The use of TMD's by the application of additional storeys

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Abstract

When a building is in need of a seismic reinforcement an innovative way of performing such reinforcement is by adding to the building, an additional storey which will work as tuned mass damper.

The main objective of this work is to present the study of additional storeys acting as TMD's and evaluate the advantages in opting for this type of seismic reinforcement in buildings.

The idea was to create a model of a building with and without a TMD on its top. This was done in two different ways. The first using the formulation of continuous linear oscillators, and the second with a finite element model.

The finite element model was forced by a set of various earthquakes. Therefore deducing that the ratio between the TMD's mass and the main structure's should be around five percent.

Several buildings of various heights were also ran with the previous earthquakes. It was concluded the optimal first mode frequency of a building which would have the best performance under the conditions described.

Finally the additional storey from the building which had best performance on the previous study was designed with relative detail.

Keywords: buildings reinforcement, dynamic analysis, seismic analysis, tuned mass dampers, additional storeys, continuous linear oscillators.
1. Introduction

When a building requires seismic reinforcement the structure must be retrofitted. Since the aim is to improve it’s the seismic behavior the building’s rehabilitation can be implemented in several ways. The most common way is to directly intervene in its structure, reinforcing the elements that absorb the seismic force, such as walls, beams, columns, foundations. An innovative way of doing it is adding to the building an additional storey whose main function is to act as tuned mass damper.

These devices work as follows, when the main oscillator is requested, the device produces inertial forces proportional to the mass of the TMD, which will exert a reaction on the system in the opposite direction to the main structure’s movement. This will result as a decrease in the mains structure’s displacements by energy transfer from the primary to the secondary oscillator, and a tendency to increase the TMD’s displacements. These must then be controlled by the usage of dampers.

![Figure 1- Model of a structure of a first GDL coupled TMD (Adapted from Parente, 2013)](image)

In which:

$M_{TMD}$ – Represents the TMD’s mass;

$K_{TMD}$ – Represents the stiffness of the springs which support the structure of the TMD;

$M_{Main\ Structure}$ – Represents the main structure’s mass;

$K_{Main\ Structure}$ – Represents the stiffness along the structure.
The figure 2 shows how a TMD functions.

![Figure 2: TMD's function mode (Parente, 2013)](image)

An additional storey is a TMD comprising of:

- two slabs spaced at a given height and where most of the mass will be concentrated. The rest it will be materialized at the expense of equipment that will serve as additional masses;
- an n number of supports that will act as elastic springs deforming by distortion and sustain the additional floor;
- dampers located at the base of the additional storey which will have the objective of controlling the TMD’s displacements.

![Figure 3: Schematic of a building that has an additional storey functioning as TMD (Adapted from Parente, 2013)](image)

The TMD’s design involves a definition of its mass and the spring’s stiffness that are needed to match the frequency of a particular vibration mode of the main structure. When this happens, the TMD is tuned. Only one TMD can be used to control the movements of a particular building’s vibration mode.
In order of better understanding this phenomenon, a 60 meter (20 storeys) frame structure was studied, with rectangular dimensions of 30 by 20 meters and 3 meters of storey's height. All these features are constant along the building's height. The objective was to evaluate the advantage of adding on its top an additional storey functioning as a TMD tuned to the building's first vibration mode in one of the directions.

2. Modelling the finite element structure

The building was modelled in the finite element program SAP 2000. Buildings previously studied during the course where used to determinate values of mass per unit length (m) and the volume weight ($\gamma$) distributed along the building's height. The reached value was $m = 239.14$ ton/m and $\gamma = 3.91$ kN/m$^3$.

Therefore the mass value adopted for each building's slab was:

$$M_{\text{Slab}} = m \times 3 = 239.14 \times 3 = 717.43 \text{ ton}$$  

(1)

In which:

$M_{\text{Slab}}$ – Is the slab's mass.

The building can be seen in 3D on figure 4.

The TMD was modeled as being an additional storey, separated from the main structure and only supported by four elastic supports placed at each corner of the additional storey's base. They were imposed to have distortional deformation, a quadrangular top area of 1 per 1 square meters and 0.3 meters in height. The TMD was tuned to operate on the main building's first vibration mode according to its Y direction.
3. Preliminary seismic analysis

The finite element models were used to study the seismic response of buildings with and without TMD when acted by a number of different earthquakes. 10 type 1 and 10 type 2 earthquakes were run in both structures, the value of the maximum displacement for each earthquake was captured and an average of every value for each type of earthquakes was undertaken and the displacements reduction that the TMD imposed on the main building was calculated. Concluding that the TMD reduced the building’s displacements for about 18% to type 1 earthquake and 16% to type 2 earthquake.

4. Parametric analysis of the TMD’s mass

In order of optimizing the additional storey’s efficiency, an analysis was made to the response of the structure with TMD, varying the TMD’s mass. The objective was to evaluate the ratio between the tuned
mass damper’s mass and the building’s mass that provided a better performance to the additional storey. The previous 20 earthquakes were run on the building’s model with and without TMD varying the percentage of the TMD’s mass in relation to the building's mass by 1%, 2.5%, 5%, 7.5%, 10% and 12.5%. In every situation the TMD was tuned to operate on the main structure’s first vibration mode. Therefore, it was concluded that the ratio between the masses of both structures (building’s and TMD’s) that provided the best performance would be when the TMD’s mass represents about 5% of the main structure’s mass.

The results are summarized in Table 1.

Table 1 - Obtained results summarized (Adapted from Parente, 2013)

<table>
<thead>
<tr>
<th>Percentage of the weight of TMD in relation to the building</th>
<th>Reduction obtained</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type 1 earthquake</td>
</tr>
<tr>
<td>1,0%</td>
<td>15,14%</td>
</tr>
<tr>
<td>2,5%</td>
<td>21,49%</td>
</tr>
<tr>
<td>5,0%</td>
<td>18,18%</td>
</tr>
<tr>
<td>7,5%</td>
<td>15,50%</td>
</tr>
<tr>
<td>10,0%</td>
<td>12,80%</td>
</tr>
<tr>
<td>12,5%</td>
<td>11,98%</td>
</tr>
</tbody>
</table>

5. Building’s height analysis

Subsequently, an analysis was made for building’s height. The aim was to conclude what type of building added with an additional storey had the best seismic reaction. So, buildings with the same characteristics of the previous 60 meter (20 storeys) building were studied but only different in its height. In addition to the 20 storey building, other 16, 12, 8 and 4 storeys buildings were studied. All of the buildings had the respective TMD’s tuned to the first vibration mode and also had a ratio between its mass and the main structure’s of 5%.
In Table 2 the data for the various buildings are summarized.

**Table 2 - Characteristics calculated for the various buildings (Adapted from Parente, 2013)**

<table>
<thead>
<tr>
<th>Number of storeys</th>
<th>Frequency (Hz)</th>
<th>Total mass (ton)</th>
<th>TMD’s mass (ton)</th>
<th>Mass per floor (ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>1.00</td>
<td>14348.60</td>
<td>717.43</td>
<td>358.72</td>
</tr>
<tr>
<td>16</td>
<td>1.28</td>
<td>11478.88</td>
<td>573.94</td>
<td>286.97</td>
</tr>
<tr>
<td>12</td>
<td>1.75</td>
<td>8609.16</td>
<td>430.46</td>
<td>215.23</td>
</tr>
<tr>
<td>8</td>
<td>2.65</td>
<td>5739.44</td>
<td>286.97</td>
<td>143.49</td>
</tr>
<tr>
<td>4</td>
<td>5.24</td>
<td>2869.72</td>
<td>143.49</td>
<td>71.74</td>
</tr>
</tbody>
</table>

After running the previous 20 earthquakes for every building it was concluded that a building possessing a first mode frequency equal to the first mode frequency of the 12 storeys building would be the type of building which would have the best performance when added an additional storey and an earthquake occurred.

The results are summarized in Table 3.

**Table 3 - Results obtained summarized for the various buildings (Adapted from Parente, 2013)**

<table>
<thead>
<tr>
<th>Number of storeys</th>
<th>Obtained reduction</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type 1 earthquake</td>
<td>Type 2 earthquake</td>
</tr>
<tr>
<td>20</td>
<td>18.18%</td>
<td>15.75%</td>
</tr>
<tr>
<td>16</td>
<td>13.80%</td>
<td>16.21%</td>
</tr>
<tr>
<td>12</td>
<td>20.09%</td>
<td>29.07%</td>
</tr>
<tr>
<td>8</td>
<td>18.31%</td>
<td>24.39%</td>
</tr>
<tr>
<td>4</td>
<td>8.94%</td>
<td>17.92%</td>
</tr>
</tbody>
</table>

Parallel to the study done before, a Fourier analysis was also made for the accelerations of the type 1 number 5 earthquake. The conclusion reached was that the frequencies that had greater energy in this earthquake and in type 1 earthquakes in general, were the frequencies between 1.5 Hz and 2.5 Hz.

It is for that reason that the 12 storeys building, which has a first mode frequency of about 1.75 Hz, had the best performance among all buildings analyzed.

### 6. Additional storey’s design

Taking into consideration the 12 storeys building and its respective TMD, the additional storey was designed with detail for when the type 1 number 5 earthquake occurs.
For the 12 storeys building, its total mass will be of:

\[ M_{\text{building}} = M_{\text{slab}} \times 12 = 717.43 \times 12 = 8609.16 \text{ ton} \]  \hspace{1cm} (2)

In which:

\( M_{\text{building}} \) - Is the building’s total mass.

Thus the mass of the additional storey corresponding to 5% of the mass calculated previously will be of 430.46 ton. The area’s calculation of the additional storey’s slab was done as follows (Parente, 2013):

\[ M = \frac{\gamma g}{2} \times A \times h \iff \frac{430.46}{9.81} \times A \times 3 \iff A = 180 \text{ m}^2 \]  \hspace{1cm} (3)

In which:

\( g \) – is the gravity acceleration’s value;

\( A \) – is the slab’s area;

\( h \) – is the additional storey’s height.

In figure 7 the storey’s slab area (whose obtained dimensions were of 16.5 for 11 meters) compared to the current building slab’s area is shown. It was chosen to support the additional storey on 9 cylindrical supports.

\[ \text{Figure 7- Additional storey design (Adapted from Parente, 2013)} \]
The support’s dimensions were calculated in the following order of calculus (Parente, 2013).

\[ f = \frac{1}{2\pi} \sqrt{\frac{K_{TMD}}{M_{TMD}}} \Leftrightarrow K_{TMD} = (1.75 \times 2\pi)^2 \times 430.46 = 52043.76 \frac{kN}{m} \] (4)

In which:

\( f \) – is the additional storey’s frequency.

The stiffness of a TMD that is supported by a 9 rubber supports is shown in expression (5) (Parente, 2013).

\[ K_{TMD} = \frac{9GA}{h} \] (5)

In which:

\( G \) – is the support’s distortional modulus.

\( A \) – is the support’s top area.

Therefore, the ratio between the support’s area and height is shown in expression (6) (Parente, 2013).

\[ K_{TMD} = \frac{9GA}{h} \Leftrightarrow 52043.76 = \frac{9 \times 1000A}{h} \Leftrightarrow \frac{A}{h} = 5.78\frac{m^2}{m} \] (6)

The results are summarized in Table 4.

<table>
<thead>
<tr>
<th>Diameter (mm)</th>
<th>Area (m²)</th>
<th>Height (mm)</th>
<th>Area/Height (m²/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>0.50</td>
<td>86.90</td>
<td>5.78</td>
</tr>
<tr>
<td>900</td>
<td>0.64</td>
<td>110.00</td>
<td>5.78</td>
</tr>
<tr>
<td>1000</td>
<td>0.79</td>
<td>136.00</td>
<td>5.77</td>
</tr>
</tbody>
</table>

The additional storey was chosen to be supported on 9 neoprene circular based supports of 900 mm diameter and 110 mm in height which are located at the intersections between beams and columns as shown on figure 7.

The damping values were calculated to support the 12 storeys building TMD’s deformation for the above mentioned earthquake. The value obtained was about 1888 kNsm\(^{-1}\). A damper with the former value will result in the displacements shown in table 5 for the earthquake in question.
Table 5 - results obtained for the additional storey’s displacements (Adapted from Parente, 2013)

<table>
<thead>
<tr>
<th></th>
<th>Without damping</th>
<th>With damping</th>
</tr>
</thead>
<tbody>
<tr>
<td>TMD’s displacement (m)</td>
<td>0,126</td>
<td>0,088</td>
</tr>
<tr>
<td>Buildings displacement (m)</td>
<td>0,037</td>
<td>0,039</td>
</tr>
<tr>
<td>Variation of displacement (m)</td>
<td>0,089</td>
<td>0,049</td>
</tr>
</tbody>
</table>

A variation of displacements of 0.049 meters when the additional storey is damped is seen as good value for it is about 16% of the initial height of the supports (0.3 meters).

It is important to note that the study that was undergone above can also be applied to buildings classified as structurally different (in this case the building was structurally classified as being framed) and built with different kinds of materials.

7. Conclusions

In this paper, the advantages in opting for an innovative type of seismic strengthening of buildings were studied (the application of additional storeys). The following conclusions were obtained:

- The optimal ratio between the mass and the mass of the additional floor of the building to which the TMD is attached should be around 5%;
- The building type that will work best with an additional floor with the characteristics described above will be a building that the first frequency, and the frequency to which the TMD will be tuned stand at around 1.75 Hz;
- Therefore a building added with an additional floor, with the characteristics described in the two preceding items, when subjected to an earthquake, the effect of TMD may reduce the main building’s vibrations up to about 20 to 30% depending on the type of earthquake.

8. References