Optimization of Vibration Control Using Outrigger and Pendulum Tuned Mass Damper System for High-Rise Building

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Abstract

The rapid population growth and economic development lead to higher demand for urban spaces and public centers. Therefore, high-rise buildings have been quickly increased worldwide. The taller building is, the less stiffness building has, this affects the stability and serviceability of the structure, which is related to the roof displacement and stories drift. Vibration control plays a key role to keep the stability of the structure, especially for high-rise buildings. In this study, two well-known methods are Pendulum Tuned Mass Damper (PTMD) and Outrigger system and their combination are applied then compared to investigate the best option in controlling vibration. Thirteen models representing various cases of properties such as the mass ratio of Pendulum or the numbers and locations of Outrigger to obtain the most productive model in each method. These optimum cases allow designers to compare and know which method can improve the response behaviors of structural systems better.

Keywords: *Vibration Control, Outrigger Braced Frame System, Pendulum Tuned Mass Damper.*

1 Introduction

Structure are usually vulnerable under any kind of vibration excitation and it is difficult to prevent these effects by itself, therefore installing some additional devices to dissipate the energy is essential. Nowadays, researchers try to invent new devices for controlling the structure, which are more effective and practical. A number of approaches are available to apply, which can protect structures and improve their performance under a dynamic loading condition such as earthquake or strong wind. During lifetime of service, some potentially catastrophic consequences affect directly to human life and economic also. Design of buildings is a complicated process and get many challenges, which involves approximate analysis and preliminary design. In order to assess the efficiencies of high-rise buildings, some requirements should be satisfied such as strength, stability, serviceability etc. which is evaluated by the displacement and drift of the structure. Various methods are proposed by researchers and engineers in order to mitigate unexpected vibration on structures. The main purpose of these inventions is to reduce excessive vibration and keep the stability of structural response within tolerable limitation under any unpredicted seismic hazard. The main goal of this study is to present the approach for the optimization of structural systems, mainly used for high-rise building in vibration control. The two systems "Outrigger braced frame system" and "pendulum tuned mass damper (PTMD) system" and their combination are compared for the same dynamic loading condition. PTMD are generally suggested for tall structures with large masses and low natural frequencies (Sacks and Swallow, 1993). The frequency of the PTMD can be adjusted in the field by changing the pendulum suspended length. This is accomplished by changing the pivot point of the suspended mass using a sliding clamp or by changing the height along the auxiliary mass where the cable connects (Kwok and Samali, 1995). Outriggers are horizontal structures connecting a building core or spine to external columns, which takes advantage of the increased moment arm between these columns (Choi and Joseph, 2012). (Smith and Salim, 2001) and (Smith and Coull, 1991) presented a detailed analysis for the optimal locations and numbers of outriggers with the objective of maximizing drift reduction.
The objective of the present study as follows:

- Simulate the behavior of building with and without Pendulum Tuned Mass Dampers system, Outrigger system as well as the combination system in various cases.
- Selecting the optimum cases of each method in minimizing the responses.
- Showing and comparing the effectiveness of proposed system through the response results.

The following flow-chart in Figure 1 provide a brief overview of the process of this study.

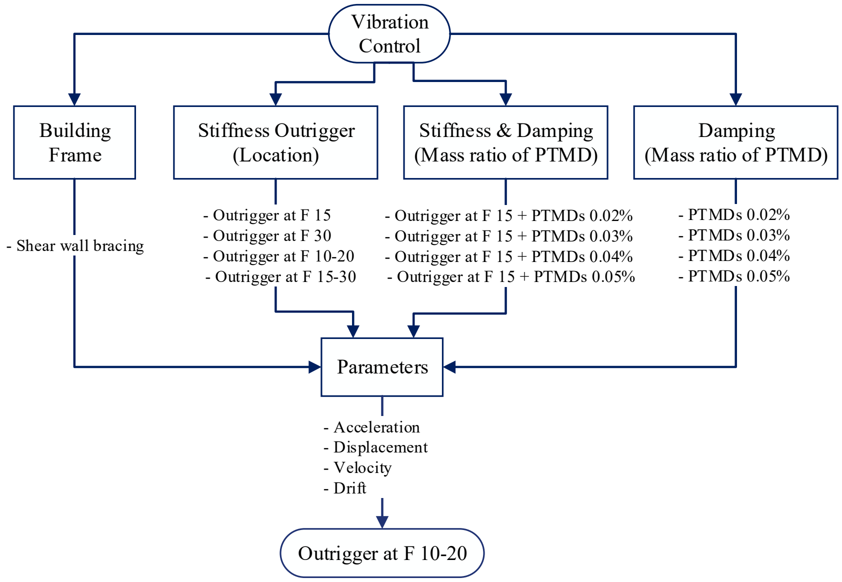


Figure 1. Optimization of vibration control process

2 Methodology

2.1 Pendulum Tuned Mass Damper

Common types of dynamic vibration absorbers are Tuned Mass Damper (TMD) and Pendulum Tuned Mass Damper (PTMD) (Constantinou et al., 1998). Translational TMD systems have been implemented in large scale structures for over 40 years (Kareem et al., 2007). The design methodology for both the translational TMD system and PTMD systems are identical (Conner, 2003). A major motivating factor for using a PTMD system over an equivalent translational TMD system is the absence of any bearings to support the TMD mass. Figure 2(a) shows a simple pendulum attached to a floor. Movement of the floor excites the pendulum; the relative motion of the pendulum produces a horizontal force that opposes the floor motion. This action can be represented by an equivalent SDOF system that is attached to the floor, as indicated in Figure 2(b).

Figure 2. A simple pendulum tuned mass damper

The equation of motion for the horizontal direction is:

$$T \times \sin\theta + \frac{W_d}{g}(\ddot{u} + \ddot{u}_d) = 0 \quad (1)$$

$$u_d = L \times \sin\theta \approx L \times \theta \quad (2)$$

$$T \approx W_d \quad (3)$$

The natural period of the pendulum is:

$$T_d = 2\pi\sqrt{\frac{L}{g}} \quad (4)$$

2.2 Outrigger System

An outrigger braced in high-rise structure consists of a reinforced concrete or braced steel frame connected to the exterior columns by flexural stiff horizontal cantilevers. Outrigger systems represent a very efficient structural system because the outriggers can reduce top deflection and core base moment (Taranath, 1988). (Smith and Coull, 1991) presented a method for determining the optimum location of the outriggers based on simplifying assumptions. For simplicity, Figure 3 shows the graphical concept of two-outrigger layers system in structure.

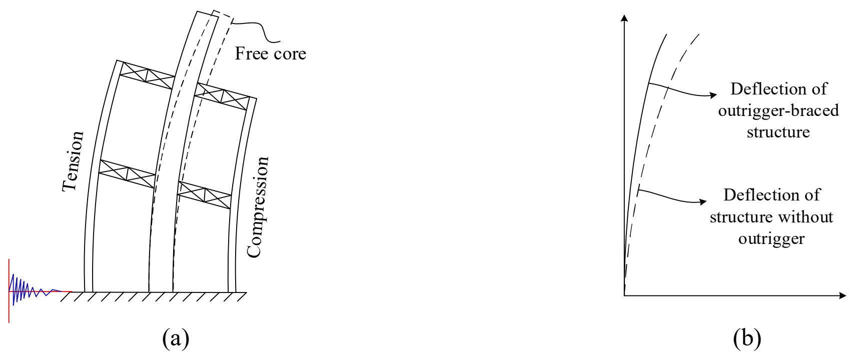


Figure 3. (a) Two-outrigger structure; (b) deflection of structure

3 Mathematical Modeling Procedures

3.1 Time History

In this study, two different methods having different philosophy are compared for the same structural parameters, one system uses the structural stiffness (outrigger deep beams) and the other use the structural mass (pendulum mass) to control vibration of the system, both the systems are related to one another by the well-known Equation 5 define the time period of structure.

$$T = 2\pi\sqrt{\frac{m}{k}} \quad (5)$$

For investigating the effectiveness of these methods, a thirty-story building structure is modeled by Sap2000 and installed the devices corresponding with the methodologies above. The results from these structures will be compared with the result of uncontrolled structure under earthquake excitation. We also have been taken into account the combination of these methods which is “Outrigger & PTMD” to compare and to investigate the effectivity of vibration control. Outrigger systems are installed at different story level, PTMD system and the combination “Outrigger & PTMD” are install with different mass ratio of Pendulum to reduce the top floor displacement as well as story drift of structure under earthquake load. In this study, to evaluate the performance of PTMD and Outrigger system, the earthquake loads El-Centro is applied with 1560 load steps, having a time interval of 0.02 sec and peak ground acceleration was 0.319g, which is illustrated in Figure 4.

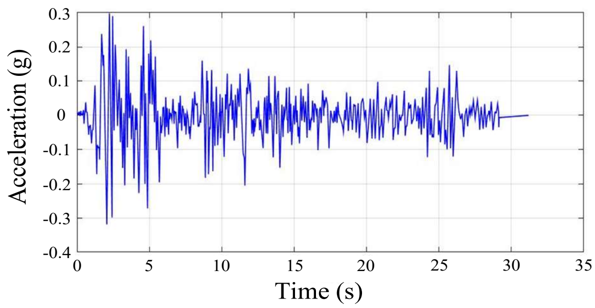
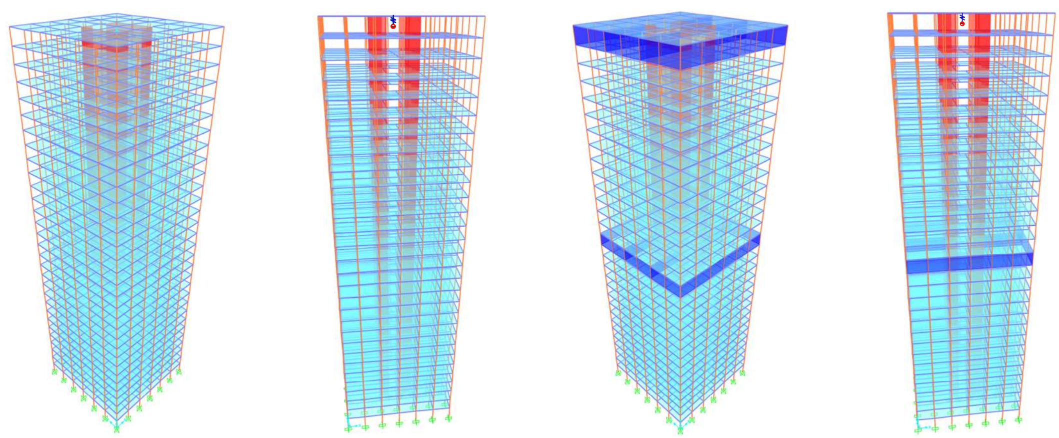


Figure 4. Time history of El-Centro Earthquake

3.2 Structural Model

In this study, trial analysis was applied to find out the optimum option of each method to mitigate the responses. For implementing this purpose, there are four typical models of different methods, which are shown in Figure 5 bellow:



(a) Building frame (b) PTMD system (c) Outrigger system (d) Combination system

Figure 5. Structural models with different systems

4 Results

After analyzing thirteen cases of different systems, the best option in each method is chosen then compare with each other to evaluate the efficiency. The cases of PTMD 5%, Outrigger system at the floor 10^{th}-20^{th} and the combination of Outrigger-PTMD 5% are the optimum case, their results are compared and shown in following sections.

4.1 Displacement Responses

As a serviceability index, the top displacement of the structure is considered as a key factor in the analysis and design of the high-rise structural systems. As the horizontal displacement of tall buildings is one of the major problems in its design to withstand against the strong dynamic loads. The Figure 6 shows top displacement of structural systems in time domain and Figure 7 shows the overall displacement of the structure. From the obtained results, it is observed that in case of outrigger system installed at 10^{th}-20^{th} floor had a minimum value of top displacement and it is the best option for controlling vibration. The use of outrigger system reduced the top displacement by 30.1%, for PTMD and combination system are obtained only 23.06% and 29.03%, respectively when compare with building frame system.

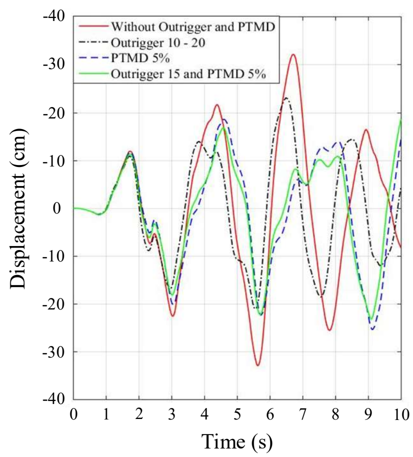


Figure 6. Displacement on the top of different systems

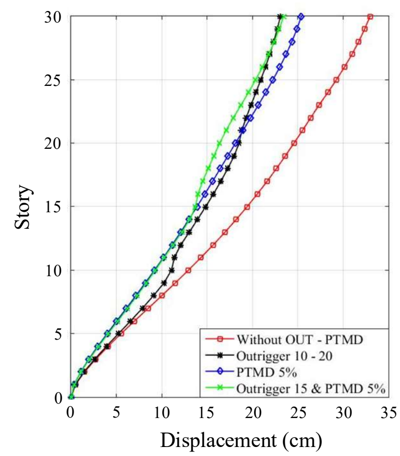


Figure 7. Displacement versus height

4.2 Drift responses

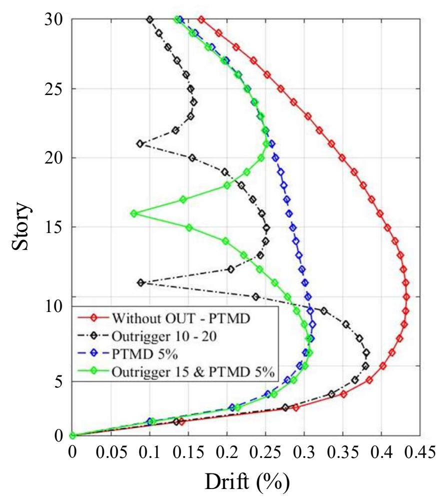


Figure 8. Drift reduction in structural systems

The story drift is a factor of safety for the structural members and also an index of structural health monitoring unit and drift is also a key factor to assess the serviceability of structures. Figure 8 shows the reduction in maximum story drift is achieved up to 11.63% due to outrigger and is lower than that of 27.91% for PTMD and 27.91% for combination system reduction. But from Figure 8, it is easy to recognize that all of values of drift ratio of these systems is smaller than the limitation of drift, which is often 2.5%. Although the maximum value of drift ratio in case of using outrigger is greater than PTMD system, but almost values are small and stable, so we can say that using outrigger system can be a good option in controlling drift of structure.

4.3 Velocity and acceleration responses

In figure 9, the use of outrigger system reduced the top velocity only 20.35%, for PTMD and combination system are obtained 38.94% and 34.51%, respectively when comparing with building frame system. Figure 10 shows the graphical view of the acceleration history in the time domain of the systems. Comparing with the building frame system, the acceleration reduction capacity of outrigger system at 10^{th}-20^{th} floor is found to be 14.76 % and that of PTMD and combination system are found to be 10.04% and 20.47%, respectively. For the acceleration, it is really tough to understand the effectiveness of controlling system to evaluate only the maximum value of acceleration. However, when we see the time history response of acceleration then we can notice that from the maximum values of acceleration are decreased after applying vibration control systems.

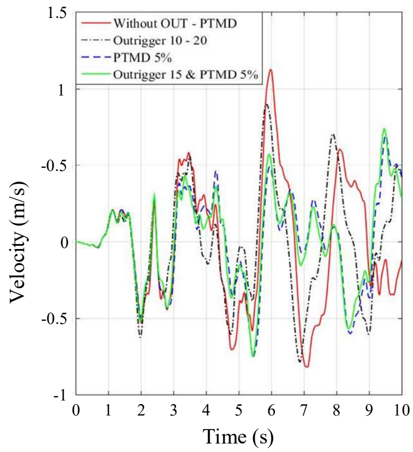


Figure 9. Velocity on the top of different systems

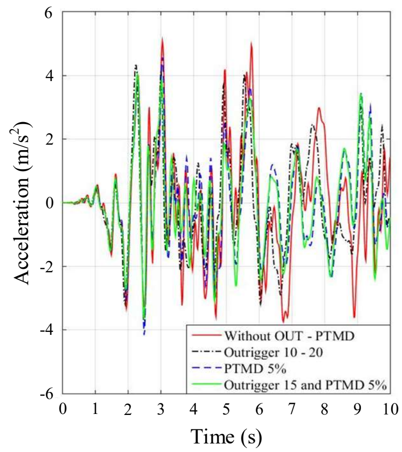


Figure 10. Acceleration on the top of different systems

5 Conclusion

From the manual calculation and computer simulation, the following results were obtained:

- Reduction in the response of structures using the Outrigger systems over the Pendulum Tuned Mass Damper system. However, this reduction changes with the number and the location of the outrigger systems.
- The efficiency of the Pendulum Tune Mass Damper was found to be less effective in controlling vibration although the mass is increased up to 5 % of structural system and it is just 3% in case of Outrigger system. Therefore, using outrigger system may be more economical.
- The comparative analysis between three structural systems and their relative efficiency are recorded and these comparisons are the results of some of the selected parameters for vibration control such as: Acceleration, Velocity, Displacement and Drift response.
- In this study, using Outrigger systems is the optimum case for controlling vibration not only about decreasing responses but also in the total mass used and these things are meaningful in economic aspects when structural members section can be reduced.
- The future scope of this study will be more rationalized when the deep analysis is carried out in soil structure interaction and economical point of view, to make the comparative economic analysis for both of systems, because it is one of the significant factors which appreciate the use of a particular system for high-rise structure.

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