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STRUCTURAL RESPONSE ANALYSIS FOR RC FRAME STRUCTURES UNDER SEISMIC ACTION

BY

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Abstract. This paper analyses the response of a set of RC frame structures, with different structural parameters, under seismic actions. The purpose is to observe how the structural response varies depending on the structural and seismic action parameters. For this analysis, four structural parameters were selected to be modified and each structure thus obtained was subjected to three seismic actions. In this study case, the structural response is given by the fundamental vibration period of the damaged structure T_f, the maximum displacement d_{max} and the inter-story drift ratio *IDR*. Two of these values, i.e. T_f and *IDR*, are related directly to the post-seismic structural damage state, which is one of the most important indicators of the structural response.

Keywords: structural response, seismic action, structural damage state, inter-story drift ratio, maximum displacement.

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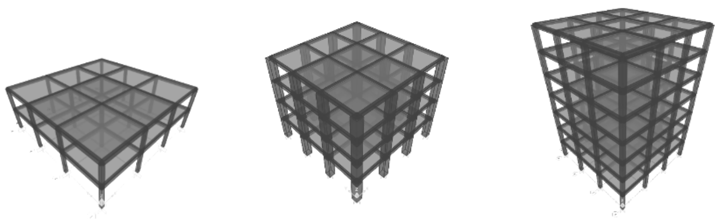
1. Introduction

When subjecting a structure to a specific seismic action, a set of results is obtained associated strictly with that structure and those seismic parameters. When dealing with large urban areas having buildings characterized by different structural parameters, e.g. height, and considering the occurrence of seismic events, it is difficult to analyze all structures. A damage analysis made in a short period after an earthquake can enhance the human safety level and speed up the city's recovery process. Therefore, it is essential to be able to approximate their response, and thus obtain the expected damage level as fast as possible and efficiently. One method is to consider several structural models with parameters' values varying in a specific range. Then, to extrapolate the results by using methods from the field of artificial intelligence.

2. Input structural and seismic action parameters

To analyze the evolution of the building's response depending on the structural parameters, it is essential to define, at first, the type of structural model and, afterward, the fixed and varying structural parameters. For this study case, a reinforced concrete frame model was selected, as illustrated in Fig. 1.



a) 2-levels b) 4-levels c) 7-levels

Fig. 1 – Reinforced concrete frame models.

The material type, reinforcement and number of bays on each building side were considered as fixed parameters. Thus, the concrete class was C20/25 for the frame and C16/20 for the slab, the minimum reinforcement was used for all concrete sections, computed according to the present seismic code P100-1/2013 and the norm SR EN 1992-1-1:2004. In what concerns the geometric shape of the building, the number of bays on each side was set as fixed for all structural models, i.e. 3 bays in the Ox direction and 3 bays in the Oy direction. In addition, four varying structural parameters were considered, as presented in Table 1.

Table 1
Varying structural parameters of the analysis models

Parameter	Measurement unit	Values
Number of floors	-	2, 4, 7
Column cross-section width	m	0.3, 0.4, 0.5, 0.7
Bay width	m	3, 4, 5
Floor height	m	2.8, 3, 3.5

From the total number of parameter combinations, only the plausible structural models were selected to be analyzed. Thus, 62 three-dimensional structural models were simulated based on the varying structural parameters' combinations, each of them being subjected to three seismic actions of different intensities, as described in Table 2, where *PGA* is the Peak Ground Acceleration, *PGV* – the Peak Ground Velocity, *PGD* – the Peak Ground Displacement and *SI* – the Spectral Intensity.

Table 2
Seismic actions parameters

No. crt.	Earthquake/ Station	PGA [cm/s^2]	PGV [cm/s]	PGD [cm]	SI [cm]
1	Vrancea 1977 NS	194.93	70.0451	89.8429	211.26279
2	Kobe 1995	338.15.07	27.67793	9.69435	141.64498
3	Northridge 1994	557.5023	51.8262	9.0347	184.00519

The seismic actions were chosen to be of different levels of intensity, considering that the structural response is influenced by the amount of seismic energy introduced in the system. The seismic recordings were obtained from the SAP2000 v 14.1.0 and SeismoSignal v 2016 databases.

3. Structural model analysis

For each structural model and each seismic action, a Nonlinear Time-History Analysis was performed using SAP2000 v 14.1.0, with the total number of scenarios reaching 186. The option of non-linearity had to be taken into account to consider the structural damages which occur during the seismic action and which influence the structural response.

The structural model was loaded statically before subjecting it to the seismic action, the considered loads being: the Dead Load, a Super-Dead Load of 3 kN/m^2 and a Live Load of 1.5 kN/m^2. Then, the Nonlinear Time-History Analysis was performed and afterward a new Modal Analysis of the damaged structure, for each of the three seismic actions was presented in Table 2. The latter analysis was performed by considering the stiffness matrix at the end of the previous analysis, i.e. the Nonlinear Time-History Analysis, thus providing the value of the fundamental vibration period of the damaged structure T_f. Through this method, information about the damage level could be obtained by comparing the initial and final fundamental vibration period of the structural model.

4. Structural response analysis

The analysis of the structural models' response under the considered seismic actions was performed by observing the variation of several output parameters, which were related to the damage state of the building. In this study case, the output parameters which were extracted directly from SAP2000 or were computed manually are the fundamental period of the non-damaged structure T_0, the fundamental period of the damaged structure T_f, the maximum displacement d_{max} and the inter-story drift ratio, i.e. *IDR*. Each of these output parameters was analyzed and comparisons were made between the results corresponding to the three seismic actions.

4.1. Variation of the fundamental vibration period

The fundamental period of the damaged structure T_f reflects the global structural damage level when compared with the fundamental vibration period of the undamaged structure T_0. Each degradation within the structure decreases its rigidity and, therefore, increases the fundamental vibration period. A comparison was made between the initial and the final fundamental period, for all scenarios. To simplify the analysis, the comparisons were grouped on seismic actions and height regime, as illustrated in Figs. 2-4, where T_0 is the fundamental vibration period of the undamaged structure and T_f is the fundamental vibration period of the damaged structure. Scenarios 1-17 were associated with the 2-story structures, scenarios 18-46 – to the 4-story structures and scenarios 47-62 – to the 7-story structures.

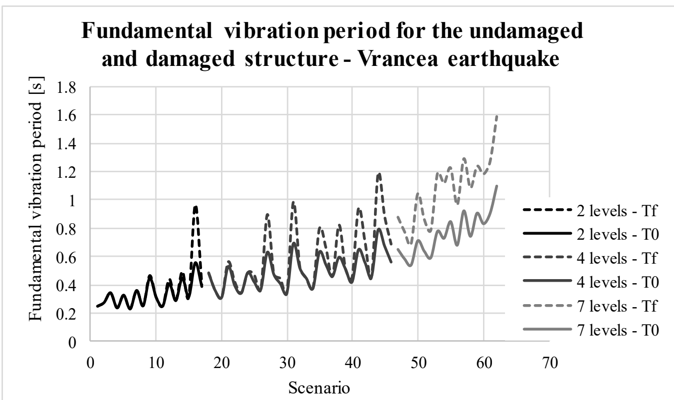


Fig. 2 – Variation of the fundamental vibration period for the undamaged and damaged structure – Vrancea earthquake.

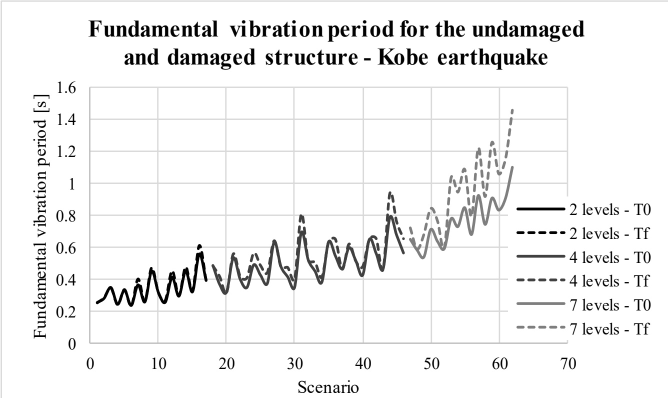


Fig. 3 – Variation of the fundamental vibration period for the undamaged and damaged structure – Kobe earthquake.

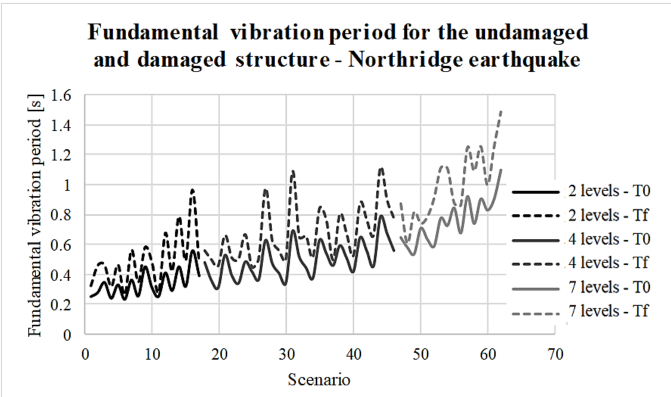


Fig. 4 – Variation of the fundamental vibration period for the undamaged and damaged structure – Northridge earthquake.

By analyzing Figs. 2-4, it was observed that the fundamental vibration period increases with the height regime, both for the undamaged and damaged state. Moreover, as the number of levels increased, the average difference between the fundamental vibration period of the undamaged structure T_0 and of the damaged structure T_f increased as well, reaching a maximum of 40.9% for the Vrancea earthquake and 23.8% for the Kobe earthquake. However, when subjected to the Northridge seismic action, the structural models registered a decrease in the average difference with the increase of the height regime. Thus, in this case, the maximum average difference of 44.9% was obtained for the 2-story structures. In addition, following the analysis of Figs. 2-4, it could be stated that the Northridge seismic action, which had the highest PGA value, caused a significant impact in all scenarios, regardless of the height regime.

In contrast, the Vrancea and Kobe seismic actions did not cause important damages within the 2-story structures, as resulting from Figs. 2 and 3, the maximum average difference between the two cases being 9.23%. The results change for the 4-story structures subjected to the Vrancea seismic action, in which case the value of the average difference was relatively important, 17.4% and was significantly higher than the one obtained for the Kobe earthquake, i.e. 9.27%. Following the comparison of Figs. 2-4, it resulted that the greatest impact on the 7-story structures was given by the Vrancea earthquake, with an average difference between T_0 and T_f of 40.87%, and not by the Northridge earthquake, which had the maximum PGA. By analyzing the seismic action parameter values from Table 2, it was observed that, although Vrancea seismic action had the lowest PGA, it also had the highest PGV. Therefore, it could be stated that the PGV had a significant influence on the structural response of high, flexible buildings.

4.2. Variation of the maximum displacement

Fig. 5 presents a comparison between the maximum displacement values of all analyzed scenarios, on seismic actions.

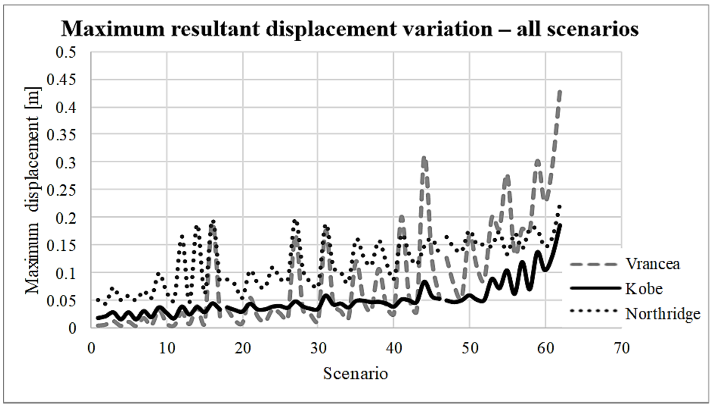


Fig. 5 – Maximum resultant displacement variation for all scenarios.

The results concerning the fundamental vibration period were reflected also in the maximum displacement variation. As the structure became more flexible, the displacement increased, the maximum value of 0.43 m being registered for a 7-story structure subjected to the Vrancea seismic action. The magnitude of this value indicated a nonlinear structural behavior, the building experiencing large deformations due to plastic hinges. By analyzing Fig. 5 it could be stated that the most destructive seismic action from the ones considered was Vrancea 1977, especially for the medium and high-rise structures. The low-rise structures are affected mostly by the high PGA seismic actions. Thus, the

Northridge earthquake induced a maximum displacement of 0.198 m in the considered 2-story structures. With the lowest PGV and a relatively medium value of the PGA, the effects of the Kobe earthquake upon the structural models were small in comparison with the effects given by the other two seismic actions. The maximum displacement of 0.187 m induced by the Kobe earthquake was obtained for a 7-story building.

4.3. Variation of the inter-story drift ratio

The maximum displacement does not reflect precisely the damage level of a structure, considering that it depends also on the building's height. However, the displacement value can be used in assessing the damage level through the inter-story drift ratio *IDR*. The IDR is defined as the ratio between the horizontal relative displacement between two adjacent floors and the corresponding story height, represented by eq. (1).

$$IDR = \frac{\delta_i - \delta_{i-1}}{h_i} \tag{1}$$

where: δ_i is the lateral displacement corresponding to the i^{th} level; δ_{i-1}, the lateral displacement corresponding to the $i-1^{th}$ level; h_i, the height of the floor between $i-1^{th}$ and i^{th} levels.

Ghobarah (2004) suggests some drift ratio limits corresponding to various damage levels, for ductile moment resisting frames MRF as presented in Table 3.

Table 3

Inter-story drift ratio limits corresponding to various damage levels

Damage level		Inter-story drift ratio [%]
No damage		< 0.2
Repairable damage	Light	(0.2;0.4)
	Moderate	[0.4;1.0)
Irreparable damage (>yield)		[1.0;1.8)
Severe damage		[1.8;3.0)
Collapse		>3.0

Fig. 6 illustrates the variation of the inter-story drift ratio *IDR* for all scenarios and each seismic action.

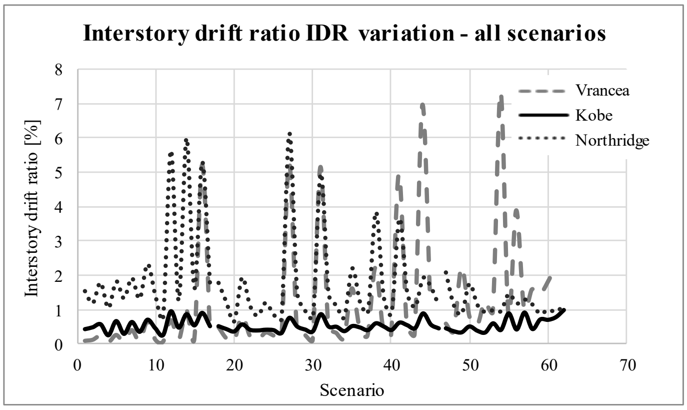


Fig. 6 – Inter-story drift ratio *IDR* variation for all scenarios.

Following the analysis in Fig. 6 and considering the drift ratio limits associated with the damage levels proposed by Ghobarah (2004), it resulted that the structures subjected to the Kobe seismic action developed, at most, some moderate repairable damages, with an IDR value smaller than 1.0%. Thus, the maximum inter-story drift ratio IDR was 0.99% taking into account all structural models subjected to the Kobe earthquake.

In contrast, the Vrancea and Northridge seismic actions caused important damage, with some structures reaching collapse, according to IDR values from Fig. 6 and the damage level limits of Ghobarah (2004). As observed in Fig. 6, the Northridge seismic action, which had the highest PGA value, affects mostly the low- and medium-height buildings, with the maximum IDR for the 2-story structures reaching 5.98%, and for the 4-story structures – 6.15%. As the structure became more flexible, the IDR value decreased for the buildings under the Northridge seismic action, the maximum value obtained being 2.1%, corresponding to the Severe damage/ Partial collapse level, according to Ghobarah (2004).

The significant impact of the Vrancea earthquake upon the medium- and high-rise buildings was reflected also in the IDR values presented graphically in Fig. 6. The highest IDR was obtained for a 7-story structure, reaching a value of 7.35%, associated with the Collapse level. For the 4-story structures subjected to Vrancea seismic action, the maximum IDR value was 6.98%. In what concerns the 2-story buildings, there was only one IDR value corresponding to the Collapse level, for the Vrancea seismic action, which corresponded to a flexible structure with a column height of 3.5 m, a bay of 5 m and a column cross-section of 0.3 m.

Based on the damage level limits given by Ghobarah (2004), from the 62 structural models analyzed, there are 7 which reach collapse for both Vrancea and Northridge seismic actions. In what concerns the repairable damage level with an upper limit of 1%, there are 44 structures subjected to the Vrancea earthquake under this limit, and 16 structures subjected to the Northridge earthquake.

5. Conclusions

Estimating the structural response requires previous analysis of several buildings with different characteristics, but having the same type of structural system. This paper presents the results of a first stage in developing a database, which used together with an artificial intelligence method, can estimate relatively fast the response and damage level of any reinforced concrete frame structure under any seismic action. The analysis of all structural models under the three considered seismic actions established that the PGV influences significantly the response of flexible structures, more than the PGA.

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ANALIZA RĂSPUNSULUI STRUCTURAL AL STRUCTURILOR PE CADRE DIN BA SUB ACȚIUNEA SEISMICĂ

Această lucrare analizează răspunsul al unor structuri de tip cadru din beton armat, cu diferiți parametri structurali, sub influența unor acțiuni seismice. Scopul analizelor este de a observa variația răspunsului structural în funcție de parametrii structurali și de cei ai acțiunii seismice. Pentru realizarea acestei analize au fost selectați patru parametri structurali, ale căror valori au fost modificate, fiecare model structural obținut fiind supus la aceleași trei acțiuni seismice. În cadrul studiului de caz, răspunsul structural este reprezentat de perioada fundamentală de vibrație a structurii degradate T_f, deplasarea maximă d_{max} și coeficientul deplasării relative de nivel *IDR*. Perioada fundamentală de vibrație T_f și coeficientul deplasării relative de nivel *IDR* sunt valori direct relaționate cu gradul de degradare structurală post-seism, care este unul dintre cei mai importanți indicatori ai răspunsului structural.