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AN EVALUATION OF MULTI-HAZARD RISK SUBJECTED TO BLAST AND EARTHQUAKE LOADS IN RC MOMENT FRAME WITH SHEAR WALL

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Abstract

Over the recent decades, many public buildings located in a region of high-seismic hazard have been subjected to simultaneous effect of abnormal loads against which they were not specifically designed. Hence, it is necessary to investigate the critical events occurring on the structure during its lifetime in order to investigate the structure's performance based on a multi-hazard approach. The current study proposes a probabilistic framework for multi-hazard risk associated with collapse limit state of RC moment frame with shear wall structure, which is subjected to blast threats in the presence of seismic risk. The annual risk of structural collapse is calculated taking into account both the collapse caused by an earthquake event and the blast-induced progressive collapse. The blast fragility is calculated using a simulation procedure of Monte Carlo for generating blast scenarios. As a case study, the blast and seismic fragilities of a generic eight-story RC moment frame with shear wall building located in high seismic zone and subjected to the effect of blast load are calculated and implemented in the framework of a multi-hazard risk. The findings of the current research show a considerable risk; finally, the importance of taking the blast measure into account when designing strategic structures in areas of high seismic risk is highlighted.

Keywords: Multi-hazard risk, Blast, Earthquake, Progressive collapse, Fragility curve.

1. Introduction

A strategic structure could be subjected to more than one critical action during its service life, including earthquake, wind, blast or fire. Typically, ordinary structures

Nomenclatures

b	Waveform parameter
H_e	Heats of combustion of the explosive substance
H_{TNT}	Heat of combustion of TNT material
$P(A)$	Annual occurrence rate
$P(B)$	Annual rate of blast occurrence
$P(C\|A)$	Fragility of the critical event
$P(C\|B)$	Explosive fragility
$P(E)$	Annual rate of earthquake occurrence
P_{max}	Peak overpressure
$P(\varphi)$	Probability density function for vector φ
R	Distance, m
t_d	Positive phase duration
t'	Blast wave duration, s
V	Speed, m/s
V_C	Probabilistic two-hazard risk
W	Explosive charge mass, kg
W_e	Explosive substance mass, kg
Z	Reduced distance, m/kg$^{0.33}$

Greek Symbols

φ	Vector of uncertain parameters
λ_c	Collapse load factor
$\lambda_c(\varphi)$	multiplied gravity loads factor

Abbreviations

DIF	Dynamic Increase Factor
MC	Monte Carlo
PDF	Probability Density Function
PSHA	Probabilistic Seismic Hazard Analysis
RC	Reinforced Concrete
SDOF	Single Degree of Freedom

with a relative importance are designed and calculated when subjected to earthquake or sometimes wind load. Rarely can we find a structure with relative importance specifically designed against critical loads such as blast or fire. Progressive collapse is one outcome of these critical loads. The progressive collapse can be defined as a situation where local failure of a primary structural component leads to total collapse of the structure [1]. Recently, some researches have been performed on the blast-induced damage in the building and its probabilistic investigations.

Recently Rong and Li [2] undertook a probabilistic assessment of the effect 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 factor of a reinforced concrete structure with flexural frames under blast loadings. Shi et al. [3] generated a new method for progressive collapse analysis of reinforced concrete (RC) frame structures by considering non-zero initial conditions and initial damage to adjacent structural members under blast loading is proposed. They compared Numerical results with those obtained using the alternative load path method, and with those from comprehensive numerical simulations by directly applying the blast loads on the frame.

Stewart and Netherton [4] investigated the effect of window glazing damage subjected to explosive blast loading. They used structural reliability techniques to derive explosive fragility curves. In this research, the structure was subjected to explosive loading for a variety of scenarios. They obtained a risk-based measure for calculating the probable damage of a structure subjected to explosive loading. Parisi and Augenti [5] performed a research on the ability and robustness of a RC building, which was designed, based on seismic design codes and subjected to explosive loads. In their research, they generated scenarios based on the location and the amount of explosives. A Pushdown analysis was performed to evaluate the robustness of the building against explosive load. Cizelij et al. [6], proposed an analysis method for a structure subjected to blast load. Their proposed method predicted failure and non-linear responses. The obtained results were comparable to dynamic simulations.

The performance of the proposed method in their work yields some information about reliability and vulnerability analysis of the existing structures. Fu [7] presented a new method for evaluation of high-rise building responses subjected to explosive loading and he made a comparison between this method and APM method. As can be understood from the above works, in all the scenarios, the buildings were just subjected to explosive load and the damage imposed on the structures were evaluated using different methods (probabilistic and non-probabilistic) in order to evaluate a building’s performance against critical actions. The current research aims to present a solution to reach a probabilistic annual rate in the structures subjected to two actions including earthquake and blast. To clearly understand the proposed method, the proposed probabilistic rate is evaluated for RC moment frame with shear wall structure and the results are presented.

2. Methodology

In conditions, where only one critical action is considered, the proposed collapse probabilistic rate (V'_c) will be as follows:

$$V'_c = P\,(C \mid A).P(A) \tag{1}$$

In Eq. (1), $P(C \mid A)$ is fragility of the critical event, $P(A)$ is annual occurrence rate of the critical action. The collapse rate presented in Eq. (1) has been used in the work of Ellingwood [8], where the structure is subjected to abnormal loads with a probability of progressive collapse occurrence.

However, if E stands for earthquake occurrence, B for blast occurrence and C for structural collapse and E and B are considered incompatible and independent from each other, that is:

$$P(B \cup E) = P(B) + P(E) \tag{2}$$

$$P(B \mid E) = 0 \tag{3}$$

Then, probabilistic two-hazard risk (V_C) can be defined as follows:

$$V_c = P\big(C \mid (B \cup E)\big) = \frac{P(C \mid B).P(B)+P(C \mid E).P(E)}{P(B \cup E)} \quad (4)$$

According to Eq. (2) and given that the total risk in this condition equals to sum of explosive and seismic risk and that the events are incompatible and independent from each other, reviewing Eq. (4), we can conclude that:

$$V_c = P(C \mid B).P(B) + P(C \mid E).P(E) \quad (5)$$

In Eq. (5), $P(C \mid B)$ is explosive fragility, $P(B)$ is annual rate of blast occurrence, $P(C|E)$ is seismic fragility, and $P(E)$ is annual rate of earthquake occurrence.

Our goal in this article is to obtain (V_c). Therefore, it is necessary to calculate the seismic and explosive fragility curves. $P(E)$ is an engineering parameter which can be calculated using probabilistic seismic hazard analysis (PSHA) for project site. $P(B)$ cannot be totally called an engineering parameter and it should be approximately quantified based on Poisson distribution function.

2.1. Progressive Collapse Mechanism

The most critical outcome of a blast is usually the instability generated by strong local damage referring to progressive collapse. Nowadays, progressive collapse in structures has been the focus of attention for many researchers in structural engineering associations. More specifically, it is necessary to prevent and evaluate progressive collapse in important and sensitive structures whereby exceptional events may occur during the service life of a structure. Therefore, several research projects have been performed to evaluate progressive collapse mechanisms [9].

In the current study, blast-induced progressive collapse in a structure is described using a Bernoulli distribution function, whereby 1 is considered for progressive collapse occurrence and 0 for non-occurrence. Therefore, the probability of blast-induced progressive collapse can be calculated in terms of the expected value of Bernoulli variable in all explosive scenarios. Explosive fragility, shown with $P(C|B)$, is defined as Conditional probability for the occurrence of progressive collapse whereby a blast occurs near or inside the strategic structure under discussion. The real vector φ represents the uncertain quantities of interest, related to structural modeling and loading conditions. The positive real number of $P\ (\varphi)$ represents probability density function (PDF) for vector, φ. $P(C|B)$ can be written as follows:

$$P(C|B) = \int I_C(\varphi).\, p(\varphi).\, d(\varphi) \quad (6)$$

In Eq. (6), $I_C(\varphi)$ is an index function which is equal to unity in the case where φ leads to blast-induced progressive collapse and zero otherwise. Here, the probability of progressive collapse $P(C|B)$ is calculated using standard Monte Carlo (MC) simulation for generating N_{sim} scenarios. Here, vector φ is the amount of explosive and its position with respect to the structure. Component analysis is performed to investigate the local damage induced by each explosion. Based on the results obtained from component analysis, a number of members that have been broken (or experienced severe damage) can be identified and removed. Then, a non-linear state analysis is performed on the structure which has lost some of its elements. The event of progressive collapse is identified by the ratio index $\lambda_c(\varphi)$ which is the factor by which the gravity loads should be multiplied in order to create a global collapse mechanism. The probability of blast-induced progressive collapse can be generally estimated by the ratio of total collapse conditions to total number of the considered combinations.

2.2. Non-linear analysis of the damaged structure

After identifying and removing the damaged elements, it should be verified whether the damaged structure can withstand the applied vertical loads. Non-linear state analysis can be cinematically done to find the minimum allowed load for which the following effects occur:

- Equilibrium conditions are satisfied.
- A sufficient number of plastic hinges are formed in the structure in order to activate a collapse mechanism in the whole structure or in a part of it, assuming that non-linear behavior in the structure is concentrated at the element ends and the member ends are capable of developing their fully plastic moment.

An allowed cinematic load corresponds to a mechanism in which both the external work done by applied forces on allowed deformations and internal work done by final elements on allowed rotations are positive.

The mechanism corresponding to minimum cinematic allowed load is calculated in terms of a linear combination of a number of possible principal mechanisms in the structure, as shown in Fig. 1. The presence of shear wall affects only the internal work done by storey mechanisms. The internal work done by shear wall is ignored in the current research.

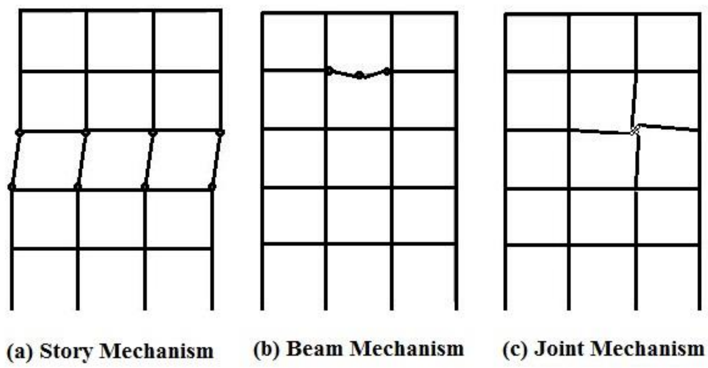

Fig. 1. Important and principal fracture mechanisms are defined in [10]. a) storey mechanism, b) beam mechanism, c) joint mechanism.

2.3. An evaluation of general annual collapse rate of the structure

This collapse rate, in Eq. (5), is implemented for calculating annual risk of structural collapse. In order to calculate the seismic contribution to the risk of Eq. (5), the seismic fragility curve should be integrated with the hazard for spectral acceleration at a period close to the fundamental period of the structure. The seismic fragility is calculated using a non-linear static analysis. However, it should be noted that annual rate of $P(B)$ cannot be easily quantified as it highly depends on the socio-political circumstances and the strategic importance of the structure.

Approximately, in case of a non-strategic structure $P(B)$ can be in order of 10^{-7}, making blast contribution to the annual risk of collapse negligible. Alternatively, in case of a strategic structure, $P(B)$ can be greater than 10^{-7} [11].

3. Numerical Example

3.1. Structural model description

The case-study building is a generic 8-story RC moment frame with shear wall structure. The structural model is illustrated in Fig. 2, presenting a plan of the generic storey. Figure 3 shows a 3D view of the model.

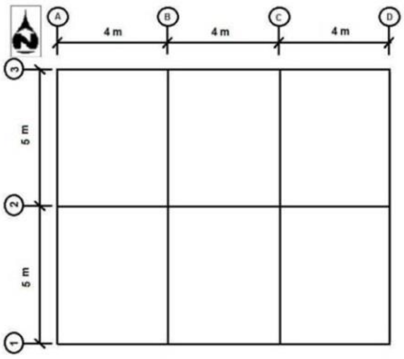

Fig. 2. Storey plan (dimensions in m).

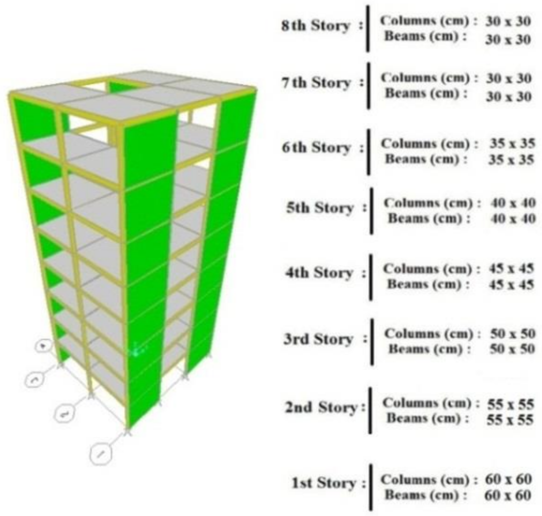

Fig. 3. 3D model view.

Each storey is 3.2 m high. The non-linear behaviour in the sections is modelled based on the concentrated plasticity. It is assumed that the plastic moment in the hinge sections is equal to the ultimate moment capacity in the sections which is calculated using the Mander model [12] for concrete model. The case study building includes an office building (a strategic structure with high importance) designed according to the European seismic provisions. Gravity load includes live and dead loads. Dead load of floors was considered 550 kg/m^2, live load 200 kg/m^2 and roof load 150 kg/m^2. Other types of loading including wind load and snow load were ignored. Moreover, structure-soil interaction was ignored and columns are assumed to be fixed in base. The roof is supposed to be one-way slab, 0.25m thick. The shear walls of the building, based on the architectural plan of the building, are assumed to be without any opening. On this basis, three types of shear wall are designed. Table 1 presents the properties of shear wall in each storey. During blast scenario, materials are rapidly loaded by higher strain rates. Thus, plastic deformations are much less than those in the case of static loading at normal strain rates. It was found that the mechanical properties of materials during blast loading are increased. The ratio between the material property under rapid dynamic load and the some property under static loading is defined as the dynamic increase factor (DIF) [13].

Table 1. The properties of the shear walls used.

Re-inforcement ratio (ρ)	Re-inforcement	Thickness of wall (cm)	The storey of interest	Shear wall name
0.01	φ22@15cm	35	1,2,3	W1
0.007	φ18@15cm	35	4,5,6	W2
0.0035	φ16@15cm	30	7,8	W3

3.2. Characterization of the uncertainties

The uncertain quantities of interest in this study are the amount of explosive W and its position with respect to a fixed point within the structure denoted by R. The vector of uncertain parameters contains two uncertain quantities: $\varphi = \{W, R\}$, the distance R changes such that blast may take place both within the structure and outside. Once the explosion scenario occurs inside the structure, it can take place at one of the five floors of the building, since, as mentioned earlier, the building is office building and it can be available to the public, though the last three stories are for administrative staff only. Furthermore, in case the explosion occurs outside, it is assumed that the explosion takes place on the second roof (ground floor), outside a 10 m standoff [14] distance from the structure.

For each simulation realization, the centre of explosion is determined assuming that the explosion occurs within the structure or outside, with a probability of 30% and 70%, respectively. Once the explosion scenario occurs inside the structure, with the same probability it can take place at one of the five floors of the building. Then, the amount of explosive is simulated to be between 20 and 40 kg of equivalent TNT, assuming that explosion takes place within the structure from the second to the fifth floor, if the explosion occurs at the first floor, corresponding to the underground level the amount of explosive is assumed to be between 270 to 600 kg of equivalent TNT. Furthermore, in case the explosion occurs outside, the amount of TNT has the 10% of probability to vary between 20000 to 30000 kg of equivalent TNT and 90% probability to vary between 200 and 500 kg of equivalent TNT. All uncertain quantities are assumed to be uniformly distributed.

3.3. Characterization of the local dynamic nonlinear analysis parameters

A local dynamic analysis is performed on a series of columns which have been drastically damaged by blast. In case of inside explosion, it is assumed that only the columns on the same floor as that of the explosion are affected by it. This assumption is supported by the fact that the columns on the other floors are sheltered from the blast wave by the floor slab system. However, in case of outside explosion, only the external columns are affected directly by the explosion (since the internal columns are sheltered by the perimeter walls).

For each of the columns hit by the explosion at the distance R from the canter of the charge, given the amount of explosive W, the reduced distance ($Z = \frac{R}{W^{\frac{1}{3}}}$) is calculated. Once Z is calculated, triangular impulse loading parameters can be calculated. It is further assumed that the intensity of the impact loading is uniform across the column height. On this basis, the maxima for bending moment and the shear force applied on the column can be evaluated and they are compared against the ultimate bending and the corresponding shear capacity. It should be mentioned that the applied load on the column is divided into two components which trigger an angle and then affect the explosives of the column and hit that.

Explosive loading

Explosion is a chemical process that prompts an increase in the pressure and temperature of the blast environment. In case of an explosion, a wavelet with the same speed and force as the blast, spreads in a specific period of time, which does not exceed 10^{-2} s. the explosion would also produce flames and high speed pressure ($V > 10^3 \frac{m}{s}$). A sudden explosion can raise the dust as well, and thus it is gravely destructive. In keeping with what is discussed, this research paper investigates the effects of sudden abnormal blast pressures on structural elements. However, the impact of the dust raised in the air and also the flames are ignored in this research. Blast overpressure time history is measured in two phases. The positive phase: it is quick and forceful; negative phase: it lasts longer but is never as strong as the positive phase. Presupposing an infinite quantity, it is possible to determine post-blast pressure time history by the use of modified Friedlander equation [15].

$$P(t) = P_0 + P_{max}\left(1 - \frac{t'}{t_d}\right)EXP(-\frac{bt'}{t_d}) \tag{7}$$

where t' is the blast wave duration from the moment (t_a) when the pressure wave enters the target ($t' = t - t_a$). P_o is the ambient atmospheric pressure; P_{max} is the peak overpressure; t_d is the positive phase duration and b is the waveform parameter [16]. The first phase of overpressure time history can be assessed as a triangular force according to its rise time. Therefore, assuming the initiation time to be equal to t_a and $t < t_d$ equation (7) can be substituted by the following:

$$P(t) = P_0 + P_{max}\left(1 - \frac{t}{t_d}\right) \tag{8}$$

where p_{max} is blast parameter dependent on the reduced distance ($z = \frac{R}{w^{1/3}}$) in which R is the distance of the target from the blast centre (meter); and w is explosive charge mass (kg, eq TNT) [17].

Blasts caused by various explosive materials of different weights produce the same peak overpressure, only when their reduced distances (z) are the same. As a result, the mass (in TNT) of any explosive material can be estimated by the following:

$$w = \frac{H_e}{H_{TNT}} W_e \tag{9}$$

where H_e is the heats of combustion of the explosive substance and H_{TNT} is the heat of combustion of TNT material. W_e is explosive substance mass. Peak overpressure (P_{max}) in (kg/cm^2) can be calculated in this way [17]:

$$P_{max} = \frac{14.0717}{Z} + \frac{5.5397}{Z^2} - \frac{0.3572}{Z^3} + \frac{0.00625}{Z^4} \quad \text{if } Z \in [0.05\ , 0.3] \tag{10}$$

$$P_{max} = \frac{6.1938}{Z} - \frac{0.3262}{Z^2} + \frac{2.1324}{Z^3} \quad \text{if } Z \in [0.3\ , 1] \tag{11}$$

$$P_{max} = \frac{0.662}{Z} + \frac{4.05}{Z^2} + \frac{3.288}{Z^3} \quad \text{if } Z \in [1\ ,10] \tag{12}$$

Positive phase duration of overpressure time history (s) can be deduced from the following [18]:

$$t_d = 10^{-3} k \sqrt[6]{w} \sqrt{R} \tag{13}$$

where k is a constant usually assumed to be 1.3.

3.4. Blast fragility

A standard Monte Carlo simulation technique is used to generate 500 blast scenario realizations, assuming that the structure was subjected to its gravity loads and to the 30% of the characteristic live loads. For each of these realizations, the collapse load factor λ_c is calculated and compared with $1 < \lambda_c < 2$ leading to progressive collapse in the structure. The cumulative distribution function for the load factor denoted by $P(C|B)$ for possible values of λ_c is illustrated in Fig. 4. As can be seen in Fig. 4, there is a 20% probability for the structure that a blast event leads to progressive collapse. Samples which lead to progressive collapse can give us further insight into vulnerability of locations to explosions as well as the amount of explosives which can be destructive and lethal. These data can be very useful in designing the strategic structures resistant to blast.

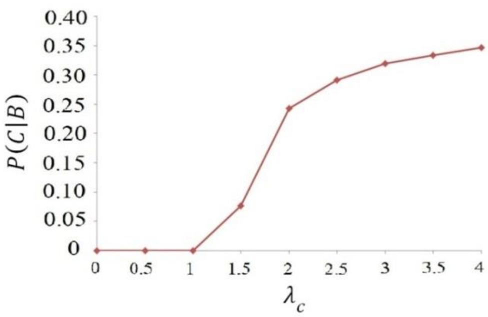

Fig. 4. Blast fragility.

3.5. Evaluating seismic risk and hazard

The seismic fragility for the case-study structure is calculated in two steps. In the first step, a non-linear static analysis (Fig. 5) is performed on the structure model using SeismoStruct (version 6) software based on the concentrated plasticity concept to obtain static Pushover curve to control displacement versus the base shear. The collapse threshold is verified at a point at which the first element in the structure reaches its ultimate rotation capacity (state dramatic damage). The equivalent elastic SDOF system corresponding to the pushover curve for the whole structure is approximated using a procedure recommended in European Seismic Guidelines [12].

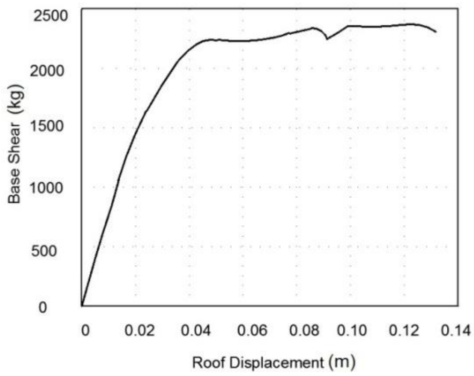

Fig. 5. Static pushover curve of structure.

In the second step, non-linear dynamic analysis method is used to obtain seismic fragility. A suite of 50 ground motion accelerations are scaled to increasing levels of spectral acceleration and are used for SDOF system. These accelerations are taken from PEER institute database, having a magnitude of 6.5 to 7.5 and the distance of source to the site is 15-30 km. the damping of soil type C and D is 5%. Scaling and filtering of these records are done within SiesmoSignal software. The simple displacement SDOF responses are equivalent. In each spectral acceleration, fragility probability is estimated by a part of accelerations which generates maximum displacement response rate than the ultimate displacement. The obtained fragility curves are plotted in Fig. 6, showing the probability of failure as a function of structural acceleration for the structure.

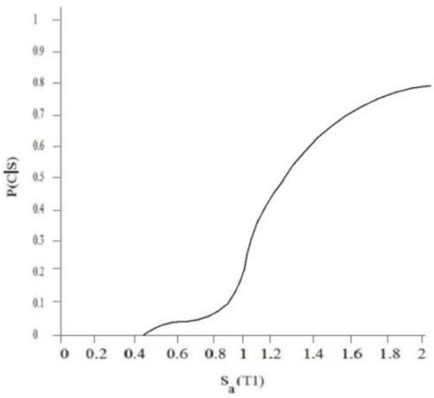

Fig. 6. Seismic fragility.

In the next step, the seismic fragility with the hazard for spectral acceleration at a period close to the fundamental period of the structure (T-0/7) is obtained to calculate the annual collapse rate caused by earthquake (seismic risk). The seismic risk of the principal structure is equal to 4.7×10^{-4}.

3.6. Annual collapse rate

To calculate the annual collapse rate, a structure subjected to blast and earthquake should be taken into account in terms of Eq. (5); however, as mentioned earlier, the annual rate of $P(B)$ cannot be easily quantified. It is assumed that $P(B)$ = 5×10^{-3}. Therefore, based on Bernoulli distribution function, there is a 60% probability that a considerable blast may take place every 200 years, annual collapse rate for the structure, using blast fragility and seismic fragility, can be calculated as follows:

$$v_c = 4.7 \times 10^{-4} + (0.2 \times 5 \times 10^{-3}) = 1.47 \times 10^{-3} \tag{14}$$

3.7. Discussion on the case study

Given that the proposed method in this article addresses an evaluation of probabilistic collapse risk of the structure subjected to two critical events, it can be expected that the amount of this risk is more compared to a situation where the structure is subjected only to one critical event. The results of the case study in this article show that the amount of structural damages is considerable when more than one critical event such as blast takes place, as it was mentioned in Introduction [2 - 4]). Therefore, it can be emphasized that for strategic structures, which may be subjected to explosive loads and are located in a region of high-seismic hazard, we should employ a method such as the one presented in this article which takes into account the effects of both critical events in a structure for a limited time frame (e.g., one year).

4. Conclusion

Applying an explosive loading, the probability of progressive collapse is calculated using Monte Carlo simulation. The simulation method implements the effective nonlinear state analysis which is programmed as a problem and is linearly formulated and solved. Collapse probability caused by an earthquake can be calculated for the site by integrating seismic fragility and seismic hazard. Once the effect of seismic and explosive loads is investigated, they can be summed to present annual collapse risk. This result also highlights the emphasis on taking the blast measure into account in designing strategic structures in seismic zones. This methodology can implement blast scenarios which lead to progressive collapse. The methodology presented herein evaluates a specific strategy in terms of annual collapse rate.

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