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Seismic Retrofit of Elevated Steel Water Tanks

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ABSTRACT

The Indian Standard "Criteria for Earthquake Resistant Design of Structures: IS 1893-1984" has been revised. Areas in earthquake zone 1 have been merged to earthquake zone 2 and Killari is now in earthquake zone 3. The seismic zone factors have been also changed. Response spectra are now specified for 3 types of founding soil strata and a response reduction factor has been introduced. Elevated water tanks are vulnerable to earthquake, owing to large mass concentrated at the top of a relatively slender supporting structure. Existing elevated steel water tanks in India designed using IS 1893-1984 is checked for safety as per revised code (IS 1893-2002) by carrying out static and forced dynamic analysis. It is observed that the structure is unsafe due to under-estimation of seismic load as per old code provisions. Retrofit measures such as additional structural elements and passive devices like viscous and friction dampers are modelled and structure analysed again to check for compliance with the revised code. Conclusions drawn from this study are presented.

Keywords: *Seismic Zone factors, Water tank, Dynamic properties, Passive devices, damper.*

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1. INTRODUCTION

The elevated Water Tank (WT) consists of tank supported by staging system composed of columns, braces and foundations. Only steel WTs have been considered. The steel tanks are designed according to IS 805 [1] and IS 800[2]. The criteria for aseismic design of structures are given in IS 1893-2002 part 1 [3] and the explanatory code [4]. Elevated WTs have generally performed well in aseismic zones. However large number of tank collapses have been observed during earthquakes from as early as the 1906 San Francisco Earthquake to the 2001 Bhuj Earthquake[5]. The seismic zone maps have been recently revised. The new zone map has only four seismic zones – 11, 111, 1V and V instead of the five zones in the earlier version.

2. LITERATURE REVIEW

Ramaiah and Gupta [6] investigated the factors such as size of columns, braces, number of panels and initial tension of bracing rods, effecting seismic design of water towers. The lateral shear force and stresses in the rods are higher for towers with more panels. With increase in size of bracing rods, the period was found to decrease, while the lateral force and seismic coefficient increased.

As per IS 1893-1984[7], an elevated water tank may be modelled by a single degree of freedom system. However research indicates that the single degree of freedom idealisation is approximate only for closed tanks, which are completely filled with liquid. Sheperd [8] presented the two- mass idealisation of elevated water tanks.

Jain and Sameer [9] proposed approximate methods to estimate the lateral stiffness of the tank staging. Ingle[10] suggested an approximate method for calculation of lateral stiffness and fundamental time period for tank structures with rectangular configuration of columns and braces in plan. He also proposed an equation for the lateral stiffness of the staging of the overhead tank.

The vulnerability of the staging structure is primarily responsible for the failure of elevated water tanks. Thus for seismic safety a correct assessment of the maximum force which may be generated in the various frame members due to seismic shear in staging is necessary. The effect of soil structure interaction changes the lateral stiffness of the staging structure. Several studies incorporating soil structure interaction effects in the water tank analysis has been reported [11-14].

Retrofit measures are adopted to upgrade the seismic resistance of a damaged or weak structure to make it safe under future earthquakes. Srisanthi et al.[16] carried out analysis of braced steel frame with friction damper using finite element software. The size of dampers was 0.5m x 0.5m and solid modeling was done for the dampers. Increasing the size of dampers will cause reduction in the response and deflection in the structure. It was found that the load carrying capacity of the steel frame with friction damper was 20% more than that of the frame without a damper. For a particular frame, deflection in the frame without damper was 20% less than that of the frame with friction damper.

3. SCOPE OF WORK

Based on the literature review, the scopes of the current work are:

1. Assessment of the safety of existing steel water tanks (designed using IS1893-1984) under revised provisions of IS1893-2002
2. To check the efficiency of additional structural members and dampers as retrofit measures

3. To find the optimum position of dampers for minimum seismic response

4. CURRENT STUDY

4.1 Introduction

Elevated Steel Water tanks are designed for DL, LL, WL (using provisions of IS 875 Part 3 1987) and seismic loads using IS 1893-2002. In this work only the performance of the staging is considered. The staging consists of columns and bracings. The members are essentially subjected to axial forces with the vertical loads transferred through columns in compression. The horizontal loads are transferred as tensile forces, through the diagonals.

The design procedure of water tanks is available from standard books. In this work an interactive C language program has been developed for the design of circular and rectangular water tanks. Eigen value analysis is performed on the structure using NISA [17]. The time period of vibration obtained from the NISA analysis is then input into the second part of the C program, which evaluates the design lateral forces. The structure is then checked for safety under the design lateral force and vertical load. Suitable member sections for columns and braces for rectangular tanks with 4, 8 and 9 columns and circular water tanks with 4, 6 and 8 columns with capacities 50, 100, 150 and 200 m^3 in different wind and seismic zones have been reported in [18].This was used for the parametric study which formed the first part of thesis and is not a part of this paper.

Since complete replacement of structures is not possible due to various reasons, seismic strengthening or retrofit are considered, usually costing 12 to 15% of the cost of rebuilding the structure. Two methods are proposed namely adding structural elements and passive devices like friction dampers and viscous dampers. The effect of retrofit measures on the seismic response is studied by carrying out transient dynamic analysis (TDA) using NISA.

4.2 Modelling of Steel Water tanks using NISA and validation of model

The staging is designed as a space frame in DISPLAY 111 and the mass of the tank and water is distributed at the top level as a 3D general mass. The columns and braces are designed as 3D beam elements. Eigen value analysis is performed to get the period of vibration, natural frequencies and mode shapes. The eigen value problem is solved by conventional subspace iteration method, available in NISA. The tank used for validation of modelling process consists of a four-column, two storey, single bay space frame of water tank (Figure1).

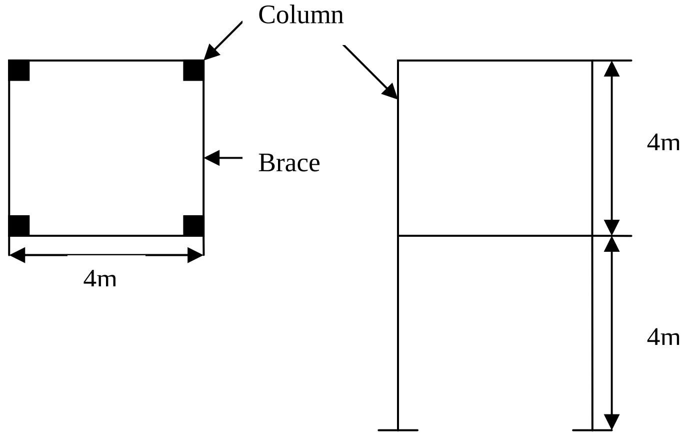


Figure1. Plan and elevation of tank staging used for validation of modelling

The area of column is 300 mm x 300 mm and brace size is 200 mm x 600 mm. The mass considered is 80.0 kN/m and Modulus of elasticity is 2.85 x 107 kN/m^2. The validation is done by comparing the time period obtained from NISA by Eigen value analysis with the results reported by Ingle [10] (table 1). It is found that the time period obtained from the present work is very close to values obtained by Ingle [10].

Table 1 Validation of the model

Time period (sec)			$\left(\frac{2}{1}\right)$	$\left(\frac{3}{1}\right)$
Present work	Method proposed by Ingle	Dynamic Analysis by Ingle		
1	2	3	4	5
0.7242	0.7209	0.7261	0.9954	1.0026

4.3 Assessment of safety of steel WT under revised provisions of IS 1893-2002

For assessment of compliance of existing steel WTs (designed as per IS 1893-1984 for a structure in zone 1) to the provisions of IS 1893-2002, a rectangular tank of capacity 100m^3, staging height 8m and number of panels 2 is considered (figure 2).

Table 2 Coefficients used in the analysis of lateral force on the water tank

	IS 1893-1984 (zone 1)	IS 1893-2002 zone 2)
Seismic zone factor	0.05	0.1
Period of vibration	0.96 sec	0.96 sec
Seismic coefficient	0.14	Soft soil 2.38
		Medium soil 1.96
		Hard soil 1.4
Importance factor	1.5	-
Damping	2%	2%
Performance factor	1.3	-
Response reduction factor	-	5
Design Lateral force	8.03 kN	Worst case soft soil 38.45 kN
Increase in lateral force due to revision	$\left(\frac{38.45}{8,03}\right)$ **=4.79**	

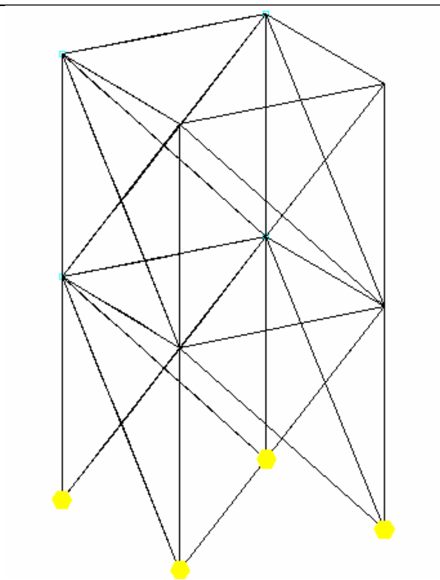


Figure 2 Model of Staging of Steel WT used in the analysis

The dynamic response of the water tank when subjected to lateral force calculated as per IS 1893-2002, is evaluated. Note that the structure is now in zone 2 since zone 1 has been merged with zone 2. The assumptions used in the analysis are given in table 2. Importance factor has been taken as 1.5 since WT is an important service and community structure. Performance factor for framed structures with steel bracing members is 1.3 and damping for steel structures varies between 2 to 5% of the critical.

The increase in lateral force due to the revision of code is 4.79 times. The main reasons for this increase are doubling of the seismic zone factor from 0.05 to 0.1 and incorporation of the three soil conditions. The increase in member forces and stresses due to the application of the increased force are shown in table 3.

Table 3 Member forces and Stresses on members of the water tank

Member	Section	Permissible stresses	IS 1893-1984			IS 1893-2002		
			Force	Actual stress	Comment	Force	Actual stress	Comment
	ISA	N/mm^2	kN	N/mm^2		kN	N/mm^2	
Column	150x150x18	70.69	239	69.23	Safe	356	70.09	Safe
Diagonal bracing	40x40x4	199.5	23.07	171.31	Safe	68	506.19	Unsafe
Horizontal bracing	60x60x6	32.96	12.10	17.02	Safe	28.44	40.93	Unsafe

TDA is carried out to get the response of the structure under the revised and old code loading conditions. TDA involves computation of the response of a given system when the loads are arbitrary, but known functions of time. In NISA, TDA can be performed by the use of modal TDA. It is clearly seen from figure 3 that the response of the structure under the revised provisions of code, is about twice that of previous response. Hence retrofit measures are necessary to upgrade the structure.

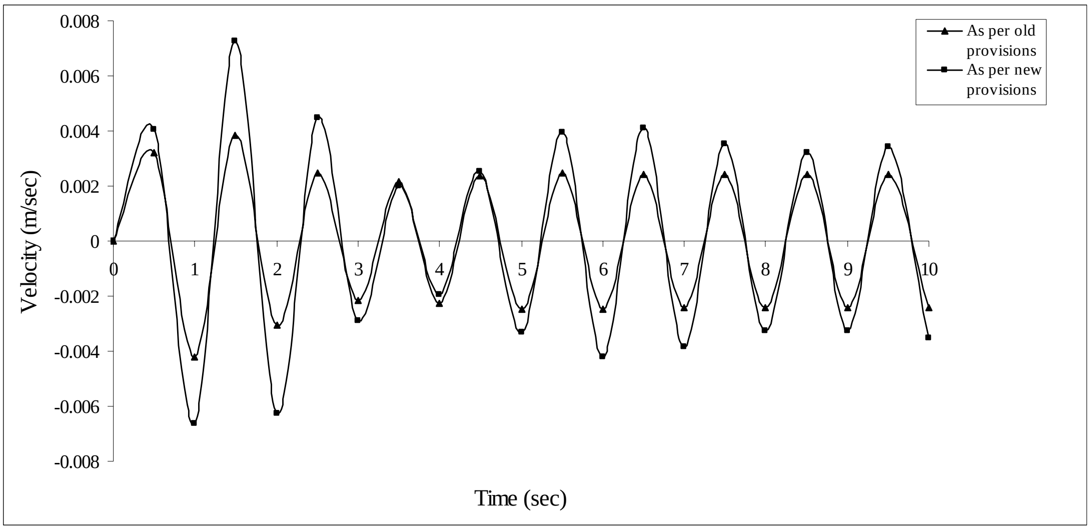


Figure 3. Velocity response of the structure under seismic loads

5. Retrofit measures for Steel water tanks

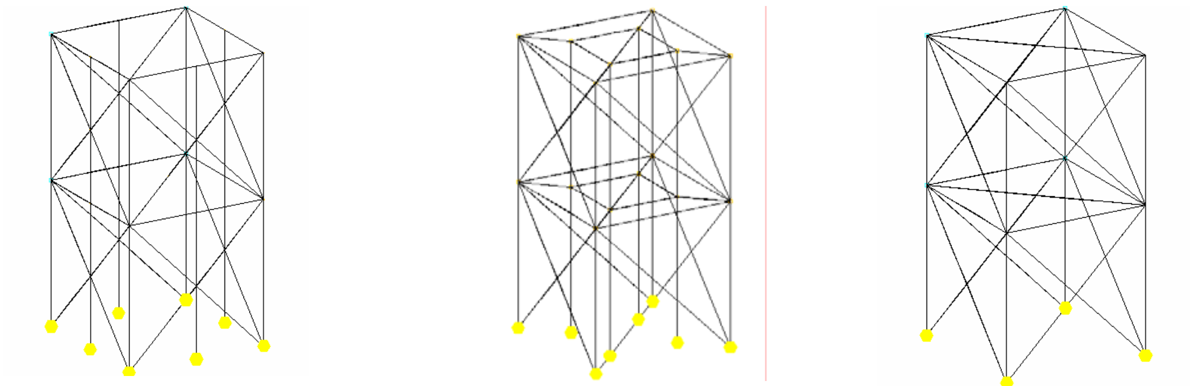
5.1 Introduction of Additional Structural Members

Additional structural elements are introduced by the following methods:

1. Provision of angle sections as vertical members at the centre of the diagonal bracings (figure 4a). These vertical members reduce the column load and effective length of the bracings. The members designed as vertical members are of ISA 150 x 150 x 18.
2. Provisions of concentric row of columns connected by circumferential and radial bracing members (figure 4b). The loads are thus transferred to more members reducing

the vulnerability of each member. The inner columns are of ISA 150x150x18. Circumferential bracings are ISA 60x60x5 and radial bracings 40x40x3.

3. Provision of radial bracings (figure 4c). This will help in carrying the lateral loads considerably. The section provided is ISA 75x75x10.
4. Doubling the area of the horizontal and diagonal bracing members by connecting back to back the same section as provided for diagonal bracing. This method is simple and vulnerability of the bracing members can be eliminated.



(a) Additional Vertical members (b) Concentric row of columns and radial and circumferential bracings (c) Radial bracings

Figure 4. Retrofit by Additional Members

The retrofitted structures are re-analysed. Structures retrofitted by methods 1, 2 and 4 are seen to be safe, while diagonal bracings retrofitted by method 3 are still unsafe. Much reduction in seismic response is observed by the addition of members. The response reduction is more for method 4 (doubling area of braces) compared to other methods and the reduction is about one-fourth times that of original response.

5.2 Introduction of Viscous dampers and Friction Dampers

Viscous Dampers: Three-dimensional (3-D) damper elements are used to incorporate the viscous dampers at various levels of staging. One of the diagonal bracings is replaced with 3 D damper element and a damping coefficient of 0.2 is provided. Dampers are provided at bottom level, top level and at both levels and Transient Dynamic Analysis is performed for all the three cases. Figure 5 shows the WT modelled with Viscous Dampers.
In figure 7, the maximum velocity response occurs for “no damper” case. The provision of dampers at the bottom level and top level is found to have almost the same effect on the response of the structure. This curve is seen below the “no damper” curve. Providing dampers at both levels will reduce the response further as seen in figure 7, but the reduction is not significant. Thus provision of damper at a single level is sufficient. From the velocity response (figure 7) and acceleration response of the structure it is observed that the provision of viscous dampers on the bracings reduces the response by about four times.

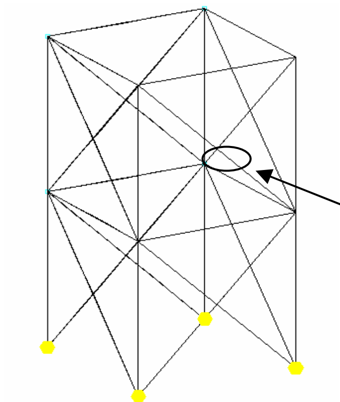


Figure 5. WT modelled with Viscous Dampers

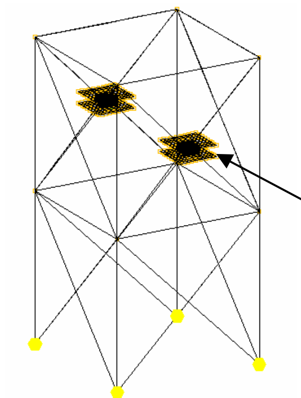


Figure 6. WT modelled with Friction Dampers

Friction Dampers rely on the friction developed between two solid interfaces sliding relative to one another. During seismic response the device slips at a predetermined load providing the desired energy dissipation by friction. The friction damper modelled consists of alternate layers of steel plates and rubber. Shell element is used to model the damper and it is connected to the cross braces (figure 6).

The damper consists of alternate layers of rubber and steel plates, which were connected by beam members at every node. The much more effective method will be modelling as 3D, but it couldn't be done because of the limitation of NISA version. This block is sandwiched between two steel plates. Standard values of E for steel for steel plates and E for rubber for rubber layer were used. The size of damper block sandwiched between steel plates was 0.5m x 0.5m and of thickness 0.02m for each plate. Such 6 or 8 plates are joined together. The steel plates at the top and the bottom were 0.7m x 0.7m and have thickness 0.02m. The dampers are connected to cross bracing at bottom storey, top storey or both storeys on two sides or four sides. The force is applied at the top nodes of the structure in the lateral direction. It is observed that the damper slides between the steel plates and maximum deflection occur on the damper element while there is response reduction in all other elements. The deflected shape of the structure is shown in figure 9. The response of the structure at top node when the earthquake force is acting normal to the damper can be plotted (figure 8). The maximum velocity response of the structure, when dampers are provided at top or bottom storey is 0.0004m/sec (from figure 8) and that of the structure without damper is 0.008m/sec (from figure 7). The acceleration response reduced from 0.1m/sec^2 to 0.0035m/sec^2 when dampers are provided at top or bottom storey on two sides. The reduction in response is higher when dampers are provided at both the storeys. It is observed that there is 20 times reduction in response when friction dampers provided.

When the force is acting normal to the damper, provision of dampers on two sides will be effective in reducing the response. When the force acts at an angle to the damper, provision of damper on four sides will be more efficient. In figure 10 and figure 11, the maximum structural response is seen when dampers are provided on two sides for both storeys, intermediate curve for dampers provided on all four sides of bottom storey and minimum response when dampers are provided on all four sides of top storey. It is also seen that when the structure is fitted with dampers on four sides, the response is 7 times lower than the structure with dampers on two sides, when the force is acting diagonally. It is also observed that the response is two times lower when dampers are provided at top storey compared to that when provided at bottom storey.

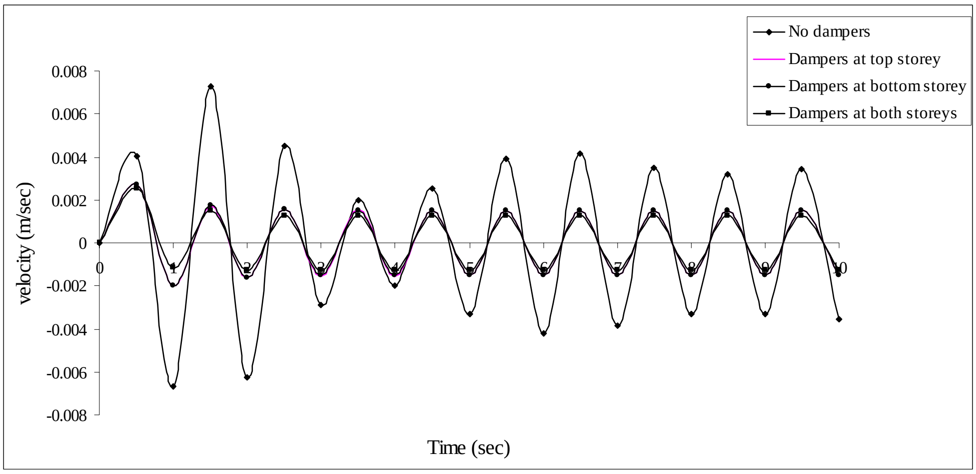


Figure 7. Velocity Response of the structure for different positions of the Viscous damper

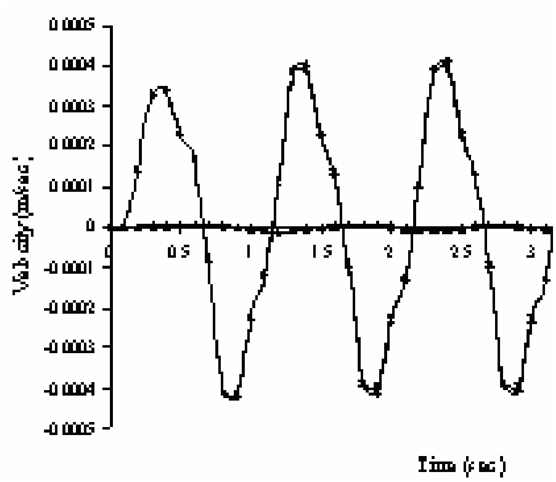


Figure 8. Velocity Response of WT to forces acting normal to the friction damper

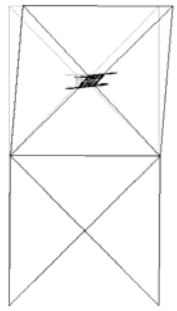


Figure 9. The Deflected Shape of the Frame Provided with Friction Damper

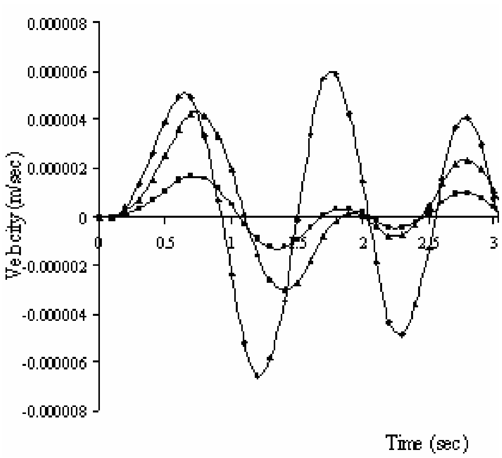


Figure 10. Velocity response of WT to force is acting diagonal to the damper

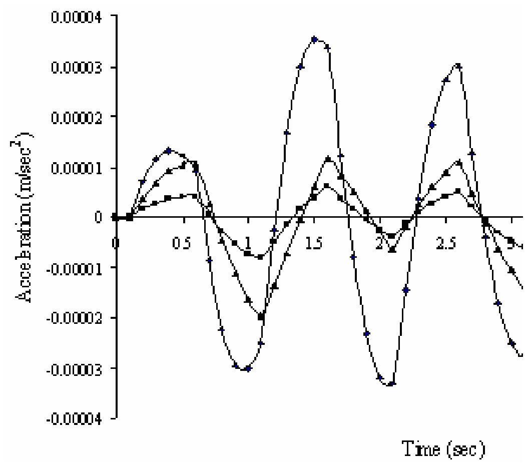


Figure 11. Acceleration response of WT to force is acting diagonal to the damper

6. CONCLUSIONS

The following were the conclusions from the study:

a) The safety of elevated steel WT was checked under revised provisions of code IS 1893-2002. The structure was found to be unsafe and hence retrofit measures were necessary to upgrade the structure. Seismic retrofitting was proposed by adding structural elements and by incorporating passive devices like viscous and friction dampers in the structure.
b) The introduction of additional structural elements such as vertical, diagonal and horizontal members in different configurations was found to reduce structural response considerably. The most effective and easy method was to double area of bracing members.
c) The provision of viscous dampers on the bracings reduced the structural response to 25%.
d) The structural response was reduced to 5% when friction dampers were provided on the WT frame. The reduction in response was higher when the dampers were provided at both the storeys. The response was lower when dampers were provided at top storey compared to that of the bottom storey.
e) When the force was acting normal to the damper, provision of dampers on two sides was effective in reducing the response. When the force was acting at an angle to the damper, provision of dampers on four sides was more efficient. The response was lower for structure provided with dampers on four sides than structure with dampers on two sides, when the force was acting diagonally.
f) The most efficient method of retrofit is the use of friction dampers since greater reduction in response is observed. More practical and economic method may be doubling the area of bracing members.

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