Mitigation of Earthquake Induced Structural Vibrations Using Bioinspired Tuned Mass Damper

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Abstract - *The recent trend towards constructing high rise structures to maximize the space utilization in urban areas resulted in a new generation of earthquake sensitive buildings in which, conventional control systems are ineffective. Therefore, newer structural control mechanisms are to be developed for the mitigation of vibrations. An energy dissipation mechanism found in abalone shells and bones, 'Sacrificial bonds and hidden length' has the ability to increase the stiffness in the constituent molecules substantially. Inspired by the mechanism evolved over millions of years, its conceptual underpinnings are being used to develop a bioinspired Tuned Mass Damper. This study focuses on developing a passive actuator based on the above concept and is implemented on a tuned mass damper. The effectiveness of the bioinspired tuned mass damper was studied for earthquake excitations. A 76-storey building subjected to three different recorded earthquake data was subjected to dynamic analysis. From the study, the bioinspired TMD was found to reduce the peak displacement of the structure by 20% with respect to normal passive Tuned mass damper. It was also found to reduce the velocity and accelerations along along various floor levels of the structure, where the normal passive TMD has a negligible effect.*

Key Words: Earthquake, Bioinspired, Tuned Mass Damper, Structural control, Buildings.

1. INTRODUCTION

An earthquake refers to the random movements of the ground caused as a result of plate tectonics. The movement may be in horizontal or vertical directions. The vibration of the soil gets transferred to the structures that rest on the ground, developing forces of inertia in the structure. Earthquakes are cyclic in nature, causing stress reversal in structures, which can lead to large deformations, cracks and drifts, making the structure unusable. The social, structural and economic damages caused due to an earthquake can be vastly reduced by preparing for such a calamity since earthquakes are almost unpredictable. From the engineering point of view, to prevent loss of life and property damages due to earthquakes, buildings are to be designed as earthquake resistant structures. In conventional systems, seismic energy is dissipated using inelastic mechanism s like flexural and shear hinging of elements like beams, columns and walls, axial tension yielding, brace buckling etc.

The recent trends towards constructing extremely tall and slender buildings to maximize the space utilization in urban areas have contributed to a new generation of earthquake sensitive structures. These tall structures are quite flexible and have very low damping values. The design of these structures involves resisting the lateral forces due to the earthquake as well as wind using the inherent strength, stiffness and damping of the system in combination with novel structural control methods. Since conventional methods are not much effective when it comes to the case of high rise buildings. There have been significant developments in the field of earthquake engineering in the past few decades and various devices like base isolators, mass dampers, liquid dampers, sensors and actuators etc., are used for structural control mechanisms.

2. TUNED MASS DAMPER

A tuned mass damper is a vibration suppression device, which is attached to the vibrating main structure to mitigate structural vibrations. It consists of a mass, spring and a viscous damper. The tuned mass damper is tuned such that its frequency is near the natural frequency of the main system. Hence the vibration of the main system causes the damper to vibrate in resonance and vibration energy is dissipated through damping in the viscous damper. The solution for determining the optimum tuning frequency and the optimum damping of the tuned -mass damper for undamped main systems subjected to harmonic external force, thereby reducing the steady-state response of the main systems to a minimum over a broad band of forcing frequencies, is given by Den Hartog (1956). The effectiveness of a TMD depends on tuning its stiffness and damping properties for a given primary structure and attached mass such that a significant kinetic energy is transferred from the main structure to the TMD mass and dissipated. Vibration suppression capacity of the TMD depends on its inertial property, i.e., larger the attached mass, greater will be its energy dissipation properties. However, in practice, the mass of about 0.5 – 1% of the total building mass is provided.

The effectiveness of a TMD is dependent on its tuning frequency ratio, mass ratio and damping ratio of the TMD with respect to the structure. TMDs are generally provided on the top of the building. However, multiple small tuned mass dampers can be provided along the height of the building to save space in the building.

The Equation of motion of Tuned Mass Damper is given by,

$$M_2\ddot{x}_2 + C_2(\dot{x}_2 - \dot{x}_2) + K_2(x_2 - x_2) = 0 \qquad \text{- (1)}$$

$$M_1\ddot{x}_2 + C_1(\dot{x}_1) + C_2(\dot{x}_1 - \dot{x}_2) + K_1(x_1)$$
$$+ K_2(x_2 - x_2) = F \qquad \text{- (2)}$$

Where M_1, M_2, C_1, C_2, K_1, K_2, x_1, x_2 are the Mass, Damping, stiffness and displacement of structure and TMD respectively.

Factors affecting the response and damping performance of a TMD are

- **Mass ratio (μ)** of a TMD is the ratio of mass of damper (m_d) to the generalised mass of primary structure (M') for a suppressed vibration mode. It significantly affects the performance of a TMD and is given by

$$\mu = \frac{m_d}{M'} \qquad -(3)$$

- **Tuning Ratio (Ω)** of a TMD is the ratio of frequency of mass damper (f_{tmd}) to that of natural frequency of the structure (f_n). It is given by

$$\Omega = \frac{f_{tmd}}{f_n} \qquad -(4)$$

- **Damping ratio (ξ)** of a structure is given by

$$\xi = \frac{c}{2m\omega_n} \qquad -(5)$$

Using a TMD creates a lower and higher natural frequencies from the natural frequency of the structure and this causes resonance at the two resonant frequencies if the damping ratio is too low. Again, if the damping value is high, the energy dissipation ability is reduced.

The efficiency of tuned mass damper is constrained by the huge space requirement and practicality of placing a heavy mass on top of the structure. So, a number of TMDs of smaller sizes are provided along the elevation of the structure to overcome this problem. These multiple TMDs are also effective in reducing vibrations emanating from higher modes. Also in order to increase the efficiency of TMDs, various control devices like actuators and sensors are attached to the mass.

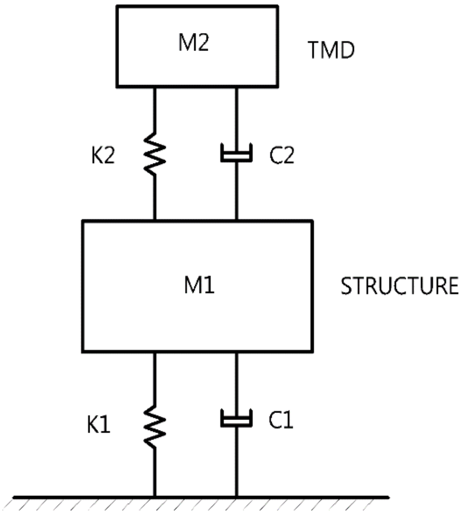

Fig -1: Tuned Mass Damper

3. BIOMIMICRY

Biomimicry is the study of emulation and imitation of nature, where it has been used by designers to solve human problems. For centuries, designers and architects have viewed nature as a huge source of inspiration. Biomimicry argues that nature is the best, most influential and guaranteed source of innovation for designers following the 3.85 billion years of evolution of nature, as it has a huge experience on problem-solving for the environment and its inhabitants. The emerging field of biomimicry deals with new technologies perfected by bio-inspired engineering at the micro and macro scales. Architects sought nature's answers to their complex questions about different types of structures, and they imitated many forms of nature to create better and more efficient structures for different architectural purposes. Without computers, these complex shapes and structures could not be imitated, Thus the use of computers tended to imitate and take inspiration from nature, using sophisticated and accurate tools for simulation and computing, making the imitation of natural models easier despite its complexity (Aziz et al. 2015).

4. BIOINSPIRED TUNED MASS DAMPER

In a bioinspired structural control system, the ability of biological organisms to prevent damages is mimicked. These systems are passive and has a higher energy dissipation capacity compared to the conventional systems. An energy dissipation system found in bones and abalone shells called ‘Sacrificial Bonds and Hidden Length’ is used to develop a passive structural control system. The efficiency of the system used in cross bracings, base isolators and tuned mass dampers are found to be higher than other passive and semi-active structural control systems.

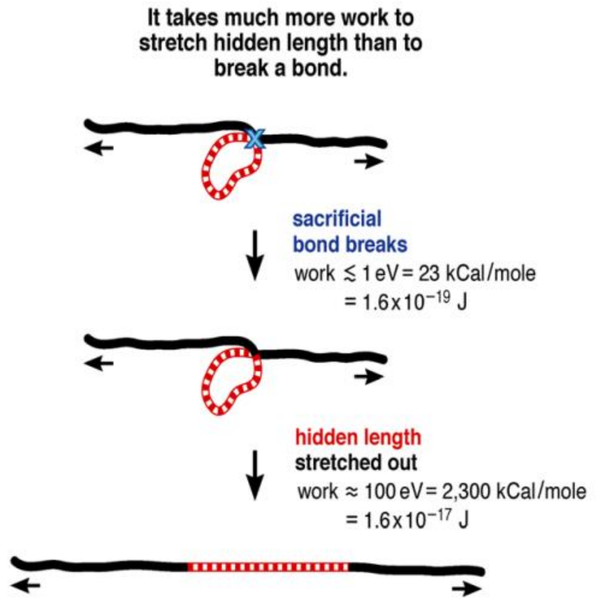

Fig - 2: Sacrificial bond and hidden length mechanism (Fantner et al. 2006)

A bioinspired tuned mass damper consists of a bioinspired passive actuator fitted onto a tuned mass damper. The actuator is to be designed to replicate the force displacement relationship depicted in Fig. 3.

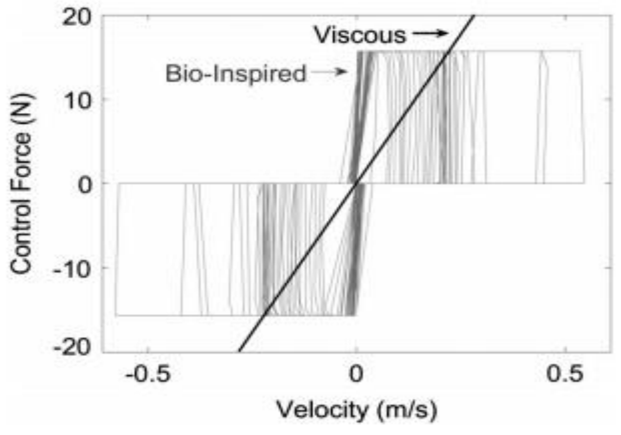

Fig – 3: Force vs Velocity behaviour of bioinspired actuator and conventional viscous damper (Kwon et al. 2017)

The actuator is able to allow energy dissipation in selective direction of the displacement, which provides unique advantages to achieve maximal energy dissipation and structural response reduction. Fig. 4 shows the schematics of a SDOF system fitted with a bio inspired tuned mass damper. Kwon et al. (2017) developed a novel passive hydraulic actuator to replicate the F-V-D relationship of sacrificial bonds and hidden length mechanism. This small-scale bioinspired actuator has an input shaft that engages the hydraulic cylinders when it is far from equilibrium. When the shaft is moved by external excitation, it applies a specified force by pushing hydraulic fluid through the pressure relief valve along the high-pressure line. The applied force can be regulated by a pressure relief valve which can be adjusted to a specified force. When the shaft returns to equilibrium, a unidirectional valve allows the fluid to flow freely back into the hydraulic cylinder along the low-pressure line requiring little or no force.

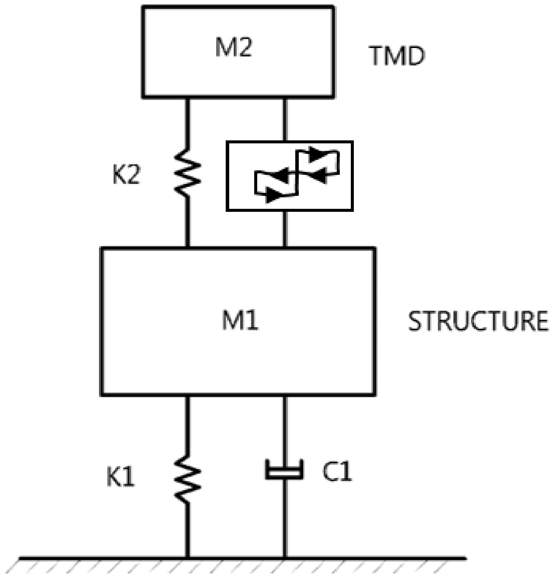

Fig – 4: Schematics of a SDOF system fitted with a bioinspired TMD

For a system fitted with bioinspired TMD, the equation of motion (Craig,1981) is given by

$$M_s\ddot{x} + C_s\dot{x} + K_s x = \Gamma f - M_s \Lambda \ddot{x}_g \qquad - (6)$$

Where, M_s, C_s, K_s are the mass, damping and stiffness matrix of the linear system, Γ and Λ are the location matrices, F is the control force applied by the bioinspired control and $\ddot{x}_g$ is the ground acceleration.

To replicate the energy dissipation behaviour shown in Fig 3, the piecewise damping function (Kwon, 2017) is expressed as

$$F(xd, vd) = \begin{cases} F_{max}\left(\frac{2}{1+e^{-k_{steep}\, x_d}}\right) & x_d \cdot v_d > 0 \\ 0 & x_d \cdot v_d < 0 \end{cases} \qquad - (7)$$

Where, $x_d = x_{md} - x_s$ and $v_d = v_{md} - v_s$ displacement and velocity of the tuned mass with respect to the main mass , $k_{steep} = 200 \times F_{max}$, steepness of the curve.

5. BUILDING MODEL

A 76- storey high rise building proposed by J N Yang et al. (2004) is used to test the efficiency of a bioinspired TMD. The building is a 306m high slender office tower with height to width ratio of 7.3. The RC building has a concrete core and concrete frame consisting of perimeter beams and columns. The building has a square shape with chamfer at two diagonal corners. Mass of building including plant machinery is about 153000 tonnes.

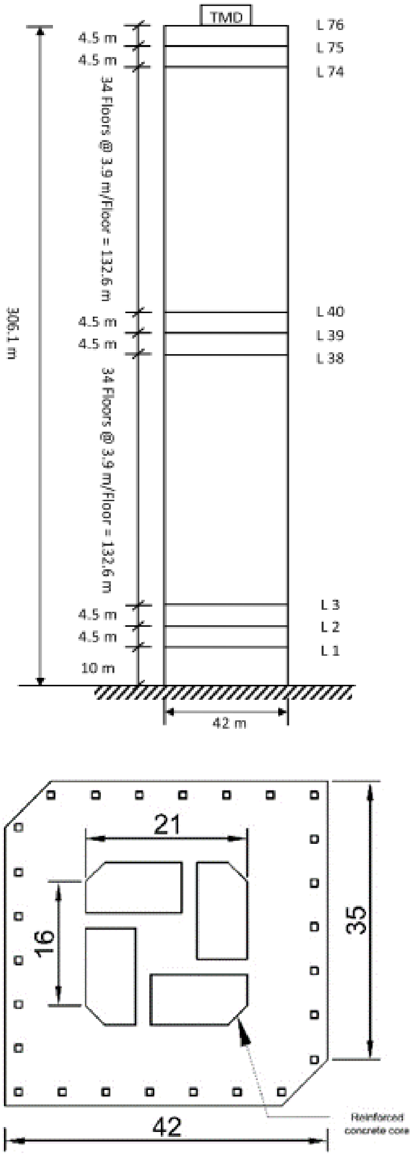

Fig – 4: Plan and Elevation of the 76- storey building (Yang et al. (2004))

The RC core inside has a dimension of 21m x 21m. The perimeter frame consists of RC columns spaced at 6.5m apart, connected to a 0.9m x 0.4m spandrel beam on each floor. The slab is 120mm thick with a metal deck and steel beams. The building is modelled as a vertical cantilever beam with portion between two floors are modelled as a classical beam element of uniform thickness leading to. For simplicity, the translational degrees of freedom are only retained by static condensation. The lowest 5 natural frequencies of the building are 0.16,0.765, 1.992, 3.790 and 6.395.

A bioinspired TMD with a mass of 500 tons is installed on the top floor, which forms a 77 DOF system. The mass is approximately 45% of the top floor mass and about 0.327% of the total mass of the building.

For typical earthquake loading, Elcentro earthquake, Hachinohe earthquake and Kobe earthquake time history data are taken.

6. BIOINSPIRED TMD MODEL

The control system is also developed using Simulink. It takes the earthquake excitation as an input and which is fed into the full order state space model and the response is stored. For replicating the energy dissipation as in the prototype developed by Kwon (2017), the relative velocity and displacement of the TMD is calculated using MATLAB functions. If their product is greater than zero, the TMD force is used to calculate the bioinspired force that is used to push the system back to equilibrium. The negative bioinspired force is then fed back to the input force, thus reducing the response of the system.

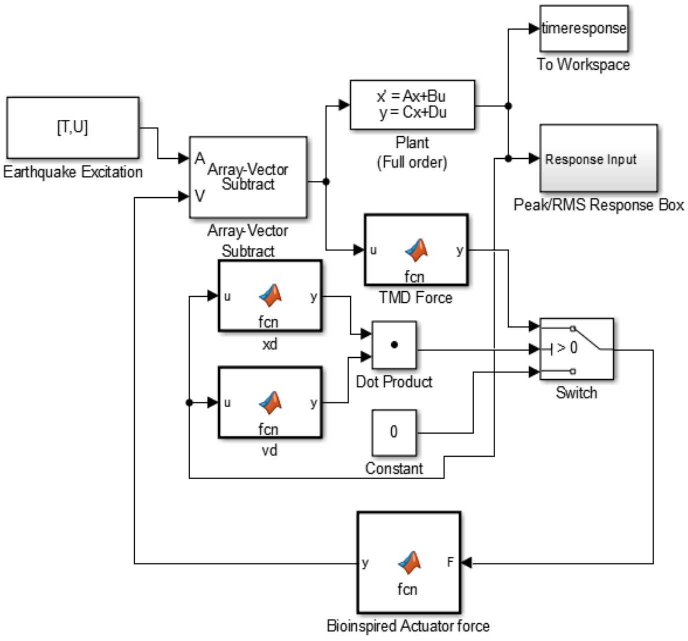

Fig – 5: Simulink model of bioinspired control system7

5. RESULTING RESPONSE OF EXCITED BUILDING

For earthquake analysis the integration time step is taken as 0.001 s and sampling time step as 0.001 s. The TMD is tuned to the first mode, at a frequency of 0.16Hz. The simulations are run for full order of the uncontrolled building and building with TMD. The response of buildings with and without TMD towards the three earthquakes are given below.

Table – 1: Peak displacements of floors under Elcentro earthquake (1940)

Elcentro			
	NoTMD	Normal TMD	BioTMD
Floor	Displacement (cm)	Displacement (cm)	Displacement (cm)
1	0.2163	0.1957	0.1545
30	18.9962	16.504	12.5006
50	36.2715	30.9628	22.3258
55	40.3164	34.2324	24.366
60	45.865	37.8192	36.6934
65	53.7969	44.5413	31.3878
70	63.4454	52.092	37.3566
75	73.8439	60.6659	44.284
76	76.1828	62.5984	45.8418
77	-	141.7548	116.6028

Table – 2: Peak displacements of floors under Kobe earthquake (1995)

Kobe			
	NoTMD	Normal TMD	BioTMD
Floor	Displacement (cm)	Displacement (cm)	Displacement (cm)
1	0.4722	0.4655	0.3967
30	31.9951	31.546	26.5242
50	32.8773	32.3795	26.0646
55	26.7407	26.2946	20.4275
60	28.6701	28.7079	21.6321
65	35.3744	35.2091	27.1275
70	54.4083	54.2091	42.9788
75	75.2716	74.9687	60.3144
76	79.9796	79.654	64.2262
77		91.7103	130.3352

Table – 3: Peak velocities of floors under Kobe earthquake (1995)

Kobe			
	NoTMD	Normal TMD	BioTMD
Floor	Velocity (cm/s)	Velocity (cm/s)	Velocity (cm/s)
1	4.0974	4.069	3.4881
30	153.1257	152.0571	129.9744
50	172.5463	172.4063	140.2921
55	156.6405	156.495	125.1942
60	124.2164	123.8523	97.7143
65	118.3247	117.9578	94.3812
70	187.8659	186.2032	157.4216
75	302.8214	300.1019	255.2797
76	329.703	326.7644	278.1026
77		360.1901	410.1901

Table – 4: Peak velocities of floors under Elcentro earthquake (1940)

Elcentro			
	NoTMD	Normal TMD	BioTMD
Floor	Velocity (cm/s)	Velocity (cm/s)	Velocity (cm/s)
1	2.1431	2.1387	1.8001
30	46.077	44.1734	16.2482
50	70.9225	70.8048	56.2255
55	75.872	75.7218	59.6077
60	75.4545	75.3127	58.8221
65	66.7815	60.5045	43.985
70	94.8637	81.902	64.6726
75	133.6	118.4685	95.2096
76	142.386	126.7664	102.1417
77		194.3692	163.8728

Table – 5: Peak acceleration of floors under Elcentro earthquake (1940)

Elcentro			
	NoTMD	Normal TMD	BioTMD
Floor	Acceleration (cm/s^2)	Acceleration (cm/s^2)	Acceleration (cm/s^2)
1	45.2055	45.06	37.1376
30	666.9077	665.15	553.9531
50	606.449	604.9731	496.0232
55	625.5538	625.0592	533.4689
60	743.6431	742.8207	633.123
65	638.8603	638.1316	555.3091
70	396.9653	396.5765	293.3471
75	1172.7648	1171.1881	982.5118
76	1486.5378	1484.6182	1248.5181
77		181.874	640.5832

Table – 6: Peak acceleration of floors under Kobe earthquake (1995)

Kobe			
	NoTMD	Normal TMD	BioTMD
Floor	Acceleration (cm/s^2)	Acceleration (cm/s^2)	Acceleration (cm/s^2)
1	55.2122	54.9365	47.4798
30	1185.9823	1184.2686	987.0265
50	1279.2615	1277.5915	1064.0787
55	1284.6286	1281.8338	1044.5561
60	1140.9168	1139.2099	915.8507
65	1074.1583	1070.249	868.5746
70	1499.1659	1494.2598	1157.2182
75	2474.8904	2463.2528	1956.6215
76	3003.7458	2990.367	2359.3748
77		179.0015	2552.735

Table – 7: Displacement of Floors under Hachinohe earthquake (1968)

	Hachinohe		
	NoTMD	Normal TMD	BioTMD
Floor	Displacement (cm)	Displacement (cm)	Displacement (cm)
1	0.1029	0.1049	0.0861
30	9.3653	9.2598	7.2259
50	19.8037	18.238	13.172
55	23.0783	21.8488	15.7367
60	27.0736	25.6716	18.561
65	31.2784	29.7258	21.5777
70	35.6255	33.9493	24.7397
75	40.2195	38.3684	28.7446
76	41.2539	39.3598	29.8196
77		154.7104	105.0429

Table – 8: Peak velocity of Floors under Hachinohe earthquake (1968)

	Hachinohe		
	NoTMD	Normal TMD	BioTMD
Floor	Velocity (cm/s)	Velocity (cm/s)	Velocity (cm/s)
1	0.7308	0.7193	0.6125
30	33.1032	33.1893	26.938
50	42.3227	42.6233	32.7637
55	38.3239	38.7385	28.6096
60	42.6644	40.7655	30.5856
65	52.0814	49.6202	37.7476
70	65.621	66.7052	53.0479
75	86.4462	87.4992	70.5089
76	91.1958	92.1941	74.4547
77		332.4303	230.8304

Table – 9: Peak acceleration of Floors under Hachinohe earthquake (1968)

	Hachinohe		
	NoTMD	Normal TMD	BioTMD
Floor	Acceleration (cm/s²)	Acceleration (cm/s²)	Acceleration (cm/s²)
1	14.9432	14.9033	12.7282
30	292.1015	292.3164	242.4175
50	292.5672	293.0996	237.4187
55	260.3881	261.0269	209.2903
60	243.9551	245.0159	201.4532
65	250.5153	250.6522	207.6712
70	323.6919	324.5524	249.8977
75	512.3675	513.3101	414.8923
76	614.4044	615.4956	494.3993
77		2345.9749	1599.0111

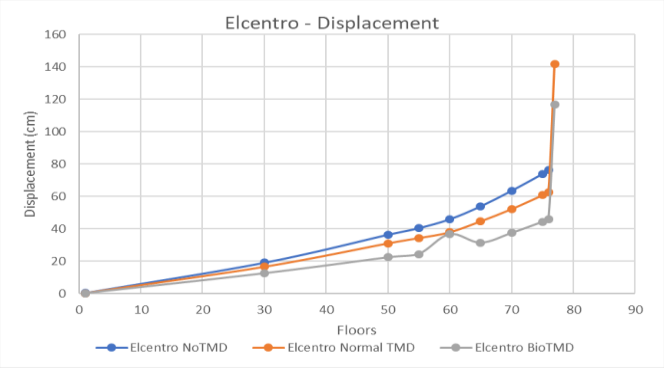

Chart -1: Peak displacements of floors for Elcentro Earthquake

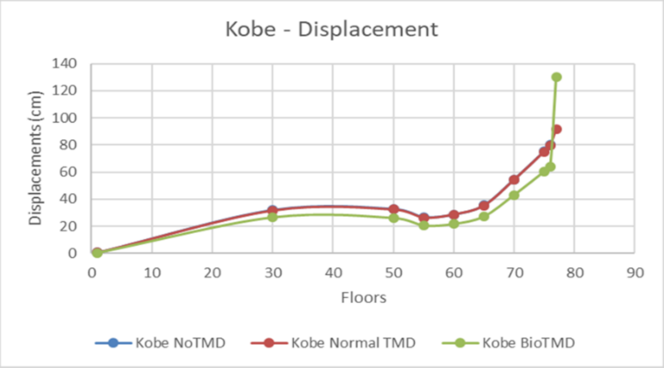

Chart -2: Peak displacements of floors for Kobe Earthquake

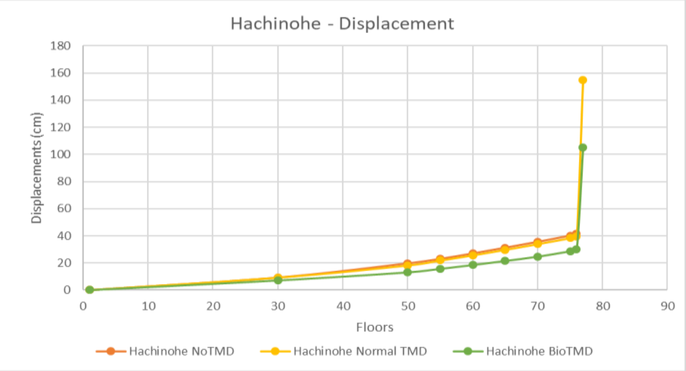

Chart -3: Peak displacements of floors for Hachinohe Earthquake

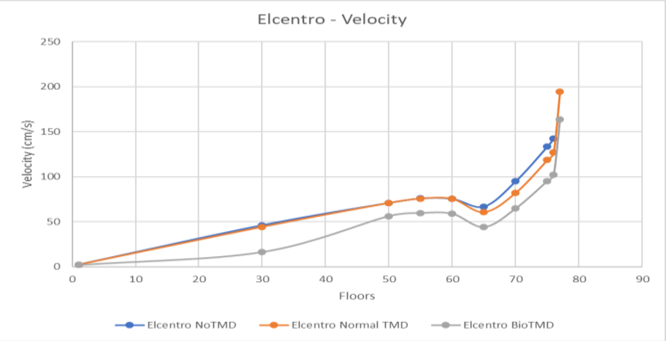

Chart -4: Peak velocity of floors for Elcentro Earthquake

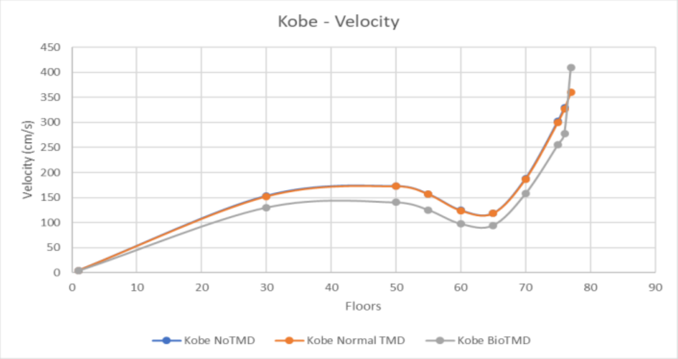

Chart -5: Peak velocity of floors for Kobe Earthquake

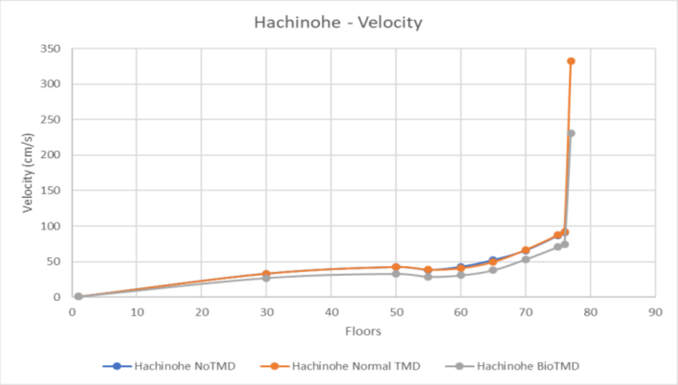

Chart -6: Peak velocity of floors for Hachinohe Earthquake

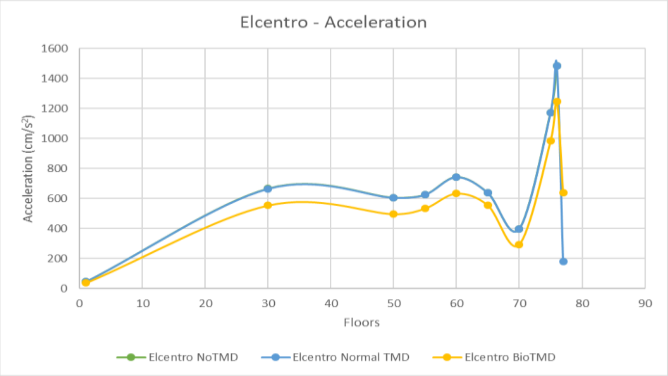

Chart -7: Peak acceleration of floors for Elcentro Earthquake

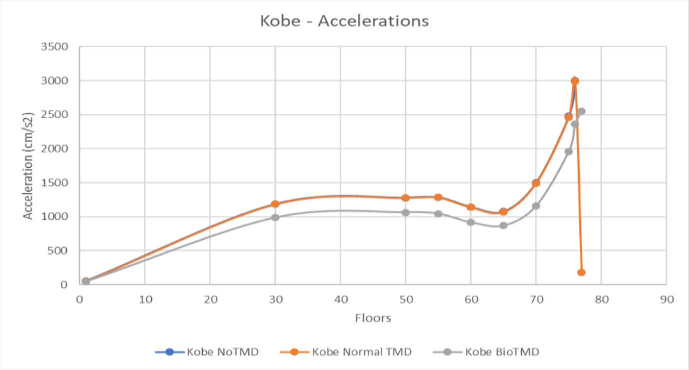

Chart -8: Peak acceleration of floors for Kobe Earthquake

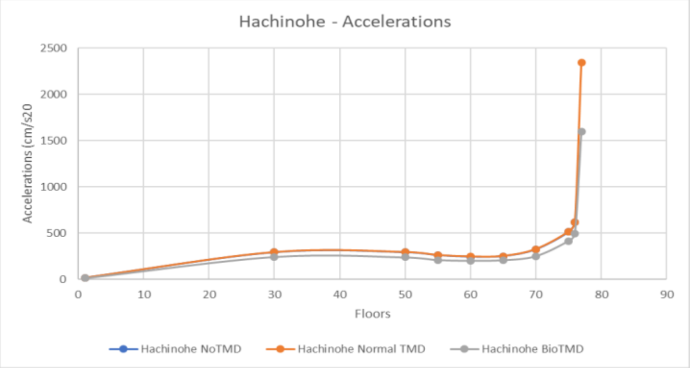

Chart -9: Peak acceleration of floors for Hachinohe Earthquake

The peak displacements of the top storeys during each earthquake excitations are very high. With the addition of a TMD, there is a small reduction in the peak displacement. With the addition of a bioinspired actuator, a percentage reduction of about 20% with respect to normal TMD is attained. The peak velocity of the structure under earthquakes are found to have a small effect with the addition of a normal TMD. When a bioinspired TMD is used, the peak velocity of the system was reduced by 16% - 18% on an average.

The peak acceleration on the top of high rise buildings are too large and the addition of TMDs have a very negligible effect on the structure. Addition of bioinspired TMDs are found to reduce the acceleration of top storey of structure by 20% but may not be enough to stabilize the structure.

CONCLUSION

A tuned mass damper fitted with a bioinspired passive actuator was developed and its effectiveness is studied using a 76-storey benchmark building model subjected to earthquake excitations. From the numerical studies, the bioinspired TMD showed a better performance compared to a passive TMD.

- From the study, it is found to reduce peak displacement of the structure under two different earthquake excitations by around 20% compared to a normal TMD.
- Peak velocities were found to reduce by a margin of 15% and acceleration by 18% when compared to a ordinary TMD.
- Normal TMDs didn't have a significant effect on reduction of earthquake induced storey accelerations.
- Bioinspired TMDs are 20% more efficient compared to normal TMDs in mitigation of acceleration due to earthquake.

- The bioinspired actuator is passive and thus requires no power to operate, which makes it a reliable structural control mechanism since, earthquakes and other natural disasters are often followed by power outages.

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