ASSESSING THE SEISMIC PERFORMANCE OF A R.C. FRAME STRUCTURE BY NUMERICAL SIMULATIONS – AN EFFICIENT TOOL FOR A SUSTAINABLE FUTURE

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Abstract. The assessment of the seismic performance of RC frame structures after one or more major seismic events is of paramount importance from the point of view of public safety. Numerical simulations by means of FEM proved to be efficient tools in assessing the seismic performance of civil engineering structures. They offer the advantage of varying several parameters in order to obtain the safety margin against structural collapse without the need of expensive experimental tests. The paper proposes a method for assessing the seismic performance of a RC frame structure by means of non-linear time-history analysis (THA). The use of numerical simulations is, in this particular case, the only solution of obtaining the safety margin to seismic actions of an existing building.

Keywords: safety margin, efficient tool, lateral displacement, storey drift.

1. Introduction

Reinforced concrete (RC) frame structures are one of the most frequently met type of structure in urban areas due to their relatively low cost of construction, compared to other materials, and their high durability. Due to their wide use, such type of structure is bound to be met in highly active seismic areas. Even though initially designed to ensure certain levels of safety in case of earthquakes, the damage accumulated in a RC structure during its lifetime due to seismic events will ultimately require its strengthening or being retrofitted to either comply with the new seismic design regulations [1] or to prevent losses during future earthquakes.
The assessment of the seismic behaviour of RC structures, with particular interest to frame structures, after one or more major seismic events is of paramount importance from the point of view of public safety. A correct estimation of the remaining strength and deformation capacity of a building [2] can be a powerful tool for decision makers in terms of whether repairs were deemed necessary or the demolition of the building would be a more viable solution [3, 4]. Either decision involves temporary shutting down some or all activities in the building and evacuation of inhabitants and providing temporary shelter / accommodation. This could have significant economic consequences, especially in the case that demolition of the building was the only option. There are also secondary effects, such as waste generation, energy consumption for producing new building materials and constructing the new building, all of these with dire consequences upon the environment [5, 6].

Numerical simulations based on the finite-element method (FEM) proved to be efficient tools in assessing the seismic performance of civil engineering structures [7]. They offer the advantage of varying several parameters in order to obtain the safety margin against structural collapse without the need of expensive experimental tests usually conducted on shake tables, in themselves a costly equipment [8]. Another advantage of numerical simulations versus traditional experimental investigations is that they create, virtually, no wastes that need to be disposed and/or recycled. In view of the recent advances in energy efficiency in terms of computational power versus required electrical power of the new computer hardware, the numerical simulations become more attractive even in terms of power consumption and generated heat and CO₂ emissions.

However, there are some drawbacks, too. For instance, in order to generate reliable numerical models, experimental investigations still need to be carried out [8]. Moreover, in case of RC frame structures, there are still some difficulties in generating a reliable numerical model mainly due to the complex nonlinear behaviour of concrete. Consequently, there are numerous research works that attempt at creating more accurate and efficient numerical models in order to grasp this complex phenomenon [9, 10].

The paper presents a method of assessing the seismic performance of a RC frame structure, frequently met in Romanian urban areas, by means of non-linear THA. The use of numerical simulations is, in this particular case, the only solution of obtaining the safety margin to seismic actions of an existing building. The obtained results could be used by competent authorities in their decision-making process in terms of public safety.

2. Numerical Model

As already mentioned, the numerical model was developed based on an existing layout of a building that is frequently met in Romanian urban areas. It is a condominium building having 7 storeys, with a total height of 26.7 meters. The numerical model was generated by means of SAP2000 software.
2.1. Geometry of the structure

The in-plane layout of the structure is shown in Fig. 1, whereas the 3D view is presented in Fig. 2. The ground floor had a height of 4.35 m and the upper floors had a height of 2.75 m. From Fig. 1 it can be observed that even though the rim of the in-plane layout would have an axis of symmetry, in this case Y axis, due to the presence of the staircase and elevator shaft, the geometrical symmetry and the distribution of rigidities would not be ensured. Consequently, it was expected that the fundamental mode of vibration would not be a purely translational one but torsional effects would also be present.

Since the purpose was to conduct a non-linear time-history analysis, the occurrence of plastic hinges is therefore expected and should be modelled into the program. The plastic hinges were allowed to form at the end of both beams and columns. The behaviour of plastic hinges for the beams was considered based on Table 6-7 from FEMA 356 code, whereas the plastic hinges at the end of the columns were defined according to Table 6-8 from FEMA 356 [11]. The formation of the plastic hinges at the ends of beams is generally governed by the bending moment whereas the plastic hinges at the end of columns are governed by the combined effect of the axial force and bi-axial bending. [12].

Although the beams had a constant cross-section along the height of the structure, the columns had different cross-sections. The storeys corresponding to a change in cross-section of the columns as well as changed layouts of the longitudinal reinforcement were 2, 4 and 6.
2.2. Loading Scenarios

The loading scenarios consist of five earthquakes that occurred during the lifetime of the structure. All earthquakes were produced by the Vrancea fault in 1977, 1986, two earthquakes in 1990 (8 hours apart) and another one in 2004. The defining elements of the seismic motions are presented in Table 1. For the 1977 Vrancea earthquake (analysis code 771) the recordings from Bucharest were used whereas for all other considered earthquakes the recordings from Iasi were considered.

**Table 1**

*Characteristics of the considered earthquakes*

| Nr. Crt. | Analysis code | Duration [s] | Peak ground accelerations (PGA) |
|----------|---------------|--------------|---------------------------------|
|          |               |              | Longitudinal component [m/s²] | Time [s] | Transversal component [m/s²] | Time [s] |
| 1        | 771           | 40.14        | 1.62                           | 5.58     | 1.95                         | 6.12     |
| 2        | 861           | 21.15        | 0.641                          | 20.385   | 1.46                         | 19.93    |
| 3        | 901           | 31.18        | 1.262                          | 14.33    | 1.095                        | 14.61    |
| 4        | 902           | 26.45        | 0.389                          | 12.025   | 0.458                        | 0.52     |
| 5        | 041           | 73.09        | 0.582                          | 22.72    | 0.658                        | 22.81    |
The seismic motions were input into the program as time history functions in the form of time versus acceleration. An example of the time-history functions for the 1977 Vrancea earthquake is shown in Fig. 3.

2.3. Analysis Procedure

The own-weight of the entire structure was partly automatically considered from the geometry of the model (length of the elements, cross-sectional dimensions, thickness of slabs, ramps for stair-case and elevator shaft) and the material characteristics (density) and partly manually input as dead loads (e.g. weight of the exterior walls, partitioning walls, floor finishing). The self-weight was defined as a non-linear static case and served as the starting point for all subsequent non-linear time-history cases. Although no plastic hinges or damages were expected from this initial loading case, by defining it as a non-linear case it offered the possibility of using the stiffness matrix of the numerical model, computed by the program at the end of the analysis step, as input stiffness matrix for the next non-linear analysis case.

Before any non-linear THA case was considered, a modal analysis was performed to obtain the dynamic characteristic of the model in the form of the fundamental period of vibration. It represents a dynamic property of the initial, undamaged, structure and serves as a reference value for the subsequent analysis cases.

Each non-linear THA case used the stiffness matrix of the numerical model computed at the end of the previous non-linear analysis case. In this way, any damage the model might have developed during a certain analysis case, it would be reflected in the stiffness matrix in the form of decreased values of the stiffness for the damaged element or elements.
After each non-linear time-history loading scenario, an additional modal analysis case was considered in order to obtain the new dynamic characteristics of the model. By comparing the newly obtained values for the fundamental periods of vibration with the initial one, it would be possible to assess whether any damage occurred in the model as it would result in increased values for the first period of vibration due to a decreased stiffness.

It would therefore be possible to classify the extent of damage into several intervals based on the degradation coefficient, $\delta_M$, proposed by DiPasquale and Cakmak in 1990 [13]. The degradation coefficient can be assessed by using the following equation:

$$\delta_M = 1 - \frac{T_0}{T_{degr}}$$

where $T_0$ is the fundamental period of vibration of the initial, undamaged, model and $T_{degr}$ is the fundamental period of vibration of the damaged model. Its usefulness and practical application has been proven by previous research works [14, 15].

In this paper, the relative lateral displacements between storeys is used as an indication of the damage accumulation after each earthquake scenario. The obtained values are compared to the maximum values prescribed by the design codes [16].

3. Results and Discussion

The obtained results are discussed in terms of lateral displacements and storey drifts. These are key parameters when assessing the behaviour of a structure to seismic loads since they can give valuable information with respect to the safety degree of a building.

Fig. 4 presents the maximum lateral displacements obtained for each non-linear time history scenario shown in Table 1. The displacements are along the longitudinal direction represented by X axis in Fig. 1.

From Fig. 4 it can be concluded that the higher the storey number, the larger the lateral displacement. Moreover, there is a certain accumulation of damage, leading to a lower lateral stiffness, with each loading scenario since the maximum lateral displacements tend to increase. The 1986 Vrancea earthquake (analysis code 861) produces smaller lateral displacements compare to the stronger 1977 earthquake.

The relative lateral displacements between storeys, in X direction, are shown in Fig. 5. The relative displacement of the first storey with respect to the ground is larger than the relative displacement between second and first storey. This is due to the fact that the considered building has a higher ground floor height, 4.35 m, compared to the subsequent storey heights, 2.75 m. However, there is an increase in the relative
displacements between lower storeys, especially for the last three earthquake scenarios. This sharp increase corresponds to the storeys where the cross-section of the columns changed along the height of the structures, leading to different lateral stiffness from one storey to another.

According to the Romanian seismic design code P100-1/2013 [16] the relative displacement between storeys for the Serviceability Limit State (SLS) is 0.005h whereas for the Ultimate Limit State (ULS) is 0.025h, where h is the storey height, expressed in meters.
It follows that even though the building was subjected to five consecutive earthquakes, the relative displacements between storeys do not exceed the limits prescribed in the design code for either the serviceability or the ultimate limit states.

The inter-storey drifts for each earthquake scenario are presented in Fig. 6. The trend is similar to the one observed for the relative displacements, Fig. 5.

![Fig. 6 – Inter-storey drifts (longitudinal direction).](image)

From the obtained results it can be concluded that there is a certain accumulation of damage in the structure due to the seismic events that occurred during its lifetime. However, the degree of degradation, after the fifth earthquake, analysis code 041, is still expressed in terms of relative displacements between storeys or in terms of inter-storey drifts, is well below the limits prescribed in the design codes [16].

Subsequent field investigations by experts confirmed the conclusions of the numerical analyses. The building was found to have sustained minor damages and, therefore, it posed no threat to the safety of its inhabitants. The report mentioned the presence of hairline cracks in non-structural components (e.g. portioning walls) and beams but without compromising the integrity of the structure. Non-destructive tests and measurements were conducted on the ground-floor columns but no internal damages were detected.

This could offer insightful information for the decision makers when analysing the opportunity for a building to undergo rehabilitation, retrofitting or simply being demolished. Either decision should not be taken lightly in view of the consequences in terms of resulted wastes, relocation of inhabitants and/or equipment, a.s.o. Accurate numerical simulations could represent an efficient tool and could bring a significant contribution to a sustainable future.
4. Conclusions

The paper presents the results of a numerical investigation on the seismic performance of a reinforced concrete frame structure subjected to several earthquake scenarios that occurred during its lifetime. The purpose was to assess whether or not numerical simulations could represent and efficient tool for decision makers and, therefore, contribute to a sustainable future.

Based on the obtained results it can be concluded that the chosen structure, frequently met in Romania urban areas, still offers a sufficiently high degree of safety to its inhabitants against future seismic events.

Even though the obtained results in terms of relative lateral displacements between storeys and the inter-storey drifts shown an accumulation of damage with each analysis case, the values are well below the limits imposed by the design codes. Subsequent field investigations confirmed the findings from the numerical simulations.

Numerical simulations can be an efficient and accurate tool for the decision makers when deciding whether a building needs to undergo rehabilitation, retrofitting to comply with the new codes or needs to be demolished. Each scenario has its own strong points and weak points that have to be assessed and analysed carefully.

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