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Energy distribution in RC shear wall-frame structures subject to repeated earthquakes

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ABSTRACT

Repeated earthquakes are possible events in seismic zones. The aftershocks can grow so large that they can be regarded as design-level earthquakes. These can affect the nonlinear behavior of structures. Different studies indicated that the destructions caused by earthquakes were highly influenced by the seismic energy induced to the structure during the earthquake. This study investigated the seismic behavior of RC shear wall-frame structures and the structural response and energy distribution in these structures subject to single and sequence of natural records. To this end, 10-, 15-, and 20-story structures were assessed for the selected structural system. Previous studies assessed the displacement, maximum drift, maximum residual drift, and energy distribution in structures. Therefore, this research aimed to study the records of the repeated sequences and their energy concepts. The results of analyses revealed that repeated earthquakes led to increase in seismic requirements of RC shear wall-frame structure, but it did not cause structural collapse. In addition, the presence of the second record reduced the residual structural displacement in some cases. Nevertheless, the effect of repeated earthquakes should be taken into consideration in the assessment of the reliability of structures. Other results on energy distribution indicate that an increase in the structure height will possibly increase the contribution of $\alpha[M]$ and decrease the contribution of $\beta[K]$ in dissipation of input energy.

1. Introduction

Seismic sequence has been observed in many spots around the globe. This phenomenon is caused by accumulation of energy at faults and their continuous rupture (repeated earthquake phenomenon). Considering the mechanism of energy release at faults, it can be asserted that a single earthquake is always accompanied by aftershocks and foreshocks, and in some cases their magnitude is so great that they can be considered design-level earthquakes. Therefore, the structural behaviors can be different subjects to such repeated earthquakes compared to those behaviors under a single earthquake.

Given the drawbacks of the force-based design and the fact that such events are not taken into account, the energy-based design is expected to replace the current design methods with appropriate development in the future. On the other hand, the level of structural damage caused by earthquake is closely related to the capacity of the structure in absorption and dissipation of energy, which will lead to more interest in energy-based methods in assessment and design of structures. A practical concept in seismic structural design is the relative potential of the earthquake damage. The purpose of the seismic design is to provide life safety for people and make a correct evaluation on damages to the structure. To determine the potential of the damage, the type of the structural behavior, earthquake record, and the interaction between these two parameters should be evaluated [1].

Repeated earthquakes may take hours, days, or even months, and their frequency of occurrence might decrease over time. However, the duration between the occurrences of earthquakes is so close that seismic retrofitting is not possible. For instance, the Northridge earthquake with a magnitude of 6.7 was followed by 76 aftershocks in 1994, the Mammoth Lakes was hit by an earthquake in 1980 with a magnitude of 6.2 followed by 5 aftershocks of 5.7–6.2 Richter magnitude, and the earthquake of October 1987 at the very same Mammoth Lakes with a magnitude of 5.9 had insignificant damages, but an aftershock with a magnitude of 5.3 that occurred three days later increased the damages. The 2012 East Azerbaijan earthquake occurred near the cities of Ahar and Varzaqan in Iran, where the magnitude of the mainshock was 6.4 followed by 4 aftershocks over a magnitude of 5. The April 2015 Nepal earthquake was measured 7.8 on the moment magnitude scale with 30 aftershocks over 5 so far [2].

Many researches, such as Amadio et al. [3]; Luco et al. [4]; Kojima and Takewaki [5,6]; Mostafa and Takewaki [7] mostly focused on the single degree-of-freedom (SDOF) response of the system subject to synthetic/as

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recorded seismic sequence records, while a few studies addressed the nonlinear response of multi-DOF systems subject to such records. Hatzigeorgiou and Beskos [8] presented a simple and effective method to estimate inelastic displacement ratio (IDR) of structures subject to sequence of earthquakes and/or multiple records. This study points out that effective parameters such as post-yielding stiffness and ground conditions have been previously assessed in regions with rare occurrence of earthquakes, and hence, the effect of such parameters on the maximum inelastic displacement has been overlooked under seismic sequences.

Ruiz-Garcia et al. [2] published a paper titled “Evaluation of relative drift demands in existing steel frames under as-recorded far-field and near-fault mainshock–aftershock seismic sequences”. Based on the results of this investigation, it was suggested that the effect of aftershocks during performance-based assessment of existing structures should be taken into account by using real mainshock–aftershock seismic sequences instead of artificial sequences as well as site-specific seismic scenarios due to the particular dependency on ground motion features (e.g. frequency content) of mainshock–aftershock ground motions. Zhai, Van, Lee and Zhie [9] studied time-history response in SDOF inelastic systems subject to various ground motions. They compared the different responses of structural demand parameters such as maximum acceleration, maximum velocity, and maximum residual displacement during aftershocks with their corresponding values in the mainshock. Kojima and Takewaki [10] presented a simple evaluation method on the seismic resistance of residential houses under two consecutive severe ground motions with intensity 7. Their modeling enables a simple evaluation of earthquake response of a non-linear system under consecutive near-fault ground motions in terms of free vibration.

Several studies have been conducted on 2D structures [2,11–18]. Hatzigeorgiou et al. [19] investigated nonlinear responses of 3D structures subject to seismic sequences for the first time. They studied two 3-story and two 5-story RC buildings with both regularities and non-regularities along with their height subject to 5 multiple earthquake sequences. The values of two horizontal components and one vertical component were considered for the records. The investigation results focused on maximum displacements, maximum residual displacement, damage index, and ductility demand. Furthermore Raghunandan et al. [20] described a probabilistic methodology to quantify building fragility to earthquake induced damage and collapse considering sequences of earthquakes, while accounting for the variability of damage possible in mainshock and aftershock events. The method was applied to a portfolio of reinforced concrete (RC) frame buildings. The results indicated that damage indicators related to the drift experienced by the damaged building best predicted the reduced aftershock collapse capacities for these ductile structures. Jalayer et al. [21] showed that even when the fragility of intact structure is employed, the approximate solution (considering only the time-dependent rate of aftershock occurrence) leads to higher risk estimates compared with those obtained based on only the mainshock. Hosseinpour et al. studied fragility curves and nonlinear behavior of RC frame structures subject to multiple earthquakes [22,23].

Researchers demonstrated that a portion of the energy transferred to the structure is stored by damping energy and hysteresis in the structure, while the rest is dissipated through the kinetic and strain energies. Eq. (1) is the equation for the structure in which E_i is the input energy; E_k, the kinetic energy; E_ξ, the strain energy; and E_h, the Hystersis energy [24].

$$\begin{aligned} &E_i = E_k + E_\xi + E_s + E_h \\ &E_k = \frac{1}{2} m \dot{u}_t^2 \\ &E_\xi = \int C \dot{u}^2 dt \\ &E_s + E_h = \int f_s \, du \\ &E_i = -\int m \ddot{u}_t \, du_g \end{aligned} \tag{1}$$

Where m is mass of the structure, C is the damping coefficient, f_s is the restoring force, u is the displacement of the mass, $\dot{u}$ is the velocity of the mass, $\ddot{u}$ is the acceleration of the mass, u_g denotes the foundation displacement, and t is time.

The actual input energy induced to a system during an earthquake event is thus dissipated in its entirety by means of viscous damping and hysteretically absorbed energies. The hysteretic energy is the energy dissipated through the inelastic excursions during the seismic excitation, whereas the damping energy is related to the work done by the damping force [25]. Hysteretic Energy (E_h) is the energy which is wasted in inelastic behavior of the system after the members yield. Due to the direct relationship of the damage inflicted on the structure and Hysteretic Energy, this part of the energy is the most important part of this equation. The rate of energy, inserted into the structure, and the amount of its absorption or waste can indicate the general performance of the structure against the earthquake, though it shows no model of its behavior. In other words, Hysteretic Energy in a structure is an index of its damage level or its different parts or the process of yield or collapse. Energy distribution in the structure follows the structural model and its traits to a great extent. The terms $\alpha[M]$ and $\beta[K]$ were used in this study to express Rayleigh damping, where α and β are real scalars (coefficients) with 1/sec and sec units respectively. [M] and [K] are mass and stiffness matrix of a structure.

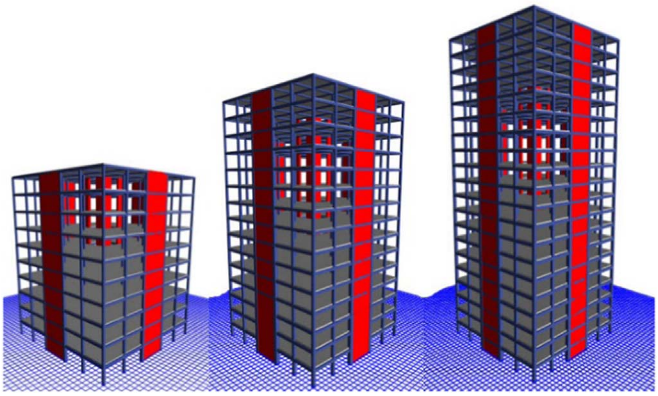

Fig. 1. 3D view of the designed structures.

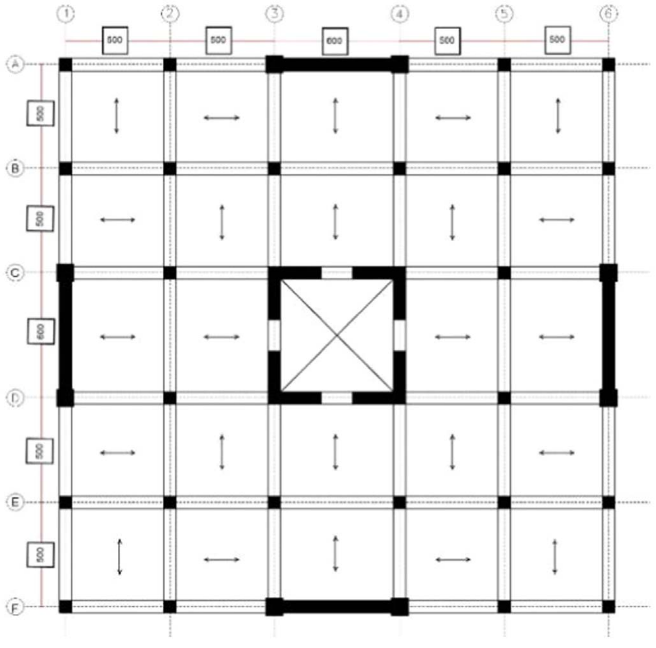

Fig. 2. Plan of the designed structure.