TUNED MASS DAMPER (TMD): A STRUCTURAL CONTROL DEVICE FOR EARTHQUAKE-THREATENED STRUCTURES

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Abstract: *The problems that occur regarding the dynamic loading on structures have been a matter of great concern for a very long time. The standardized codes have gone through a number of modifications as the aftermath of large earthquakes made these revisions essential. Though code revisions promise better safety in future buildings provided the code specifications are followed properly, yet the stability of the structures already constructed following old codes of practice are in real threat. This paper is going to review popular control mechanisms and possibility of using those as retrofitting measures on already constructed buildings. A particular control mechanism namely Tuned Mass Damper (TMD) system is studied and the behavior of the building with a TMD is also presented in this paper. Finally the paper recommends the aspects of using the TMD in seismic control of buildings of importance.*

Introduction

One of the most destructive phenomena of nature is a severe earthquake with its terrible aftermath. An earthquake is a sudden movement of the Earth-crust, caused by the abrupt release of strain, accumulated over a long time. For hundreds of millions of years, the forces of plate tectonics have shaped the Earth, as the huge plates that form the Earth's surface move slowly over, under, and past each other. Sometimes the movement is gradual. At other times, the plates are locked together, unable to release the accumulating energy. When the accumulated energy grows strong enough, the plates break free. And the result is an earthquake.

Threat of Earthquakes for Bangladesh

During the last 150 years, seven major earthquakes (with M>7.0) have affected Bangladesh. Out of them, three had epicenters within Bangladesh. In a study on major earthquakes affecting Bangladesh (Ali and Choudhury, 1994) it is clearly suggested that earthquake is a potential threat to the country and the chronology of occurrence shows that by the year 2000 an earthquake of significant magnitude is on schedule; i.e., it is already overdue in Bangladesh.

The post quakes in the region didn't cause too much devastation, which has resulted in a complacency in the attitude of people towards earthquake. The increasing concrete construction in the urban and rural areas in addition to the negligence in following codes in design and construction poses much greater threat in recent times. The most important concern is of buildings that have already been constructed and are not designed to survive an earthquake of such magnitude, which is unfortunately due by now. Therefore the study required for retrofitting the existing buildings is of immense importance.

Retrofitting and Structural Control Mechanisms

The term retrofitting is used to fit any RC structure, often element by element; i.e. to take any engineering measures to increase the strength of the structural elements against undue lateral loads. The structural seismic performance can be achieved also by altering the overall dynamic behavior of the structure with some engineered measures. To alter the dynamic behavior of an already constructed structure requires some kind of control mechanism and these mechanisms are called `Structural Control Mechanisms'. Modifying rigidities, masses, damping or shape, and by providing passive or active counter forces are a few of these control mechanisms.

The notion of structural control roots back more than 100 years to John Milne. He built a small house of wood and placed it on ball bearings to demonstrate that a structure can be isolated from earthquake shaking. This idea initiated primary research on Structural Control in the field of aerospace engineering. But recently civil engineering has taken up the control mechanism, especially after the initial conceptual study by Yao in 1972 (Caughey, et al 1997). The field has continued to mature culminating in the First World Conference on Structural Control, held in Los Angeles in August 1994. The formation of the International Association for Structural Control (IASC) as a governing body and sponsor of the future conferences formed in the same year as a result of the successful conference. Japan in parallel, developed their own methods for structural control and more than 20 full-scale buildings are currently implemented with active control systems. In the USA and elsewhere, passive base isolation systems in low and medium-rise buildings for seismic protection have become an accepted design strategy. Various active, passive and hybrid control schemes offer great promise in controlling structural vibrations both for wind load as well as seismic vibration.

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Discussion on the Structural Control Measures

Active Control System: An active control system is one in which an external source powers control actuators that apply forces to the structure in a prescribed manner. These forces can be used to both add and dissipate energy in the structure. In an active feedback control system, the signals sent to the control actuators are a function of the response of the system measured with physical sensors. These systems are used to control the response of structures to internal or external excitation. The safety or comfort level is of prime importance in designing such system, while the structures are subjected to earthquake loads. Active control devices make use of a wide variety of actuators, including active mass dampers, tendon control, which may employ hydraulic, pneumatic, electromagnetic, or motor driven ball-screw actuation. An essential feature of active control systems is that external power is used to effect the control action. This makes such system vulnerable to power failure, which is always a possibility during a strong earthquake.

Passive Control System: A passive control system does not require an external power source. Passive control devices develop mechanical forces within themselves in response to the motion of the structure. Passive control depends on the initial design of the structure, on the addition of viscoelastic material to the structure, on the use of impact dampers, or on the use of tuned mass dampers and other dampers as well. The initial design may use a tapered distribution of mass and stiffness, or use techniques of base isolation, where the lowest floor is deliberately made of very flexible devices, thereby reducing the transmission of forces in the upper stories.

A passive control system is chosen for the study because it is relatively inexpensive, it consumes no external energy (as energy may not be available during a major earthquake), it is inherently stable and it works even during a major earthquake.

Hybrid Control System: The common usage of the term ‘hybrid control’ implies the combined use of active and passive control systems. For example, a structure equipped with distributed viscoelastic damping supplemented with an active mass damper on or near the top of the structure, or a base isolated structure with actuators actively controlled to enhance performance. The only essential difference between an active and a hybrid control scheme is the amount of external energy used to implement control. Hybrid control schemes can sometimes alleviate some of the limitations that exist for a passive or active control acting alone, thus leading to an improved solution. Another side benefit of a hybrid control is that in the case of power failure, the passive component of the control mechanism still offers some degree of protection unlike an active control system.

Semi-active System: Semi-active control systems are a class of active control systems for which the external energy requirements are orders of magnitude smaller than typical active control systems. It may therefore operate on battery power, which is critical during seismic events when the main power source to the structure may fail. Semi-active control systems do not add mechanical devices to the structural system. Semi-active devices are often viewed as controllable passive devices.

Principle, Behavior and Application of a TMD as a Passive Control Device

The concept of the Tuned Mass Damper dates back to the 1940’s (Den Hartog, 1947). It consists of a secondary mass with properly tuned spring and damping elements, providing a frequency-dependent hysteresis that increases damping in the primary structure. In a particular early study in 1994, three different buildings were analyzed, in which the first one was a 2D 10-story shear building, the second was a three-dimensional (3D) one-story frame building and the third was a 3D cable stayed bridge, using nine different kinds of earthquake records. Numerical and experimental results showed that the effectiveness of the TMD in reducing the response of the same structure under different earthquakes or of different structures during the same earthquake is significantly different. This implies that there is a dependency of the attained reduction in response on the characteristics of the ground motion that excites the structure. This response reduction is large for resonant ground motion and it diminishes as the dominant frequency of the ground motion gets further away from the structure’s natural frequency to which the TMD is tuned. TMD’s effectiveness is limited under pulse-like loading. These advantages of the device made it popular for use but the limitation on the other hand opened the door for further research in this relatively new engineering development.

TMD is applicable in many structures for structural control. There are a few generalized areas where TMD can be installed with due success. These generalized areas of TMD application is represented in the schematic diagram in Fig. 1.

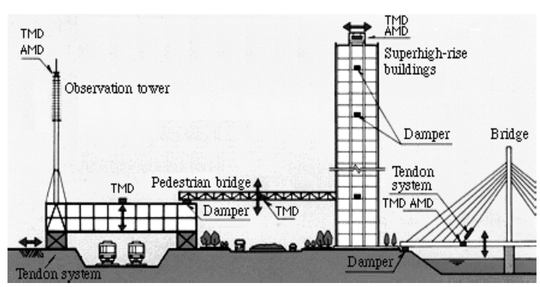

Fig. 1: TDM, A Structural Control Device for Earthquake-Threatened Structures

Analytical Formulation of a Tuned Mass Damper

The system considers the building or the structure to have nominal damping; i.e., $C_{structure} = 0$. The masses M and m are concentrated masses of the building (i.e., modal mass) and TMD respectively; while K and k are the two stiffnesses. The damping of the TMD is c.

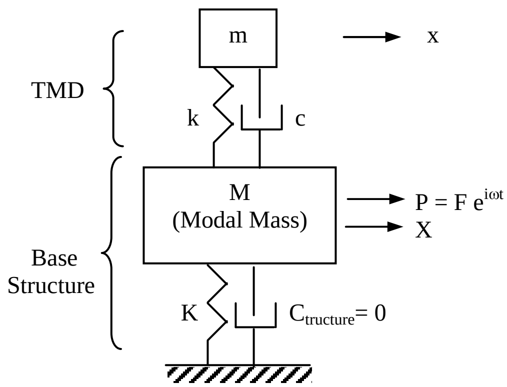

Fig. 2: Operating Principle of a TMD

For a harmonic force of $Fe^{i\omega t}$ operating at a frequency of ω, the displacements X of the structure (of mass M) and x of the TMD (of mass m) are obtained from the following equations of motion, derived from the free body diagrams of M and m.

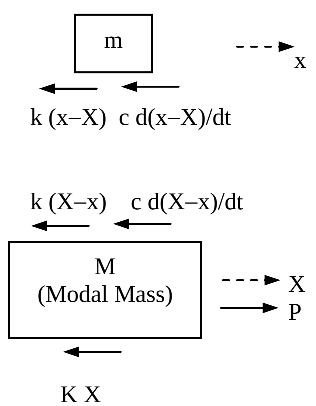

Fig. 3: Free-body Diagram of the TMD and Structure

Free-body diagram of the TMD gives,

$$m\, d^2x/dt^2 = -k\,(x-X) - c\, d(x-X)/dt$$

$$\Rightarrow m\, d^2x/dt^2 + c\, dx/dt + k\,x - k\,X - c\, dX/dt = 0 \quad \ldots(1)$$

Free-body diagram of the base structure gives,

$$M\, d^2X/dt^2 = Fe^{i\omega t} - k\,(X-x) - c\, d(X-x)/dt - K\,X$$

$$\Rightarrow M\, d^2X/dt^2 + c\, dX/dt + (K+k)\,X - c\, dx/dt - k\,x = Fe^{i\omega t} \quad \ldots(2)$$

The solution of these two basic equations is found firstly by assuming X and x to be harmonic of frequency ω. Minimizing the amplitude of the structural responses based on the optimization of the parameters results in the optimized frequency ratio λ_{opt} (ratio of the natural frequency of the TMD and the structure) and damping ratio β_{opt} (TMD damping as a ratio of the critical structural damping) as follows,

$$\lambda_{opt} = \sqrt{(k/m)/(K/M)} = 1/(1+\gamma) \quad \ldots(3)$$

$$\beta_{opt} = c/2\sqrt{(KM)} = 3\gamma^3/8(1+\gamma)^3 \quad \ldots(4)$$

where γ = Mass Ratio = m/M

In order to minimize the structural vibration, TMD with the required mass is tuned according to this optimized frequency.

Numerical Analysis of a Structure with an Installed TMD

Analytical solution of the equation of motion for a single-degree-of-freedom (SDOF) system is usually not possible if the excitation; i.e.; the applied force p(t) or the ground acceleration $\ddot{u}_g(t)$ varies arbitrarily with time or if the system is nonlinear. Such problems cannot be tackled by the linear methods in numerical analysis. Numerical time-stepping methods for the solution of differential equations are rather required to deal with such problems.

The study considered the structure as SDOF system while TMD as the second degree. But for a realistic simulation, the structure should be considered as a multi-degree-of-freedom (MDOF) system. Moreover, the behavior of such a system could be nonlinear. These two reasons guided the choice in choosing the numerical time-stepping methods for solution of differential equations so that the analysis of the two-degree-of-freedom system can be extended into a nonlinear MDOF system analysis. Central difference method is used in the analysis and to write a computer program for computing displacements. Displacement of a proposed building is analyzed for ground acceleration assuming the building to be a SDOF, which is compared to the displacement of that building with an optimized TMD installed in it.

Findings from the Study

The results from the study show that the amplitude of structural displacement depends on the mass ratio, decreasing with γ as shown in Fig. 4. Computational values of the amplitude of structural displacement with an optimized TMD installed in it are considerably lower than the displacements of the same structure without any control mechanisms. Fig. 5 demonstrates an example for a building assumed to be a SDOF system with mass ratio $\gamma = 0.01$, ground acceleration amplitude $A_g = 100$ gal and frequency of vibration $\omega = \pi = 3.14$ rad/sec. Computer programs for a SDOF system gave the maximum displacement of the structure to be 20 cm and another program for a two-degree-of-freedom (TDOF) system gave values of the displacement of the structure to be 5 cm assuming

TMD to be an additional degree of freedom. It clearly shows that TMD can reduce displacement of a structure significantly and thereby can be used as an effective control measure for earthquake structure.

Mass of a TMD system should be changed for different earthquake intensity. The reason behind it is that higher intensity of earthquake causes higher displacements and hence to minimize the effect of higher ground acceleration TMD with a higher mass ratio may be a solution. Therefore for the locations of higher seismic sensitivity TMD mass-selection criteria are governed by assessed earthquake intensity rather than economy of structural control and construction. TMD systems need appropriate mass ratio for a certain structure and optimization is necessity because cost involvement increases with the increase of mass of the TMD. Purpose and importance of the building in addition to the affordability of the beneficiary are the two governing factors in case of the selection of the TMD mass to retrofit a building.

Future Recommendation

International Association for Structural Control (IASC) has been established in 1995 and since then research on this field is fast developing. Study on different structural control mechanisms need to be performed in order to choose the appropriate control measures in the context of Bangladesh.

TMD requires further research, as the tuner to be installed is very expensive and therefore appears to be unfeasible in the context of developing countries. Economizing the tuner to make it more available to the developing world has a greater potential of further research.

The cost analysis for different mass ratio of a TMD system is recommended which will help to study the optimality and feasibility condition of installing TMD in Bangladesh.

The issue of retrofitting structures, which is not too popular in Bangladesh, has been given importance in the study. The study of engineered measures of retrofitting is recommended.

The study considered the building to be a SDOF system and recommends that the TMD application should be analyzed considering the building as a MDOF system.

The study also keeps an enquiry to be addressed by a future study for analyzing the effect of TMD on a structure under lateral harmonic load having frequency close to the natural frequency of the structure.

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