$: is progressive collapse probability under the explosion scenario outside the building. Figure 7 shows the probability of progressive collapse, happening outside the building blast for different weights of explosive mass.

$$P(C_1) = 0.7 \times \frac{56}{96} = 0.41 \tag{5}$$

Table 5. Material properties

Number of Scenarios	Number of Progressive Collapse after Explosions with Various Weight of TNT		
	$W = 200$ kg	$W = 400$kg	$W = 600$ kg
96	0	28	28

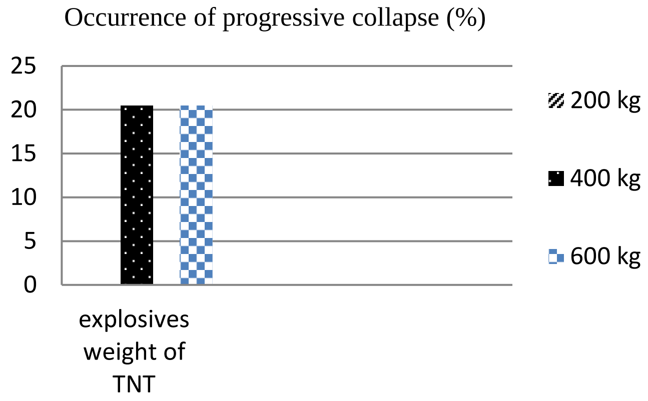

Fig. 7. Probability of progressive collapse in an explosion outside the building for different explosive weights

For blast scenarios inside the building, 44 probable points each with 3 weights of explosive mass (3, 5, and 7 Kg of TNT), in total a sum of 132 scenarios, are considered in each floor of the building. Within these 132 scenarios for each floor, the progressive collapse has occurred in 64 cases for the 1st and 2nd floor and in 76 cases for the 3rd or the 4th one. In the 1st and 2nd floor, the explosive with the weight of 3 Kg TNT did not cause a progressive collapse in the building, though it resulted in one in 12 points in 3rd and 4th floors, indicating that the risk of the progressive collapse varies in different floors of the building, so that the upper floors are more vulnerable than the lower ones. The explosion scenarios with 5 and 7 Kg TNT have caused the progressive collapse in all of the considered points in all floors. This fact shows that the high risk of entrance and the damage caused by these weights and more of TNT and it is necessary to ban the entrance by increasing security and control layers or by making the building resistant to these weights of explosion (Table 6). According to assumed probability of 30% of explosion inside the building with 25% probability for each floor, the progressive collapse probability is 3.6% for 1st and 2nd and 4.3% for 3rd and 4th floors, by using Eq. (8) for each probable scenario. The total probability of progressive collapse is 16%. In Eq. (8), $P(C_2)$ is the probability of progressive collapse for blast scenarios inside the building. Figure 8 shows the progressive collapse probability for scenarios inside the building.

$$P(C_2) = 2 \times \left[0.3 \times 0.25 \times \frac{64}{132}\right] + 2 \times \left[0.3 \times 0.25 \times \frac{76}{132}\right] = 0.16 \tag{8}$$

Table 6. Number of progressive collapses inside the building

Floor Number	**Number of Progressive Collapse after Explosions with Various Weight of TNT**		
	$W = 3$ **Kg**	$W = 5$ **Kg**	$W = 7$ **Kg**
1st	0	32	32
2nd	0	32	32
3rd	12	32	32
4th	12	32	32

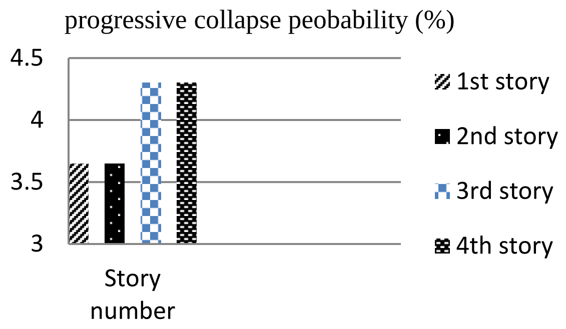

Fig. 8. Probability of progressive collapse in an explosion inside the building for different stories

Finally, using the Eq. (4), pertaining to the conditional probability, and by assuming that the blast happens with 70% probability outside and 30% inside the building, it can be proven that the probability of the progressive collapse in the building under the possible terrorist-explosive scenario is 57%:

$P(C) = P(C_1) + P(C_2) = 0.41 + 0.16 = 0.57$

where $P(C_1)$ and $P(C_2)$: are the occurrence probability of progressive collapse for explosion inside and outside the building respectively. Therefore, the reliability of the building against the explosive-terrorist scenarios is 43%, according to Eq. (6).

$R_o = 1 - 0.57 = 0.43$

CONCLUSIONS

In this research, the probability of progressive collapse and the reliability of an important building were evaluated under probable blast scenarios inside and outside the building and the following points can be concluded:

- Results show that progressive collapse probability and reliability of the building are 57% and 43%, respectively.
- For the blast scenarios inside the building, the intensity and the risk of the progressive collapse in the upper floors is more than those in the lower ones. Thus, the explosion with 3 Kg of TNT or more caused progressive collapse in the 3rd and 4th floor but in the 1st and 2nd floor, despite the same local damage, no progressive collapse occurred. This fact indicates higher failure potential of upper floors.
- The blast inside the building under 5 Kg or more TNT has caused progressive collapse beside the local damage of the columns.
- In explosion outside the building, the most critical location for the explosion is placed against the middle part of the building's front face. In this case, more members of the building are damaged by the explosion and progressive collapse risk is increased more.
- The blast of an automobile with 200 Kg TNT of explosive weight around the building's fence causes local damage of the building columns but the explosives with the weight of 400 Kg TNT or more which are easier to carry in the trucks, in addition to local damage of the columns, has caused progressive collapse in the building. Therefore, it is necessary to increase fence distance and reinforce building's members.

REFERENCES

ABAQUS/CAE version 10.1. (2010). Hibbitt, Karlsson & Sorensen Inc., Pawtucket, R.I.

Abdollahzadeh G.R. and Faghihmaleki H. (2016a). "Effect of seismic improvement techniques on a structure in seismic-explosive probabilistic two-hazard risk", *International Journal of Structural Engineering*, 7(3), 314-331.

Abdollahzadeh G.R. and Faghihmaleki H. (2016b). "Seismic-explosion risk-based robustness index of structures", *International Journal of Damage Mechanics*, DOI:10.1177/1056789516651919.

Abdollahzadeh G.R. and Nemati M. (2014). "Risk Assessment of Structures Subjected to Blast", *International Journal of Damage Mechanics*, 23(1), 3-24.

Abdollahzadeh, G.R., Sazjini, M. and Asghari, A. (2015). "Seismic fragility assessment of Special Truss Moment Frames (STMF) using the capacity spectrum method", *Civil Engineering Infrastructures Journal*, 48(1), 1-8.

ANSI/AISC 360-05 (2005). An American national standard, specification for structural steel buildings, American Institute of Steel. Construction, Chicago, Illinois.

Asprone, D., Jalayer, F., Prota, A. and Manfredi, G. (2010). "Proposal of a pobabilistic model for multi-hazard risk assessment of structures in seismic zones subjected to blast for the limit state of collapse", *International Journal of Structural Safety*, 32(1), 25-34.

Bangash, M.Y.H. and Bangash, T. (2006). *Explosion-resistant buildings, design, analysis, and case studies*, Springer.

Brode, H.L. (1959). "Blast wave from a spherical charge", The Physics of Fluids, Hydrodynamics Cambridge, The American Institute of Physics.

Cizelj, L., Leskovar, M., ˇCepin, M. and Mavko, B. (2009). "A method for rapid vulnerability assessment of structures loaded by outside blasts", *Nuclear Engineering and Design*, 239, 1641-1646.

Cullis, I.G., Schofield, J. and Whitby, A. (2010) "Assessment of blast loading effects e types of explosion and loading effects", *Pressure Vessels and Piping*, 87, 493-503.

Dusenberry, D.O**.** (2010). *Handbook for blast -resistant design of buildings*, John Wiley & Sons, INC.

Ellingwood, B.R. (2006). "Mitigating risk from abnormal loads and progressive collapse", *Journal of Performance of Constructed Facilities*, 20(4), 315-23.

FEMA-426 (2003). "Reference manual to mitigate potential terrorist attacks against buildings", Federal Emergency Management Agency.

FEMA-356 (2000). *Standard and commentary for the seismic rehabilitation of buildings*, Federal Emergency Management Agency.

Godinho, J., Montalva, A. and Gallant, Sh. (2007) "Analysis of steel columns for air blast-loads", *Structure Magazine*, November, 13-14.

Maleki, M. and Rahmaniyan, S. (2011). *Guide for Finite Element software, ABAQUS*, Simaye Danesh Publication, Tehran, Iran.

Nowak, A.S. and Collins, K.R. (2000). *Reliability of structures*, 2nd Edition, CRC Press, Portland.

Rong, H.C. and Li, B. (2007). "Probabilistic response evaluation for RC flexural members subjected to blast loadings", *Structural Safety*, 29(2) 146-163.

Shi, Y., Li, Z.X. and Hao, H. (2010). "A new method for progressive collapse analysis of RC frames under blast loading", *Engineering Structures*, 32(6), 1691-1703.

Stewart, M.G., Netherton, M.D. and Rosowsky, D.V. (2006). "Terrorism risks and blast damage to built infrastructure", *Natural Hazards Review, ASCE*, 7(3), 114-122**.**

Stewart, M.G. and Netherton, M.D. (2008). "Security risks and probabilistic risk assessment of glazing subject to explosive blast loading", *Reliability Engineering and System Safety*, 93(4), 627-638.

Tavakoli, H.R. and Kiakojouri, F. (2015). "Threat independent column removal and fire-induced progressive collapse: Numerical study and comparison", *Civil Engineering Infrastructures Journal*, 48(1), 121-131.

UFC, Unified Facilities Criteria (2008). "Structures to resist the effects of accidental explosions", Department of Defense United States of American, 5 December.

UFC, Unified Facilities Criteria (2009). "Design of building to resist progressive collapse", Department of Defense, United States of American, 14 July.

Zahrai, S.M. and Ezoddin, A. (2014). "Numerical study of progressive collapse in intermediate moment resisting reinforced concrete frame due to column removal", *Civil Engineering Infrastructures Journal*, 47(1), 71-88.