Effect of Aftershocks on the Seismic Performance and Fragility of Steel Self-Centering Structures

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ABSTRACT

The aim of this study is to evaluate the seismic performance and calculate the fragility of self-centering structures under mainshock and mainshock–aftershock sequences. For this purpose, two three- and nine-story structures were designed based on available references in the field of self-centering structures and then modeled nonlinearly in Perform software. Twenty mainshock records along with aftershocks were selected and applied to the structures through nonlinear dynamic analysis. Finally, various performance evaluation parameters of the structures, such as roof horizontal displacement, distribution of dissipated strain energy in the structure due to the mainshock and aftershock, and rocking displacement under both cases were investigated. Subsequently, incremental dynamic analysis (IDA) curves and fragility curves were calculated and presented. The fragility results indicate that, firstly, the fragility of shorter structures (three-story) is greater than that of taller ones (nine-story). Secondly, the fragility values for aftershock and mainshock at different performance levels are close to each other with only slight differences. For example, in the three-story structure at the LS performance level and maximum PGA = 1.8g, the probability of exceedance in the mainshock-only case was calculated as 0.87, while in the mainshock–aftershock case it was 0.93. In the nine-story structure at the LS performance level under the same maximum acceleration, the probability of exceedance in the mainshock-only case was 0.78, and in the mainshock–aftershock case it was 0.88.

KEYWORDS

Self-Centering Structures, Earthquake, Aftershock, Seismic Performance, Fragility

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1. Introduction

One of the fundamental challenges in earthquake engineering is the design of structures that, in addition to having sufficient strength and stiffness against seismic forces, are able to return to their original state after an earthquake [1]. In recent years, Self-Centering Systems have been introduced as an innovative solution to reduce residual deformations and improve post-earthquake functionality [2]. The main feature of these systems is that after an earthquake, they are capable of returning to their initial position without significant permanent deformations, thereby minimizing the need for post-earthquake repair [3]. This approach is in contrast with conventional systems such as Moment-Resisting Frames or Concentrically Braced Frames, which, despite providing adequate stiffness and resistance, usually experience permanent deformations and extensive damage in their members [4]. On the other hand, self-centering structures, through special mechanisms such as post-tensioned elements or energy dissipation devices, not only provide lateral stiffness but also ensure the stability of the structure after an earthquake [5].

Based on these necessities, the present study aims to evaluate the seismic performance of self-centering structures and to investigate their fragility curves under mainshock and aftershock sequences. In this research, two structures with three and nine stories were designed and modeled nonlinearly in Perform software. Subsequently, a set of twenty mainshock–aftershock records was applied, and various parameters such as roof displacement, dissipated strain energy, and rocking-induced displacement were assessed. Finally, fragility curves were derived and analyzed in order to provide a comprehensive understanding of the performance of these structures under realistic seismic conditions.

2. Structural Model Description

In this study, in order to evaluate seismic performance, two self-centering steel structures with three and nine stories were designed and investigated. The design process of these structures was carried out based on the provisions of ASCE 7-05 using the force-based design method. The seismic response modification factor was considered as R=8R = 8R=8, and the soil type was assumed as D according to ASCE Table 20.3-1.

For nonlinear modeling, Perform 3D software was used. In this modeling, the properties of steel materials, element stiffness, and the specifications of post-tensioned cables and dampers were calibrated according to the relationships presented in the literature and reliable references. In addition, a set of twenty mainshock–aftershock earthquake records was selected and applied to the models.

The modeling was carried out by considering the rocking mechanism and energy dissipation devices in such a way that the actual behavior of self-centering structures against mainshock and aftershock excitations could be accurately simulated. This made it possible to investigate key parameters such as roof displacement, dissipated strain energy, and rocking-induced displacement.

After the preliminary design of the structure, nonlinear modeling was carried out in Perform-3D software. Figure 3 illustrates the structural model developed in Perform. For nonlinear modeling, the concentrated plastic hinge approach was adopted, and the structures were modeled accordingly. In this study, the beams were designed as simply supported members; therefore, their nonlinear behavior was neglected, and only two mechanical hinges were assigned at their ends.

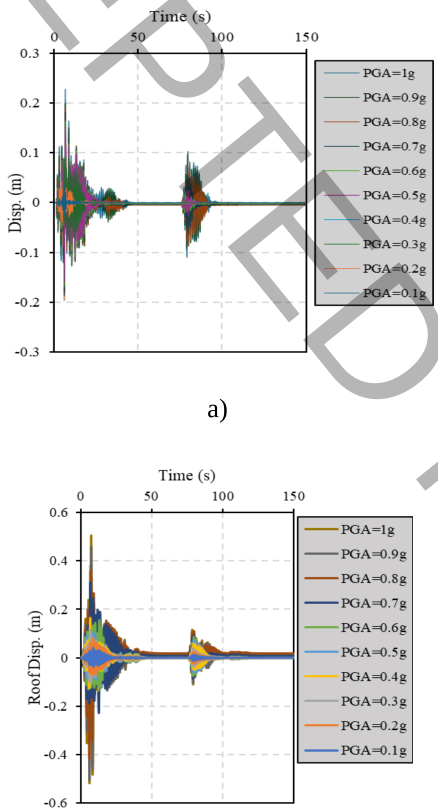
To define the nonlinear properties of the column hinges, the FEMA Column, Steel Type model was used, which incorporates the interaction between axial force and bending moment. For assigning the nonlinear behavior of the braces in Perform-3D, the Steel bar/Tie/Strut – Simple Bar element, which can only resist axial force, was utilized. For this purpose, in the nonlinear material properties, the Inelastic Steel Material, Buckling option was selected to represent the buckling-prone steel material.

To model the soil and simulate the uplifting and rocking effects of the structure, the Gap element was employed. For modeling the cables with prestressing effect, the Cable element was used, and for the dampers, the Seismic Isolator, Rubber Type element was applied. The damper properties required for the modeling were defined in the software according to the specifications presented in Section 3-2.

3. Seismic Performance and Response Evaluation

In this section, based on several important parameters, the performance of the three- and nine-story self-centering structural systems under mainshock and aftershock records is investigated. First, the roof horizontal displacement of the structures is evaluated. Roof horizontal displacement is considered one of the most important parameters in assessing the seismic behavior of structures. The smaller the horizontal displacement experienced by a structure, the better its seismic performance will be.

Figure 1 presents the time-history curves of roof horizontal displacement for the three- and nine-story structures under the Niigata earthquake record introduced in the previous chapter. For this purpose, the structures were analyzed using Incremental Dynamic Analysis (IDA) under this record at different peak ground accelerations. The results were obtained and presented based on acceleration increments of 0.1g, ranging from 0.1g to 1g.



a)

b)

Figure 1. Time-history curves of roof horizontal displacement for the structures: (a) three-story and (b) nine-story under mainshock and aftershock records

Fragility curves for three performance levels—Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP)—have been calculated and presented for both mainshock-only and mainshock–aftershock scenarios. The probability of exceedance at each performance level was computed, converted into lognormal curves, and finally presented in Figure 2.

For instance, at the LS performance level and PGA = 1.8g, the probability of exceedance is 0.87 for the mainshock-only case and 0.93 for the mainshock–aftershock case, indicating a difference of approximately 0.06. Similarly, at the CP performance level and PGA = 2g, the probability of exceedance is 0.56 for the mainshock-only case and 0.63 for the mainshock–aftershock case, showing a difference of around 0.07.

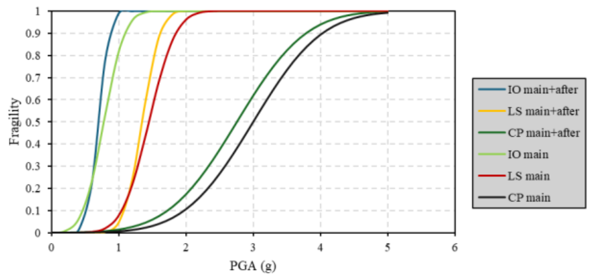


Figure 2. Fragility Curve

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