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Experimental study on the efficiency of tuned liquid dampers for vibration mitigation of a vertically irregular structure

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A B S T R A C T

This paper investigates the efficiency of Tuned Liquid Dampers (TLDs) in mitigating dynamic responses of vertically irregular structures. For this purpose, a three-story steel structure was specifically designed and subjected to free and forced vibration tests. In addition, the dynamic responses of eight structure-TLD systems were investigated through three cases. In the first and second cases, TLDs were tuned to the first and second natural frequencies of the steel structure and they were installed on each floor separately. In the third case, which was referred to as the combined case, two TLDs that were tuned to the first and second natural frequencies were first placed simultaneously on the third floor and then separately on the third and second floors. The results indicated that the installation of the combined TLDs on the third floor reduced the peak acceleration and displacement responses of the third floor more than the other cases. It was also observed that, in all the studied cases, the peak displacement response of the third floor was significantly increased when the structure-TLD systems were excited at the second resonance frequency. In addition, at the second resonance frequency, the TLD which was tuned to the first natural frequency and installed at the third floor increased the peak acceleration responses of all floors. It was concluded that, unlike the case in regular structures, a TLD which is tuned to the first natural frequency and installed at the highest level of an irregular structure may not satisfactorily mitigate the structural response of all floors.

1. Introduction

Tall and slender structures together with long-span bridges are often susceptible to wind or seismic induced vibrations. Mitigation of such structural vibrations has been a challenging task for structural engineers and in order to have a safer structure against vibrations many studies have been carried out. As the low damping ratio of structures makes them more susceptible to ambient vibrations, auxiliary damping devices have been invented and employed by engineers to enhance the energy dissipation of structures. Tuned Mass Dampers (TMD), Tuned Liquid Column Dampers (TLCD) and Tuned Liquid Dampers (TLD) are among the widely employed damping systems in buildings. In the literature, many successful applications of TMDs have been reported for real full-scale structures [1–3]. However, in spite of their better performance, when compared with

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TLCDs and TLDs, the construction and maintenance costs of TMDs are higher and their optimal design is also more sophisticated [4,5]. Similarly to TMDs, TLCDs have been employed successfully for vibration mitigation of structures [6,7] and have been modified to show a better performance [25,26]. However, due to their low maintenance and operating costs, the ease of installation and design, and relatively good performance, TLDs have been a more popular damping system for vibration mitigation of structures. TLDs are composed of a rigid tank filled with water and are among the passive damping devices which do not need an external supply of power for operation. TLDs dissipate the applied external energy through the intrinsic friction of the liquid, wave breakage, and liquid boundary layer friction [8]. Moreover, when subjected to dynamic forces, the tuned liquid inside the water tank imparts an anti-phase inertial force to the structure, resulting in a reduced vibration.

During past decades many modifications have been applied to conventional TLDs in order to make them more efficient in reducing structural vibrations. Zhao and Fujino [12] employed metal screens to enhance the lower damping accompanying deeper-water TLDs. It was shown that the presence of the screens attenuated the nonlinearity of liquid motion and augmented the damping of water sloshing. Cassolato et al. [13] proposed usage of inclined slat screens for adjusting the damping ratio of TLDs. They reported that an increase in the screen angle decreased the damping ratio of the TLD. It was also found that the proposed TLD system could maintain a constant damping ratio over a range of excitation amplitudes. Shad et al. [14] studied the effect of bottom-mounted baffles on the dynamic response of a structure-TLD system. The results of forced vibration tests indicated that when the vertical blockage ratio (VBR) increased the natural frequency of the TLD decreased; however, the increase in the VBR enhanced the damping ratio of the modified TLD. Zahrai et al. [15] proposed a TLD system with rotatable baffles and examined its efficiency experimentally for vibration control of a 5-story scaled-down steel structure. Results of free vibration tests indicated that compared to the case where no baffle was installed inside the TLD, the presence of baffles reduced displacement and acceleration responses by 2.5% and 3.9%, respectively. Moreover, under harmonic excitations, the maximum reduction in the dynamic magnification factor was 2.7%. In another study, Ruiz et al. [16] proposed a new type of TLD with a floating roof for controlling structural vibration. The presence of the floating roof prevented the wave breaking in the sloshing water and led to a linear response even under a large excitation amplitude. They proposed a numerical model for the invented TLD and validated it by scaled experimental tests. Samanta and Banerji [17] proposed a modified configuration for TLDs by adding a flexible rotational spring to the bottom of a TLD tank. They observed that for the optimal rotational stiffness of the spring the modified TLD was more effective and robust for structural control under both harmonic and broad-band earthquake base excitations when compared with the standard type of TLDs. In an attempt to increase the effectiveness of conventional TLDs, Fujino and Sun [18] investigated the use of multiple tuned liquid dampers [MTLDs]. The MTLDs consisted of a number of TLDs whose sloshing frequency was distributed over a certain range around the natural frequency of a structure. It was shown that, for a small amplitude of excitations, MTLDs were more effective in suppressing structural vibrations when compared with the single TLD. However, when the sloshing amplitude was large the MTLDs had almost the same effectiveness as a single TLD. In another study on MTLDs, Love and Tait [20] concluded that MTLDs were less sensitive to detuning and structural excitation amplitudes, thus, an improved structural control performance could be achieved at little additional cost.

For several decades, conventional TLDs have been widely employed for mitigation of vibrations in real full-scale structures. One of the first applications of TLDs to ground structures was proposed by Modi and Welt [9]. Later, TLDs were successfully employed for vibration mitigation of many types of structures, including air traffic control towers [19,21], jacket offshore platforms [22], tall buildings [10], elevated water tanks [29] and bridges [11]. In the previous applications, the sloshing frequency of TLDs has been mostly tuned to the first natural frequency of structures, because in regular structures the first mode of vibration has the highest contribution to the dynamic responses. However, in irregular structures, in addition to the first mode shape, higher mode shapes often play a significant role in the dynamic behavior. Therefore, tuning the sloshing frequency of a TLD to the first natural frequency of an irregular structure may not effectively decrease structural dynamic responses. It should be also mentioned that, in regular structures, TLDs are often installed at the highest level, where displacement responses under lateral loads are larger than on other floors. However, considering the significant effects of higher mode shapes on the dynamic responses of irregular structures, the highest level may not be the optimal location for installation of TLDs in irregular structures. This study investigates the efficiency of conventional TLDs for vibration mitigation of vertically irregular structures. A structure may have horizontal irregularity (i.e. in plan) and/or vertical irregularity. The vertical irregularity occurs when the mass of any story is more than 150% of the mass of an adjacent story [30]. Such sudden change in the mass can alter the dynamic behavior of the structure and can result in a significant increase in the role of higher mode shapes. In this study, a three-story one-bay scaled steel structure was designed to represent a vertically irregular structure. It was then subjected to the free and forced vibration tests with and without the presence of TLDs. In this study, eight different arrangements were considered for the installation of conventional TLDs on the test structure. The displacement and acceleration responses of each floor were measured and compared. In the next section, the design and dynamic characteristics of the test structure are explained and, the conventional TLDs employed are then described. Finally, the conducted tests and the results obtained are presented and discussed.

2. Design of test structure

As can be seen from Fig. 1 the test structure was a three-story one-bay steel moment-resisting frame which was specifically designed to represent a vertically irregular structure. The heights of the first, second and third story of the test struc-