DAMPING OF SEISMIC VIBRATIONS OF A 3D ASYMMETRICAL BUILDING MODEL WITH MULTIPLE TMD’S

J.-P. Pinelli¹, K. Chen², H. Gutierrez³, and R. Rusovici⁴

ABSTRACT

In this paper, the authors investigate the control of the seismic response of a three dimensional asymmetrical tier-building model, with a combination of three tuned mass dampers (TMD) located on the upper floor of the building. The 3D frame model represents a 3-story steel building designed for the SAC project in Los Angeles, California. All the dynamic analyses of the 3D structure are performed in ANSYS. The frequencies of the three TMD’s and excitations are tuned to the appropriate fundamental frequencies of the model. The optimal number and location of the TMD’s on the top floor are investigated, to reduce the horizontal displacements in two orthogonal directions, and the in plane rotation of each story. The authors compare the dynamic response of the 3D asymmetrical building under unidirectional and bidirectional sinusoidal excitations, and earthquake excitations, with no TMD’s, or with combinations of one, two, and three TMD’s. The combination of three TMD’s yields the largest response reduction. In the final series of tests, a “floating” top floor, resting on rubber bearings, provides the mass for the three TMD’s. The results show a significant reduction of the displacements and rotations of the building. The effect of non-linear behavior of the structure is also investigated.

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ABSTRACT

In this paper, the authors investigate the control of the seismic response of a three dimensional asymmetrical tier-building model, with a combination of three tuned mass dampers (TMD) located on the upper floor of the building. The 3D frame model represents a 3-story steel building designed for the SAC project in Los Angeles, California. All the dynamic analyses of the 3D structure are performed in ANSYS. The frequencies of the three TMD’s and excitations are tuned to the appropriate fundamental frequencies of the model. The optimal number and location of the TMD’s on the top floor are investigated, to reduce the horizontal displacements in two orthogonal directions, and the in plane rotation of each story. The authors compare the dynamic response of the 3D asymmetrical building under unidirectional and bidirectional sinusoidal excitations, and real earthquake excitations with no TMD’s, or with combinations of one, two, and three TMD’s. The combination of three TMD’s yields the largest response reduction. In the final series of tests, a “floating” top floor, resting on rubber bearings, provides the mass for the three TMD’s. The results show a significant reduction of the displacements and rotations of the building. The effect of non-linear behavior of the structure is also investigated.

Introduction

Earthquakes may cause extreme structural and economic damage. Assessing earthquake risk and  

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improving engineering strategies to mitigate damage are thus the only viable options to create more resilient cities and communities. One of the methods to reduce the tragic consequences of natural hazards is using structural damping control devices that can reduce the response of civil engineering structures and protect them from damage under seismic or wind load. The challenge for control systems, whether passive, semi-active, or active is to reduce both the lateral swings, as well as the in-plane rotation of an asymmetrical building.

A tuned mass damper (TMD) system is one of the most popular passive systems. The tuned mass damper (TMD) is a passive energy absorbing device consisting of a mass, a spring, and a viscous damper attached to a vibrating system to reduce undesirable vibrations [5]. The designer can adjust the natural frequency of the TMD to be the same or close to the fundamental frequency of the structure. When the main structure is excited, the tuned mass damper through its inertial response will absorb energy and reduce the response of the structure.

Most of the analytical studies of TMD’s have been done on 2D models. The main goal of this paper is to study an effective tuned mass damper system to reduce not only displacements in two orthogonal directions, but also the in plane rotation of each story of a building. The authors compared the dynamic response of a 3D asymmetrical building under unidirectional and bidirectional sinusoidal excitations and real earthquake excitations with no TMD’s, or with combinations of one, two, and three TMD’s. The concept of a “floating” top floor of the structure as part of a TMD is then investigated.

Analytical modeling

In this study, a 3-story steel building designed for the SAC project in Los Angeles, California, is modeled as a tier-building. Fig. 1 shows the detail of this 3-story building from Ohtori et al. (2004) [3]. The building is symmetric in the N-S direction, but in the E-W direction there is an eccentricity between center of mass and center of stiffness ep=3.42m

The 3-story benchmark-building model depicted in Fig. 1 was modeled in ANSYS as a three-dimensional, nonlinear, isotropic finite element model. In both directions, the connections between perimeter beams and perimeter columns are moment-resisting connection, except for the northern most bay in the N-S direction, according to Fig. 1. The rest of the connections between columns and beams are pin connections. All the central columns are pin connected at the base. All the perimeter columns are fixed at the base in one direction.

Frequencies and mode shapes of the building

The first three natural frequencies of the 3-story model are 1.19, 1.72, and 2.26Hz. Fig. 2 shows the first three mode shapes for the 3-story building, which correspond to one translational mode in the NS direction, a combination of translation in the EW direction and rotation, and a
predominantly rotational mode.

Figure 1. 3-Story benchmark building N-S MRF [3]

Figure 2. First three mode shapes of the 3-story benchmark buildings in ANSYS

**Analysis of tuned mass damper systems**

The building model was then retrofitted with a combination of one, two, or three TMD’s, installed on the third floor in the 3D model. The mass of each TMD is 5% of the mass of the building, and the damping ratio of each TMD’s is 2%. Table 1 lists the stiffness and damping value of the TMDs. The TMD’s in the NS direction were tuned to the first mode of the building, while the TMD’s in the EW direction were tuned to the second mode.

The analyses included five cases: 1-TMD model A, 1-TMD model B, 2-TMD model, 3-TMD model A and 3-TMD model B. Fig. 3 shows all five cases TMD models. In the directions with only one TMD, the TMD was aligned with the center of mass.
Table 1. Properties of the TMDs

<table>
<thead>
<tr>
<th>Position</th>
<th>Frequency(Hz)</th>
<th>Mass(kg)</th>
<th>Stiffness(kN/m)</th>
<th>Damping(kNs/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TMD in the NS direction</td>
<td>1.19</td>
<td>147500</td>
<td>8238</td>
<td>44</td>
</tr>
<tr>
<td>TMD in the EW direction</td>
<td>1.72</td>
<td>147500</td>
<td>17287</td>
<td>64</td>
</tr>
</tbody>
</table>

Figure 3. All five cases TMD models (TMD installed on the third floor).

Unidirectional and bidirectional sinusoidal excitations were applied to all models. In all cases, the frequency of the sinusoidal excitation in the NS direction was tuned to the frequency of the first mode of the model without damper; the frequency of the sinusoidal excitation in the EW direction was tuned to the frequency of the second mode of the model without damper; all the excitations had an amplitude of 2 m/sec². The authors compared the peak displacement in each direction and rotation between no-TMD, 1-TMD-A, 1-TMD-B, 2-TMD, 3-TMD-A, and 3-TMD-B. Table 2 shows the results for all cases under bidirectional sinusoidal excitation. Table 3 shows the TMD strokes for all cases under bidirectional sinusoidal excitation.

Fig. 4 and 5 show the time histories of the third floor under bidirectional sinusoidal excitation (between No TMD mode, 2-TMD model and 3-TMD-B model). The green line is the time history of No TMD model. The purple line is the time history of 2-TMD model and the red line is the time history of 3-TMD-B model.

In every model, it was verified that the most effective location of a single TMD is when it is aligned with the center of mass of the story. The 3-TMD-A model is 10% more effective than
the other models with 1-TMD-A or 2-TMD in reducing orthogonal displacements, under both the NS and the bidirectional excitations. Similarly, the 3-TMD-B model is 10% more effective than the other models with 1-TMD-B or 2-TMD in reducing orthogonal displacements, under both the EW and the bidirectional excitations. In addition, the 3-TMD-B model is 20% more effective than the 1-TMD-B or 2-TMD model, in reducing rotation under both the EW and the bidirectional excitations. It is also 5% and 10% more effective than the 3-TMD-A model in reducing rotation and displacements, under the same conditions. It is therefore clear that the most effective configuration of TMDs is with two TMDs in the direction where there is an eccentricity between centers of mass and stiffness, and a third TMD in the orthogonal direction aligned with both center of mass and stiffness, i.e. the 3-TMD-B model.

Table 2. % Reduction of response for each model under bidirectional sinusoidal excitation

<table>
<thead>
<tr>
<th>Floor</th>
<th>Displacement in the NS direction</th>
<th>Displacement in the EW direction</th>
<th>Rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1A</td>
<td>1B</td>
<td>2</td>
</tr>
<tr>
<td>3rd</td>
<td>55</td>
<td>0</td>
<td>55</td>
</tr>
<tr>
<td>2nd</td>
<td>56</td>
<td>0</td>
<td>56</td>
</tr>
<tr>
<td>1st</td>
<td>57</td>
<td>0</td>
<td>57</td>
</tr>
</tbody>
</table>

Table 3. TMD stroke under bidirectional sinusoidal excitations

<table>
<thead>
<tr>
<th>In the NS direction(m)</th>
<th>In the EW direction(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>2</td>
</tr>
<tr>
<td>Front</td>
<td>Back</td>
</tr>
<tr>
<td>0.54</td>
<td>0.54</td>
</tr>
</tbody>
</table>

Analysis of roof isolation system

If concrete were used for the mass of each TMD, the required volume would be approximately 4x4x4m³. Because 3 masses of that size would be too large to be installed on the third floor, the authors investigated the use of the top floor mass as the mass of the TMD’s. Feng et al. (1995) [2] and Sadek et al. (1997) [5] investigated the concept of mega substructure as part of the mass of a TMD. The concept was extended by Villaverde et al. (1999) [7] who first explored using the mass of the upper floor as the mass of the TMD. Actual implementations of similar concepts are reported by Dutta et al. (2008) [1], Tasaka et al., (2008) [6], as well as Yamane et al., (2003) [8] and Ryan and Earl, (2010) [4]. The intent here is to apply this concept to the case of an asymmetric 3D tier building subjected to bidirectional excitation. The roof becomes a “floating roof” isolated from the rest of the structure, supported for example on elastomeric bearing.
An intermediate horizontal frame structure with full X-bracing was added to provide a rigid support to the floating roof. The first three natural frequencies of the model without top plate are 1.7, 2.3, and 3.12 Hz. Fig. 6 shows the first three mode shapes for the 3-story building without the top plate.

The three connections between the building roof and the top frame are modeled as three spring-damping elements. The resulting 3 TMDs are tuned to the first 2 natural frequencies of the building without the roof mass. See Table 4. The position of these three spring-damping elements is identical to the position of the 3-TMD-B model. In this idealized preliminary study, the two bearings elements in the EW direction have stiffness and damping properties different than the spring and stiffness properties of the bearing in the NS direction. In practice, the spring damping connecting elements could be a series of elastomeric bearing in both directions. The first three natural frequencies and mode shapes of the model with top plate (floating roof model) are 1.0, 1.31, and 1.52 Hz. Fig. 7 shows the first three mode shapes for the floating roof model.

Table 4. TMD properties in the floating roof model

<table>
<thead>
<tr>
<th>Position</th>
<th>Frequency(Hz)</th>
<th>Mass(kg)</th>
<th>Stiffness(kN/m)</th>
<th>Damping(kNs/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TMD in the NS direction</td>
<td>1.7</td>
<td>1.04x10^6</td>
<td>121075</td>
<td>449</td>
</tr>
<tr>
<td>TMD in the EW direction</td>
<td>2.3</td>
<td>1.04x10^6</td>
<td>218008</td>
<td>602</td>
</tr>
</tbody>
</table>

The floating roof model was tested under sinusoidal excitations. Table 5 compares the reductions in peak displacement and rotation between no-TMD, 3-TMD-B, and floating roof models. Table 6 shows the displacement of the center of mass for floating roof model under bidirectional sinusoidal excitation. Notice that although the displacements of the floating roof are of the same magnitude than the original uncontrolled roof, the rest of the structure experiences significant response reductions.
Figure 6. First three mode shapes of the 3-story building without top plate in ANSYS

Figure 7. First three mode shapes of the floating roof model in ANSYS

Table 5. Response reduction of 3-TMD-B vs. floating roof model under bidirectional sinusoidal excitations

<table>
<thead>
<tr>
<th>Floor No.</th>
<th>NS displacement</th>
<th>EW displacement</th>
<th>Rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3-TMD B Floating roof</td>
<td>3-TMD B Floating roof</td>
<td>3-TMD B Floating roof</td>
</tr>
<tr>
<td>3rd</td>
<td>55% 82%</td>
<td>45% 80%</td>
<td>58% 65%</td>
</tr>
<tr>
<td>2nd</td>
<td>56% 84%</td>
<td>46% 77%</td>
<td>59% 77%</td>
</tr>
<tr>
<td>1st</td>
<td>57% 80%</td>
<td>46% 76%</td>
<td>58% 76%</td>
</tr>
</tbody>
</table>

Table 6. Displacement of center of mass for floating roof model under bidirectional sinusoidal excitation (Original refers to roof without passive control).

<table>
<thead>
<tr>
<th>In the NS direction(m)*</th>
<th>In the EW direction(m)*</th>
<th>Rotation(Rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original Floating roof</td>
<td>Original Floating roof</td>
<td>Original Floating roof</td>
</tr>
<tr>
<td>0.296 0.204</td>
<td>0.078 0.08</td>
<td>0.00193 0.0026</td>
</tr>
</tbody>
</table>

*The displacement of the center of mass of third floor in the floating roof model.

Fig’s 8 to 10 show the time histories of third floor between No TMD mode, 3 TMD-B model and floating roof model under bidirectional sinusoidal excitations. The green line is the time history of No TMD model. The purple line is the time history of 3-TMD-B model and the red line is the time history of floating roof model.
The floating roof model is 20% to 25% more effective than the 3-TMD-B model in reducing orthogonal displacements and rotations, under the NS, the EW, and the bidirectional excitations.

Nonlinear and linear analysis of “floating” roof.

In the previous analyses, the authors assigned a large value to the steel yield stress to force the structure to behave linearly. Next, they reduced the values of the yield stress for beams and columns to 248 MPa and 354MPa (see Fig. 1). The amplitude of the sinus excitations was also increased to 10 m/sec^2 in order to activate the nonlinear behavior of the model. Fig. 11 shows the degradation of the response between linear and nonlinear behavior of the floating roof model under bidirectional sinusoidal excitation. These results show that, as expected, the nonlinear behavior of the structure leads to a degradation of the effectiveness of the “floating” roof of up to 23%.

Testing of the floating roof model under real earthquake excitation

To evaluate the proposed control strategies under seismic excitation, two historical records were selected: the N-S and E-W components of the Imperial Valley, California earthquake of May 18, 1940, recorded at the Imperial Valley Irrigation District substation in El Centro, California. The preliminary results reported here are for the simultaneous application of the NS seismic record to the NS direction of the model and the EW direction of the seismic record to the EW direction of the model. In addition, to ensure nonlinear behavior of the structure, the amplitudes of the records were multiplied by two. Fig. 12 shows the EW translation and rotation time-histories of the third floor for no TMD model and floating roof model under El Centro excitation. The green line is the No-TMD model and the purple line is floating roof model.

In this particular case, with minimal non-linear behavior, there is a 44% reduction in the peak EW translation and a 49% reduction in the peak rotation of the third story. However more studies are needed, with different earthquake records with different frequency content, and to assess the influence of nonlinear behavior.

Conclusion

This study investigated the effectiveness of combining 2 TMD’s in conjunction with a third TMD in an orthogonal direction to control translations and in-plane rotations of an asymmetric structure subjected to in-plane dynamic torsion. The 3 TMDs scheme proved to be more effective than a one TMD or two TMDs scheme, when subjecting an asymmetrical 3D 3-story tier-building to bidirectional sinusoidal excitations tuned to the first two natural frequencies of the structure. The concept was extended to the case of a “floating roof”, where the mass of the roof of the building, which could be supported on elastomeric bearing, could provide the mass for the 3 TMDs. The floating roof model was 30% more effective than the 3 TMDs model. However, the studies also show, as expected, that the nonlinear behavior of the structure, which
leads to detuning of the TMD’s degrades the effectiveness of the TMD scheme.

A preliminary study explored the behavior of the building with a floating roof under seismic excitation. Not surprisingly, the effectiveness of the control appeared to be highly dependent on the earthquake characteristics, including amplitude and frequency contents, as well as the amount of non-linear behavior of the structure. Future studies will explore the suitability of the proposed scheme to taller buildings, and the possibility of replacing the passive spring and damping connections of the TMD masses with semi-active magneto-rheological dampers.

Figure 8. Time history of NS direction(m)  Figure 9. Time history of EW direction(m)

Figure 10. Time history of rotation(rad)

Figure 11. Degradation of response between linear and nonlinear model under bidirectional sinusoidal excitation
Figure 12. Time histories of third floor EW translation (in meters) and rotation (in radians) for no TMD model and floating roof model under El Centro excitation

References