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ANALIZA ROBUSNOSTI AB ZGRADE ZA RAZLIČITE SCENARIJE UKLANJANJA IVIČNIH STUBOVA

Rezime:

Analiza robusnosti konstrukcija je veoma kompleksna sa velikim brojem uticajnih parametara na ponašanje sistema izloženeg određenom dejstvu. Robusnost predstavlja mogućnost konstrukcije da se, u slučaju lokalnog/delimičnog loma odupre progresivnom rušwnju. U ovom radu analiziran je uticaj uklanjanja ugaonih stubova na robusnost konstrukcije AB višespratne zgrade. Upoređene su razlika odgovora konstrukcije pri uklanjanju stubova na uglu zgrade i izvorne konstrkcije. Komparativna analiza izražena je sračunatim vrednostima graničnih stanja, krivih povredljivosti i procenjenih gubitka.

Ključne reči: AB zgrada, robusnost, granična stanja oštećenja, povredljivost, gubitak

ROBUSTNESS ANALYSIS OF A RC BUILDING FOR A DIFFERENT CORNER COLUMNS REMOVAL SCENARIOS

Summary:

The robustness of structures is a very complex problem with a large number of parameters that influence the analysis settings and the results that describe the behaviour of the system exposed to a certain action. Robustness represents the ability of a structural system to resist the progressive collapse. In this paper, the effect of the removal of the corner columns on the structural response and robustness of the structure was analysed. The goal of this research was to compare the difference of the structural response of the building, before and after the removal of the corner columns. In this paper, the effect of the removal of the corner columns was described through the limit state values comparison, fragility and vulnerability curves. Based on the analysis, obtained results are compared and final remarks and conclusions were formulated.

Key words: RC building, robustness, damage limit states, fragility, vulnerability

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1. INTRODUCTION

The robustness of the structure is its ability to prevent the complete collapse of the building or of its major part in the event of its partial failure. Robustness analysis is a very complex problem with a large number of parameters that influence the analysis settings and results that describe the behaviour of the system exposed to a certain action. At the same time, damage and collapse of structures cause accidental actions with a low probability of occurrence and often strong effects on the structure. However, in the case of accidental actions, local damage most often occurs, so it is important to assess the extent and location of the damage and their impact on the integrity of the structure, and/or possible loss of the system load bearing capacity.

The progressive collapse of a RC building structures most often occurs when one or more vertical supporting elements lose their load bearing capacity due to accidental actions. These can be terrorist attacks, vehicle impacts, gas explosions, etc. As previously stated, accidental actions occur very rarely, but are often accompanied by major consequences, even progressive collapse of the structure.

The most comprehensive review of numerical and experimental research and technical regulations dedicated to progressive collapse, with comparative analyses is presented in [1]. In the paper [2], a broader review of the literature and regulations for assessing robustness and appropriate recommendations and measures to prevent or mitigate the progressive collapse is presented. Some provisions from international documents related to the robustness of RC building structures were compared.

The paper [3] proposed a definition according to which robustness represents the ability of the structural system to resist progressive collapse. Beside the ones mentioned in the papers [1] and [4], there are several other definitions taken from the DoD UFC Guidelines [5], GSA [6] and corresponding literature. Significantly more precise improvements in the definition and reliability of methods for increasing robustness were proposed in the report COST Action TU-06012 - Robustness of Structures [7].

In the research [8], the results of the analysis of the structural system of buildings were presented, on the basis of which the bearing capacity of new and existing buildings and their influence on progressive collapse would be described. Fragility of RC building structures, which are predominantly present in Europe, is the subject of the paper [9].

The building structure was analyzed using a set of Eurocodes (EC0 to EC8), while the procedure described in [10] was used for the constitutive relations of RC and steel reinforcement.

In this paper, the effect of the removal of the corner columns A1, A2, A3, A4 and A5 on the structural response and robustness of the structure was analysed. A1 is the corner column on the 1st level (ground floor), A2 corresponds to the corner column on the 2nd level, A3 is on the 3rd, A4 is at the 4th and A5 is a corner column at the last floor of the building. The goal of this research was to compare the difference of the structural response of the building, based on the removal of the corner column, but on different level for each column removal scenario. The model of the building that was used in the analysis was used in the paper [11] in which the robustness of the structure was described using fragility curves, for the removal scenarios of all ground columns. In this paper, the effect of the removal of the corner columns was described through limits state values comparison, fragility and vulnerability curves.

Based on the analysis, obtained results are compared and final remarks and conclusions were formulated.

2. METHODOLOGY OF THE ANALYSIS

2.1. PROPERTIES OF THE STRUCTURE, LOADS AND ACTIONS

The subject of the analysis is office-residential building (Fig. 1) with 5 levels (ground floor+4 stories). The structural system exhibits the properties of a frame structural system [4]. The plan view and the 3D model of the structure are shown in Fig. 1. The length of one span in both directions is 4.8 m which makes the total length of the building 19.2 m in both directions. The height of the first story is 3.6 m and the height of the other stories is 3.2 m which makes the total height of the building 16.4 m. In order to simplify the modelling and calculation process, all vertical elements are fixed at the bottom level of the structure, i.e. soil-structure interaction is not included in the calculation and design. [11]

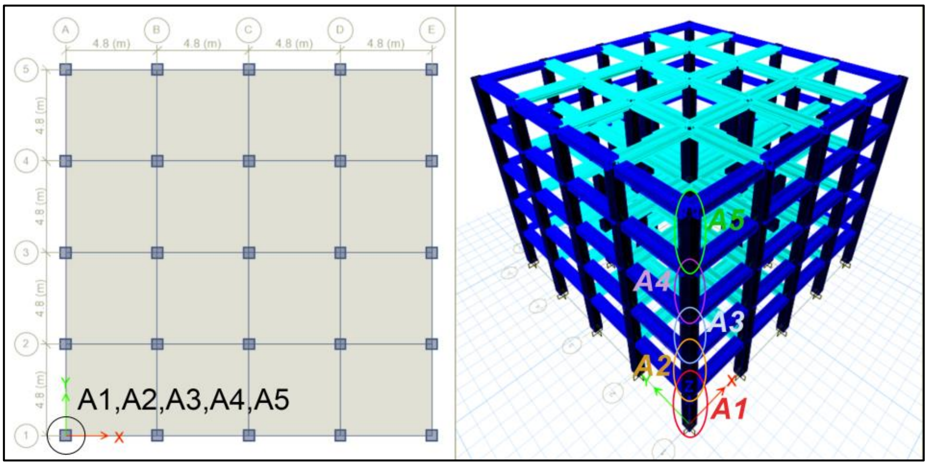

Figure 1 - Building plan with marked removed columns (left) ; Structure model (right)

The design of the structural model is done according to the recommendations given in the set of structural Eurocodes [12], [13], [14], [15]. Structural properties of the model and the loads acting on the structure are described in detail in the paper [11].

Load combinations, for the nonlinear robustness analysis, are used according to [5], [6]:

$$W = 1.2 \cdot G_i + 0.5 \cdot Q_i \quad (1)$$

$$Q_R = \Omega_R \cdot (1.2 \cdot G_i + 0.5 \cdot Q_i) = \Omega_R \cdot W \quad (2)$$

where W represents the gravity loads combination and Ω_R represents additional gravity loads parameter or dynamic increase factor (DIF) of the additional gravity load for the analysis of the non-linear behaviour of the structural system. DIF (Ω_R) is incrementally increased for the robustness analysis until the collapse, demanded state or non-convergence of the model is reached. In NDA procedure, loading of the structure and the column removal scenario in the NDA is done according to the [5], [6] provisions.

2.2. MODAL ANALYSIS

Rayleigh viscous (mass – tangent stiffness) proportional damping was used in NDA. Calculation parameters of interest for the robustness analysis are the first and the last period of vibrations $T_{1,i}$ and $T_{2,i}$, which is thoroughly described in [11]. Values of the used periods in seismic and robustness analysis are shown in Table 1.

Table 1 – Relevant vibration periods of models for robustness analysis

Vibration periods	T_1 [s] (Σm_{eff} [%])	T_2 [s] (Σm_{eff} [%])
A1	0.2 s (1.45%)	0.023 s (92.69%)
A2	0.223 s (0.36%)	0.022 s (92.52%)
A3	0.201 s (0.85%)	0.022 s (93.40%)
A4	0.206 s (0.36%)	0.022 s (91.34%)
A5	0.255 s (0.20%)	0.022 s (93.29%)

2.3. NONLINEAR ANALYSIS AND PLASTIC HINGE PROPERTIES

The assumptions, simplifications and plastic hinge properties used in models for post-elastic analysis of structural response to the removal of individual vertical elements are described in the paper [11].

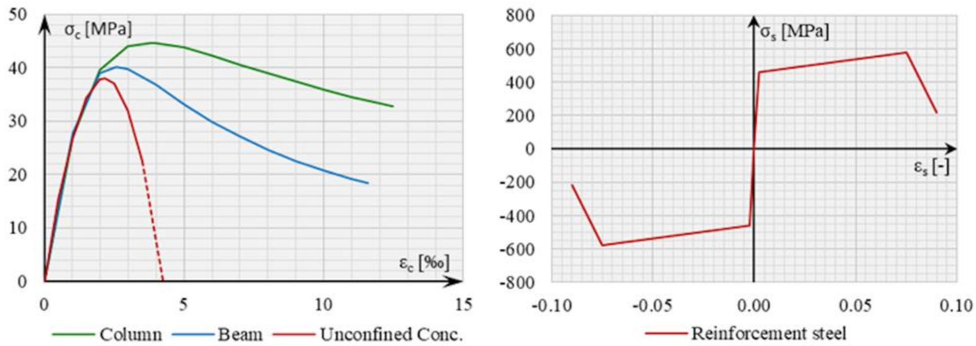

Figure 2 - Material properties of concrete (left) and rebar (right) [11]

3. METHODOLOGY OF THE ANALYSIS

3.1. NONLINEAR DYNAMIC PUSHDOWN ANALYSIS

The results for sudden column removal and its effect on vertical displacement are shown in Fig. 3 and the results of nonlinear dynamic pushdown analyses are shown in Fig. 4.

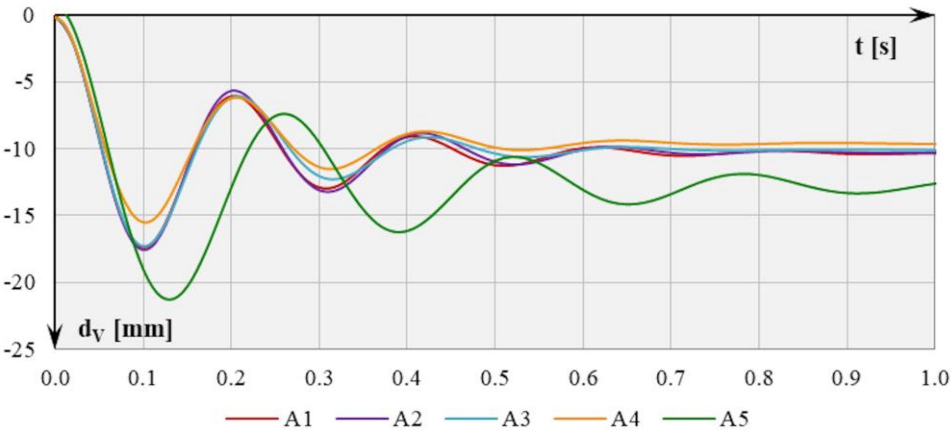

Figure 3 – Vertical displacements after sudden column removal

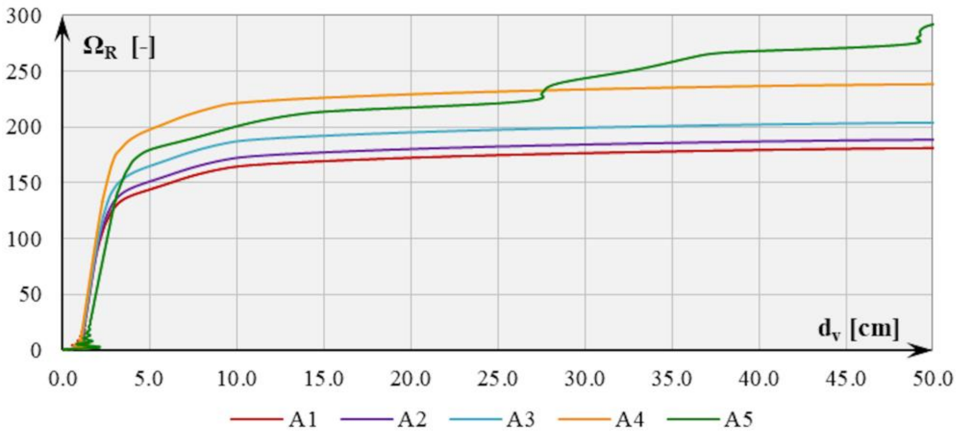

Figure 4 – Nonlinear dynamic analysis pushdown curves

The results show, as expected, that the structural system is more robust and resilient to progressive collapse if the removed corner column is located on the higher level.

3.2. DAMAGE LIMIT STATES

To quantify and compare the results of the corner column removal scenarios, from the perspective of the progressive collapse risk, methods proposed by [8] for the determination of damage LS, based on NDA are used. Limit states in this paper are defined in a following way:

- ***LS1*** (minor damage): LS1 occurs either in the first step, when reaching the reinforcement creep limit $(\varepsilon_{sy} = 0.23\%)$ or the stress limit of concrete with maximum strength in the protective layer of concrete $(\varepsilon_{c,1} = 2.16‰)$.

- ***LS2*** (moderate damage): Occurs when the vertical displacement, obtained as the ratio of displacement of the top above the removed column and the length of the beam span, exceeds the determined threshold $d_V = 1.0\%$.
- ***LS3*** (significant damage): This level of damage is assumed to occur when reaching the stress limit in the protective layer of concrete $\left(\varepsilon_{c,u} = 3.5‰\right)$ or the maximum stress of the confined concrete core $\left(\varepsilon_{cc,1} = 2.56‰\right)$.
- ***LS4*** (severe damage): Occurs in the first step, when the ultimate stress is reached in the confined concrete core $\left(\varepsilon_{cc,u} = 11.56‰\right)$.
- ***LS5*** (progressive collapse): It is determined as the state at the dilatation value in steel at which tensile fracture in the longitudinal reinforcement bar occurs $(\varepsilon_{su} = 7.5\%)$.

Damage limit states LS1-LS5 for different column removal scenarios A1-A5 are displayed in Figure 5 as a function of additional load intensity Ω_R.

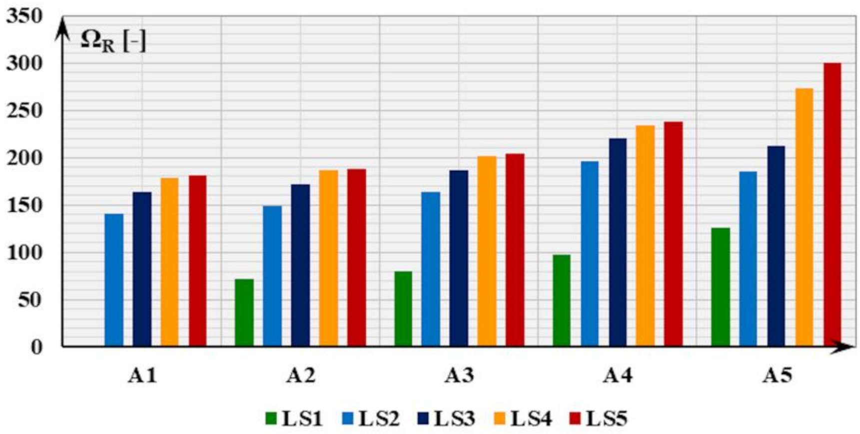

Figure 5 – Damage limit states LS1-LS5 for different corner column removal scenarios

The difference between the referent scenario A1, which is established as the most critical case among the chosen scenarios, and the rest A2-A5, $\Delta\Omega_R$ is displayed in Figure 6.

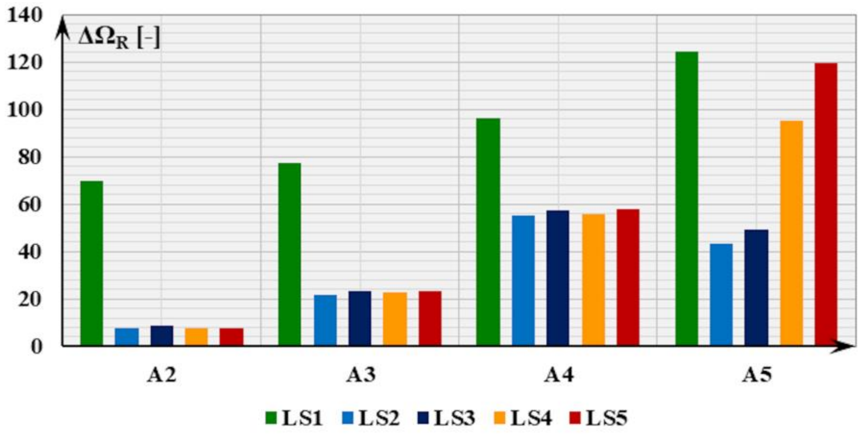

Figure 6 – Difference between damage limit states LS2-LS5 and LS1

Same as NDA, the damage limit state assessment results show, as expected, that the structural system is more robust and resilient to progressive collapse if the removed corner column is located on the higher level and it can be described in general as: $\Omega_R^{A1}(LSi) < \Omega_R^{A2}(LSi) < \Omega_R^{A3}(LSi) < \Omega_R^{A4}(LSi) < \Omega_R^{A5}(LSi)$ with some minor exceptions in case of scenario A5 for damage limit states *LS2* and *LS3*.

3.3. FRAGILITY ANALYSIS

Based on the results obtained through NDA, normal distribution was adopted for the robustness fragility curves calculation. In case of the calculation of robustness fragility curves, using $\Omega_{R,i}$, the fragility function is calculated as analytical cumulative distribution function (CDF) for normal distribution:

$$P_{LS_i|\Omega_{R,i}}\left(\Omega_{R,i}, \mu_{LSi}^{\Omega_R}, \sigma_{LSi}^{\Omega_R}\right) = \Phi\left(\frac{\Omega_{R,i} - \mu_{LSi}^{\Omega_R}}{\sigma_{LSi}^{\Omega_R}}\right) \tag{3}$$

where Φ is the cumulative distribution function of the standard normal distribution, $\mu_{LSi}^{\Omega_R}$ and $\sigma_{LSi}^{\Omega_R}$ are the mean and standard deviation of normal distribution values shown in Fig. 7.

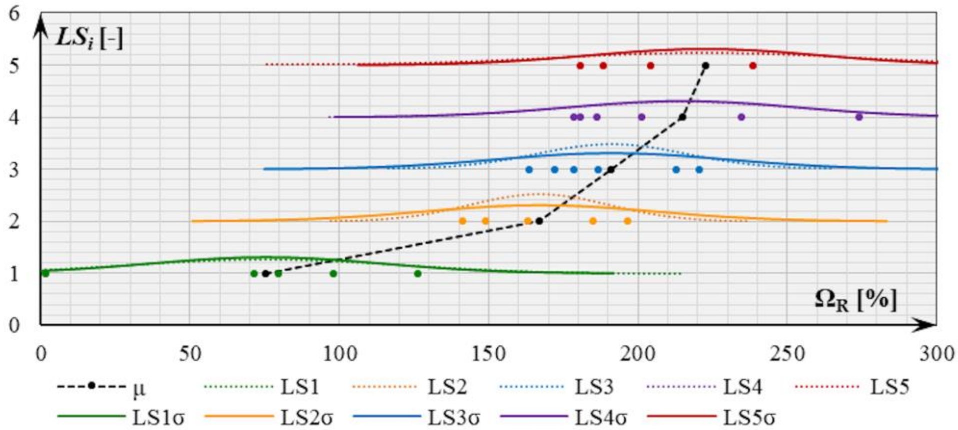

Figure 7 – Calculated (LS_i) and corrected ($LS_i\sigma$) normal distribution probability density functions (PDF)

To avoid the overlapping of the fragility functions, their correction is performed by adopting the same standard deviation value for all LS, using the MLE method described in [16], [17]. $\mu_{LSi}^{\Omega_R}$ and $\sigma_{LSi}^{\Omega_R}$ for uncorrected and corrected fragility curves are shown in Table 2 and robustness fragility curves are displayed in Fig. 8.

Table 2 – Robustness fragility parameters

Ω_R [%]	$\mu_{LSi}^{\Omega_R}$	$\sigma_{LSi,unc}^{\Omega_R}$	$\sigma_{LSi,corr}^{\Omega_R}$
LS1	75.44	46.258	38.748
LS2	166.96	23.318	
LS3	191.12	24.959	
LS4	214.88	39.327	
LS5	222.44	48.917	

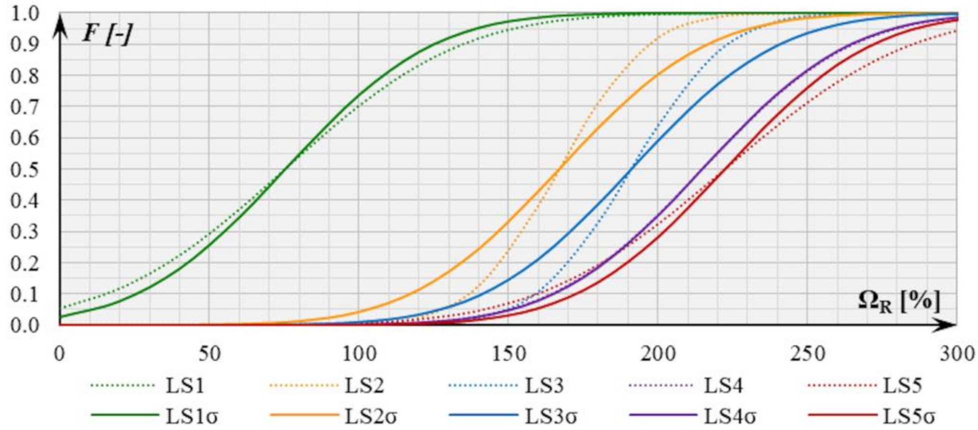

Figure 8 - Robustness fragility curves for A1-A5 corner column removal scenarios

Calculated fragility functions represent the probability of exceedance of certain damage LS for all different corner column removal scenarios. They can be used to compare the structural response of the building in case of the analogy chosen scenarios for other column positions in the building and give an insight in the fragility of the structure in dependence of the positions of the removed elements.

3.4. VULNERABILITY ANALYSIS

To calculate the vulnerability function for the used scenarios, normal distribution PDFs for mentioned LS_i and no damage limit state (*LS0*) are calculated, according to the equation:

$$\begin{aligned} P_{LS_0} &= 1 - P_{LS_1}\left[\Omega_{R,i}, \mu_{LSi}^{\Omega_R}, \sigma_{LSi}^{\Omega_R}\right] \\ P_{DS_i} &= P_{DS_i}\left[\Omega_{R,i}, \mu_{LSi}^{\Omega_R}, \sigma_{LSi}^{\Omega_R}\right] - P_{DS_{i+1}}\left[\Omega_{R,i+1}, \mu_{LSi+1}^{\Omega_R}, \sigma_{LSi+1}^{\Omega_R}\right] \\ P_{DS_n} &= P_{DS_n}\left[\Omega_{R,n}, \mu_{LSn}^{\Omega_R}, \sigma_{LSn}^{\Omega_R}\right] \end{aligned} \quad (4)$$

Vulnerability curve represent the cumulative distribution of the total repair cost of the structure. The transformation of the fragility curves into vulnerability curves can be conducted by using the following total probability relation, according to [18], where: $E(C|LS_0) = 0\%$, $E(C|LS_1) = 1\%$, $E(C|LS_2) = 10\%$, $E(C|LS_3) = 35\%$, $E(C|LS_4) = 75\%$, $E(C|LS_5) = 100\%$.

$$E(C|\Omega_R) = \sum_{i=0}^{n} E(C|LS_i) \cdot P(LS_i|\Omega_R) \quad (5)$$

where *n* is the number of limit states (LS_i) considered, $P(LS_i|\Omega_R)$ is the probability of a building sustaining LS_i given intensity, Ω; $E(C|LS_i)$ is the complementary cumulative distribution of the cost (loss) given the LS_i; and $E(C|\Omega_R)$ is the complementary cumulative distribution of cost (or loss) given a level of intensity, Ω_R. [18]

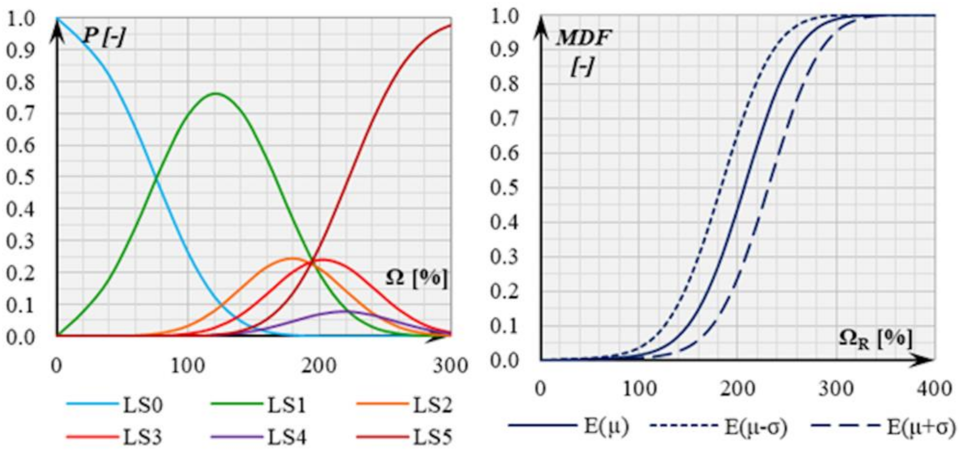

Figure 9 - Normal distribution PDFs (left) and vulnerability curves with ±1 standard deviation value (right)

Calculated vulnerability functions represent the value of the mean damage factor (MDF) of the analysed structures and intensity measure (dynamic increase factor - DIF (Ω_R) in this case). In this way, it is possible to gain insight into the threat to the usability of the structure under accidental actions. They can be used to compare the structural response of the building in case of the analogy chosen scenarios for other column positions in the building and give an insight into vulnerability of the structure in dependence of the positions of the removed elements.

4. CONCLUSIONS

In this paper, the robustness analysis of an RC frame building for the removal of corner columns along all levels is performed. Columns are removed according to the mentioned scenarios and the response of the structure is analysed using nonlinear dynamic pushdown analysis method. Damage limit states are determined and fragility and vulnerability curves were constructed. Based on the obtained results, as expected, it can be concluded that the structural system is more robust and resilient to progressive collapse if the removed corner column is located on the higher level. Through the applied analysis, it was possible to gain the insight into the robustness of the structure. This approach can be used to compare the structural response of each column in the vertical in the building for analogy chosen scenarios for other columns in the building and to gain an insight into the fragility and vulnerability of the structure in dependence of the positions of the removed elements.

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