Implementation of energy method and evaluation of ductility reduction factors accuracy to estimate the seismic response of self-centering structures

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ABSTRACT

Self-centering structures have been introduced to overcome the financial and social difficulties of rebuilding structural damage caused by the residual deformation of structures. On the other hand, applying the force method as a common approach to the design of many structural systems cannot predict the actual performance of this advanced system. Meanwhile, energy-based approaches provide more accurate results than force-based approaches by selecting the desired yield mechanism and the desired displacement at the outset of the design process. In this study, the feasibility of using the energy method to compute the seismic performance of the self-centering concentrically-braced frame (SC-CBF) was evaluated for the first time. Comparing the calculated results with the laboratory and analytical outputs showed that the energy method is an efficient technique, where can accurately estimate the structural response without any complex modeling. Also, by comparing the different ductility reduction relationships, it was observed that the equation presented by Lai-Biggs is the most appropriate relationship with more than 80% accuracy because of artificial earthquake records applications. Furthermore, the results revealed that the structure's ultimate rotation and ductility ratio decreased by raising the structure elevation. The height increase improved the accuracy of predicted values from the energy method with other relationships to estimate the structural response.

KEYWORDS

Self-centering structure, Energy-based approach, Residual deformation, Ductility reduction factor, Energy modification factor

1. Introduction

Self-centering (SC) structures proposed by Roke et al. [1] and developed by other researchers can considerably reduce the damage caused by seismic forces. The utilized cables with different configurations cause these structures to return to their original state after unloading. In most previous studies, the design concept of SC structures was based on applying a constant behavior factor without considering the dimensions and location of these structural elements. Therefore, more attempts should be conducted to assess the induced forces in these advanced structures more accurately for design purposes and to overcome this restriction. On the other hand, the performance-based design approach (energy method), by selecting the desirable behavioral mechanism and target drift, has been appropriately utilized to calculate the magnitude of the internal forces of different structural systems. Accordingly, the energy method's capability to estimate SC-CBF structures' response has been investigated in this study. The equality of the external work with internal work in the target drift is the primary principle of the energy-based approaches to analyzing the structural systems. In this method, to consider the energy dissipation due to hysteresis of ductile members, the total input energy should be modified by the energy modification factor.

In this paper, four SC-CBF structures have been analyzed using this method to evaluate the feasibility of the energy method application in the analysis of SC structures. Also, to calculate the ductility reduction factor ($R\mu$), in addition to the Newmark-Hall relation [2], the proposed relations by Nassar and Krawinkler [3], Miranda and Bertero [4], Lai and Biggs [5], Riddell et al. [6], and Lee et al. [7] were used and assessed.

2. Methodology

In this section, the feasibility application of the energy method for the analysis of SC structures is reviewed. For this purpose, this concept was initially implemented to analyze a three-story structure tested previously by Gupta and Krawinkler [8]. In the following, by introducing the principles of the energy method in the form of a multi-step process, the seismic response of three structures with different elevations under eleven modified records have been considered and reviewed. Also, in this article, the accuracy of the proposed method has been assessed by applying various existing equations for calculating the ductility reduction factor.

2.1. Energy method for analysis of SC structures

In the energy-based design methods, the base shear and forces of the structural members are calculated by equating the internal work and the external work in the target drift under the desirable yield mechanism of the structure [9] (eq. 1).

$$E_e + E_P = \frac{1}{2}\gamma m S_v^2 = \frac{1}{2}\gamma m\left(\frac{T}{2\pi}S_a g\right)^2 \qquad (1)$$

Where γ is the energy modification factor and is obtained from equation 2.

$$\gamma = \frac{2\mu_s - 1}{R_\mu^2} \qquad (2)$$

2.1. Energy method implementation in SC-CBF structure

The energy technique steps to analyze the SC structures are discussed in this section. First, a three-story SC-CBF structure (Fig. 1a) is appointed to evaluate the accuracy of the energy approach. For this destination, the rotation of the frame was computed by the energy method employing five proposed relationships for $R\mu$ and compared with the test result according to cited steps in Fig. 1b.

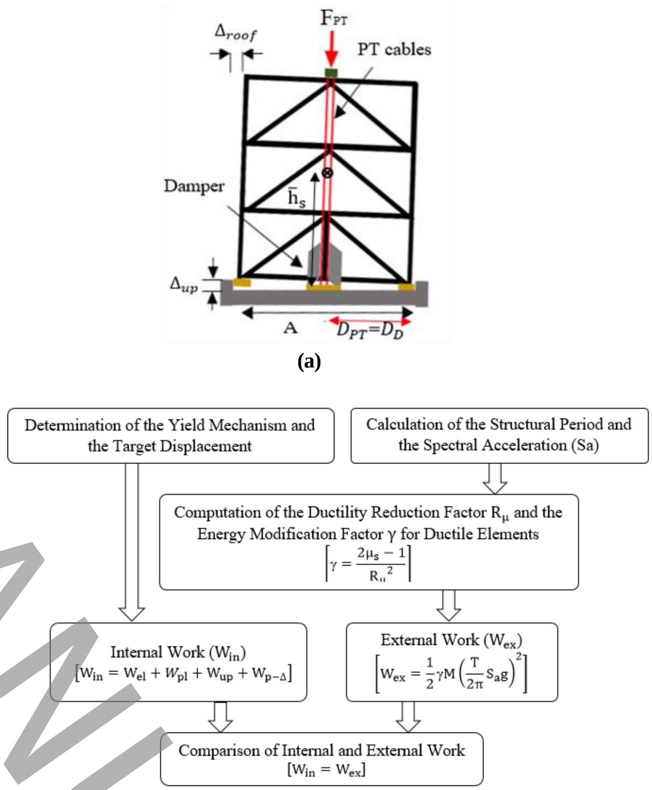


Figure 1. The studied SC-CBF b) Multi-step process to analysis the SC-CBF by energy method

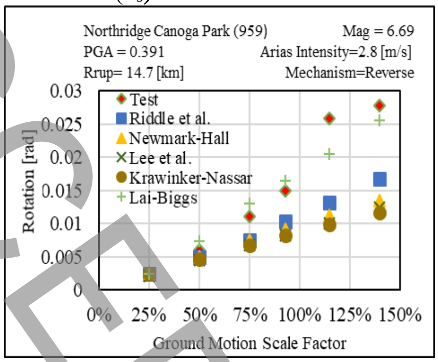
According to Fig. 1b, considering the frame uplift (Fig. 1a) and the behavioral mechanism of the structure, the ultimate rotation of the structure was calculated to analyze structures by energy method. In the following, the calculated rotation is compared with the declared test results [8] to evaluate the accuracy of the energy method.

3. Results and Discussion

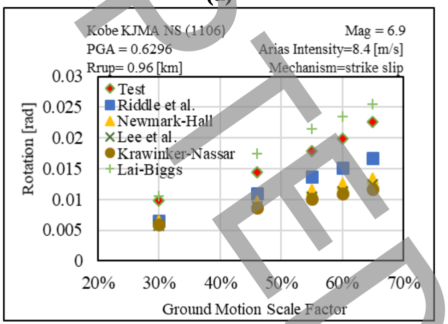
The selected SC-CBF structures were analyzed by implementing the energy method, and the results are outlined in this section.

3.1. Comparison of structural responses

As discussed previously, by equating external and internal work in different values of Rμ, the ultimate structural rotation (θ_s) was obtained.



(a)



(b)

Figure 2. Calculated rotation from energy method and test results a) Northridge earthquake b) Kobe earthquake

As shown in Fig. 2, the calculated results are very accurate at low ductility due to the lower effect of the γ on the external work. Nevertheless, with ductility rising, the accurate calculating of the γ gets more critical. According to the obtained results, amongst the mentioned equations for Rμ values, the Lai-Biggs relation in the studied structures provides more precise outcomes.

3.2. The structural elevation effect on the ductility reduction factors

In order to determine the elevation effect, the 3, 6, and 9 stories structures with a similar specification of Fig. 1 frame were considered. These structures were designed with a target rotation of 0.015 radians corresponding to the yield of the cable and analyzed in Perform 3D software [10] to assess the energy method. The results showed that with increasing the height of the structure, the drift decreases due to assigning a constant behavior factor to all structures in the force method. Therefore, stronger structures will be designed by raising the structures' height. From the reported test results, the Lai and Biggs method provides more accurate results (more than 89%) than the other ones at the MCE earthquake level. While, in the analytical structures, the accuracy of the Lai and Biggs method is more than 80%. The results obtained from the energy method show that the average results have an accuracy of 71% in the Kobe earthquake and 61% in the Northridge earthquake in the tested structure. While in the analytical structures, the accuracy of results is more than 75%. Also, in analytical structures, the accuracy of the Riddle et al. method is more than 80%, which indicates the acceptable accuracy of the energy method application in the analysis of SC-CBF structures.

4. Conclusions

In this article, the feasibility application of the energy method for the analysis of SC structures is assessed. For this aim, the ultimate rotation of several SC-CBF structures was calculated with the energy method and compared with the test and analytical results. A summary of the results of this study is presented below:

- The energy method, by considering the desirable yield mechanism, can provide an acceptable estimate of the structural response and can be introduced as an effective computational method.
- In low ductility, the ductility reduction factors are close to each other in all relations. However, with increasing ductility, this difference increases. As a result, the Lai-Biggs method provides more accurate results in forecasting structural responses in studied structures.
- According to the obtained results from the energy-based method, with increasing structure elevation, the ultimate rotation of the structures decreases, and the accuracy of all Rμ calculation methods increases due to reduced ductility.

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