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Minimum life-cycle cost-based optimal design of yielding metallic devices for seismic loads

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ABSTRACT

The yielding metallic devices have been used to improve the performance of building structures at design level intensities. They dissipate large levels of vibration energy through yielding of disposable steel plate elements but they may also enhance acceleration response related damage of mechanical and electrical components. This paper addresses the optimal design of these devices that minimizes the expected life-cycle object cost considering the story drift and acceleration related damages over the entire spectrum of seismic intensities that can occur on a building site. Genetic algorithm is used to calculate the optimal design parameters of the devices. The uncertainties associated with the frequency of occurrence of earthquakes of different intensities and random characteristics of the structural response are included in the life-cycle failure cost and the object cost calculations. It shown that these devices can be used effectively to reduce the overall life-cycle object cost and can be considered as good protective investment for structural designs in seismic regions.

1. Introduction

This paper is focused on the optimal use of the yielding metallic devices (YMD) to minimize the life-cycle failure cost of building structures located in seismically active regions. Appropriately designed yielding metallic devices when subjected to seismic loading can dissipate high levels of vibration energy through hysteresis of their yielding elements. The primary objective of using these devices has been to prevent the yielding of main structural members and reduce major damage in building systems at design level intensities. The yielding elements of the device that excessively deform can be easily replaced to restore the structure to its original resilience.

The idea of utilizing yielding metallic devices as energy dissipation mechanisms began with the work of Kelly et al. [1] and Skinner et al. [2]. Since then, a wide variety of efficient yielding metallic devices has been proposed. Among these devices, the Added Damping and Stiffness (ADAS) and the Triangular-plate Added Damping and Stiffness (TADAS) devices are perhaps the most popular in seismic retrofitting of existing structures as well as in the seismic design of a new structures. The ADAS is made with an X-shaped mild steel plate that deforms in double curvature, whereas TADAS is a variation of ADAS utilizing triangular plates that deform as cantilever beams. Fig. 1 show a TADAS device assembly. Such devices are supported on the braces installed in the structural bays. A device consists of several yielding plates, the bottom edges of which are rigidly assembled in a base attached to the supporting brace whereas their tops are attached to the floor beam above. These devices accommodate story drifts through bending of their plates which because of their shape cause uniform flexural strains along their lengths. Yielding occurs when the maximum strain reaches the yield level, which progressively spreads throughout the plates.

Before the introduction of the performance-based design philosophy with several performance objectives in seismic design of building structures, the design of these devices primarily focused on enhancing the life-safety performance for the design level earthquake by reducing the structural response through hysteretic dissipation of vibration energy in the device (Xia and Hanson [3]). The reduced story deformations due to added stiffness, and thus the lower levels of story-drift related structural and nonstructural damages at seismic levels other than the design level, also made these devices popular in seismic structural design applications.

However, since these devices also increase floor accelerations, the acceleration sensitive nonstructural components are likely to become more vulnerable to damage leading to possible dysfunctionality of the building and higher life-cycle cost. In earlier studies [4–8] related to optimal design of these and other protective devices the effect of acceleration response was often ignored,

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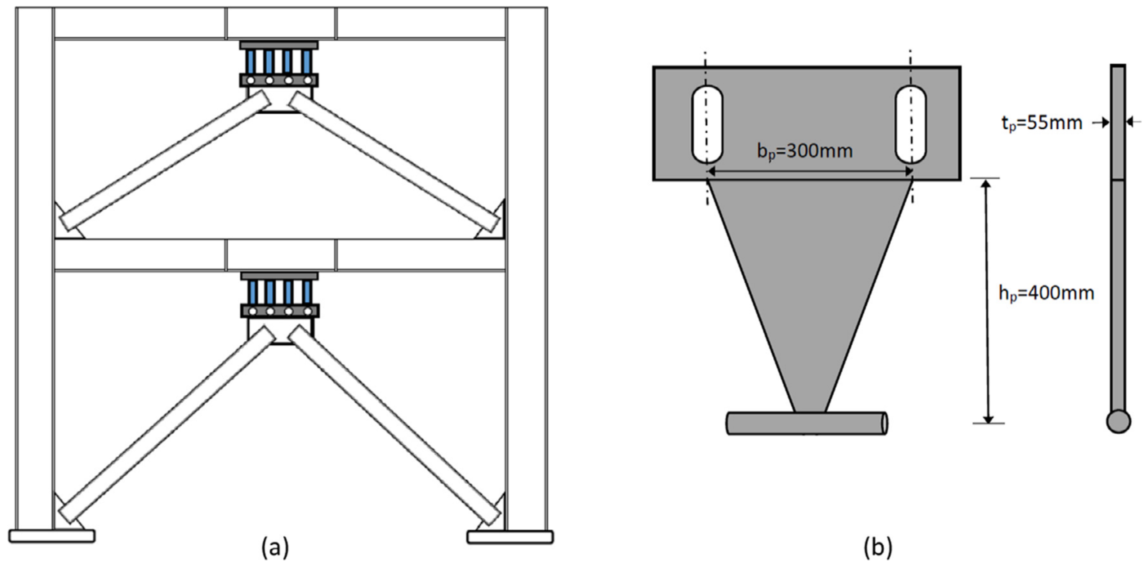

Fig. 1. (a) Typical Installation of TADAS devices with Chevron braces, (b) Triangular-plate Added Damping and Stiffness (TADAS) element.

although there were also other studies on the building performance measures [9–11] as well as on the damage cost related studies [12–15] wherein the effect of acceleration was recognized and considered. In the optimal design of some protective devices such as viscous and visco-elastic dampers, the consideration of acceleration dependent damage costs is usually not a critical issue in the optimality search for the distribution of the devices on the structure as in most cases these protective devices tend to decrease both the dynamic deformations and acceleration responses. However, in the design of yielding metallic devices (as well as the friction dampers), the consideration of acceleration related damage can significantly alter the optimal design arrangements. In this study, thus, the impact of the acceleration dependent damage cost on the optimal design is explicitly considered.

Herein, the optimally designed devices are utilized to minimize the life-cycle cost, which is decreased by the reduced drift levels on one hand and increased by the enhanced acceleration on the other hand, considering the entire spectrum of earthquake intensities that are likely to occur on the building site. Herein, to illustrate the impact of enhanced accelerations when yielding metallic devices are used as protective measures a set of 9-story buildings situated in two seismically active locations of Los Angeles and Seattle are chosen. The geometric configurations and layouts, as well as the mechanical properties, of these buildings are given in FEMA -355C [16]. A building with similar layout considered in this FEMA study for a Boston site was also analyzed, but because of the relatively lower levels of the seismicity at this site it was not necessary to use any TADAS devices. Thus no further results for this model are included in this paper. The structural framework of the buildings consists of the moment resistant steel frames which are enhanced by the installation of optimally selected TADAS devices. Herein the details of calculating the optimal design parameters of the devices to minimize the expected life-cycle cost are described. The same building models were also used in an earlier study by the authors [8,17] in which viscous dampers were utilized as the energy dissipation devices. The step-by-step response time history analysis is used to appropriately capture the hysteretic characteristics of the yielding device elements as well as the main structural members. To select the optimal design parameters of the device, the genetic algorithm is used.

2. Device and system characteristics

The stiffness and yielding characteristics of the protective devices affect the total stiffness and yield capacity of the system which influence the structural response and associated damage cost when an earthquake occurs. First the device parameters that affect the stiffness and yielding parameters of the system most are identified so that they can be varied to provide optimal results expressed in terms of the minimum life-cycle cost. Schematically, a structure with yielding metallic devices can be represented in terms of three elements that affect the stiffness of the system: the structural members, the yielding metallic element, and the brace that supports the device and connects it with the structure. The metallic device and the brace elements are in series and the combined brace-device system is in parallel with the story stiffness elements. The combined stiffness k_{DB} of the brace and device assembly in a building story stiffness can be expressed by the following equation:

$$k_{DB} = \frac{1}{\frac{1}{k_D} + \frac{1}{k_B}} = \frac{k_D}{1 + \frac{1}{r_{BD}}} \tag{1}$$

where k_D and k_B represent the stiffness of the metallic device and the brace, respectively; r_{BD} is the stiffness ratio of the brace to device expressed as $r_{BD} = k_B/k_D$. The stiffness of the device-brace assembly can be considered in parallel with the inter-story stiffness of the structure to provide the total story stiffness of the system. It is assumed that the structural system properties are fixed based on the design considerations for other loading demands so the remaining choice is now to alter the device-brace system to provide minimum life-cycle cost. It is also assumed that the re-distribution of the loads due to the installation of the device-brace system is not likely to degrade the performance of the structural system for other loads. Earlier studies by Xia and Hanson [3] and Moreschi and Singh [4] have shown that the stiffness ratio r_{BD} of the yielding device to the supporting braces does not influence much the response of the structural system. Thus, in this study it is assumed that the parameter r_{BD} has a constant value equal to 2 during the optimization procedure. With this fixed value of r_{BD} the stiffness of the bracing and device assembly and thus the total stiffness of the structural system can be defined in terms of the stiffness of the yielding metallic devices.