Earthquakes and Structures, *Vol. 12, No. 1 (2017) 47-54*
DOI: https://doi.org/10.12989/eas.2017.12.1.047

A method to evaluate the risk-based robustness index in blast-influenced structures

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(Received May 19, 2015, Revised October 23, 2016, Accepted November 2, 2016)

Abstract. Introduction of robustness index in the structure is done in three ways: deterministic robustness index, probabilistic robustness index, and risk-based robustness index. In past decades, there have been numerous researches to evaluate robustness index in both deterministic and probabilistic ways. In this research, by using a risk analysis, a risk-based robustness index has been defined for the structure. By creating scenarios in accordance with uncertainty parameters of critical and unexpected gas blast accident, a new method has been suggested for evaluating risk-based robustness index. Finally, a numerical example for the evaluation of risk-based robustness index of a four-storey reinforced concrete moment frame, designed and built based on Eurocode 8 code, has been presented with results showing a lower risk of robustness.

Keywords: risk analysis; risk-based robustness index; gas blast; uncertainty parameters; direct and indirect consequences

1. Introduction

General consequences and outcomes in a structure should be appropriate with primary events. Robustness in a structure prevents the transformation of a local damage to a general one (Nielsen 2009, Abdollahzadeh and Nemati 2014, Abdollahzadeh and Faghihmaleki 2016a, Abdollahzadeh *et al*. 2016). On one hand, robustness depends on internal features of the building like redundancy, ductility, connection behavior, progressive collapse, and key elements and on the other on the type of scenarios in which an unexpected critical event can lead to damage or collapse (Abdollahzadeh and Faghihmaleki 2016b, Soltani and Sadjadi 2014, Khaloo *et al*. 2016). Unexpected critical events can be categorized to many groups like random events (blast, impact, fire, etc.), unwanted differences between the structure behavior in design and in reality, unwanted differences in assumed building materials in design and in reality, unexpected geometrical defects, etc. (Sørensen 2011, Abdollahzadeh and Faghihmaleki 2014). The importance of robustness is known in most advanced designing codes but it has not been dealt with in details. For example in Eurocodes (Eurocode 0 2002, Eurocode 1 2006), initial designing needs of each structural member or the connections are related to an adequate rate of reliability. Such rate of reliability with safety coefficients, calibrated in adequate rate of reliability, is usually supplied with failure annual possibility equal to 10-6 (JCSS 2002, André *et al*. 2015, Cassiano *et al*. 2016). Generally codes need to either reduce or eliminate the effect of design and execution errors as well as the unexpected deterioration of the components.

Nowadays there have been researches in terms of evaluating robustness indicators. Branco and Neves (2001), by considering the similarities between robustness evaluation and quake design, have obtained results and a case study led to the analysis of the effect of redundancy and flexibility on both quake behavior and the robustness of a long-span timber structure. Khandelwal and El-Tawil (2001), introduced a robustness scale in progressive collapse based on pushdown analysis which is evaluated in accordance with the remaining capacity and sustainability of collapse conditions of a damaged structure. Jahromi *et al*. (2013), suggested the modeling methods to evaluate a multi-storied steel-composite building. In this study, the robustness index is regarded as deterministic. By taking the features of connection behavior, ductility, as well as internal features of the building the robustness index has been evaluated. Baker *et al*. (2008), introduced the robustness index based on the decision-making analysis theory, which is evaluated by calculating direct risk (local damage) and indirect risk (comprehensive damage).

Guedri *et al*. (2012), by defining two kinds of uncertainty in materials and geometrical features (aleatory and epistemic uncertainty) as well as the importance and significance of each, evaluated the robustness in accordance to building's reliable analysis. Lu *et al*. (2010), presented a robustness indicator against buildings' progressive collapse by using pushdown analysis, dealing with the impact from the omission of structural elements in the evaluation of this indicator. Podroužek *et al*. (2014), offered a method to evaluate the robustness of bridge system's margin under traffic loading. It has been done by analyzing the limited non-linear element based on a precise 3D model which has

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ISSN: 2092-7614 (Print), 2092-7622 (Online)

the highest capacity potential in different risk stages. In addition, some methods have been developed based on the new approach for general engineering buildings.

In general, a robustness index is defined in three ways: deterministic, probabilistic, and risk-based robustness index. In carried out projects, it can be seen that robustness index is generally evaluated deterministically or in some cases probabilistically. On the other hand, critical and unexpected events like fire or blast have not been considered in the estimation of robustness analysis. In this study, based on a risk analysis, a risk-based robustness index is defined. The considered critical event, is gas blast. By considering uncertainty parameters of this event in different scenarios, a new method has been offered to evaluate risk-based robustness index. Eventually a case study on a RC frame building with its results reported.

2. Robustness index

During the past decades, there have been numerous attempts to develop and evaluate robustness in the buildings. Methods to define a robustness index can be categorized into the three levels below:

- *Risk-based robustness index*: Based on a complete risk analysis where consequences and outcomes are divided in a linear or non-linear risk.
- *Probabilistic robustness index*: Based on failure possibility of structural systems in damaged and undamaged building conditions.
- *Deterministic robustness index*: Based on structural scales, capacity of pushover tolerance in damaged and undamaged building conditions.

This study aims to obtain a risk-based robustness index for which an essential framework have been designed in accordance with the below function. In this risk analysis (R), local damage (direct consequences) and general damage (indirect consequences) are of high account (Baker *et al*. 2008, JCSS 2008)

$$R = \sum_i \sum_j C_{dir,ij} P(D_j \mid EX_i) P(EX_i) + \sum_i \sum_j \sum_k C_{ind,ijk} P(S_k \mid D_i \cap EX_i) P(D_j \mid EX_i) P(EX_i) \tag{1}$$

In Eq. (1), $C_{dir,ij}$ is the number of local damage (direct consequences); D_j, is the local failure; EX_i, is the critical and unexpected event; $C_{ind,ijk}$, is the number of general damage (indirect consequences); S_k, is general damage due to local damage; $P(D_j \mid EX_i)$, is the possibility of local damage in case of critical event occurrence; $P(EX_i)$, is the annual rate of critical events' occurrences; and $P(S_k \mid D_i \cap EX_i)$, is the possibility of general damage in case of local damage in a critical event.

In this risk analysis, the collapse possibility, related to Eq. (1) is equal to

$$P(Collapse) = \sum_i \sum_j P(Collapse \mid D_j \cap EX_i)\ P(D_j \mid EX_i) P(EX_i) \tag{2}$$

In Eq. (2), $P(Collapse \mid D_j \cap EX_i)$ is the collapse possibility in case of local damage in a critical event. According to the explained points and robustness definition in EN1990 code (2002), robustness has an essential relation with the decrease in the possibility of $P(D_j \mid EX_i)$ and $P(Collapse \mid D_j \cap EX_i)$.

In general one can define a risk-based robustness index (I_{Rob}), based on the explained risk analysis and related to direct and indirect consequences, as the following (Sørensen, 2011)

$$I_{Rob} = \frac{R_{Dir}}{R_{Dir} + R_{Ind}} \tag{3}$$

In Eq. (3), R_{Dir} and R_{Ind} are direct and indirect risks, being equal to the first and second term of Eq. (1) respectively so that

$$I_{Rob} = \frac{\sum_i \sum_j C_{dir,ij} P(D_j \mid EX_i) P(EX_i)}{\sum_i \sum_j C_{dir,ij} P(D_j \mid EX_i) P(EX_i) + \sum_i \sum_j \sum_k C_{ind,ijk} P(S_k \mid D_i \cap EX_i) P(D_j \mid EX_i) P(EX_i)} \tag{4}$$

This index (Eq. (4)) is a number between zero and one in which bigger amounts (close to one) indicates a structure with direct risk, great local damages but with low total damages, hence showing an acceptable robustness of the structure. In contrast, this index for smaller amounts (close to zero) is a structure with low direct risk but with high indirect risk, hence resulting in an unacceptable robustness of the structure. The current study aims to obtain risk-based robustness index (I_{Rob}). The critical event, considered, is gas blast which by taking uncertainty parameters of gas blast in different scenarios, the terms of Eq. (4) are obtained. As a result, it can be a new method to evaluate the considered robustness index (I_{Rob}).

3. Case example of determining risk-based robustness index in buildings, under blast loading

In order to more explain the suggested method in risk-based robustness index calculation, the rate of this index for an assumed building, in danger of gas leak and CNG blast are dealt with.

3.1 Modeling

A RC moment frame building, located in a region with high seismicity with design acceleration of 0.35 g for a return period of 475 year was selected. The building was residential and based on Eurocode 8 code (2005). The building is composed of four stories and ordinary reinforced concrete beam-columns, without shear walls. Fig. 1 gives the floor plan and Fig. 2 gives the 3D model of the building.

Gravitational loading includes both dead and live loadings. Dead load of the floors was 5.5 $\frac{kN}{m^2}$; live load was 2.0 $\frac{KN}{m^2}$; and the load of the ceiling's floor was 1.5 $\frac{KN}{m^2}$. Other types of loadings such as wind or snow loadings were not taken into consideration. Moreover, soil-building interaction was not considered as well and the columns' bases were assumed as stable. The floor's heights were 3.2 meters, concrete pressure resistance, 21 MPa, and the concrete slab's thickness on the floors 15 cm. Stirrups with a diameter of 8 mm and with a distance of 20 cm in building elements have been used.

Each column is numbered as $D_{i,j}$, where i indicates the position of each column in a story so that i=1, 2, 3 … 12 (according to Fig. 1) and j shows the in which story the intended column is located. Since the intended building has four stories, hence j=1, 2, 3, and 4. Hence the 48 columns of this building are numbered accordingly.

3.2 Scenario making

In this study, scenario making is done in accordance to uncertainty parameter of gas blast. In general, uncertainty parameters in a blast event are three factors of blast success, explosives' amount, and explosives' type. But if a critical event like earthquake or fire is to be regarded as compatible and dependent on the blast event, the time of blast occurrence becomes the other uncertainty parameter. In the critical event of gas blast, the parameters of type and amount of the explosives possess certainty. The explosives' type is Compressed Natural Gas (CNG), whereas their amount, due to the existence of seismic sensor in the gas-meter, gas disconnection at the time of the earthquake, and the amount of the confined gas from the gas-meter until heating and mechanical facilities can be well calculated. It should be pointed that in order to calculate the amount of the explosives, it is needed to know a set of basic information like total heating level, the entire building's heating capacity, CNG's heating value, the amount of the required input gas into the building in the unit of time, the gas-meter capacity, and the diameter and length of gas pipes from the gas-meter until the mechanical facilities.

In this study, blast situation does not have any certainty. The mechanical and heating facilities on the building's first floor are intended and blast occurs at one of the sites of the gas pipe from the gas-meter to the mechanical-heating facilities. Therefore, it can be concluded that the blast takes place at one of the sites in the first story's floor. The intended scenario will happen in a discrete case space. Initially by meshing the first story's floor plan, surface center (index points) of each surface element is obtained. The blast in any of the obtained index points is selected as the blast center in different scenarios. In order to obtain the length and width of the surface elements, a blast scenario has to happen in its most critical way possible. In this way, by analyzing the maximum changes of surface stress on the surface of first story's floor plan, the elements' length and width are calculated. Fig. 3 and Fig. 4 show the maximum changes of stress and meshing on the surface of the first floor, respectively.

According to Fig. 4 and the obtained index points (blast position), 15 different scenarios are created.

3.3 Calculating R_{Ind} term

It can be said that $P(S_k \mid D_i \cap EX_i)$ is the building's fragility (total damage) in comparison to local damage of each vertical component of the building (columns). The number of total damage of the building in all scenarios, $C_{ind,ijk}$, is a constant number. In order to analyze the term $P(D_j \mid EX_i)$, it should be analyzed that in how many instances of all scenarios, each column suffers local damage. Moreover $P(EX_i)$ is not a completely engineering-oriented parameter and cannot be evaluated

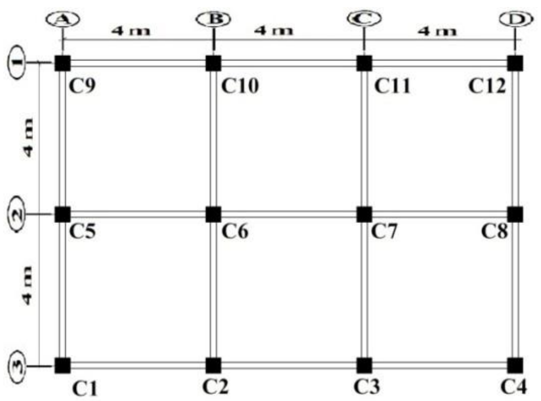

Fig. 1 Floor Plan of every storey

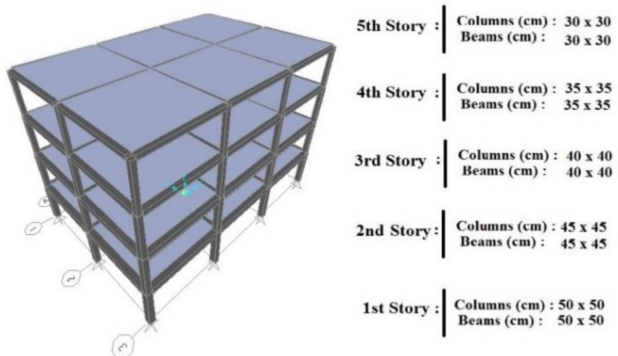

Fig. 2 3D picture of the intended building

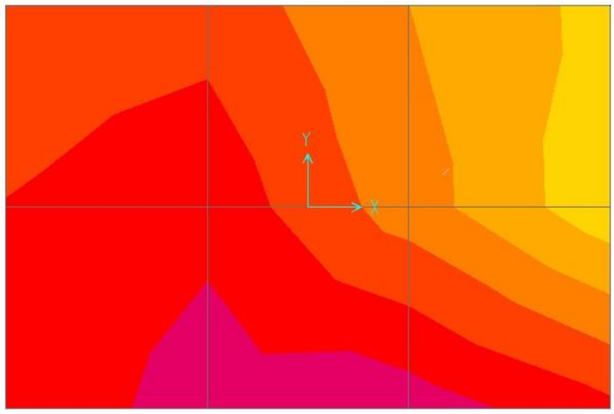

Fig. 3 Maximum changes of first floor's surface stress

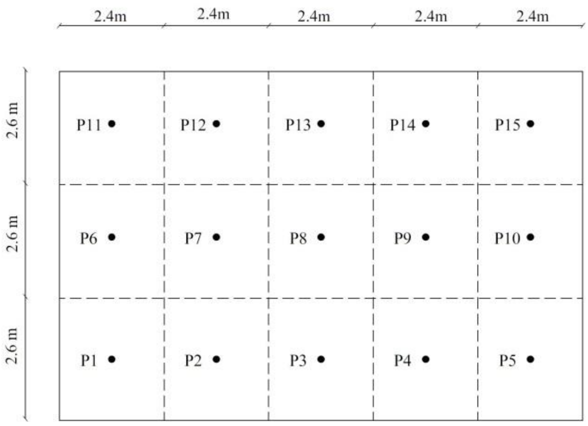

Fig. 4 Meshing the floor plan of the first story and the index points

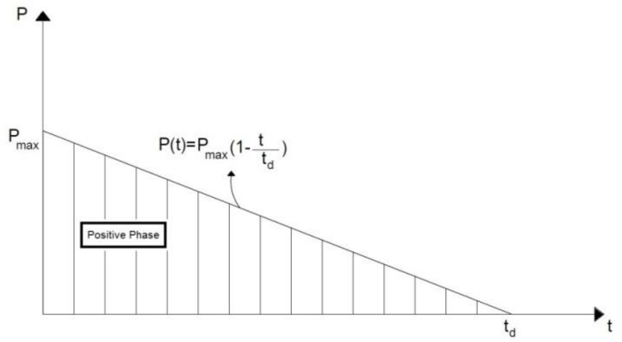

Fig. 5 The first phase of blast overpressure time historyv

precisely. This parameter is equal to the rate of annual occurrence of blasts. The possibility of a blast in all explained blast situations are presumed to be similar. By using Poisson Theory, one can find an approximate amount of this parameter which is 5×10^{-3} (Asprone *et al*. 2008).

As aforementioned, building's columns are numbered as $D_{i,j}$, therefore

$$R_{Ind} = C_{ind,ijk} \times 5\times10^{-3}[P(S_k \mid D_{1,1} \cap EX_i)\times P(D_{1,1} \mid EX_i) + P(S_k \mid D_{2,1} \cap EX_i)\times P(D_{2,1} \mid EX_i) + \cdots + P(S_k \mid D_{12,4} \cap EX_i)\times P(D_{12,4} \mid EX_i)] \quad (5)$$

In order to calculate the terms in Eq. (5), the total fragility rate of the building should be evaluated for local damage of each column.

3.3.1 Required analyses

3.3.1.1 Local dynamic analysis of the blast

In each scenario, a local dynamic analysis of the blast should be made. 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 (Baker 1973)

$$P(t) = P_0 + P_{max}\left(1 - \frac{t'}{t_d}\right)EXP\left(-\frac{bt'}{t_d}\right) \quad (6)$$

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 (Baker *et al*. 1983).

The first phase of overpressure time history can be assessed as a triangular force according to its rise time (Fig. 5). Therefore, assuming the initiation time to be equal to t_a and $t<t_d$ Eq. (6) can be substituted by the following

$$P(t) = P_0 + P_{max}\left(1 - \frac{t}{t_d}\right) \quad (7)$$

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 center (meter); and w is explosive charge mass (Kg, eq TNT) (Henrych 1979).

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

$$w = \frac{H_e}{H_{TNT}}W_e \quad (8)$$

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 ($\frac{kg}{cm^2}$) can be calculated in this way (Henrych 1979)

$$P_{max} = \frac{14.0717}{Z} + \frac{5.5397}{Z^2} - \frac{0.3572}{Z^3} + \frac{0.00625}{Z^4} \quad \text{if } Z\in [0.05\ ,0.3] \quad (9)$$

$$P_{max} = \frac{6.1938}{Z} - \frac{0.3262}{Z^2} + \frac{2.1324}{Z^3} \quad \text{if } Z\in [0.3\ ,1] \quad (10)$$

$$P_{max} = \frac{0.662}{Z} + \frac{4.05}{Z^2} + \frac{3.288}{Z^3} \quad \text{if } Z\in [1\ ,10] \quad (11)$$

Positive phase duration of overpressure time history (s) can be deduced from the following (Sadovsky 1952)

$$t_d = 10^{-3}k\sqrt[6]{w}\sqrt{R} \quad (12)$$

Where k is a constant usually assumed to be 1.3.

3.3.1.2 Static and non-linear analysis

In order to survey whether there is a progressive collapse or not in each scenario, after having a dynamic and local analysis of the blast, a static and non-linear one will be made based on gravitational loading with dynamic increase coefficient (DIF), which is compatible with UFC 4-023-03 code (2009). The loading of the intended analysis will be as what follows:

a) Increased Gravity Loads for Floor Areas Above Removed Column (G_N)

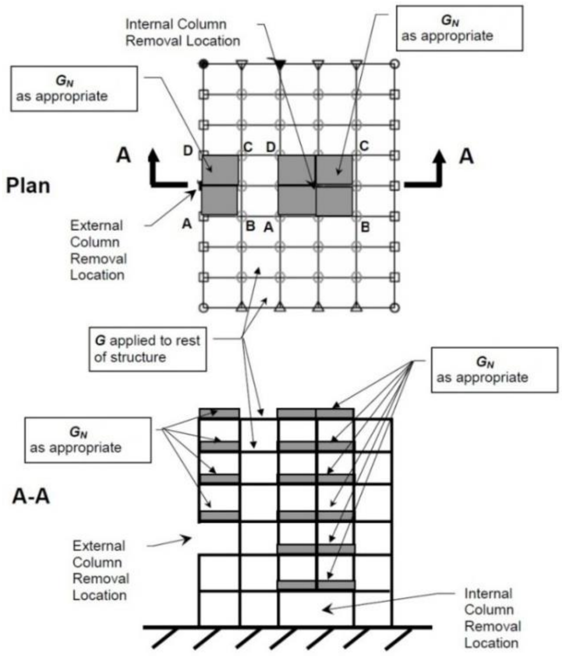

Fig. 6 The way of loading G_N or G on the building (UFC 2009)

$$G_N = \Omega_N[1.2DL + (.5LL \ \ or \ \ .25SL)] \tag{13}$$

Where G_N is the increasing gravitational load for static and non-linear analysis; DL, LL, and SL are dead, live, and snow loads respectively; and Ω_N is the increasing dynamic coefficient (a kind of DIF). UFC Manual is a new method to determine a suitable DIF based on allowed transformation and function alignment, presented below

$$\Omega_N = 1.04 + \frac{.45}{\theta_{ls}/\theta_y + .48} \tag{14}$$

Where θ_{ls}/θ_y is the lowest proportion between the element's plastic rotation and that of submission.

b) Gravity Loads for Floor Areas Away From Removed Column (G)

$$G = 1.2DL + (.5LL \ \ or \ \ .25SL) \tag{15}$$

The way of applying the loads in this step is demonstrated in Fig. 6.

3.3.2 Evaluation of total fragility of the building in proportion to the columns' local collapse ($P(S_k \mid D_i \cap EX_i)$)

In order to evaluate the intended fragility in each scenario at first in the determined positions (index points) a blast will happen. Afterwards the local failure of each column should be analyzed for which the DCR parameter is used in accordance with GSA code (2003). As a matter of fact, DCR is the ratio of the required force to the capacity of each structural member that can be obtained in curve, shear, or other methods. For each column in each scenario, the present study surveys moment and shear DCR, taking into consideration the most critical way of each column, possible. After identifying the damaged columns (with disallowed DCR) in every scenario, it should be removed from beam-column connection instantly. Fig. 7 shows the correct approach for removing the damaged column.

After removing the columns the maximum allowable collapse area for each damaged column should be evaluated in accordance to GSA code (Fig. 8).

Eventually, the intended non-linear static analysis is carried out for the damaged building. In this way if a column is found which has disallowable DCR, and is not located in the maximum allowable local collapse area of the aforementioned damaged columns, it can be concluded that the building has a progressive and total collapse against the omission of that column in the intended scenario. For example, in the seventh scenario, by making a blast local dynamic analysis, columns $D_{5,4}$ and $D_{6,4}$ are damaged (Fig. 9). After omitting them and calculating the maximum allowable local collapse area for each, a non-linear static analysis was made, showing that column $D_{4,2}$ is damaged (Fig. 10). This column is not located in the maximum allowable local collapse area of the previous ones; thus it can be concluded that progressive collapse in this scenario has happened in relation to the local collapse of columns $D_{5,4}$ and $D_{6,4}$.

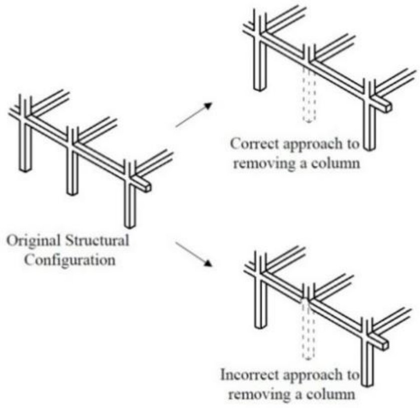

Fig. 7 Correct removal of the column in accordance with GSA code (2003)

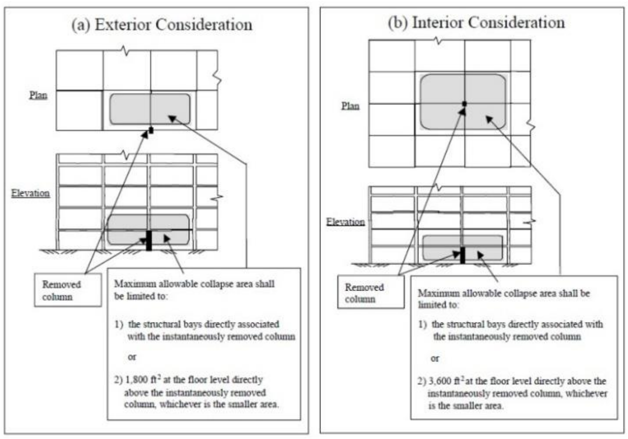

Fig. 8 Maximum allowable local collapse area in a building in relation to column removal(GSA 2003)

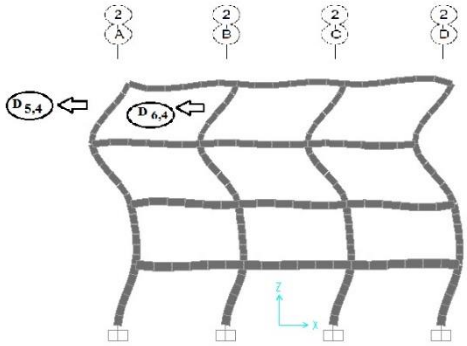

Fig. 9 Local collapse of columns $D_{5,4}$ and $D_{6,4}$ in the seventh scenario

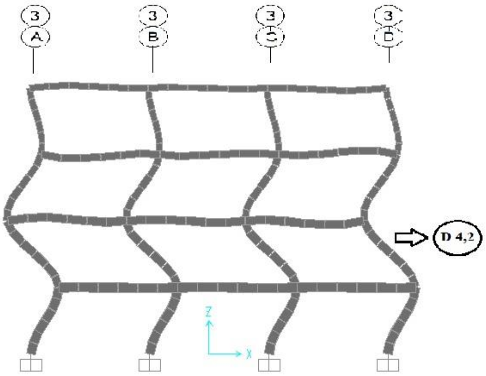

Fig. 10 Local collapse of column $D_{4,2}$ in the seventh scenario

The intended modeling and analyses have been done in SAP 2000 v14. Occurrence or no occurrence of progressive collapse is considered as Bernoulli Distribution Function in each scenario. I_c is an index, being between one and zero. If for each column's local collapse, a progressive collapse takes place it will be one; otherwise it will be zero. This index will be analyzed in this way in all scenarios. The intended fragility curve for each column can be drawn by means of the following equation

$$P(S_k \mid D_i \cap EX_i) = \frac{\sum_{i=1}^{N_{Sim}} I_c}{N_{Sim}} \tag{16}$$

Where N_{Sim} is the number of all scenarios. Fragility curve for each column is drawn in the Figs. 11 to 14. These curves have been drawn based on cumulative distribution function of Eq. (16) as well as most critical DCR changes for each column.

An extreme value of 2 for DCR can become a criterion for failure or collapse of structural member (GSA 2003); therefore, considering the produced frailty curve for each column, the fragility possibility of the entire building in case of local collapse for each column in relation to the critical event of blast ($P(S_k \mid D_i \cap EX_i)$) is demonstrated in Table 1.

On the other hand, it was observed that among 15 mentioned blast scenarios, in 11 cases there happened a progressive collapse; as a result, the $C_{ind,ijk}$ parameter will be equal to 11.

In order to calculate $P(D_j \mid EX_i)$ parameters for each column it should be studied in how many scenario out of

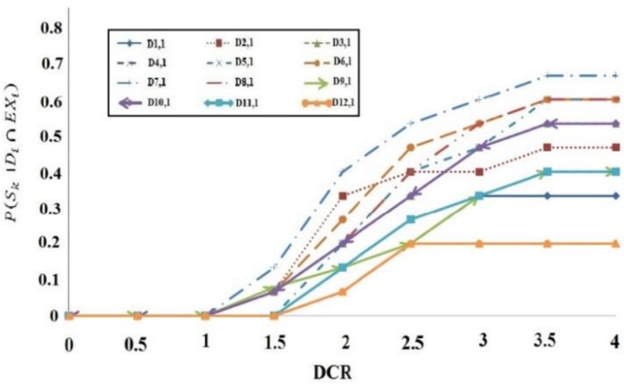

Fig. 11 Fragility curves of the first floor's columns

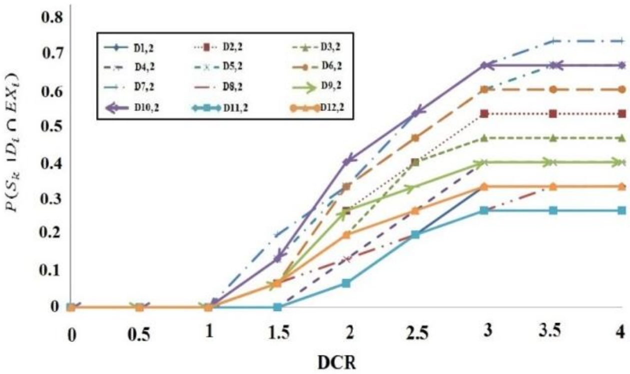

Fig. 12 Fragility curves of second floor's columns

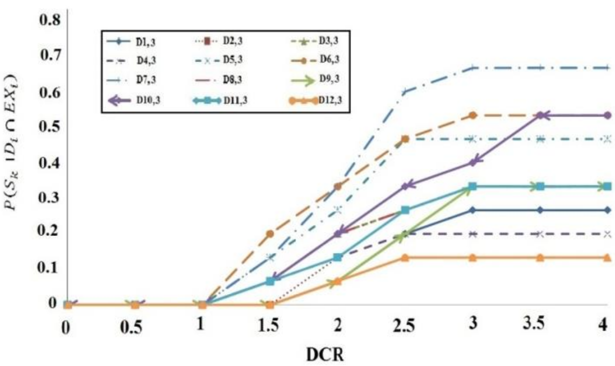

Fig. 13 Fragility curves of third floor's columns

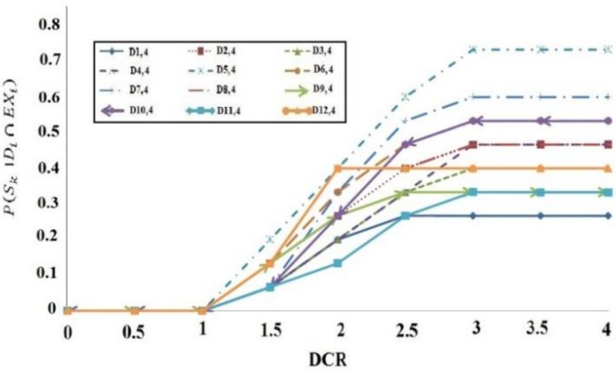

Fig. 14 Fragility curves of fourth floor's columns

Table 1 Probability of total fragility ($P(S_k \mid D_i \cap EX_i)$) in case of local collapse for each column

Column NO.	Probability of Total Fragility	Column NO.	Probability of Total Fragility	Column NO.	Probability of Total Fragility	Column NO.	Probability of Total Fragility
$D_{1,1}$	0.13	$D_{1,2}$	0.06	$D_{1,3}$	0.06	$D_{1,4}$	0.20
$D_{2,1}$	0.06	$D_{2,2}$	0.26	$D_{2,3}$	0.13	$D_{2,4}$	0.26
$D_{3,1}$	0.20	$D_{3,2}$	0.20	$D_{3,3}$	0.20	$D_{3,4}$	0.20
$D_{4,1}$	0.06	$D_{4,2}$	0.13	$D_{4,3}$	0.13	$D_{4,4}$	0.20
$D_{5,1}$	0.20	$D_{5,2}$	0.33	$D_{5,3}$	0.26	$D_{5,4}$	0.40
$D_{6,1}$	0.26	$D_{6,2}$	0.33	$D_{6,3}$	0.33	$D_{6,4}$	0.33
$D_{7,1}$	0.40	$D_{7,2}$	0.33	$D_{7,3}$	0.33	$D_{7,4}$	0.33
$D_{8,1}$	0.20	$D_{8,2}$	0.13	$D_{8,3}$	0.20	$D_{8,4}$	0.40
$D_{9,1}$	0.13	$D_{9,2}$	0.26	$D_{9,3}$	0.06	$D_{9,4}$	0.26
$D_{10,1}$	0.20	$D_{10,2}$	0.40	$D_{10,3}$	0.20	$D_{10,4}$	0.26
$D_{11,1}$	0.13	$D_{11,2}$	0.06	$D_{11,3}$	0.13	$D_{11,4}$	0.13
$D_{12,1}$	0.06	$D_{12,2}$	0.20	$D_{12,3}$	0.06	$D_{12,4}$	0.40

Table 2 Probability for each column $P(D_j \mid EX_i)$

Column NO.	$P(D_j \mid EX_i)$	Column NO.	$P(D_j \mid EX_i)$	Column NO.	$P(D_j \mid EX_i)$	Column NO.	$P(D_j \mid EX_i)$
$D_{1,1}$	0.33	$D_{1,2}$	0.33	$D_{1,3}$	0.26	$D_{1,4}$	0.26
$D_{2,1}$	0.47	$D_{2,2}$	0.53	$D_{2,3}$	0.33	$D_{2,4}$	0.46
$D_{3,1}$	0.53	$D_{3,2}$	0.47	$D_{3,3}$	0.33	$D_{3,4}$	0.40
$D_{4,1}$	0.40	$D_{4,2}$	0.40	$D_{4,3}$	0.20	$D_{4,4}$	0.47
$D_{5,1}$	0.60	$D_{5,2}$	0.67	$D_{5,3}$	0.47	$D_{5,4}$	0.73
$D_{6,1}$	0.60	$D_{6,2}$	0.60	$D_{6,3}$	0.53	$D_{6,4}$	0.53
$D_{7,1}$	0.67	$D_{7,2}$	0.73	$D_{7,3}$	0.67	$D_{7,4}$	0.60
$D_{8,1}$	0.60	$D_{8,2}$	0.33	$D_{8,3}$	0.33	$D_{8,4}$	0.47
$D_{9,1}$	0.40	$D_{9,2}$	0.40	$D_{9,3}$	0.33	$D_{9,4}$	0.33
$D_{10,1}$	0.53	$D_{10,2}$	0.67	$D_{10,3}$	0.53	$D_{10,4}$	0.53
$D_{11,1}$	0.40	$D_{11,2}$	0.26	$D_{11,3}$	0.33	$D_{11,4}$	0.33
$D_{12,1}$	0.20	$D_{12,2}$	0.33	$D_{12,3}$	0.13	$D_{12,4}$	0.40

the total 15 scenarios each column suffers local damage. Local damage of each column might cause a total damage to the building and it is in accordance with it that the Table 2 is drawn.

Based on the obtained measures, finally

$$R_{Ind} = \quad 0.273 \tag{17}$$

3.4 Calculating R_{Dir} term

$C_{dir,ij}$ Parameter is equal to the number of direct consequences (local damage) in all occurring scenarios. Accordingly, in the total 15 occurring scenarios, 43 columns suffered local damage which is equal to the amount of $C_{dir,ij}$ parameter.

Thus it can be concluded that

$$R_{Dir} = \quad C_{dir,ij} \times 5\times10^{-3}\left[P(D_{1,1} \mid EX_i) + P(D_{2,1} \mid EX_i) + \cdots + P(D_{12,4} \mid EX_i)\right] = 4.594 \tag{18}$$

4. Discussion on risk-based robustness index

In accordance to risk-based robustness index terms (I_{Rob}), analyzed in previous sections, it can be concluded that

$$I_{Rob} = \frac{R_{Dir}}{R_{Dir} + R_{Ind}} = 0.943 \tag{19}$$

Based on what was explained in section 2, the amount of I_{Rob} index would be between zero and one. As this rate moves closer to one, it means that despite severe local damage (direct consequence), total damage (indirect consequence) would be less, in which case higher robustness is attributed to the building. Due to the amount of this index in Eq. (19), an acceptable robustness with relatively high extreme value can be attributed to this building. A reason behind the achieved result is using improved design code (Eurocode 8 2005) for this building as in this code the importance and position of building's robustness is known and in terms and conditions of building design, considering building's internal features leads to suitable and acceptable robustness. In other words, it can be expected that eventual consequences and damages of critical events in such buildings are relevant to initial damages of such happenings.

5. Conclusions

This study suggested a new method to evaluate risk-based robustness in buildings. The critical event was considered to be a gas blast, which based on uncertainty parameter took place in a discrete sample space. And the terms of risk-based robustness index (I_{Rob}) were evaluated, according to such scenario making. Considering the use of an advanced designing code (Eurocode 8) an acceptable rate of robustness was obtained since in the terms and conditions of this code a great deal of attention is paid to internal features of the building such as uncertainty, flexibility, and connection features. Finally it can be said that this robustness index is capable of being expanded to two critical events (like earthquake and blast or fire). In this circumstance, compatibility or incompatibility, or dependence or independence of the critical event is of high account and it can be concluded that it has great influence.

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