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A Review on Control System- Base Isolation and Tuned Mass Dampers

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Abstract—*Scientists and engineers have been working continuously on vibration mitigation of structures undergoing dynamic forces. In today's scenario earthquake occurs very frequently, leaving behind destructions - for which structures in the seismic zone need to be made seismic resistant. This concept of making seismic resistant structure is not a new one though many new techniques evolve out every now and then. Response control is provided with active, passive, semi active and hybrid system through dampers. The vibration control concept with base isolators and tuned mass dampers is a passive way of controlling the response by providing horizontal flexibility, energy dissipation and rigidity against lateral loads. This paper highlights a review on the principle and applications of base isolation and tuned mass damper.*

Keywords: *earthquake protective system, base isolation, tuned mass damper.*

1. INTRODUCTION

From time immemorial earthquakes have been taking place in mother earth. The humans have been protecting themselves from these disasters with the help of the then available facilities and advancement. The earthquakes have caused severe damages to large-scale infrastructures. Now-a-days, mitigation of these damages is done by using controls which include dampers , base isolation devices etc.

Most of the present day high -rise buildings have low natural damping. So increasing damping capacity of a structural system or considering the need for other mechanical means to increase the damping capacity of a building has become increasingly common in the new generation of tall and super tall buildings. To protect structures from significant damages and reduction of response under such severe earthquakes has become important in structural engineering.

Conventionally, structures are designed to resist dynamic forces through a combination of strength and energy absorption. These structures may deform well beyond the elastic limit. In order to avoid such critical damages, structural engineers are working to figure out different types of structural systems that are robust and can withstand strong motions. Alternatively, some types of structural protective systems may be implemented to mitigate the damaging effects of these dynamic forces. These systems work by absorbing or reflecting a portion of the input energy that would otherwise be transmitted to the structure itself. In such a scenario, structural control techniques are believed to be one of the promising technologies for earthquake resistance design. The concept of structural control is to absorb vibration energy of the structure by introducing supplemental devices. Various types of structural control theories and devices have been recently developed and introduced to large-scale civil engineering structures.

The selection of a particular type of vibration control device is governed by a number of factors such as efficiency, compactness and weight, capital cost, operating cost, maintenance requirements and safety.

1.1 Damping

Damping is a phenomenon in which the energy of a system is gradually reduced or the amplitude of vibration goes on decreasing and finally the vibration of the system is completely eliminated. The rate of decreasing amplitude depends upon the amount of damping. Damping is described by a quality factor Q where Q is the frictional loss of energy per cycle

$2\pi/Q = -\Delta E/E$

Where,

ΔE = energy lost per cycle

E = total energy stored in the wave

$A = A_{\circ}\exp(-\pi r/Q\lambda) = A_{\circ}\exp(-\alpha r)$

$A = \omega/2QV$

1.1.1. Damper

A DAMPER is a device that deadens, restrains or depresses the vibration induced due to earthquake, wind or other man made sources and thereby protecting the structures from getting damaged. It is also called as control devices.

1.2. Types of control/protective system

They are classified as

a. Active control system

b. Passive control system

c. Semi active control system

d. Hybrid control system

a. Active Control System

The active control system uses external forces to control the vibrations because they can provide additional energy to the controlled structure and opposite to that delivered by the dynamic loading. Active control devices require considerable amount of external power to operate actuators that supply a control force to the structure. An active control strategy can measure and estimate the response over the entire structure to determine appropriate control forces. As a result, active control strategies are more complex than passive strategies. Example- Active tuned mass damper, active variable stiffness damper etc.

b. Passive control system

A passive control device develops forces at the location of the device by utilizing the motion of the structure. Through the forces developed, a passive control device reduces the energy dissipation demand on the structure by absorbing some of the input energy. Thus, a passive control device cannot add energy to the structural system. Furthermore, a passive control device does not require an external power supply. Example- Base isolation, tuned mass damper (TMD), friction dampers etc.

c. Semi active control system

Semi-active control devices combine the positive aspects of passive and active control devices. Like passive control devices, semi-active control devices generate forces as a result of the motion of the structure and cannot add energy to the structural system. However, like an active control device, feedback measurements of the excitation are used by a controller to generate an appropriate signal for the semi-active device. In addition, only a small external power source is required for operation of a semi-active control device. Example- orifice damper, controllable fluid dampers etc.

d. Hybrid control system

A hybrid control system typically consists of a combination of passive and active or semi-active devices. Because multiple control devices are operating, hybrid control systems can alleviate some of the restrictions and limitations that exist when each system is acting alone. Thus, higher levels of performance may be achieved. Since a portion of the control objective is accomplished by the passive system, less active control effort, implying less power resource, is required. A side benefit of hybrid systems is that, in the case of a power failure, the passive components of the control still offer some degree of protection, unlike a fully active control system. Example- hybrid mass damper and hybrid base isolation.

2. PASSIVE CONTROL DEVICES

All vibrating structures dissipate energy due to internal stressing, rubbing, cracking, plastic deformations and so on. The larger the energy dissipation capacity the smaller the amplitudes of vibration. Some structures have very low damping of the order of 1% of critical damping and consequently experience large amplitudes of vibration even for moderately strong earthquakes. Methods of increasing the energy dissipation capacity are very effective in reducing the amplitudes of vibration. Passive energy dissipation systems utilises a number of materials and devices for enhancing damping, stiffness and strength and can be used both for natural hazard mitigation and for rehabilitation of aged or damaged structures. This may be achieved either by conversion of kinetic energy to heat, or by transferring of energy among vibrating modes. The first method includes devices that operate on principles such as frictional sliding, yielding of metals and phase transformation in metals, deformation of viscoelastic solids or fluids and fluid orificing. The later method includes supplemental oscillators, which act as dynamic vibration absorbers.

2.1 Types of passive control devices

a. Metallic yield dampers

b. Friction dampers

c. Viscoelastic dampers

d. Viscous fluid dampers

e. Base isolators

f. Tuned liquid damper

g. Tuned mass dampers

3. TUNED MASS DAMPERS

It is a passive damping system which utilizes a

secondary mass attached to a main structure through spring and dashpot. Secondary mass system has a natural frequency closed to the primary structure which depends on its mass and stiffness. The excess energy that is built up in the structure can be transferred to a secondary mass and is dissipated by the TMD. By specifying the mass ratio of the secondary mass to the primary body, the optimum frequency ratio between the two masses and the optimum damping ratio of the secondary mass can be obtained. This secondary mass can be made of any material such as concrete or steel, while damping is generally provided by viscous damping devices.

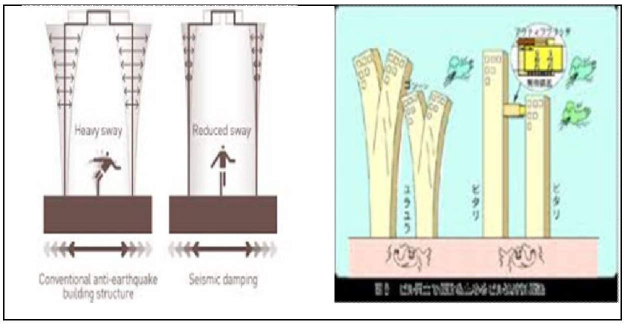

Fig. 1: Behavior of Structures with Tuned Mass Damper

3.1. Working principle of tuned mass dampers

Tuned Mass Damper theory has been adopted to reduce vibrations of tall structures. Dynamic absorbers and tuned mass dampers are the realizations of tuned absorbers and tuned dampers for structural vibration control applications. The inertial, resilient, and dissipative elements in such devices are: mass, spring and dashpot for linear applications and their rotary counterparts in rotational applications. Depending on the application, these devices are sized from a few grams to many tons. Other configurations such as pendulum absorbers/dampers, and sloshing liquid dampers have also been realized for vibration mitigation applications. The frequency of the damper is tuned to a particular structural frequency so that when that frequency is excited, the damper will resonate out of phase with the structural motion. The mass is usually attached to the building via a spring-dashpot system and energy is dissipated by the dashpot as relative motion develops between the mass and the structure.

3.2 Mathematical formulation

The equation of motion for primary mass as show in Fig. 2 is:

$$(1+\bar{m})\ddot{u} + 2\varepsilon\omega m\dot{u} + \omega^2 u = p/m - \bar{m}\ddot{u}_q$$

$\bar{m}$ is defined as the mass ratio, $\bar{m} = m_q/m$

$$\omega^2 = k/m \;,\; C = 2\varepsilon\omega m,\;\; C_q = 2\varepsilon w_q m_q$$

where, $\dot{u}$ is the velocity, $\ddot{u}$ is the acceleration, ε is the damping factor of the primary mass

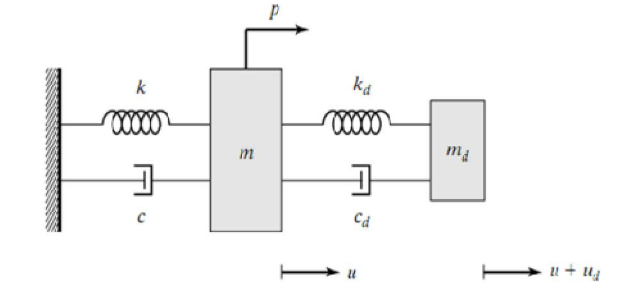

Fig. 2: Sdof-Tmd System

The equation of motion for tuned mass is given by:

$$\ddot{u}_q + 2\varepsilon_q\omega_q\dot{u}_q + \omega_d^2 u_q = -\ddot{u}$$

The purpose of adding the mass damper is to control the vibration of the structure when it is subjected to a particular excitation. The mass damper is having the parameters such as the mass m_q, stiffness k_q, and damping coefficient c_q. The damper is tuned to the fundamental frequency of the structure such that

$$\omega_q = \omega,\; k_q = \bar{m}\,k$$

The primary mass is subjected to the following periodic sinusoidal excitation

$$p = \hat{p}\sin\Omega t$$

The response u is given by

$$u = \hat{u}\sin(\Omega t + \delta 1)$$

$$u_q = \hat{u}_q\sin(\Omega t + \delta 1 + \delta 2)$$

where û and δ denote the displacement amplitude and phase shift, respectively. The critical loading scenario is the resonant condition. The solution for this case has the following form

$$\hat{u} = \hat{p}/\bar{m}\bar{k}\sqrt{}(1/\,(1+(2\varepsilon/\bar{m} + 1/\,2\varepsilon_q)2))\ldots\ldots(1)$$

$$\hat{u}_q = (1/2\;\varepsilon_q)\;\hat{u}$$

$$\tan\delta 1 = -(2\varepsilon/\bar{m} + 1/2\varepsilon_q)$$

$$\tan\delta 2 = -\Pi/2$$

The above expression shows that the response of the tuned mass is 90° out of phase with the response of the primary mass. This difference in phase produces the energy dissipation contributed by the damper inertia

$$\hat{u} = \hat{p}\;(1/2\varepsilon\;)$$

$$\delta 1 = -\Pi/2$$

To compare these two cases, one can express Eq (1) in terms of an equivalent damping ratio:

$$\hat{u} = \hat{p}\;(1/2\varepsilon e)$$

where,

$$\varepsilon e = \bar{m}/2\sqrt{}\;(1/(1+(2\varepsilon/\bar{m} + 1/\,2\varepsilon_q)^2))\ldots\ldots\ldots(2)$$

Equation (2) shows the relative contribution of the damper parameters to the total damping.

Increasing the mass ratio magnifies the damping. However, since the added mass also increases, so there is a practical limit on it.

3.3. Effect of Tuned Mass Dampers

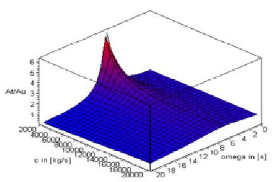

Fig. 3: Response of Structure before using TMD.

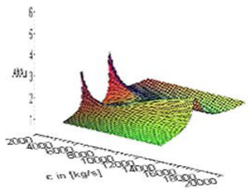

Fig. 4: Response of Structure after using TMD

3.4. Practical examples of Tuned Mass Damper

Till date TMD have been installed in large number of structures all around the globe. Taipei 101 (formerly known as the Taipei Financial Centre), Taiwan is one of world's tallest building. It rises to the unprecedented height of 508m - a significant achievement even if one disregards its geography where typhoons and earthquakes are common occurrences. The 660 tonne Tuned Mass Damper (TMD) for the building and two TMDs for the pinnacle involve the implementation of passive technology. Although the primary function of the TMDs in this project is to reduce the effects of wind-induced vibration, they have been designed to withstand the forces generated in up to a 2,500-year (mean recurrence interval) seismic event. For events less than a 100-year earthquake, the building TMD will behave relatively calmly, as does the building in which it has been installed. Approaching events with mean recurrence intervals of 1000 to 2500 years, the design challenge was to keep the TMDs from damaging the structure, and to remain in place and intact after severe event had passed and the vibration of the structure ended. The mass of TMD pendulum type is 660 tons. Reduces the frequency to (18.5-13.8)% in x & y direction respectively. The mass of two TMDs Pinnacle type weighs 4.5 tons each which was installed in 2002.Reduces the frequency to(14-17)% in x & y direction respectively.

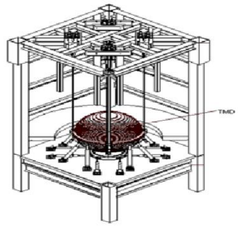

Fig. 5: TMD installed in the Taipei 101

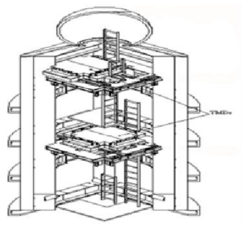

Fig. 6 : Taipei 101 Pinnacle TMDs

4. BASE ISOLATION

4.1. Objective of base isolation system

The major purpose of using the seismic isolation is to reduce the base-shear of the structure. Physically, large base shear is one of the main reasons of structural damages due to strong horizontal ground accelerations. Thus basic principle of base isolation is to lengthen the fundamental vibration period of the structure result in reduction of the pseudo-acceleration, hence reduces earthquake induced forces on the structure. From the viewpoint of design, many seismic codes use the base shear as a control parameter.

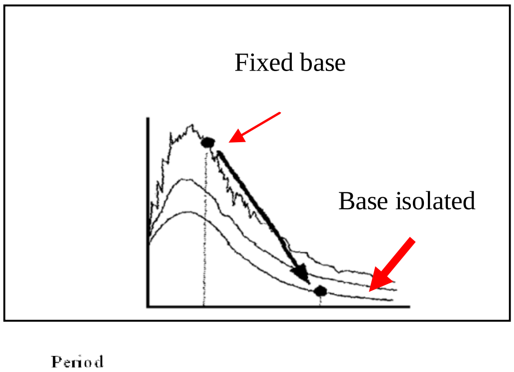

Fig. 7: Comparison of time period

In the above diagram base isolation significantly Increase the period of the Structure and the Damping so that the Response is Significantly Reduced.

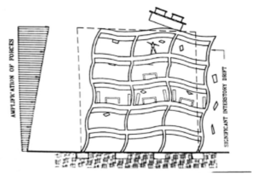

Fig. 8- Conventional structure

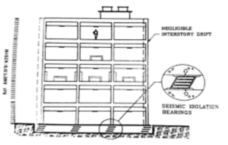

Fig. 9- Base isolated structure

4.2. Basic elements of Seismic Isolation system

There are three basic elements in any practical seismic isolation system. These are-

- A flexible mounting so that the period of vibration of the total system is lengthened sufficiently to reduce the force response.
- A damper or energy dissipater so that the relative deflection between building and ground can be controlled to a practical design level and
- A means of providing rigidity under low (service) load levels such as wind and minor earthquakes.

The reduction in force response illustrated in Fig. 10 is primarily dependent on the nature of the earthquake ground motion and the period of the fixed-base structure. Further the additional flexibility needed to lengthen the period of the structure will give rise to large relative displacements across the flexible mount. Fig11 shows an idealized displacement response curve from which displacement are seen to increase with increasing period. However as shown in Fig. 12, if substantial additional damping can be introduced into the structure, the displacement problem can be controlled. It is also seen that increasing the damping reduces the forces at a given period and removes much of the sensitivity to variation in ground motion characteristics, as indicated by the smoother force-response curves at higher damping levels.

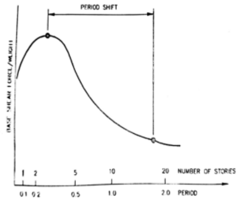

Fig. 10: Idealized forces response spectrum

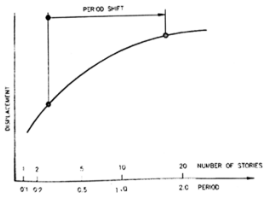

Fig. 11: Idealized displacement response spectrum

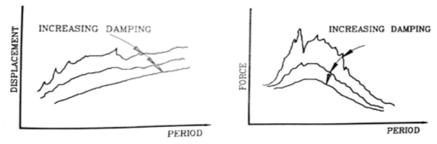

Fig. 12: Response spectra for increasing damping

4.2.1. Energy Dissipation

One of the most effective means of providing a substantial level of damping is through hysteretic energy dissipation. The term “hysteretic” refers to the offset in the loading and unloading curves under cyclic loading. Work done during loading is not completely recovered during unloading, and the difference is lost as heat. Fig. 13 shows an idealized force-displacement loop, where the enclosed area is a measure of the energy dissipated during one cycle of motion. Mechanical devices which use friction or the plastic deformation of either mild steel or lead to achieve this behavior have been developed. Friction is another source of dissipation which is used to limit deflections.

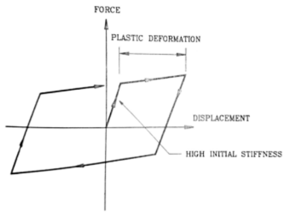

Fig. 13: Hysteretic force-deflection curve

4.3: Types of Isolators

a. Lead Rubber Bearing system

b. Friction Pendulum System

c. Base Isolation using Geo- Synthetic Materials

d. Hybrid Isolation System with Semi Active Devices

d. Hybrid Base Isolation with Passive Energy Dissipaters

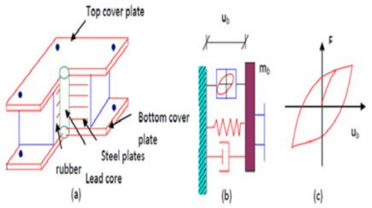

Fig. 14: (a) Lead rubber bearing (LRB) system (b) Schematic diagram (c) Force deformation behavior

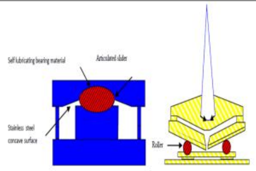

Fig. 15: Friction pendulum system and roller bearing system

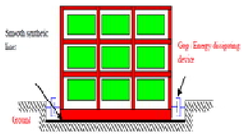

Fig. 16: Energy dissipation using geo-synthetic material

4.4. Practical example of base isolation

As of now, in India, the use of base isolation techniques in public or residential buildings and structures is in its inception and except few buildings like:

Fig. 17: Base Isolated building at IIT, Guwahati

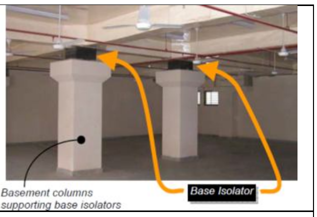

Fig. 18: View of basement in Bhuj hospital Building

5. MERITS AND DEMERITS

5.1: Merits and demerits Tuned Mass Damper

They do not depend on an external power source for their operation. They do not interfere with the principal vertical and horizontal load paths of the structure. They can respond to small level of excitation. Their properties can be adjusted in the field. They can be considered in new design as well as in upgrading work. A single unit can be effective in reducing vibrations induced by small earthquakes, wind and traffic. They require low maintenance. They can be cost effective.

A large mass is needed for their effectiveness-depends on the accuracy of tuning or a large space is needed for their installation. A TMD is only effective to control the response of a structure in one of its modes. The effectiveness of a tuned mass damper is constrained by the maximum weight that can be practically placed on top of the structure. Friction limits the effectiveness of a tuned mass damper to react to low level excitations.

5.2: Merits and Demerits of Base Isolation

Base isolation reduces the earthquake response of a structure and its design seismic forces. It reduces floor acceleration and thus the damages. Base isolation system is easy to install. It can also be used to retrofit.t existing structures.

It is only suitable for buildings with short period, founded on soils which do not produce long period motion and wind loads are not significant. Base isolation system requires an isolation gap to allow for the free lateral displacement of the isolator. The coefficient of friction in sliding isolator cannot be determined with certainty after a long period of inactivity. Stick slip process inherent to base isolation system may elicit high frequency pulses which would excite the higher modes of the building. Base isolation structures are more expensive than the fixed-base structures.

6. CONCLUSIONS

Current trends in construction industry demands taller and lighter structures, which are more flexible and having quite low damping value. This increases failure possibilities and also, problems from serviceability point of view. Several techniques are available today to minimize the vibration of the structure, out of which concept of using of TMD is found to be a better option than any other passive control devices which is because of the frequency optimization. Thereby it can be concluded that by increasing the mass ratio of the TMD the displacement response of the structure can be reduced.

Base isolation system can be considered as the “back-bone” of a structure in seismic zone. The use of base isolation technology is still an art in many countries. Therefore, the knowledge of the earthquake sources, the soil profile types and the estimation of the possible ground motions that frame the earthquake risk and hazard are very important factors to determine the potential use of base isolation for particular buildings. It can be figured out through this paper on aspects of base isolation and mass damper that if its inclusion is appropriate from a technical and first-cost perspective, then significant life-cycle cost advantages can be achieved.

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