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A Study on the Effectiveness of Tuned Liquid Damper to Reduce the Displacement Demands of Base Isolated Structures

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Abstract — *In recent years considerable attention has been paid to research and development of structural control devices with particular emphasis on mitigation of seismic response of buildings. Lead Rubber Bearing (LRB) is an efficient technique for increasing building's natural period, which is away from the seismic period range, to avoid the amplification caused by earthquakes. Various active and passive control devices are developed for response control of buildings. Tuned Liquid Damper (TLD) is a passive control device which dampens the vibration of the structure by sloshing effect of liquid in motion. Hybrid structural control system using Lead Rubber Bearing and tuned liquid dampers opted for the Reinforced concrete (RC) structure. The base isolation systems are designed for different target base displacements with the recommendation of UBC-97 code. Thereafter, the base-isolated structures are equipped with Tuned liquid dampers using equivalent spring-mass model. The effects of TLD properties such as mass ratio, depth ratio and tuning ratio on the performance of the system are studied. A widely used computer program SAP2000 is used to perform nonlinear time history analysis for different storied buildings. The results obtained from the analysis will compare in the form of the time period, story displacement, story acceleration, maximum base shear and maximum reduction in the base displacement.*

Keywords*-Base isolation, Lead rubber bearing, Tuned Liquid Damper, Multi-storied, time history analysis, SAP-2000*

I. INTRODUCTION

Strong earthquakes in the past have resulted in significant property damage and loss of lives therefore, researchers have cantered their efforts to develop new and effective seismic risk mitigation strategies for such buildings. Conventional seismic protection strategies, such as enlarging structural elements or adding new strengthening and stiffening elements (i.e. bracing systems) concentrate on improving the capability of buildings to meet likely demands. However, stiffening buildings end up in shorter vibration periods and higher floor accelerations, resulting in higher structural damage. Therefore, a preferred approach for seismic retrofitting buildings may be to decrease demands instead of to increase capacities. This can be achieved by introducing flexible devices to buildings at their ground levels to isolate them from the transfer of seismic energy. For that purpose Lead Rubber Bearing is used.

The basic idea behind the seismic isolation is to decouple the superstructure from the catastrophic effects of strong ground motions by shifting the fundamental period of the structure away from the dominant periods of the ground motions. However, increasing the isolation period results in increased displacements. By increasing the damping in the isolation system, those excessive displacements can be limited. Therefore Tuned Liquid Damper is preferred as a damper for base-isolated structure.

I.1 Lead Rubber Bearing

Lead Rubber Bearing is one of the methods of Seismic Isolation. Lead rubber bearings (LRBs) are usually made of alternating layers of steel plates and natural rubber with a central hole into which the lead core is press-fitted. When subjected to lateral shear forces, the lead core deforms almost in pure shear, yields at a low level of shear stresses, approximately 8 to 10 MPa at normal (20°C) temperature, and produces rather stable hysteretic deformation behaviour over several cycles. One feature of the lead core is that it will not encounter the problem of fatigue failure under cyclic loadings. Sufficient rigidity is always ensured by the LRBs for the structure under service loads.

I.2 Tuned Liquid Damper

The tuned liquid damper (TLD) is a liquid-filled tank that uses liquid sloshing action to dampen the oscillations of a structure. Tuned liquid dampers (TLDs) can be implemented as an active or passive device and are divided into two main categories: tuned sloshing dampers (TSD) and tuned liquid column dampers (TLCDs). Tuned Sloshing Dampers (TSDs) are rectangular or circular tanks installed at the highest floor of the building or as an objective for controlling vibration. TSD dampens the vibration of the building with a sloshing action of the liquid. It can be classified as a shallow-water type and deep water type, this classification is based on shallow water wave theory. If the ratio of the height of water 'h' against the length of tank 'L' (Diameter 'D' in case of a circular tank) in the direction of motion is less than 0.15 is classified as a shallow-water type else deep water type as a ratio greater than 0.15. Tuning fundamental sloshing frequency of the TLD to natural frequency of structure cause a large amount of sloshing and wave breaking at the resonant frequency of combined structure-TLD system which dissipates a significant amount of energy.

II. A BRIEF REVIEW OF THE LITERATURE

R.S. Jangid [1] investigate the performance of structures isolated by LRB for optimum parameters of the LRB for minimum earthquake response of the isolated system. LRB is designed as a bilinear model and response of the base-isolated structure is obtained under the normal component of six near-fault ground motion and found that LRB with higher yield displacement performs better than bearing with low yield displacement and LRB with appropriate properties is quite effective for seismic isolation of structure.

Saiful Islam [2] studied Four-moment resisting RC frame to examine the behaviour of building located at Dhaka isolated by LRB and HDRB. Response spectrum and time history analysis used in sap2000 to analyses structure and found that LRB is more effective in reducing individual floor acceleration and thereby reducing non-structural damage.

Pradipta Banerji [3] study the effectiveness of a rectangular TLD in reducing the earthquake response of structures. The whole system is analysed for varying mass ratios and found that A higher depth ratio of 0.15 for a TLD is more effective for high excitation amplitudes expected in strong earthquake ground motions and A properly designed TLD with a low mass ratio of 1 to 4 percent can substantially reduce structural response.

Ali Ashasi-Sorkhabi [4] used an SDOF system which is subjected to harmonic force input tuned to the natural frequency of structure as such TLD-structure interaction could be captured at resonance. A wide range of influential parameters are considered to explore the efficiency of the TLDs in suppressing structural vibrations, it is observed that by increasing the mass ratio from 0.5% to %3, the TLD effectiveness in structural response reduction is improved.

S.J. Li [5] projected a numerical model for the implementation of shallow rectangular TLD wherever the dynamic properties of shallow liquid in rectangular containers subjected to forced horizontal oscillations are analysed directly from the continuity and momentum equations of fluid. They projected a numerical procedure for the answer of those equations supported the finite element technique.

Aakash Bikram Rana [6] Modelled structure-TLD system in SAP2000 to analyze the effect of TLD on the structure. TLD is modelled as a spring-mass system as specified in IS 1893:2002. Time history analysis was carried out and observed that TLD can be successfully modelled in SAP2000 even though there may be many numbers of tanks by using an equivalent spring-mass system. Effect of TLD is found to increase with an increase in mass ratio.

Sun, L.M [7] could successfully develop an analytical model for TLD, based on shallow water wave theory, which proved to be very effective if the wave is not breaking. They extended this model to account for the effect of breaking waves by introducing two imperial coefficients identified experimentally. To effectively control the response of structure appropriate design parameters of the TLD is defined. That parameter includes tuning ratio, mass ratio and water depth ratio.

III.MODEL SUMMARY

3.1 Structural System

The structural system of G+3 and G+6 storey building modelled in sap2000 using column, beam and slab of properties 400mm X 400mm, 230mm X 600mm and 150mm respectively with M25 and Fe415 material property. The structure is isolated at the base by Lead Rubber Bearing base isolator as a rubber isolator in sap2000 link property. The isolator is designed for three target base displacement of 200, 250 and 300mm. the isolator of the different property of base displacement is introduced to both building system separately. The tuned liquid damper is designed as a spring-mass model for 5 different mass ratio of 1% to 5% as specified in IS 1893:2002. The G+6 story structure of typical floor plan as shown in figure 1 is analyzed for nonlinear time history analysis for a combination of the different mass ratio of TLD and Base displacement of LRB at a tuning ratio of 1 to determine the response of RC building.

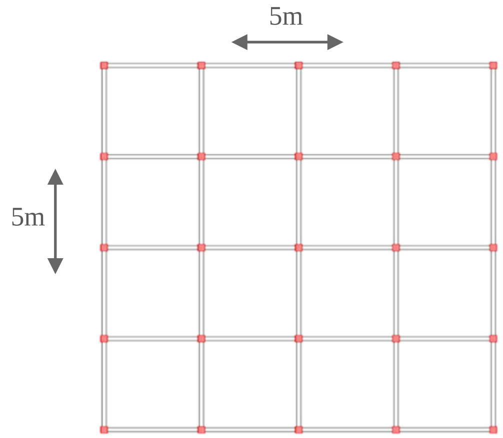


Figure 1 Plan of structure

3.2 Design Load

Dead loads are permanent loads which are acting on the structure. The unit weights of the materials that will help in calculations are as follow Reinforced Concrete: 25.0 kN/m3. However, this will be considered automatically in the sap2000 software. As for super dead load to account for floor finish 1 kN/m3 and wall load on beam 11 kN/m taken. Live load is the load that accounts for the intended use or occupancy. As per IS 875-part 2, the value of live load shall be taken as 2 kN/m2 and will be the same for all floors.

3.3 ground motion selection and scaling

For the analysis purpose 15 ground motion is selected from the factor considering Magnitude, distance to fault and Vs30 shear wave velocity. Recorded ground motion in the moment magnitude range of 6 to 7.5 and Vs30 ranging from 360 to 720 m/s as in case of stiff soil for the far-field site is selected for nonlinear time history analysis and scaled using seismomatch software using a spectral matching method of ground motion scaling with maximum 30% tolerance value allowance. The response spectrum of ground motion is matched to matching to target spectrum of IS 1893 Indian code. Table 1 shows the data about the selected ground motion.

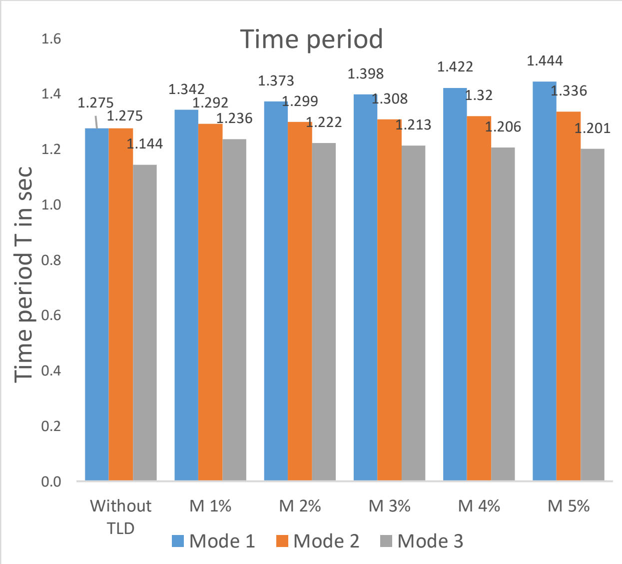
Table 1- selected ground motion

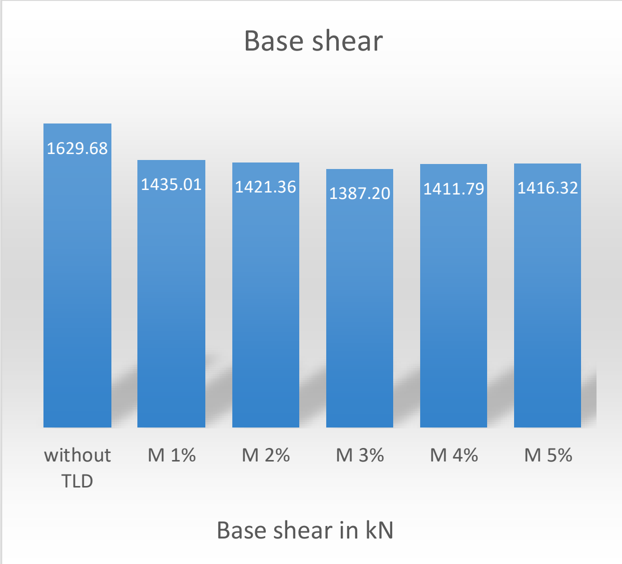
Sr no.	Earthquake	Station	Year	Magnitude	PGA	R_rup(km)
1	Bhuj Earthquake	Ahmedabad	2001	7.7	0.106g	239
2	Cape Mendocino	Fortuna Blvd	1992	7.01	0.117g	19.95
3	Chalfant Valley-02	Lake Crowley	1986	6.19	0.164g	24.47
4	Chi-Chi Taiwan-03	CHY028	1999	6.2	0.141g	24.38
5	Duzce Turkey	Lamont 362	1999	7.14	0.044g	23.41
6	Friuli Italy-01	Tolmezzo	1976	6.5	0.357g	15.82
7	Imperial Valley-06	Cerro Prieto	1979	6.53	0.168g	15.19
8	Irpinia Italy-01	Rionero In Vulture	1980	6.9	0.096g	30.07
9	Loma Prieta	Palo SLAC Lab	1989	6.93	0.195g	30.86
10	Morgan Hill	Fremont San Jose	1984	6.19	0.026g	31.34
11	Northridge-01	Lake Hughes #12A	1994	6.69	0.174g	21.36
12	Parkfield	Cholame Shandon	1966	6.19	0.060g	17.64
13	San Fernando	Old Ridge Route	1971	6.61	0.320g	22.63
14	UTTARKASHI	UTTARKASHI	1991	6.8	0.241g	34
15	Victoria Mexico	Cerro Prieto	1980	6.33	0.645g	14.37

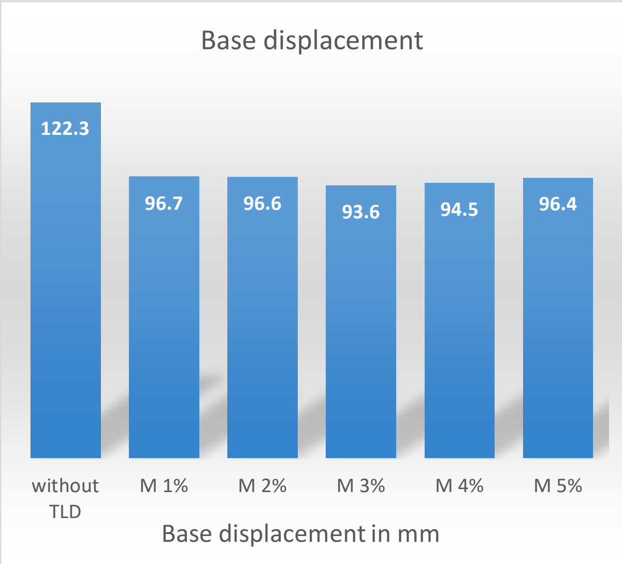
IV.RESULTS AND DISCUSSION

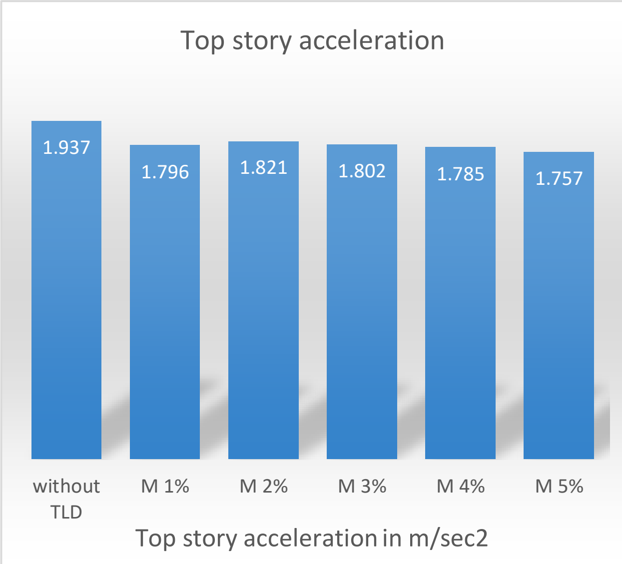
Results in the form of time period Base shear, top story acceleration, base displacement, story displacement is taken form nonlinear time history analysis of 15 ground motion for each model using sap2000. The mean value of results from 15 ground motion is used as a result for nonlinear analysis to compare it with another model as suggested by ASCE codes. Results for buildings with lead rubber bearing designed as to get 200, 250 and 300 mm base displacements are discussed here and comparisons of without TLD structure to structure with mass ratio vary from 1% to 5% for TLD is presented with graphs in this section

4.1 Results for G+3 building with 200 mm targeted base displacement

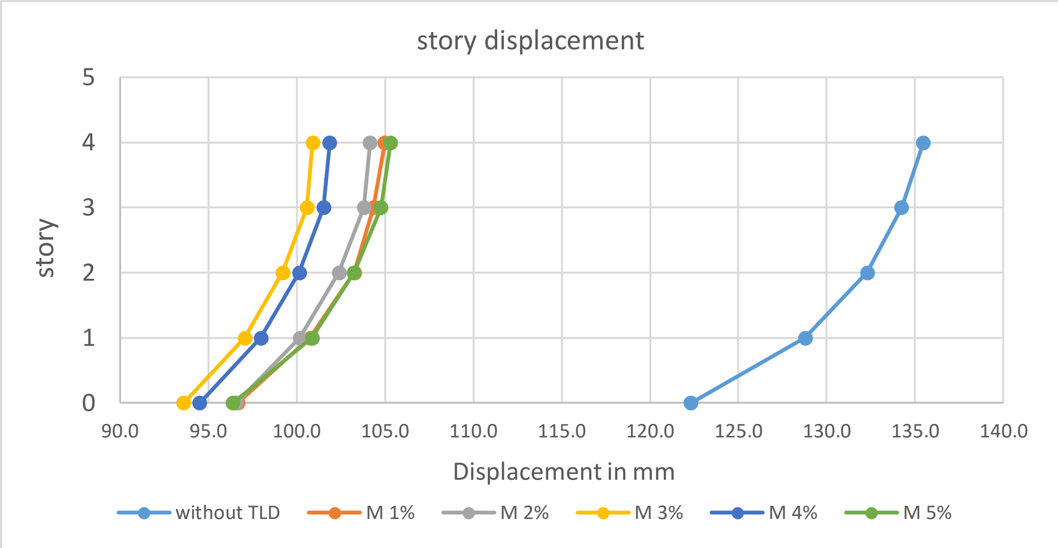




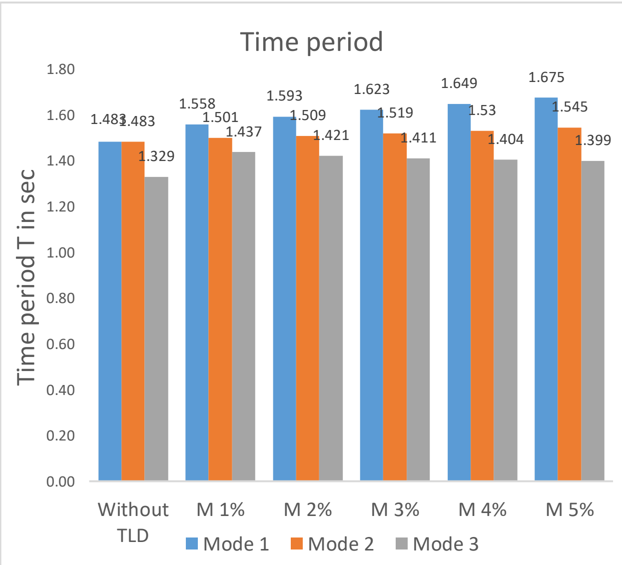


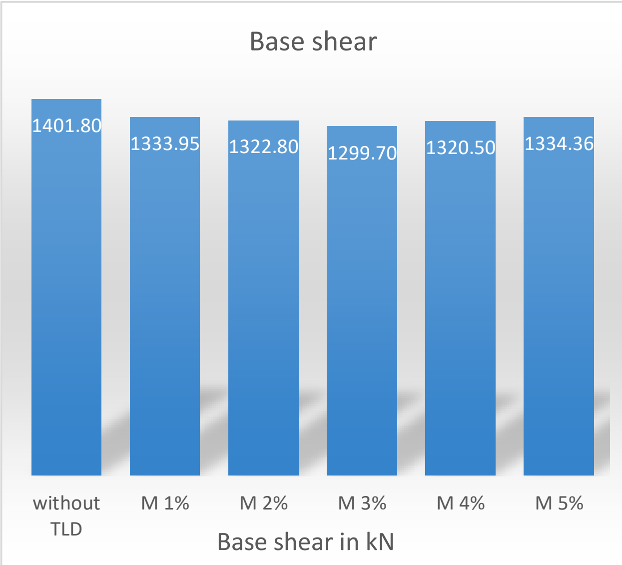


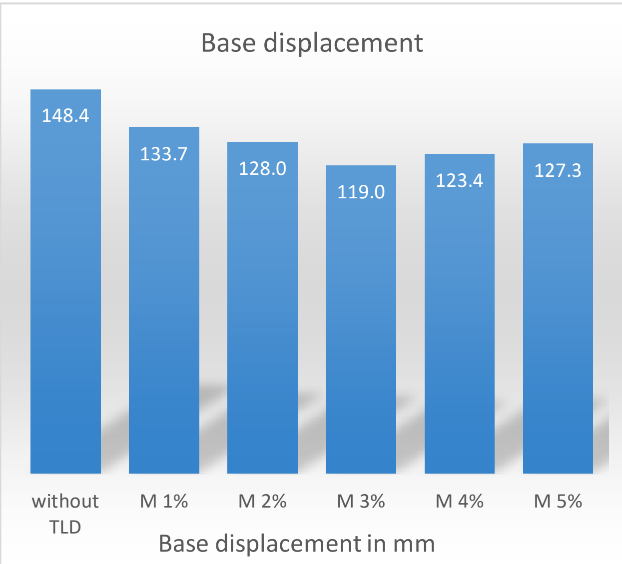
From graphs, it can be noted that there is a maximum 14.87% reduction in base shear for 4% mass ratio structure through all mass ratio shows somewhat of the same performance. Top story acceleration is reduced by 9.26% max which is from 5% mass ratio. Top story displacement is reduced by 25.51% max from 3% mass ratio of structure. Base displacement is reduced by 23.47% for the mass ratio of 3%. So from the result, it can be concluded that 3% mass ratio for TLD is given optimum result for G+3 d200 structure and a further increase in a mass ratio to 4% and 5% is a too effective but considerable increase in performance than 3% mass ratio TLD performance.

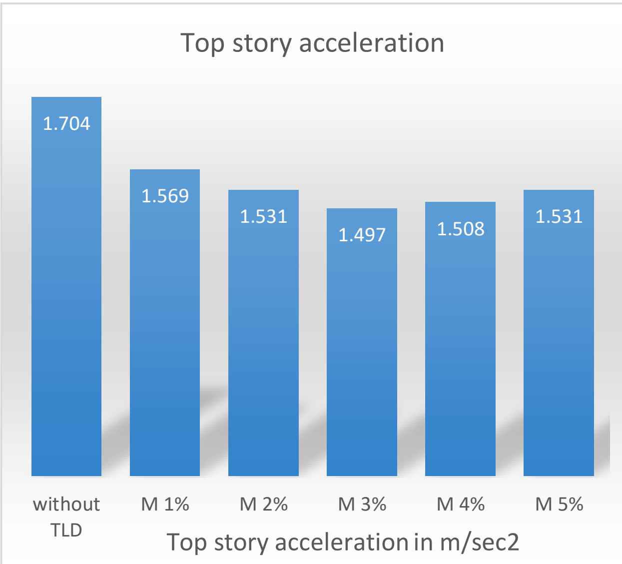


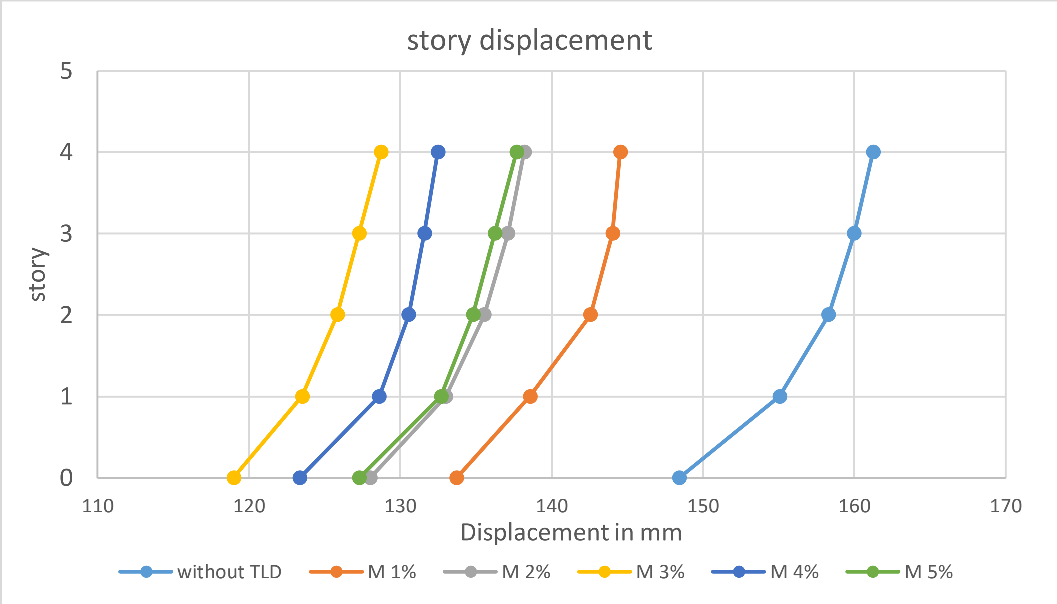
4.2 Results for G+3 building with 250 mm targeted base displacement





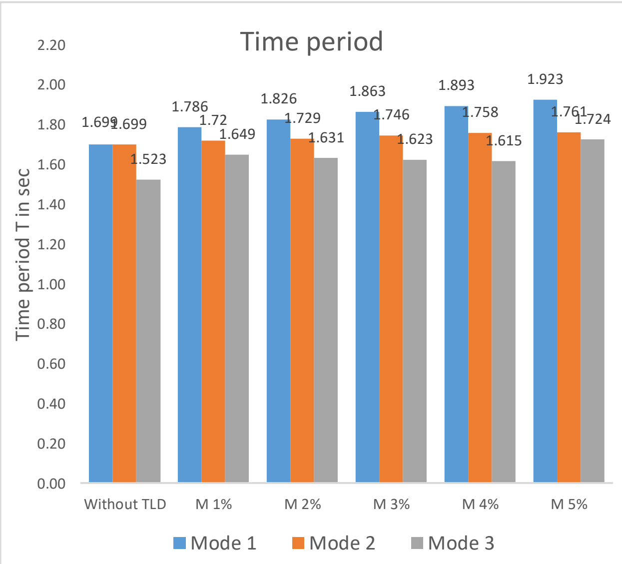


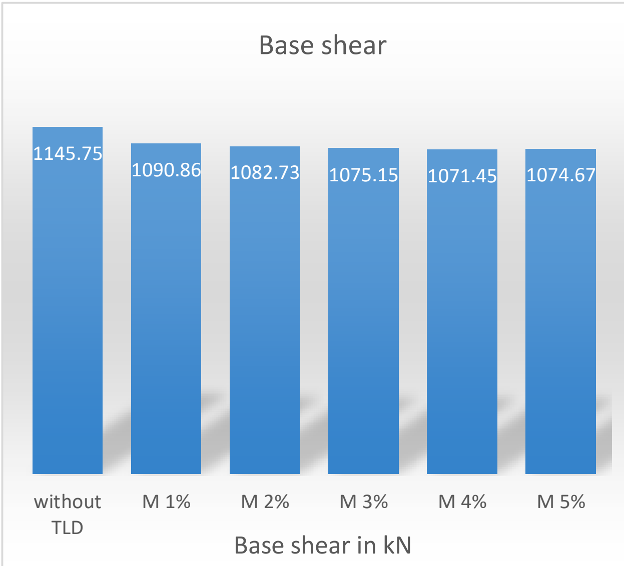




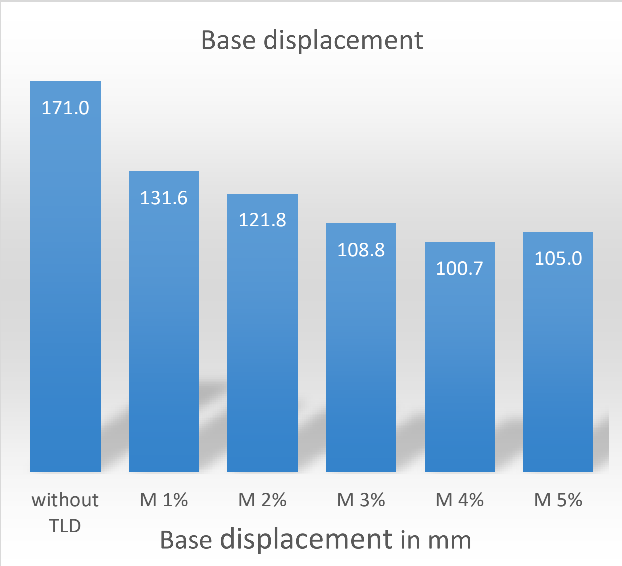
From the above graph, it can be noted that there is a maximum 7.28% reduction in base shear for 3% mass ratio structure though all mass ratio shows somewhat of the same performance. Top story acceleration is reduced by 12.17% max which is from 3% mass ratio. Top story displacement is reduced by 19.85% max from 3% mass ratio of structure. Base displacement is reduced by 20.18% for the mass ratio of 3%. So from the result, it can be concluded that 3% mass ratio for TLD is given optimum result for G+3 d250 structure and a further increase in a mass ratio to 4% and 5% is not very effective.

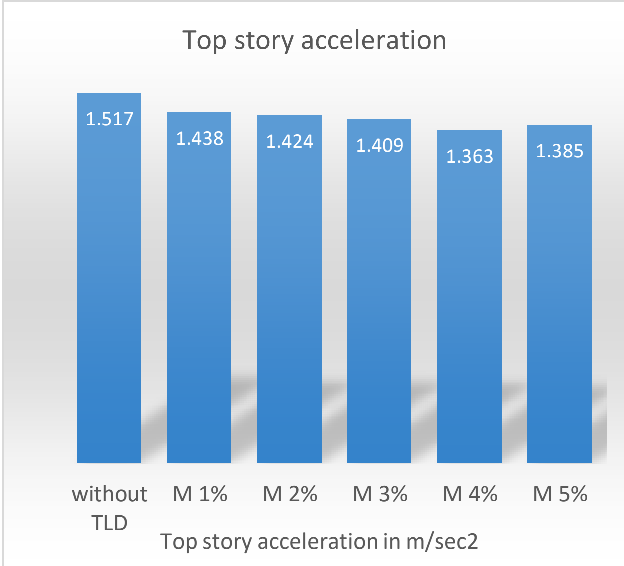
4.3 Results for G+3 building with 300 mm targeted base displacement

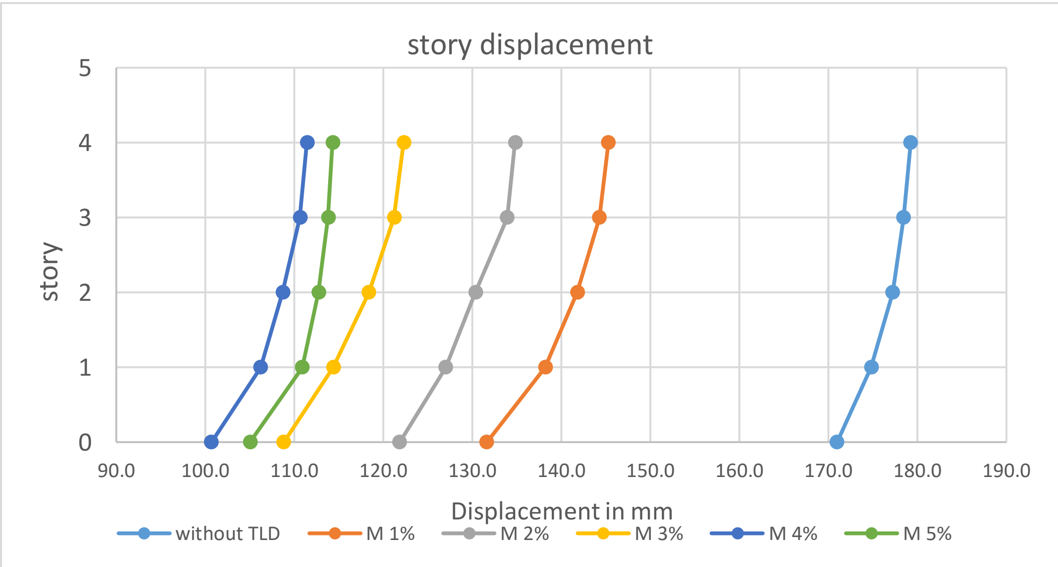




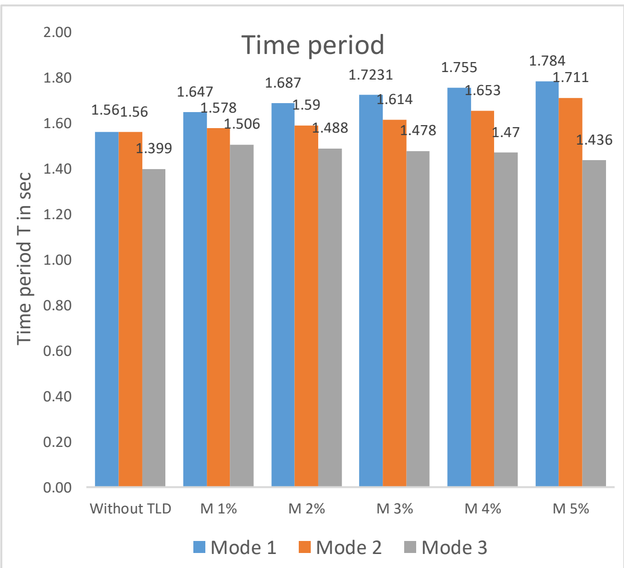
From graphs, it can be noted that there is a maximum 6.48% reduction in base shear for 4% mass ratio structure though all mass ratio shows somewhat of the same performance. Top story acceleration is reduced by 10.18% max which is from 4% mass ratio. Top story displacement is reduced by 38.58% max from 5% mass ratio of structure. Base displacement is reduced by 37.84% for the mass ratio of 4%. So from the result, it can be concluded that 4% mass ratio for TLD is given optimum result for G+3 d200 structure and a further increase in a mass ratio to 5% is a too effective but considerable increase in performance than 4% mass ratio TLD performance is not visible.

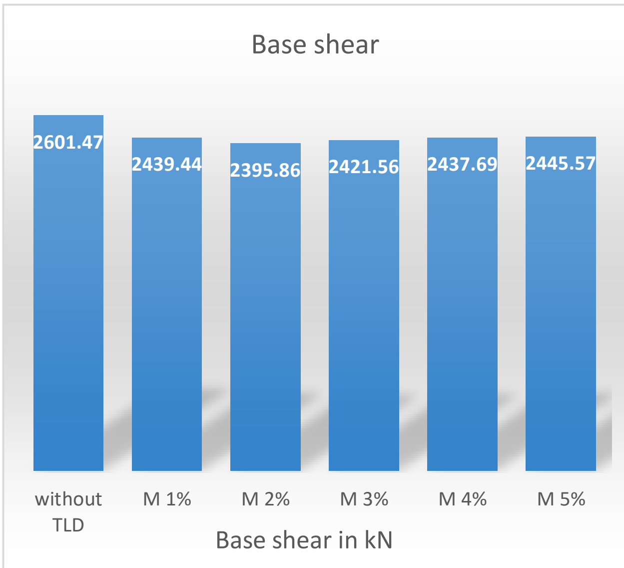


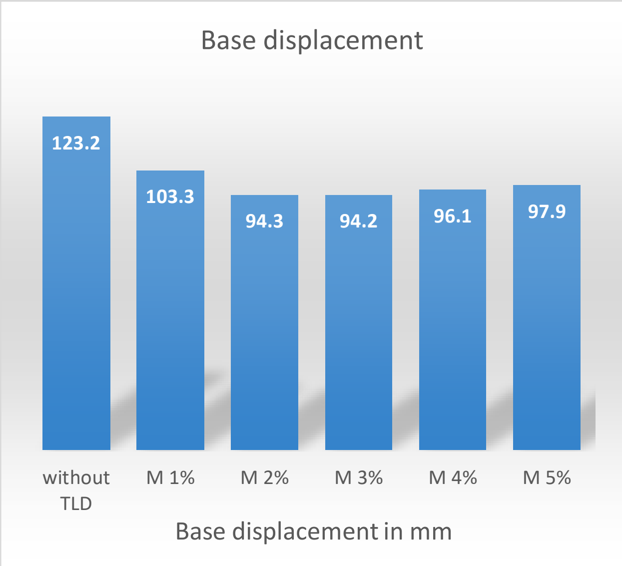


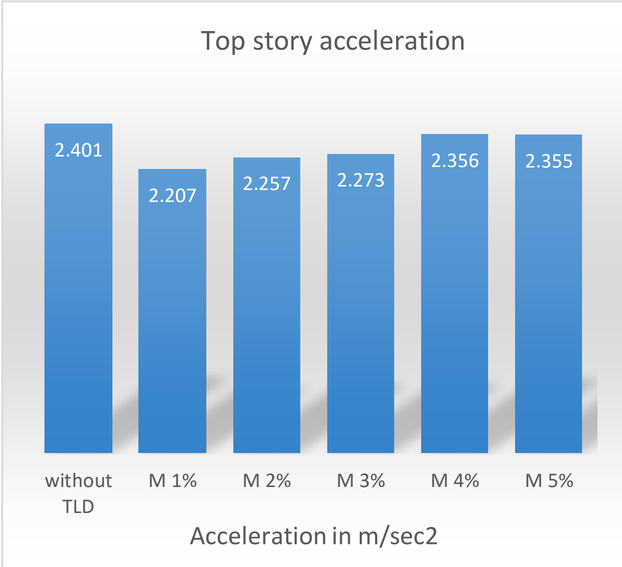


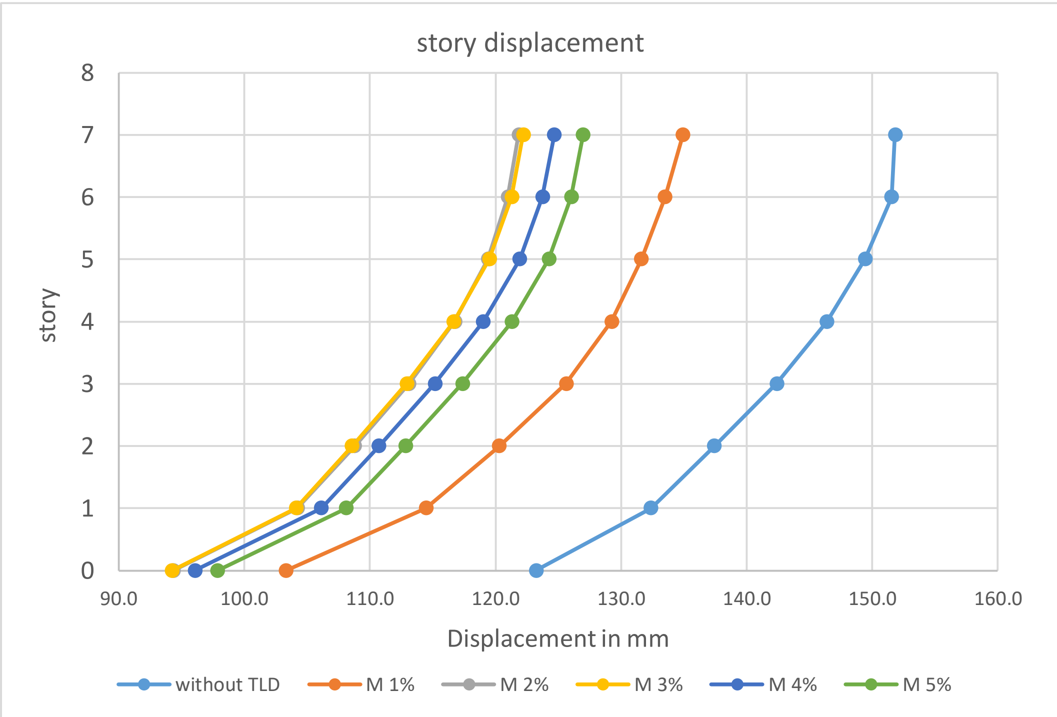
4.4 Results for G+6 building with 200 mm targeted base displacement







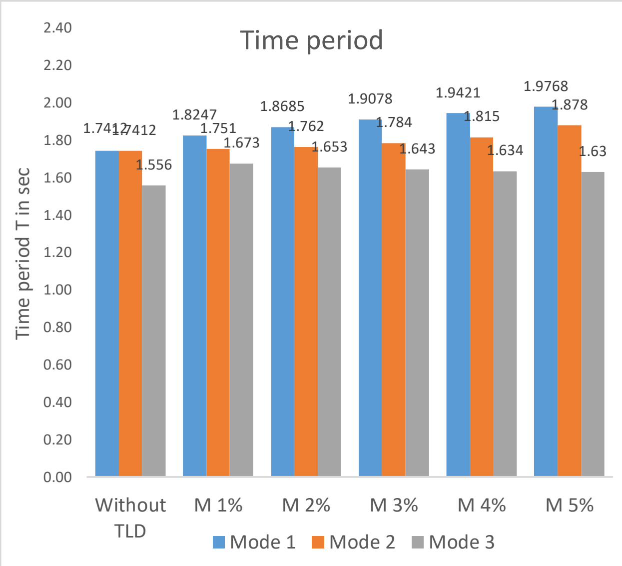


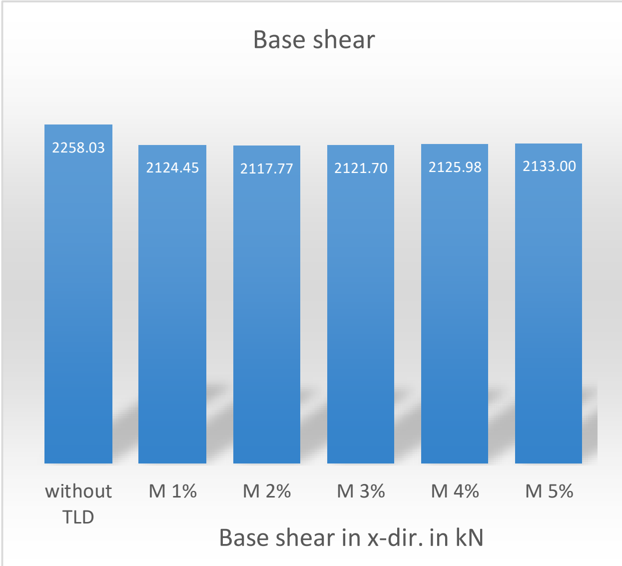


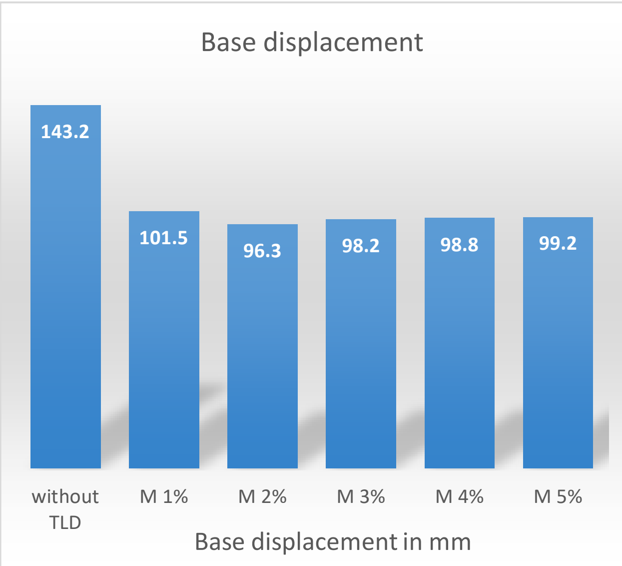
From the above graph, it can be noted that there is a maximum 7.90% reduction in base shear for 2% mass ratio structure though all mass ratio shows somewhat of the same performance. Top story acceleration is reduced by 8.10% max which is from 1% mass ratio. Top story displacement is reduced by 23.51% max from 3% mass ratio of structure. Base displacement is reduced by 19.74% for the mass ratio of 2%. So from the result, it can be concluded that 2% mass ratio for TLD is given optimum result for G+6 d200 structure and a further increase in a mass ratio to 4% and 5% is not so effective.

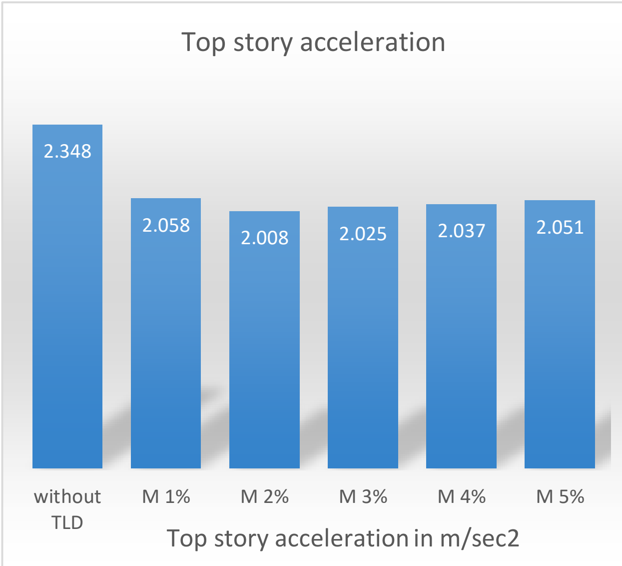
4.5 Results for G+6 building with 250 mm targeted base displacement

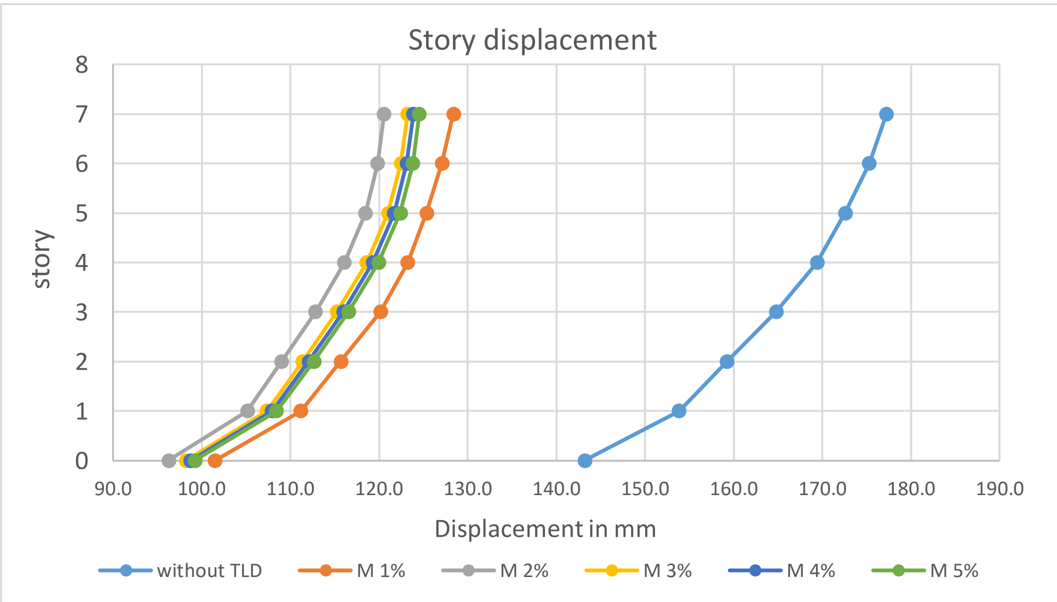
From the below graphs, it can be noted that there is a maximum 6.21% reduction in base shear for 2% mass ratio structure though all mass ratio shows somewhat of the same performance. Top story acceleration is reduced by 14.49% max which is from 2% mass ratio. Top story displacement is reduced by 31.39% max from 3% mass ratio of structure. Base displacement is reduced by 31.98% for the mass ratio of 2%. So from the result, it can be concluded that 2% mass ratio for TLD is given optimum result for G+3 d200 structure and a further increase in a mass ratio to 4% and 5% is not so effective.


Time period
Time period T in sec
2.40
2.20
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
1.7412
1.7412
1.556
1.8247
1.751
1.673
1.8685
1.762
1.653
1.9078
1.784
1.643
1.9421
1.815
1.634
1.9768
1.878
1.63
Without TLD
M 1%
M 2%
M 3%
M 4%
M 5%
Mode 1
Mode 2
Mode 3

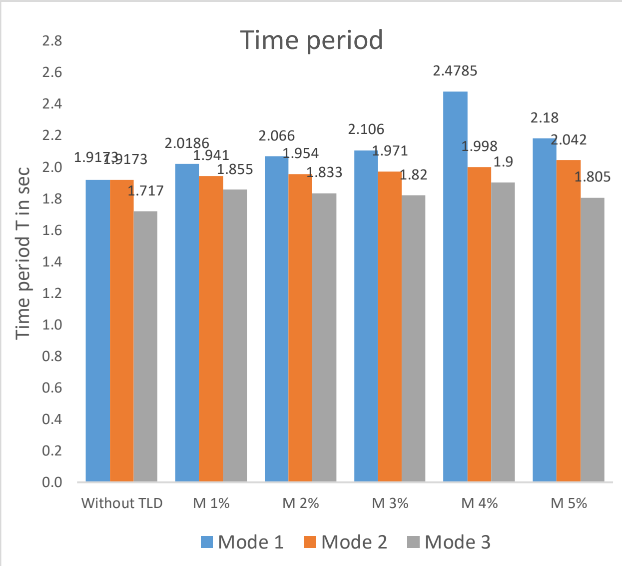

Base shear
2258.03
2124.45
2117.77
2121.70
2125.98
2133.00
without TLD
M 1%
M 2%
M 3%
M 4%
M 5%
Base shear in x-dir. in kN

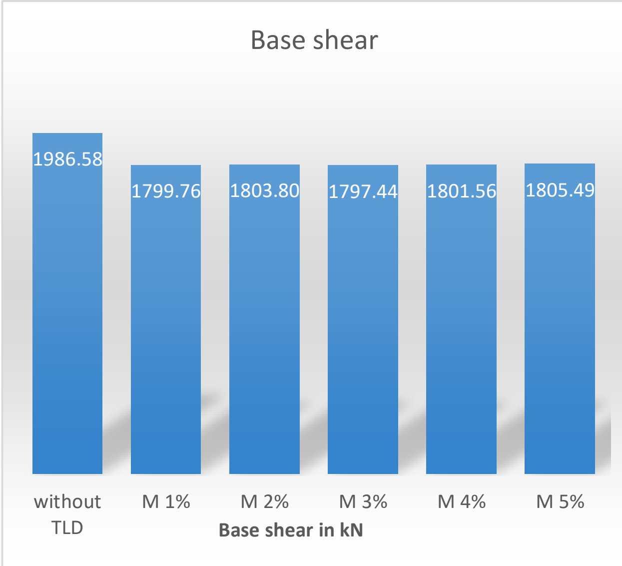

Base displacement
143.2
101.5
96.3
98.2
98.8
99.2
without TLD
M 1%
M 2%
M 3%
M 4%
M 5%
Base displacement in mm

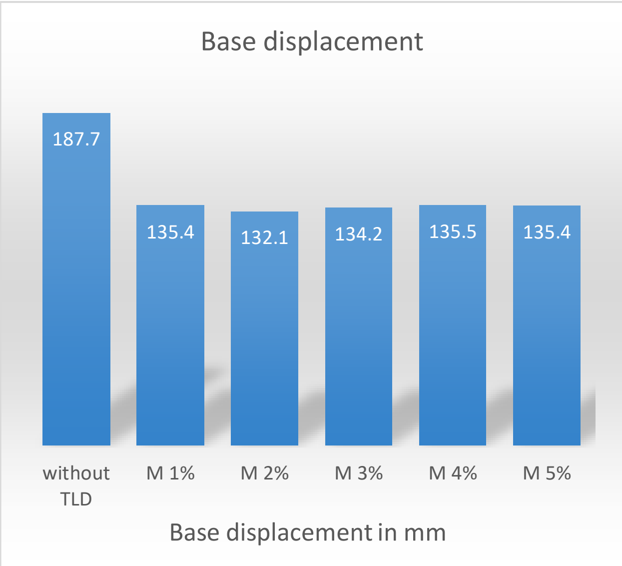

Top story acceleration
2.348
2.058
2.008
2.025
2.037
2.051
without TLD
M 1%
M 2%
M 3%
M 4%
M 5%
Top story acceleration in m/sec2

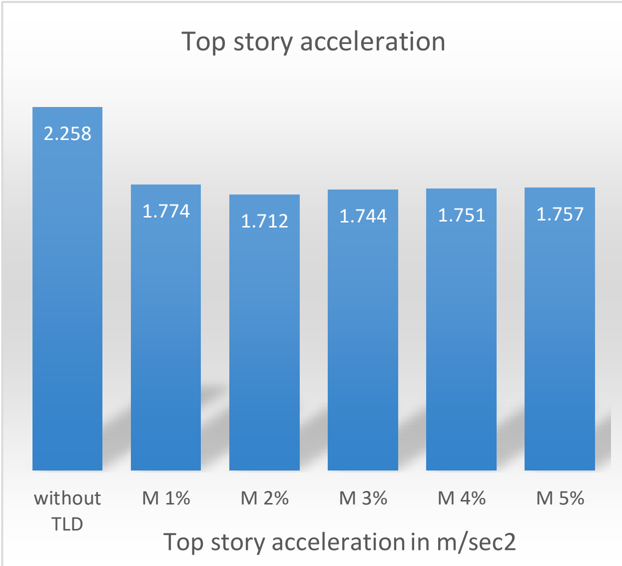

Story displacement
story
8
7
6
5
4
3
2
1
0
90.0
100.0
110.0
120.0
130.0
140.0
150.0
160.0
170.0
180.0
190.0
Displacement in mm
without TLD
M 1%
M 2%
M 3%
M 4%
M 5%

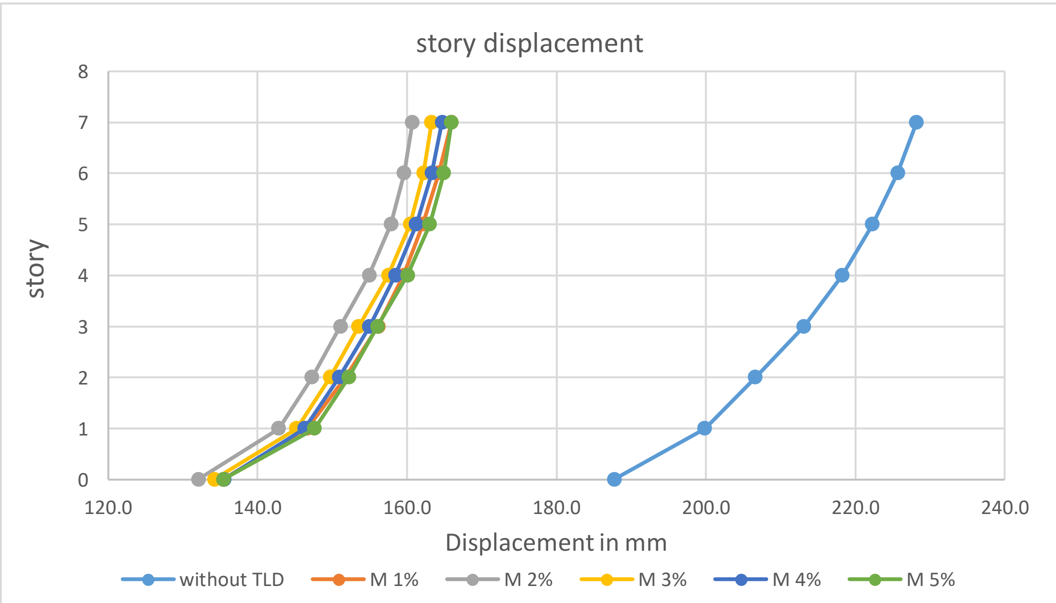
4.6 Results for G+6 building with 300 mm targeted base displacement











From the above graphs, it can be noted that there is a maximum 9.52% reduction in base shear for 3% mass ratio structure though all mass ratio shows somewhat of the same performance. Top story acceleration is reduced by 29.58% max which is from 2% mass ratio. Top story displacement is reduced by 29.64% max from 2% mass ratio of structure. Base displacement is reduced by 29.58% for the mass ratio of 2%. So from the result, it can be concluded that 2% mass ratio for TLD is given optimum result for G+6 d300 structure and a further increase in a mass ratio to 3%, 4% and 5% is effective too but considerable increase in performance than 3% mass ratio TLD performance is not visible.

V.CONCLUSION

The present study leads to the conclusion that it is advisable to use Tuned liquid damper for reduction of base displacement and mitigation of structural response under dynamic action. The analysis of G+3 and G+6 storey structure subjected to recorded ground motion shows that adequately designed TLD can substantially reduce structural response. Application of TLD can effectively improve the structural performance of RC frame building it reduces dynamic force experienced by superstructure by controlling floor accelerations, base shear, and story displacement.

As the base displacement increases TLD is more effective for reduction of response, it is observed that for LRB with 300 mm target base displacement percentage reduction in the response of the structure is more compared to 200mm and 250 mm target base displacement. More than 30% reduction is observed in base displacement and top story displacement for structure with 300 mm target base displacement.

For G+6 building as base displacement increases its efficiency of TLD also increases to control the response of the structure, with proper tuning 32% reduction in base displacement and 33% reduction in top story displacement can be achieved while for G+3 building 41% reduction in top story displacement and 38% reduction in base displacement is observed.

TLD is more effective for G+6 building in terms of reduction of top story acceleration compared to G+3 building as maximum 29% reduction is observed for G+6 and 12% for G+3 story building. And for base shear, both type of building shows near about 10 to 14 % reduction.

As design base displacement increases percentage reduction of response is increased to a very high number, the overall analysis concludes that mass ratio in the range of 2% to 3% is more effective in every structure however for mass ratio 4% and 5% TLD is an effective but considerable increase in response reduction is not evident with the increase in the mass of liquid.

VI.REFERENCES

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