Amirkabir Journal of Civil Engineering

Amirkabir J. Civil Eng., 53(6) (2021) 531-534
DOI: 10.22060/ceej.2020.17403.6551

Optimal Design and Performance Assessment of Viscous Dampers in Steel Frames Based on Life Cycle Cost

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ABSTRACT: In recent years, it is tried to express the expected performance of structures as financial and social measures. In this study, an algorithm for the optimal design of viscous dampers with the goal of achieving minimum total cost is presented. For this purpose, an appropriate cost model to determine the initial cost of equipping structures with viscous dampers has been presented and the expected costs of the structure due to possible earthquakes over its life cycle have been estimated using life cycle cost analysis (LCCA). The results of this analysis have been used in an optimization algorithm with the aim of achieving the minimum total cost of structures. To evaluate the seismic behavior of structures, the Endurance Time (ET) method is used as a dynamic analysis method which requires much less computation effort than conventional time history methods. In this regard, three-moment frames with 3,7 and 15 stories having weakness in initial design are modeled nonlinearly, and then, using a genetic algorithm, the optimum arrangement of linear and nonlinear viscous dampers along with the damping exponent (Alpha) is acquired. Two closed-form methods have also been used for the design of viscous dampers, namely energy-based damping design and displacement-based design. Finally, the performance of the structures has been evaluated and compared under 12 far-field and 12 near-fault ground motion records.

Review History:

Received: Nov. 16, 2019
Revised: Jan. 26, 2020
Accepted: Feb. 04, 2020
Available Online: Mar. 01, 2020

Keywords:

Endurance Time Method
Life Cycle Cost Analysis
Structural Optimization
Fluid Viscous Damper
Genetic Algorithm

1- Introduction

Many research works have been done on the performance assessment of structures equipped with viscous dampers [1, 2]. Life cycle cost analysis (LCCA) has been introduced in the construction industry to take into account the economic considerations in decision-making [3]. By using this analysis, one can estimate the expected costs of possible earthquakes over the life cycle of structures. In the area, Bahmani and Zahrai [4] proposed a new method to characterize the nonlinear viscous dampers. They determined the optimum retrofitting level (ORL) and used the inter-story drift ratio as the effective parameter to calculate the failure cost of structures. In 2016, Basim et al. [5] presented a novel design approach based on the total value of the structure using the benefits of the Endurance Time (ET) method. Their proposed method for calculating the life cycle cost using the ET method can greatly reduce the amount of required computation effort and allow the use of cost as an objective function in the optimization process which is addressed in the current study.

By using the aforementioned method in this study, it is attempted to propose a suitable solution for the optimized design of viscous dampers based on the life cycle cost. Thus, steel structures equipped with linear viscous dampers are designed to have the lowest total cost over their lifetime. Also, in structures equipped with nonlinear viscous dampers, in addition to the damping values, the optimal damping exponent (α) is also determined based on the minimum total cost of the structures. To estimate the initial cost, an appropriate cost model is presented here and on the other hand, expected costs due to possible earthquakes are estimated based on a common framework in the technical literature. The total cost of the structure (the sum of the initial cost and the lifetime cost) as an objective function is used in an optimization algorithm. The results of the proposed framework are compared with the results of two closed-form methods, namely, energy-based damping design (UD and SPD) and displacement-based design (DBD). In addition, the performance of the structures has been evaluated and compared under 12 far-field and 12 near-fault ground motion records.

2- Cost analysis

2- 1- Life cycle cost

Calculating the Life Cycle Cost (C_{LC}) requires determining the number of damages that occur during an earthquake in a structure. Damage may be expressed using different Damage Indices (DI). An example is a relationship

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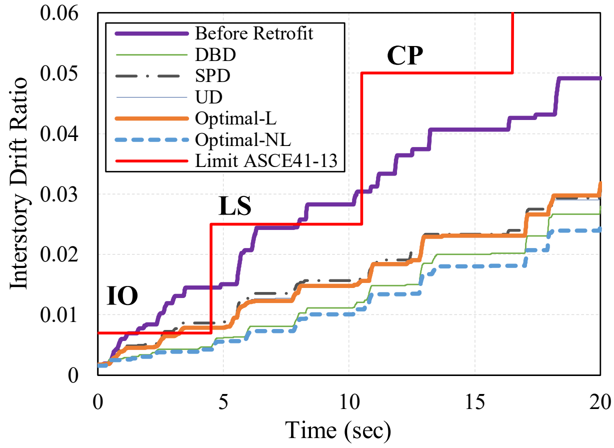

Fig. 1. . Comparison of ET Curve for 7-storey structure with different damper designs with allowable limits of ASCE41-13.

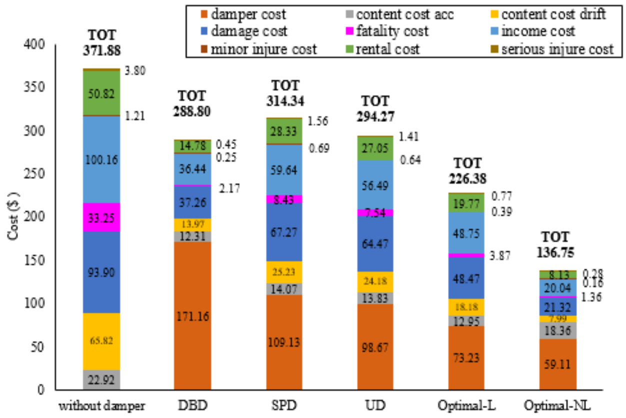

Fig. 2. Comparison of cost components for different damper designs and without damper for one square meter in the 7 story structure.

between the inter-story drift ratio and the limit states used in ATC-13 [6]. The life cycle cost (C_{LC}) is calculated as the sum of the calculated cost according to the various damage indices (Eq. 1).

$$C_{LC}(t,s)=\sum_{i=1}^{DI} C_{LC}^{i}(t,s) \qquad (1)$$

Each cost component due to a damage index is a function of the sum of the limit state costs of the system according to Eq. 2.

$$C_{LC}^{DI}(t,s)=\sum_{i=1}^{n} f(C_{LS}^{i},t,s) \qquad (2)$$

In this equation, n is the number of limit states considered for each damage index. includes damage repair cost, loss of contents cost due to inter-story drift, loss of contents cost due to floor acceleration, loss of rental cost, cost of income loss, cost of injuries, cost of human fatalities. The quantification of these damages as economic parameters depends on many local and social considerations and is addressed in work by Wen & Kang [7]. According to the method proposed by Basim et al. [5], the expected costs due to future earthquakes can be calculated using the ET method to acquire the structural responses at various hazard levels and the mean cost parameters from [6] and [8].

2- 2- Initial Cost

The initial cost of $600 per square meter is assumed for the entire area of the bare building. This study requires the estimation of the initial cost of the dampers in the process of cost analysis and since no appropriate cost model has been reported for the initial cost of FVDs, a simple cost model is proposed in this study based on a survey on Maurer's products (MHD). This model is used here to estimate the initial cost of dampers in terms of the damping force and stroke of dampers (Eq. 3).

$$\begin{aligned}&\mathit{MHD}\ \text{Price}=6295.552\times\exp(0.5\times\\&(((\log(F)\times1000-14.732)/-0.545)^{2}+(1.06E+47)\\&\times\exp(-0.5\times(((\log(stroke)-464.046)/-32.452)^{2}))\end{aligned} \qquad (3)$$

where F and stroke represent the force induced in the damper at a velocity of 1 m/s and the allowable displacement of the two ends of the damper, respectively.

3- Results and Discussion

In this study, three steel moment frames with 3, 7 and 15 stories and weaknesses in their initial design have been investigated. OpenSees software was used to conduct time history analyzes. The viscous dampers are optimally designed for structures to have the minimum total cost. In the first step, the linear viscous dampers are optimally designed and in the next step, the damping exponent (α) is added to the optimized parameters, and the damping coefficients and damping exponent (α) are optimally designed for the nonlinear dampers.

Figure 1 shows the ET Curve for the 7 story structure with various designs of viscous dampers to compare their seismic performance at different hazard levels according to ASCE41-13 [9]. The nonlinear optimum dampers have the best performance among others.

Figure 2 shows the cost components per square meter for the 7 story structure with different designs of dampers. The structure equipped with optimal nonlinear viscous dampers with an optimum alpha value of 0.3 has the lowest total cost compared to others. It should be noted that only the loss of contents cost due to floor acceleration in nonlinear design is more than the linear one. The justification is that in nonlinear viscous dampers at velocities less than 1 m/s, the force induced in the damper is higher than the linear dampers. As a result, the acceleration generated by nonlinear dampers at lower excitation intensities will be greater than those for linear dampers and this will increase the expected costs of loss of contents due to floor accelerations.

4- Conclusions

- A cost-optimal design algorithm for structures with passive control systems was presented. The endurance time method is used to estimate the seismic response of structures at different intensity levels.
- It was shown that the ET method provides a proper tool for estimation of expected costs while the amount of computational effort is kept at an acceptable level to be used in the optimization process.
- Using the life cycle cost analysis of structures equipped with nonlinear viscous dampers, the optimum damping exponent (α) is obtained 0.3. Therefore, the use of this value in the design and production of viscous dampers is suggested. It has also been shown that nonlinear dampers have a better performance in reducing the maximum inter-story drift ratio than linear dampers.
- Comparison of expected costs in structures equipped with viscous dampers for the three structures showed that the use of these dampers reduces the life cycle cost of structures and the reduction is large enough to justify the added initial cost of dampers.

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HOW TO CITE THIS ARTICLE

N. Ahadzadeh kolour, M. Charkhtab Basim , M.R. Chenaghlou, Optimal Design and Performance Assessment of Viscous Dampers in Steel FramesBased on Life Cycle Cost, Amirkabir J. Civil Eng., 53(6) (2021) 531-534.

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