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# Seismic sequence effects on three-dimensional reinforced concrete buildings

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ABSTRACT

Repeated earthquakes strongly affect the inelastic response of structures and cause in many cases more adverse effects in comparison with the corresponding single ground motions, such as the accumulation of structural and non-structural damage as well as the increment of deformation demands. Numerous research studies have been recently published in the pertinent literature to investigate this phenomenon but most of them are limited either to single-degree-of-freedom (SDOF) systems or to two-dimensional multi-degree-of freedom (2-D MDOF) systems such as multi-storey planar framed structures. With special regard to reinforced concrete (RC) buildings, this study investigates for the first time the inelastic response of three-dimensional (3-D) structures subjected to repeated earthquakes. More specifically, two three-storey and two five-storey RC buildings, which are regular and irregular along their height, are examined under five real strong multiple earthquakes where their two horizontal components as well as the vertical one are taken into account. The investigation focuses on the examination of the maximum displacements, maximum residual displacements, maximum interstorey drift ratio, maximum residual interstorey drift ratio, damage indices and ductility demands. Finally, the building structures under consideration are analyzed for different siting configurations to investigate the effect of earthquake direction incident. It is concluded that the multiplicity of earthquakes should be taken into account for the reliable seismic design of reinforced concrete structures.



## 1. Introduction

Seismic sequences take place frequently at many regions worldwide. As a consequence, the accumulated strains at active seismic faults are not released outright at the first rupture, but sequential ruptures take place leading to repeated earthquakes. In many cases, there is a significant damage accumulation as a result of multiplicity of earthquakes and frequently, due to lack of time between successive seismic events, any rehabilitation process seems to be unfeasible. There are numerous examples of buildings worldwide where the structural damage has been accumulated due to multiple earthquakes. For example, one can mention the recent Christchurch (NZ) seismic sequence where the Canterbury Television and the Pyne Gould Corp. buildings were damaged due to the first strong earthquake (4 Sept. 2010) and then collapsed during the second successive strong ground motion (22 Feb. 2011). Although the recognized observable fact for multiple earthquakes, the modern seismic design codes have not considered adequately this phenomenon and they typically focus on the single and rare 'design earthquake'.

Numerous research studies can be mentioned here examining the effects of repeated earthquake phenomena on single-degree-of-freedom (SDOF) systems. One can mention the works of Amadio et al. [1] and Luco et al. [2] where the effects of repeated earthquakes on nonlinear SDOF systems were examined and quantified. Furthermore, Hatzigeorgiou and Beskos [3] proposed appropriate inelastic displacement ratios for the case of seismic sequences. Additionally, Hatzigeorgiou [4–6] studied the ductility demands and behavior factors for nonlinear SDOF systems subjected to multiple near-fault and far-field earthquakes. Moustafa and Takewaki [7] and Takewaki et al. [8] examined simple stochastic models representing repeated seismic sequences. In addition, various research studies investigated the effects of multiple earthquakes on multi-degree of freedom (MDOF) systems. One can mention here the works of Fragiacomo et al. [9], Li and Ellingwood [10], Hatzigeorgiou and Liolios [11] and Ruiz-Garcia and Negrete-Manriquez [12], which have examined steel framed structures and Loulelis et al. [13], Faisal et al. [14], Efraimiadou et al. [15], Di Sarno [16] and Abdelnaby and Elnashai [17] which have focused on multi-storey reinforced concrete frames. It is worth noticing that all these studies, i.e., Refs [9–17], have been limited to two-dimensional/planar structures while according to the best of the authors' knowledge, there is not research work that has examined the effects of repeated earthquakes on three-dimensional reinforced

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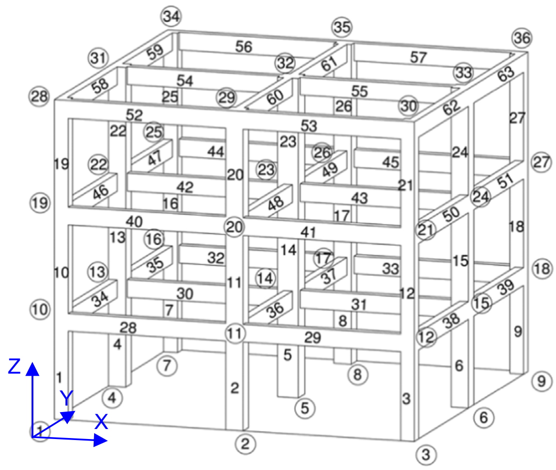


**Fig. 1.** 3-storey regular building.

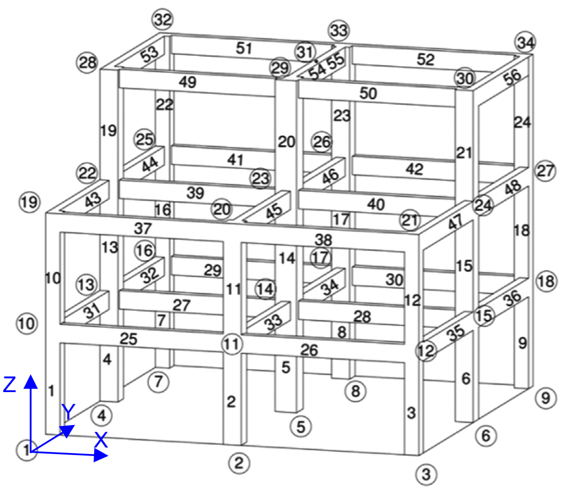


**Fig. 2.** 3-storey irregular building.

concrete (RC) structures. Thus, the need for the development of an efficient methodology for the inelastic analysis of three-dimensional RC buildings under repeated earthquakes is apparent.

This study investigates the behavior of three-dimensional RC structures under multiple earthquakes. For this objective, the non-linear dynamic response of four three-dimensional RC buildings under five real seismic sequences is investigated. These multiple earthquakes have been recorded by the same station and in a short period of time, up to three days. The time-history responses of building structures under consideration subjected to the aforementioned seismic sequences are computed using Ruaumoko structural analysis program [18]. The study focuses on the most critical structural parameters such as the structural damage, maximum displacements, permanent displacements and interstorey drift ratios. Additionally, the building structures under consideration have been analyzed for different siting configurations to examine the effect of earthquake direction incident. Examining the results of this study, very important conclusions and outcomes are found.

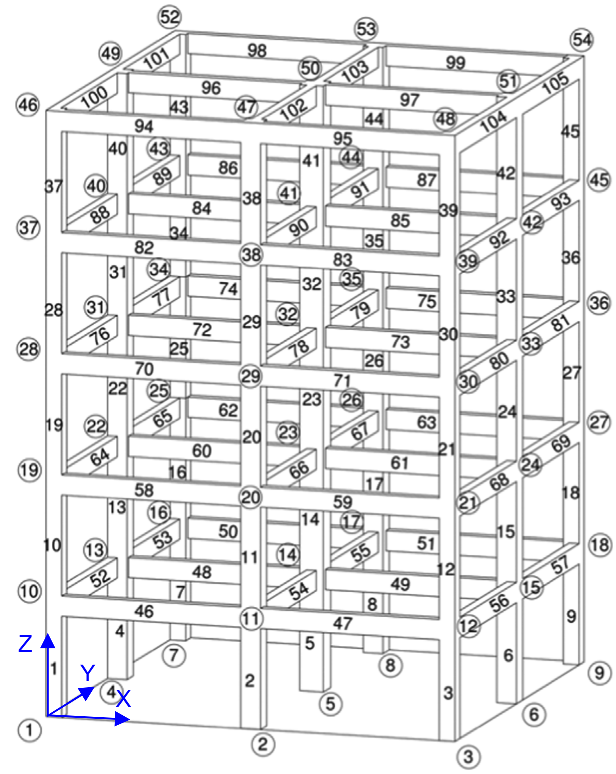


**Fig. 3.** 5-storey regular building.

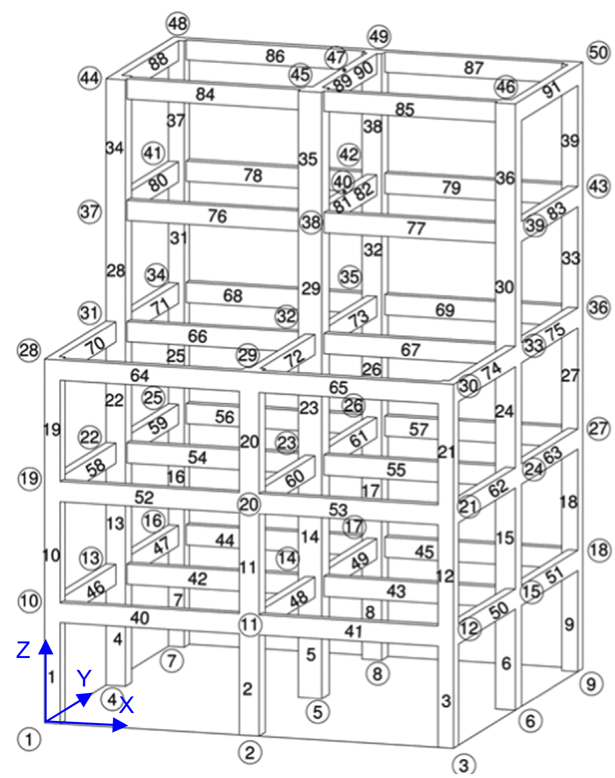


**Fig. 4.** 5-storey irregular building.

## 2. Description of structures and modeling assumptions

### *2.1. Description of structures*

In this research study, four three-dimensional buildings are investigated. The first two frames have 3 storeys, where the first one is regular and the second one is irregular along its height, while the other two frames have 5 storeys and they are also regular and irregular along their height. The examined 3- and 5-storey buildings have 2 equal bays in each direction ($x$ and $y$) with total length equal to 10.40 m. The 3-storey irregular building has a setback on the third floor and the 5-storey irregular building has setbacks on its fourth and fifth floor. Typical floor-to-floor