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Application of tuned mass dampers in torsionally coupled buildings

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ABSTRACT

High rise building structures are both a necessity and a matter of sophistication and pride for structural engineers. Forces of nature in the form of earthquakes and cyclones starts playing brutal games with the structures, higher the structure goes, and higher it attracts the forces and wrath of nature in the form of seismic force. Seismic force, predominantly being an inertia force depends on the mass of the structure causing requirement of heavier sections as mass increases. And these heavy sections further increase the mass of the structure leading to even heavier seismic forces. Structural designers are met with the huge challenge to balance these contradictory physical phenomena to make the structure safe. The structure no more can afford to be rigid. In recent year, it is common practice to install vibration control devices on structures to mitigate their dynamic response caused by different factors, mainly due to wind and earthquake excitations. Among these devices, tuned mass dampers (TMD) have been widely used in building to mitigate dynamic responses of buildings. As the structural complexity of buildings increase, their response to such excitations may become more prone to torsional motion. Torsional motion induced by such excitations can be suppressed by utilizing TMDs. The performance of TMD at different positions are important for torsionally coupled structures. In this study, the performance of bi-directional tuned mass dampers (BTMD) in reducing the torsional response of a building under bi-directional earthquake excitations was studied and evaluated.

Keywords— *Tuned mass dampers, TMD, BTMD, ATMS, Seismic analysis, Torsionally coupled buildings, Irregularities*

1. INTRODUCTION

A major part of the energy of ground seismic waves reaching the base of the building is reduced as a result of deflection of seismic waves inside the earth, but the reaming part has a devastating effect. Once the seismic waves enter the supper structure of a building or any other structure; the building or structure has either to resist by itself by its original design or assisted by other techniques to resist the effect of the vibration caused by earthquakes. Improving the building's seismic performance using vibration control devices is among the techniques used. The basic idea of most damping devices is to counteract the input energy by their own momentum.

Generally, structural vibration controlling system can be divided into four types i.e. Active control systems, passive control systems, semi-active control systems and Hybrid control systems as described in the next sections. These systems use vibration absorbers (devices) for their implementations. In recent years successful a practical vibration control has been achieved by the application or dynamic vibration absorbers. Seismic vibration control devices can be passive, active, semi-active and hybrid devices. The devices are used to improve vibration performance by dissipating the wave energy inside a superstructure; by dispersing the wave energy between a wider range of frequencies; and by absorbing the resonant portions of the whole wave frequencies.

2. TUNED MASS DAMPERS

Tuned mass dampers (TMD) have been widely used for vibration control in mechanical engineering systems. In recent years, TMD theory has been adopted to reduce vibration of tall buildings and other civil engineering structures. 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 mechanism for mitigating structural vibrating using a TMD involves transferring the vibration energy from the structure into the TMD, which dissipated this energy through the damping effect. TMDs operate by providing additional damping to the building structure. TMD provides frequencydependenthysteresis which increases damping in the frame structure attached to it in order to reduce its motion. TMDs are effective in controlling vibration of a structure subjected to long duration, narrowband excitations.

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Through intensive research and development in recent years, TMD is accepted as an effective vibration control device for both new and existing structures; to chance their reliability against winds, earthquake, and vibrations due to human activities. TMDs are devices consisting of a mass, a spring, and a viscous damper that is attached to a structure in order to reduce the dynamic response of the structure in order to reduce dynamic response of the structure as defined in the previous chapter. The TMD concept was first applied by Frahm in 1909 to reduce the rolling motion of ships as well as ship hull vibrations. The simple model used by Frahm had only absorber mass suspended by undamped spring and was able to set the vibration amplitude of the main system to zero for a single frequency. A theory for the TMD was presented later in the paper by Ormondroyd and Den Hartog (1940). The initial theory was applicable for an undamped SDOF system subjected to a sinusoidal force excitation.

2.1 Working principles of TMD

A TMD splits the natural frequency of the primary system into a lower frequency (f1) and higher frequency (f2), the frequency response graph of SIDOF system is plotted for a given mass ration along with the optimal tuning ratio y opt and optimal damping ratioξ opt for ξ =0 or $\xi = \infty$, the peak response is infinite. When $\xi = 0$, the two massed behave independently with the two peaks appearing on the frequency response graphs tending to infinity. When $\xi=\infty$, the dampers is fused (locked) with the structure and the system behaves as an SDOF with mass as the sum of the TMD and the structure. When the damping ratio is not at its optimal value such as $\xi= 0.7\ \xi$ opt tow peaks of different height appear. When both the tuning ratio damping ratio are at their optimal values, two peaks of equal height occur with the lowest peak response. So that designing a TMD having this equal response peaks. It is important to properly design the tuned mass damper to achieve its maximum performance. The performance of a TMD is mostly evaluated in terms of the effective damping added to the structure by the TMD. The effective damping ξ eff.is defined as a single dampening parameter in an SDOF structure that will give the same performance as if the structure is attached with a TMD (McNamara, 1977)

2.2 Torsionally coupled building installed with TMDs

Structure for which the centers of mass and rigidity do not coincide are referred to as asymmetric or torsionally coupled structure and the distance between these two points is called eccentricity. If centers of mass and rigidity of the floor these two points are called eccentricity. If centers of mass and rigidity of the floor diaphragms lie along the same vertical axis, a horizontal component of ground vibration will include only lateral or translation motion of the structure on which it is acting. On the other hand, if the centers of mass and rigidity to do not coincide, a horizontal component of excitation will generally induce both lateral components of motions and a rotational component about a vertical axis. Torsional actions by also induce in symmetric structures even under a pure translation component of ground excitation, if all points of the base of the structure are not excited simultaneously because of the finite speed of propagation of the ground excitation, Kau (1974). The asymmetric building will experience a coupled torsional translational motion even when they are excited by a purely translational motion of the ground. The torsional component of the response may contribute significantly to the overall response of the building, particularly when the uncoupled torsional and translational frequencies of the system are close to each other ($\acute{\Omega}$ -1) The torsional response behavior of a building depends on the parameter called uncoupled frequency ratio which is the ratio of the two uncoupled natural frequencies of the building (Ω) Ramin Tabatabaei (2011) given by,

$$\acute{\Omega} = \acute{\omega}0$$

$\acute{\Omega}$ translation

Where $\acute{\omega}$ translation and $\acute{\omega}_0$ are an uncoupled translation and torsional frequencies, respectively $\acute{\Omega}$ translation can be in x or y-direction. The values of the ratio (Ω) can be obtained by adjusting the structural parameters i.e. stiffness of the structure, and distance of the resisting elements from the center of mass.

If $\acute{\Omega}$ >1, the structure is defined as torsionally stiff and its response is mainly translational If $\acute{\Omega}$ >1, the structure is strongly torsionally coupled so that the translational and the rotational responses occur at the same time for any excitation.

In this study, the response of all the three cases with and without BTMD are considered along with different eccentricity ratios under bi-directional earthquake excitations.

Really exiting building generally possess a large number of degree of freedom, and are actually asymmetrical, even with a symmetrical plan. Such a structure will undergo Lateral as well as torsional vibrations simultaneously under pure translational excitations.

In recent researches works, the application of TMDs in controlling the torsional response buildings are being investigated jangidan Datta (1997) studied the effectiveness of MTMD on reducing the response of the torsionally coupled system, which consists of two degrees of freedom structure with rotational and translational motion under stationary random excitation.

One of the most important considerations in the design of TMDs is the position of the TMDs on the building considered especially for torsional buildings. The problem of identifying the optimum location of the TMDs so as to increase the reduction of the building seismic response have been studied by different research i.e. Lin et al (2008), Fu and Johnsen (2011) Lin et al (1995) in their study of vibration control identification of seismically excited MDOF structure and found that for planer building the floor corresponding to the tip of controlled mode shape will be the optimum location of PTMD also Ueng et al. (1999) studies the vibration control effectiveness of PTMD for reducing design the seismic response or torsionally coupled buildings. Considering the practical design issues i.e. the optimal location for the installation; planer position; and movement direction of PTMDs; their study concluded that the greater the distance between the PTMD Wu (2001) developed a sequential procedure to determine the number of modes to be controlled and the optimal distribution of TMD system consisting of dampers placed on each floor, instead of condensed in one or in a few locations, as used in traditional TMDs, and damping coefficients. |I this study the effective position of BTMD on the plan of q Single and five storey building is considered.

2.3 Torsionally coupled buildings installed with BTMDs

A number of researchers are employed and asymmetrical structural models for investigating the response control effectiveness of PTMDs and MTMDs as discussed above. Compared with the design of a single TMD, the design of MTDMD is much complex. Since in the design of MTMD additional parameters come into consideration i.e. Number of TMDs etc. to reduce this difficulty tuning a single TMD in both lateral directions is researchers.

Nagendra et al. (2005) introduced coupled turned mass dampers (CTMDs) in which the mass is connected by translational springs and viscous dampers in an eccentric way. The CTMD has coupled modes of lateral and rotational vibration that has been used to control, coupled lateral and torsional vibrations of asymmetric buildings (both in plan and elevation). They modeled three-dimensional building with two translational and one rotational degree of freedom for each floor. The principal of the rigid body transformation was incorporated into the account eccentricity between the center of mass and center of rigidity. They used a non-dominated sorting genetic algorithm (GA) to solve the problem of multi-objective optimization, idea place for TMDs and its parameters have been done for several pare to- optimal solutions obtained simultaneously.

3. MODEL CONSIDERATION AND ANALYSIS

Design Characteristics: - The following design characteristics are considered for Multi-storey rigid jointed frames

Table 1: Design data of RCC frame structures

S. No	Particulars	Dimension/Size/Value
1.	Model	2B+G+10
2.	Seismic Zones	IV
3.	Floor height	3 m
4.	Basement	3 m
5.	Building height	39 m
6.	Plan size	20mx12m
7.	Earthquake load	As per IS-1893-2002
8.	Type of soil	Type -II, Medium soil as per IS-1893
9.	Live load	2 kN/ m^2
10.	Static analysis	Equivalent static lateral force method.
11.	Dynamic analysis	Using Response spectrum method
12.	Zone factor Z	0.24, As per Is-1893-2002 Part -1 for different. Zone as per clause 6.4.2.

3.1 Torsionally Coupled Buildings

In simple words, structures whose center of mass do not coincide with its center of rigidity are called torsionally coupled buildings. One part of the structure induces torsion on another part of the building. So, no matter what be the direction of the earthquake, the building will always vibrate predominantly in torsion.

In the above building, the CM is different from the CR. Thus additional moment causes the building to rotate about its vertical axis when acted upon any lateral load.

Here an attempt was made to understand the vibration behavior of torsionally coupled buildings under seismic loads. A simple 10 story structure has been taken for study. The same structure was analyzed for seismic loads, static and dynamic. Time history analysis has also been carried out to understand its vibration behavior. The structure considered is shown below.

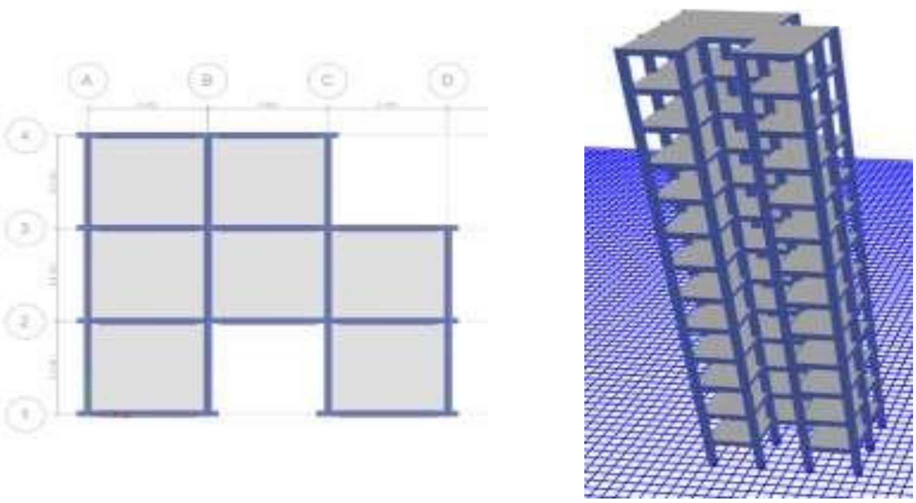


Fig. 1: Torsionally Coupled without TMD (Type A)

Storey Displacement for Type A:

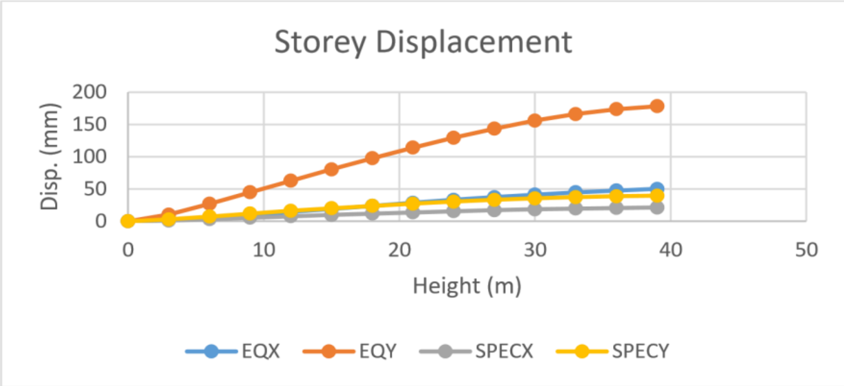


Fig. 2: The storey displacements are plotted below for EQX, EQY, SPECX, and SPECY.

Storey Shear for Type A:

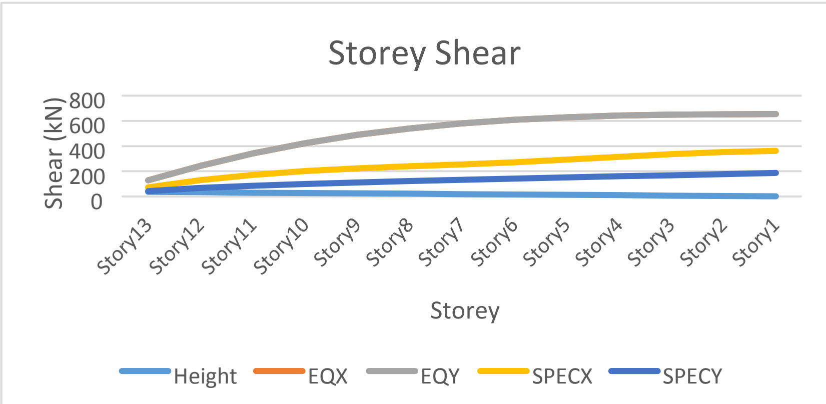


Fig. 3: The storey shears are plotted below for EQX, EQY, SPECX & SPECY.

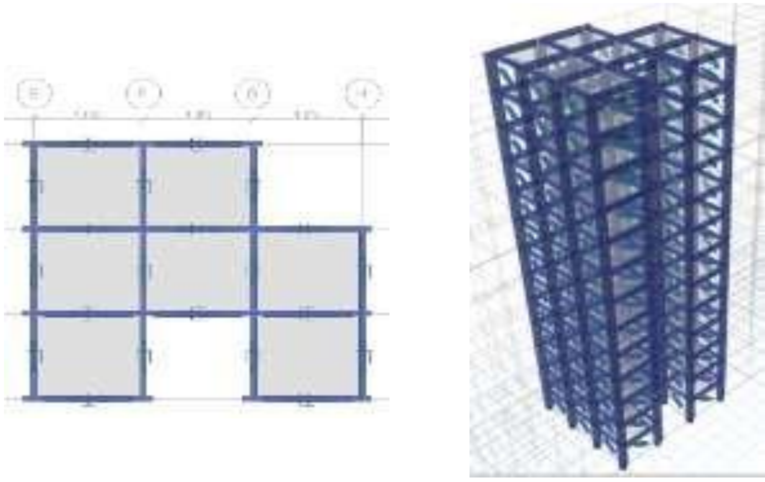


Fig. 4: Torsionally Coupled with TMD (Type B)

Storey Displacement for Type B:

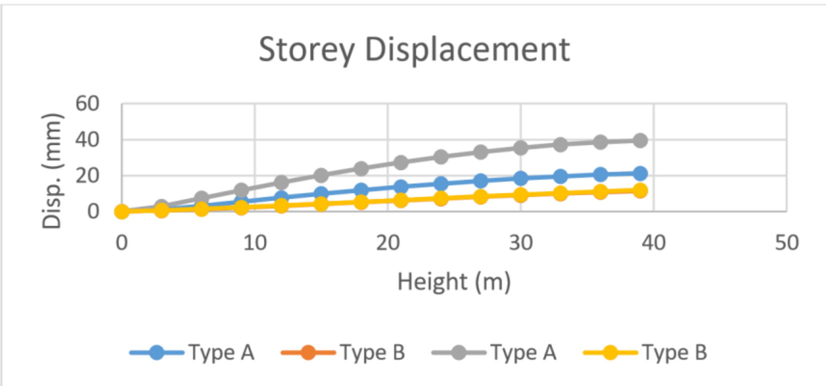


Fig. 5: The storey displacements are plotted below for EQX, EQY, SPECX, and SPECY

As expected the displacements are much reduced compared to Type A.

Storey Shear for Type B:

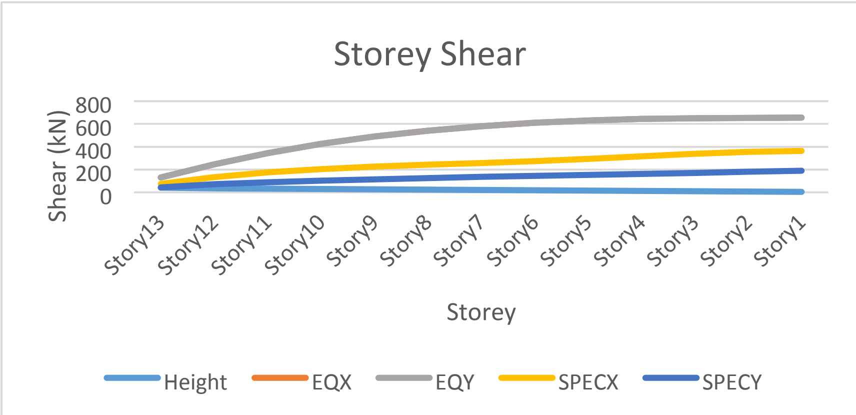


Fig. 6: The storey shears are tabulated below for EQX, EQY, SPECX & SPECY.

Here we observe the base shear is the same as Type A, as the weight of the two structures is the same. Thus the base shears are same.

Let's compare the storey displacements for both the structures for EQX and EQY.

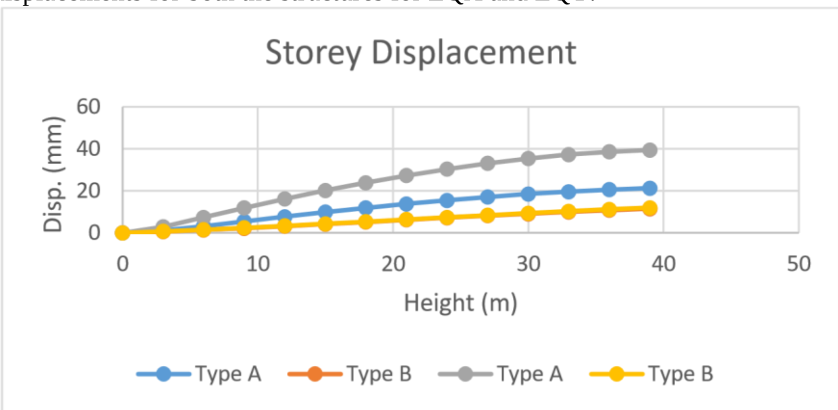


Fig. 7: The storey displacements are plotted below for EQX and EQY

Let's compare the storey displacements for both the structures for SPECX and SPECY.

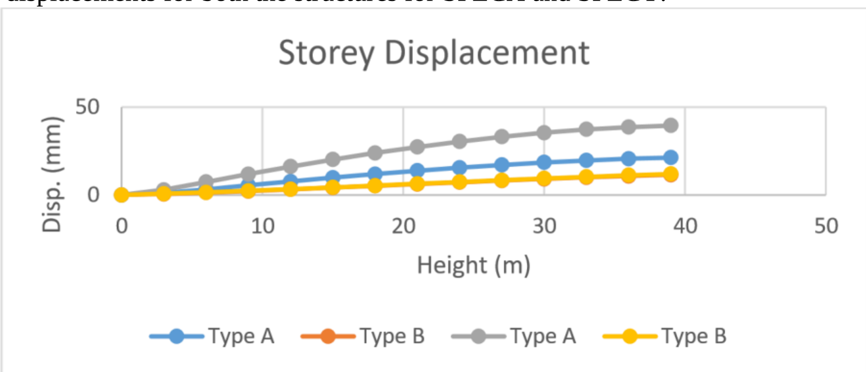
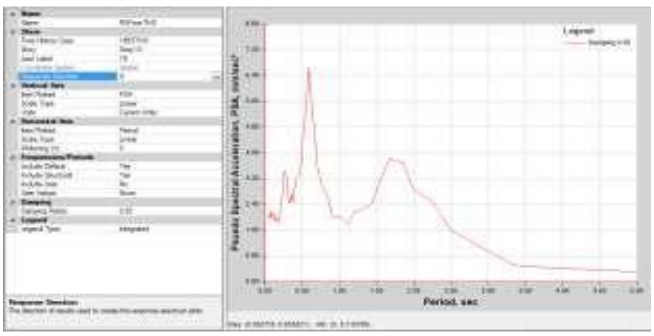


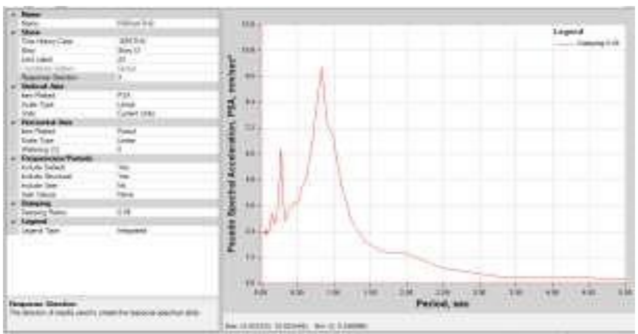
Fig. 8: The storey displacements are plotted below for SPECX and SPECY

3.2 Time History Response

Response spectrum plot for joint 18 (Type A) and Joint 22 (Type B) pseudo-spectral accelerations for time history ground acceleration compatible with IS1893 (Medium Soil).



Type A (X)



Type B (X)

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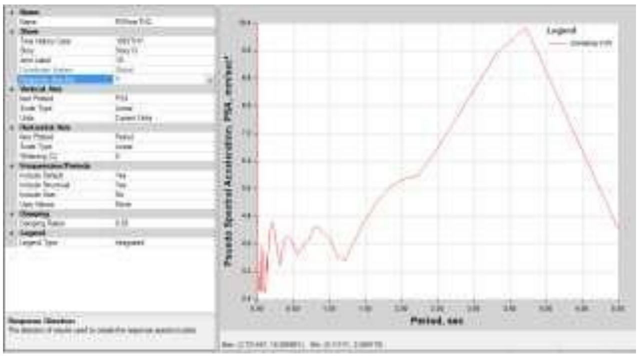
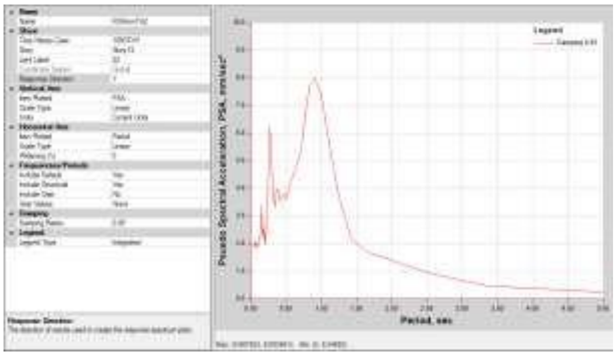
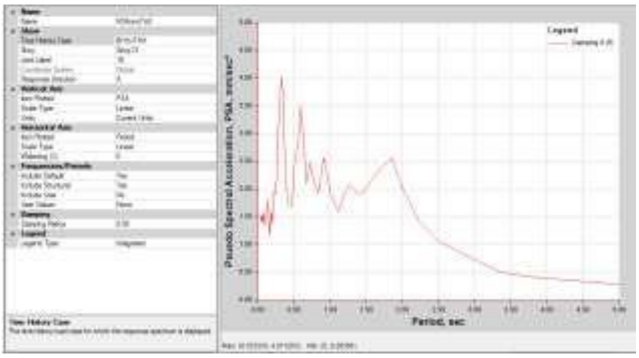


Type A (Y)

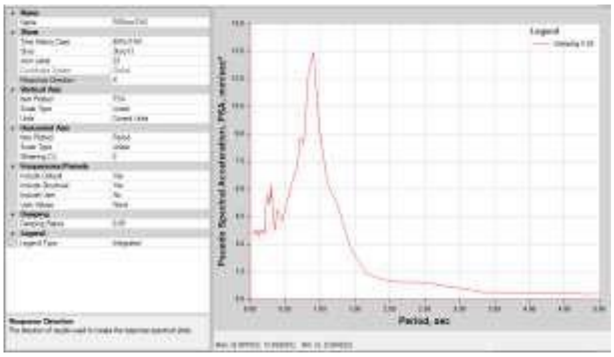


Type B (Y)

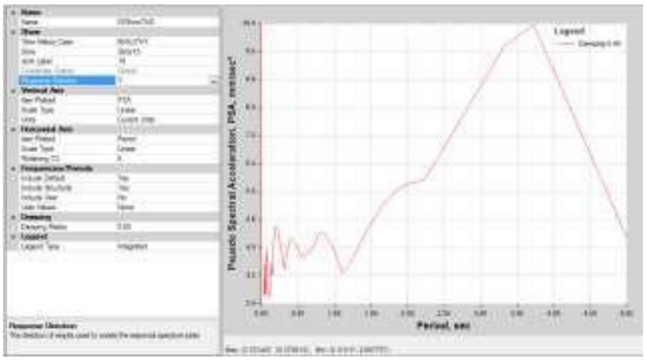
Response spectrum plot for joint 18 (Type A) and Joint 22 (Type B) pseudo-spectral accelerations for time history ground acceleration of Bhuj, Gujarat earthquake of 2001.



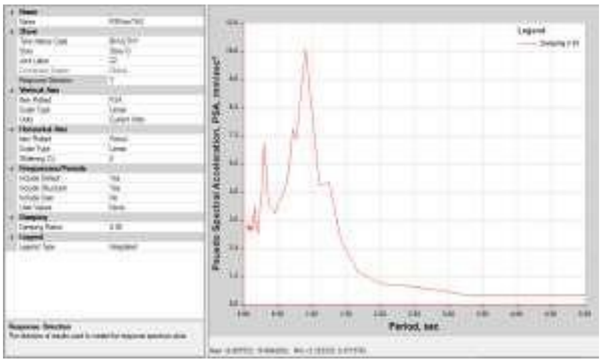
Type A (X)



Type B (X)



Type A (Y)



Type B (Y)

4. CONCLUSIONS

Time history analysis was carried out on the same models for compatible time history plot as IS1893 response spectrum curve for medium soil. The same experiment was extended for time history of BHUJ, earthquake of 2001. Here, the dynamic change considerably. For example, the base reaction for Type A structure for IS1893 time history is 139.44 kN in X direction only, which changes to 148.24 kN in X and additional 18.04 kN in the Z direction (vertical) for Type B structure. And it further changes to 1000 kN in X and additional 333.3 kN in Z direction for Type C. The change in Type C is because of the assumption of stiffness parameters of the Isolator being random. This would change, as specific Isolator values are given in the model. While in case of Type B, the diagonal link property assigned as Damper, is transferring the shear at an angle to the base.

This force is getting resolved into two components, and so is the result.

Simple Plane Frame of 10 Storeys

The dynamics of the structures do change with the addition of 6 more storeys, but the basic variation of parameters is more or less the same. As expected the displacement reduces from 27 mm at the top to 12 mm at the top after the inclusion of dampers. Also the base reaction changes. The sheer force and bending moments also reduce considerably for a static earthquake. Noticed here the displacement time history for Joint 92 at top storey of Type A (Bare Frame) is considerably higher than that of Joint 92 at top storey of Type B (With TMD) for IS1893 Time History. Similar, behavior shown for Bhuj earthquake time history.

We noticed the isolation of vibration at the base. While the entire structure displaces as a rigid unit, the relative displacement of the individual storeys is the same as the bare frame structure. The idea for a base isolated structure to be successful is to make it rigid, which is practically feasible for low height structures. Hence, it is an ideal choice for institutional buildings, commercial centers, shopping malls etc.

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We observe, no difference, in the shear force and bending moment in the structure for Type C.

The two images show the displacement time history for the acceleration history of IS1893 and Bhuj earthquake. (Refer 4.9.1) Here we see, the real difference in performance of the two structures. Joint 92 shown by orange color is for the simple structure, while Joint 95 shown by green color is the base isolated structure. We can clearly see the displacement is much higher for the base isolated structure right from the beginning of the time history. But this displacement is a controlled one, in order to dissipate the energy leaving the structure and its inhabitants safe.

The two images show the joint acceleration for Type A and Type C frames respectively for acceleration time history of IS1893 and Bhuj earthquake. (Refer 4.9.1) We notice the base isolated structure (shown by cyan color) receives almost negligible acceleration compared to the simple structure (shown by red color). This indicates much less force for the base-isolated structure and thus a safer solution.

Application of BTMD's

The same analysis was further extended to full 3D models with the application of bidirectional tuned mass dampers and the results obtained for earthquake forces in both X and Y directions. Here, one more building model was introduced with a different position of dampers being introduced into the structure. The storey displacement for EQX was as expected, maximum for Type B followed by Type A, Type D and then Type C. Type D has lesser number of dampers than Type C. Similar trend could be seen for EQY, but the difference is higher here. The storey stiffness is maximum for Type B followed by Type D, Type A and Type C both for EQX and EQY.

In the special case of torsionally coupled buildings, the storey displacement is much reduced for Type B and Type D as expected. But, interestingly here, the variation of the position of TMD's is not affecting the results at all.

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