JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

Parametric Study on Seismic Response Control of Tall Building Installed with Friction Dampers

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Abstract : Tall buildings are essential for the vertical growth in urban areas due to lack of available land, allowing efficient and pleasant land use and accommodating increasing populations density. Tall building should withstand lateral forces from wind and seismic activity to ensure the stability and occupant safety. Advanced protection techniques, active, semi-active and passive control being used to ensure resilience against seismic events. This study evaluates the effectiveness of friction damper by varying key parameters such as applied normal forces to determine slip load. By systematically selecting theses variables, the study aims to understand their influence on the various response parameters such as top storey displacement and acceleration counterpart, inter storey drift, storey displacements, base shear and damper's energy dissipation capacity to determine overall effectiveness in seismic response control. For the study, a 25-storey tall reinforced concrete building is 3D modeled and designed in ETABS to analyses uncontrolled seismic responses under the real earthquake ground motion. Then the controlled responses are derived using numerical simulation in MATLAB using state space method. The uncontrolled responses of ETABS and MATLAB is matched. The controlled response parameters are derived on optimized value of normal force derived from the range values of normal forces and coefficient of friction. The controllability index (R_e) is introduced to determine the effectiveness of friction dampers installed at all storey with optimized value of normal forces. The study concludes that optimized, rather than maximized, values of normal force critical to achieving balanced seismic performance in tall building.
Keywords: Seismic Response, Optimum, Friction Damper, Simulation, Normal Force, Coefficients of Friction, State Space Method.

I. INTRODUCTION

The growing global population and urban development have led to increased demand for tall building to make efficient use of limited land. Ensuring their stability against natural hazards like earthquake is essential for safety and occupant comfort. Structural engineers has introduced various control systems, with passive dampers standing out for their reliability and low maintenance. The passive dampers dissipate energy without external power, making them effective in reducing structural vibrations. Researchers are now focusing on seismic performance of tall buildings equipped with passive damper systems. The energy dissipation is primarily due to relative displacement in the friction damper.

Soong and Dargush (1999) presented a formulated mathematical model and outlined the fundamental principles of single-degree-of-freedom (SDOF) and multi-degree-of-freedom (MDOF) system. They also introduced an energy-based design procedure. Yang et al. (2004) presented an overview and problem statement of 76-storey, wind excited reinforced concrete office building to encourage the development of various control strategies for benchmark building. Patil and Jangid (2009) introduced a double friction damper for a wind-excited 76-storey benchmark tall building. They compared the performance of conventional friction damper, double friction dampers, and semi-active variable friction dampers, finding that double friction dampers provided enhanced vibration control. Kaur et al. (2012) studied the seismic responses of mid-rise to high-rise building (five to twenty storeys) with three structural systems: moment-resisting frames, braced frames, and systems equipped with friction dampers.

Dynamic time history analysis was performed, emphasizing the importance of accurately modelling the braces in the system. Results indicate that top-storey displacement were reduced with friction dampers, although acceleration responses increased in higher frequency ranges. Mevada (2015) conducted a comparative numerical analysis of a multi-storey asymmetric building equipped with optimally designed semi-active MR, friction, variable, variable stiffness, and nonlinear viscous dampers. The effectiveness of these devices was evaluated using the controllability indices. Friis et al. (2021) studied two-level friction dampers from multi-functional vibration control in high-rise buildings to overcome the amplitude dependence limitations of single-level friction dampers. Their results demonstrated the superior application potential of two-level friction dampers. Shirai and Sano (2022) studied the energy response of a 30-storey two-dimensional mainframe equipped with variable friction dampers. The results indicated that, compared to friction dampers, variable friction dampers effectively reduced peak storey shear forces and axial compressive forces in the lowest storey columns. Bruschi et al. (2023) presented the development and testing of a novel friction damper designed for the seismic retrofit of existing buildings. The study included the experimental characterization, mechanical modelling, and numerical simulations to asses friction damper performance. Their study proved that, the friction damper offers a practical and efficient solution for improving seismic resilience in existing buildings. Wei Liu et al. (2025) introduced a novel non-preload variable friction damper (NVFD) designed to overcome limitations of traditional friction dampers, such as preload relaxation and cold bonding. The damper's mechanical and theoretical force model were presented in detail. Pseudo-static tests and numerical comparisons using an SDOF model demonstrated that the NVFD offers stable, adaptable frictional performance across various seismic intensities. A review of existing literature reveals that less study has systematically examined the effect of normal force and coefficient of friction in friction dampers for accurate estimation of slip load. This gap highlights the need to focus the investigation to understand influence of these parameters in effectiveness of friction damper performance. So, the aim of this study is to evaluate the seismic response of tall buildings equipped with friction dampers by systematically varying normal force as a parameter to achieve an optimized slip load for effective energy dissipation.

2. METHOD

In the present study, a 25-storey tall reinforced cement concrete building is considered. The details are mentioned in Fig. **1** and Table 1.

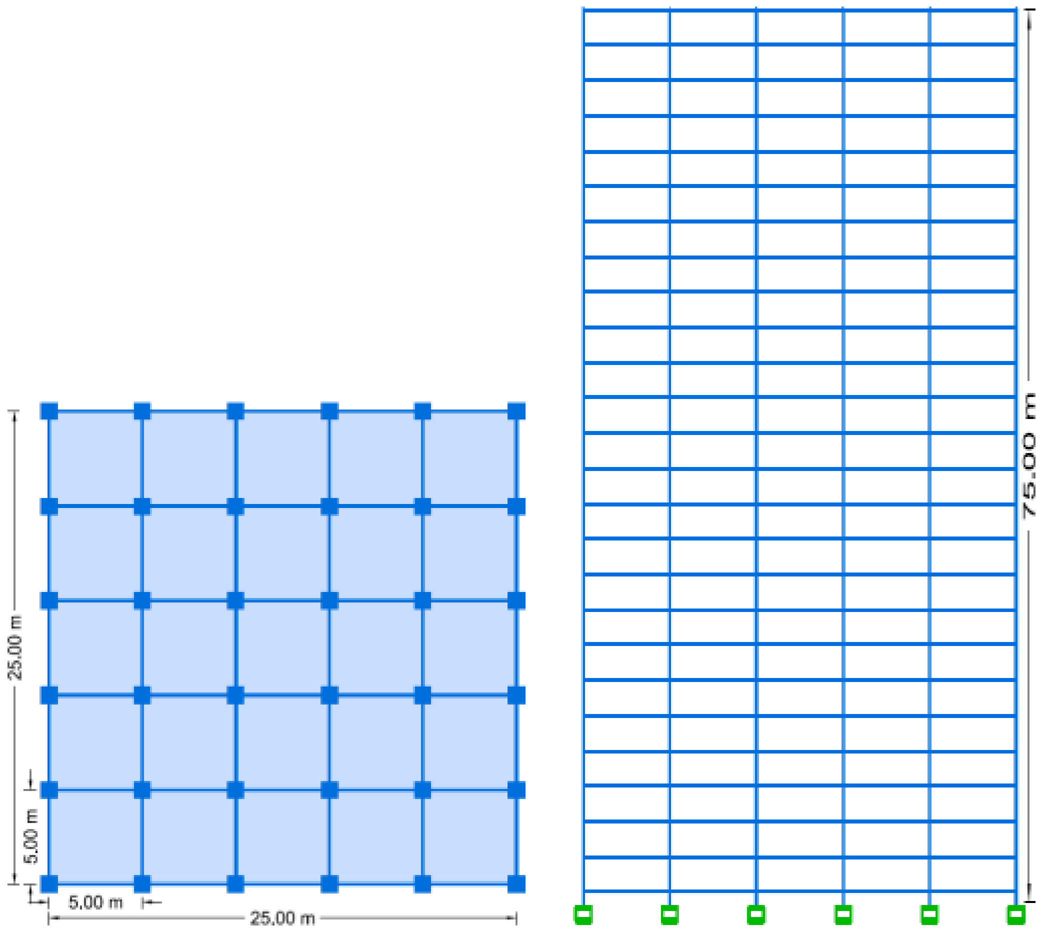

Fig. 1. Plan and elevation of 25-storey tall building

Table 1. Properties and parameters for the considered tall building

Parameter	Value
Type of building and frame	R.C.C. with special moment resisting frame.
Plan dimensions	25m x 25m
No of bays in both directions	5
Bay width	5m
Storey height	3m
Size of beams	300mm x 530mm
Size of columns	750mm x 750mm
Thickness of slab	150mm
Materials grades	Concrete: M35 – Slabs and beams, M50 – Columns. Reinforcement Steel: F_e550 Masonry: Light weight aerated cement block of 4.75 kN/m^3.
Codes	IS-875(I, II, III), IS-1893, IS-16700
Loads	Floor finish load: 1 kN/m^2 at all typical floor level, 2 kN/m^2 at top floor level. Live load: 3 kN/m^2 at all typical floor level, 1.5 kN/m^2 at top floor level.

2.1 Governing Equation of Motion and Their Solutions

The governing equation of the motion for the considered tall building having multi degree of freedom (MDOF) is as follows:

$$\mathbf{M}\ddot{x}(t) + C\dot{x}(t) + Kx(t) = -M\Gamma\ddot{x_g} + \Lambda F \quad (1)$$

For stories of n numbers, n represents the total degree of freedom, M, K, and C are system's mass, stiffness and damping respectively. $x = \{x_1, x_2, ...x_n\}^T$ is the displacement vector of ; $\dot{x}$(t) = relative velocity of the system; $\ddot{x}$(t) = acceleration; $\ddot{x_g} = \{\ddot{x_g}, 0\}^T$ is ground excitation vector, $\ddot{x_g}$ is the ground acceleration in x-direction. Γ denotes influence coefficient vector of applied ground motion; Λ is the matrix that defines the location of damper of size; $F_d = \{F_{d1}, F_{d2}, F_{d3}, ... F_{dn,}\}^T$ is the vector of damper forces; F(t) = $\{F_1(t), F_2(t), F_3(t)....F_n(t)\}$ represents the vector of external force. The mass matrix and stiffness matrices are as follows:

$$[M] = \begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_n \end{bmatrix} \quad (2)$$

$$[K] = \begin{bmatrix} k_1 + k_2 & -k_2 & 0 & 0 & 0 \\ -k_2 & k_2 + k_3 & -k_3 & 0 & 0 \\ 0 & -k_3 & \ddots & 0 & 0 \\ 0 & 0 & 0 & k_{n-1} + k_n & -k_n \\ 0 & 0 & 0 & -k_n & k_n \end{bmatrix} \quad (3)$$

From the Rayleigh's damping, the damping matrix is constructed based on 2% damping of the structural system in present study. The mass and stiffness proportional damping can be given by,

$$C = \alpha M + \beta K \quad (4)$$

The governing equations of motion is solved using state space method (Hart & Wong, 2000;). The state space equation can be expressed as

$$\dot{Z} = A\, z + B\, F + E\, \ddot{x}_g \quad (5)$$

There are two independent response variables which can be expressed as state vector z, where z = $[x \quad \dot{x}]^T$. 'A' is the system matrix. The distribution of control force is denoted by matrix B, and E is distribution matrix of excitations. These matrices can be written as:

$$A = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix};\ B = \begin{bmatrix} 0 \\ -M^{-1} & \Lambda \end{bmatrix},\ \text{and } E = -\begin{bmatrix} 0 \\ \Gamma \end{bmatrix} \quad (6)$$

where identity matrix can be expressed as I. The solution of equation of motion in an incremental form is written as:

$$z[k+1] = A_d\, z[k] + B_d\, F[k] + E_d \ddot{x}_g \quad (7)$$

where k is denoted for time step; $A_d = e^{A\Delta t}$, where Δt represents time interval in the discrete time system. The matrices that contain the constant coefficient B_d and E_d is expressed as:

$$B_d = A^{-1}(A_d - I)\, B \text{ and } E_d = A^{-1}(A_d - I)\, E \quad (8)$$

2.2 Modeling and Working of Friction Dampers

Friction dampers work by converting kinetic energy from structural motion into heat through sliding friction between surfaces. When a structure experiences lateral movement during events like earthquake, relative displacement occurs at the damper interface. This movement generates a frictional force, which resists the motion and dissipates the energy. The result is a reduction in structural vibration and improved seismic performance.

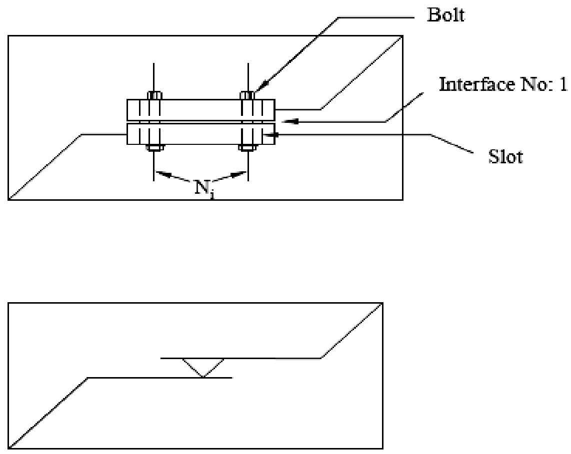

Fig. 2. Schematic and mathematical representation of friction damper

The damper force F_i, in the case of friction damper is due to plate interface is expressed by:

$$F_i = \mu N_{di} \text{ sgn } (\dot{x}_{di}) \quad (9)$$

In Equation-9, for the friction dampers, μ is the coefficient of friction, N_{di} represents normal force associated with i[th] damper. Signum function is denoted by sgn(.). The coefficient of friction, μ, in friction dampers determines the amount of resistance generated between the sliding surfaces when they come into contact. Also, the normal force (N) exerted by one surface on another, which directly influence the frictional force. The real earthquake considered to obtain above mentioned key parameters are, Imperial Valley (1940), at recording station El Centro, component LEC-180, 40 second duration, 0.31(g) PGA value. Validation of uncontrolled top storey displacement responses derived using ETABS software and MATLAB code using state space method. Followings are the assumption considered for the tall system:

1. The tall system is symmetrical 2) the center of mass and center of rigidity (CR) coincides 3) The mass of the system at all storeys are uniformly distributed. 4) The seismic ground excitation is along the X-direction of building plan. The friction dampers are installed at all storeys in the tall system as shown in Figure 3. Total 25 numbers of dampers are installed in the tall system.

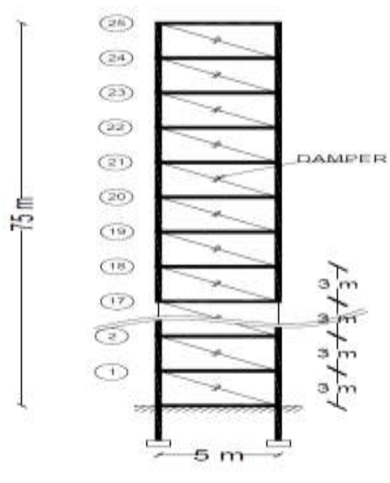

Fig. 3. Friction damper arrangement at all storey

3. RESULTS AND DISCUSSION

Limited research has focussed on systematic analysis on key parameters influencing working of friction dampers. By studying these parameters in details can enhance the efficiency and adaptability of friction dampers for tall building types and different ground motions, leading to more resilient structural systems for tall building. This study aims to fill the identified gap by conducting a detailed parametric analysis of friction dampers, focusing on the interaction between normal force and coefficient of friction. By evaluating their combined effect on slip load and structural response, the research provides insights for optimizing damper design leading to improved seismic performance of tall buildings. To assess the effectiveness of dampers, the controllability index (R_e) is evaluated, which a ratio of controlled to uncontrolled peak responses offering a nuanced understanding of damper performance. Mathematically, R_e can be expressed as follows:

$$R_e = \frac{\text{Peak response of controlled system}}{\text{Peak response of corresponding uncontrolled system}} \quad (10)$$

The range value of normal force (N) is considered as 0.00 to 1.5 x 10^5 N and 0.00 to 3.0 x 10^5 N. The value of coefficients of friction considered is 0.2. The optimum value of normal force derived for aforementioned range value of normal force from Fig. 4 is 75 x 10^3 N and 150 x 10^3 N. From these values of normal force and in combination with value of coefficients of friction, the seismic responses are derived.

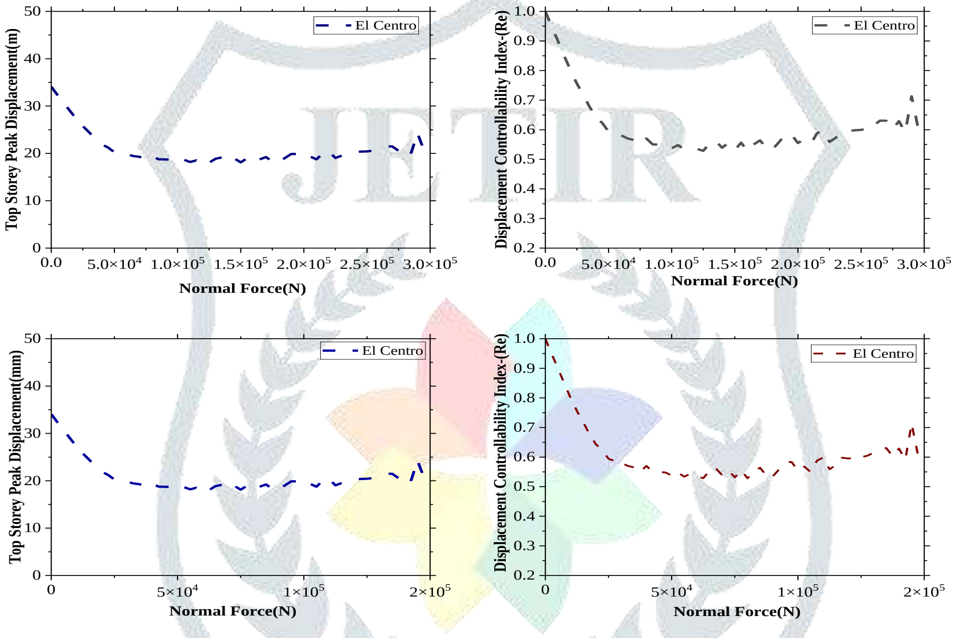

Fig. 4. Top storey peak displacement controllability Index (R_e) for the building installed with friction damper under El Centro (1940) earthquake

Table 2. Uncontrolled and controlled responses for tall building installed with friction damper under El Centro earthquake

Un-controlled Response	**Responses with Friction Dampers**	
	N= 75 x 10^3 N	*N= 150 x 10^3 N*
	μ = 0.2	*μ = 0.2*
Top Storey Displacement (mm)		
34.07	22.25 ***(34.70%)***	18.98 ***(44.30%)***
Top Storey Acceleration (m/sec^2)		
0.36	0.34 ***(5.55%)***	0.37 ***(-2.77%)***
Inter Storey Drift x 103		
0.763	***0.49 (34.56%)***	***0.48 (37.0%)***
Storey Displacement (mm)		
34.07	22.55 ***(33.81%)***	19.27 ***(43.44%)***
Damper Forces N x 10^3		
-	15	31
Base Shear (N) x 10^3		
654.47	643.73	709.92

Note: *The value written in paranthesis indicate the percentage reduction in response as compared to the uncontrolled case.*

Due to friction dampers installed at all the storeys, with varying combinations of optimized normal force (N) and coefficients of friction (μ), resulted in substantial reductions in top storey displacement under earthquake ground motions (Table 2, Fig. 5 & 6). As compared to the uncontrolled case the top storey displacement reductions observed is 34.70% and 44.30% respectively, with the highest reduction achieved at normal force value of 150 x 10^3 N and under El Centro earthquake record. These trends indicate that larger the N values enhance damper engagement, especially when paired with μ. Under moderate earthquake like El Centro, effective control was achieved even at lower N and μ values, highlighting that the effectiveness of damper parameter is not only a fuction of their magniture but also of ground motion's intensity and duration.

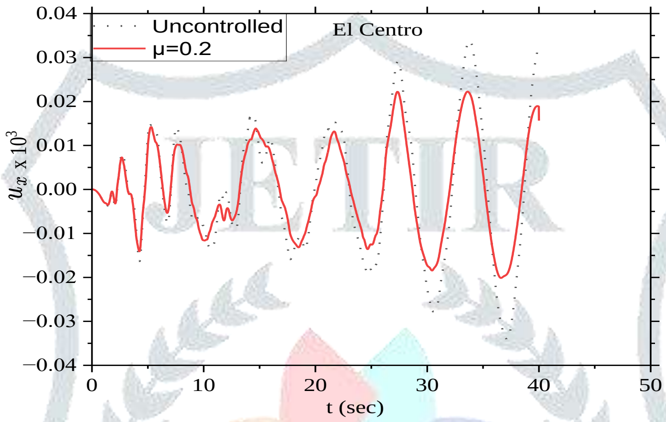

Fig.5. Top storey displacement response with optimum normal force (N = 75 x 10^3) under El Centro (1940) earthquake

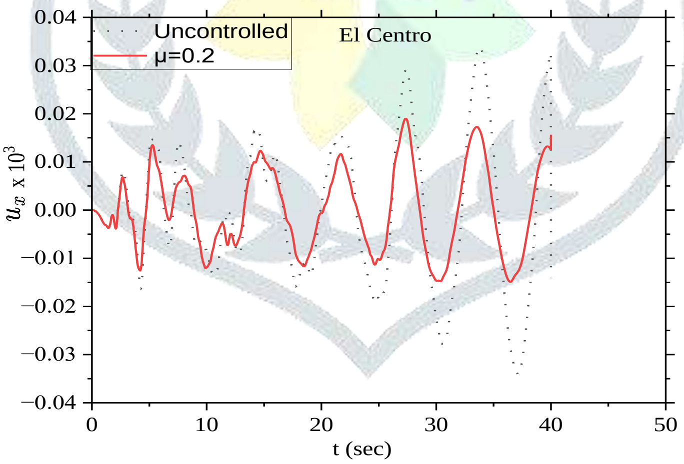

Fig.6. Top storey displacement response with optimum normal force (N = 150 x 10^3) under El Centro (1940) earthquake

Overall, the results demonstrate that the optimal seismic performance is achieved through a balanced tuning of N with μ, tailored to the specific demands of the earthquake, yielding up to 44% reduction in top storey displacement response.As per Table 2 and Fig. 7, unlike the top storey displacement, the top storey acceleration response to friction damper installation exhibited a more complex and less uniformly benificial trend. While certain combination of normal force (N) with coefficient of friction (μ) led to modest reductions in acceleration. Interstingly the El Centro ground motion, representing a moderate intensity event, followed a similar pattern where only the N and μ combination achieved a 5.55% reduction , whereas increasing normal force actually casued acceleration increases up to 2.77%. These trend suggest that while friction dampers are effective in reducing top storey displacement or generalize displacement, they may introduce sharp transient froce or stiffness like effec that amplify accelerations. This amplification is more prominent in ground motion with high frequency content or shorter durations, as seen in El Centro ground motions. This may potentially compromising occupant comfort or increasing non-strutural damage. It is observed that the inter storey drift is higher between storey-5 to storey-15. From Table 2, Fig. 8, the friction dampers led to consistent and measurable reduction in storey drift across under El Centro ground motions, demonstrating their effectiveness in limiting lateral deformation. The combined variation of N and μ showed a clear trend: as normal force increased, drift value decreased more significantly, with maximum reduction reaching up to 40.21% under El Centro earthquake. Overall, the results confirm that storey drifts is a highly responsive parameter to friction type damper tuning, with optimized value of N with considered μ contributing to significantly enhanced lateral stiffness and structural control for the tall building considered. Under El Centro earthquake, with moderate intensity and duration, showed the highest response improvement with displacement reduction for storey exceeding 44% at N= 150 x 10^3 N. This indicate that even moderate damper forces can be highly effective in

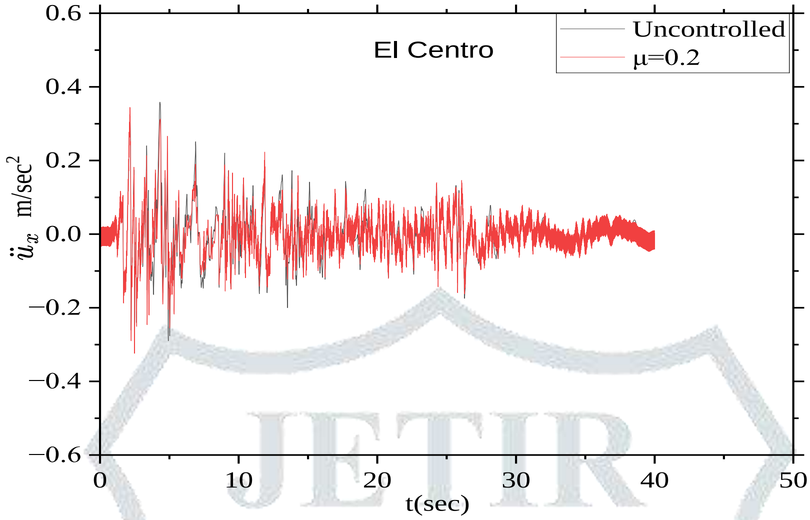

Fig.7. Top storey acceleration response with optimum normal force (N = 75 x 10^3) under El Centro (1940) earthquake

such scenarios (Table 3). The derived damper forces indicate a clear, proportional increase with higher value of normal force (N) and coefficient of friction (μ), confirming the expected frictional behavior.

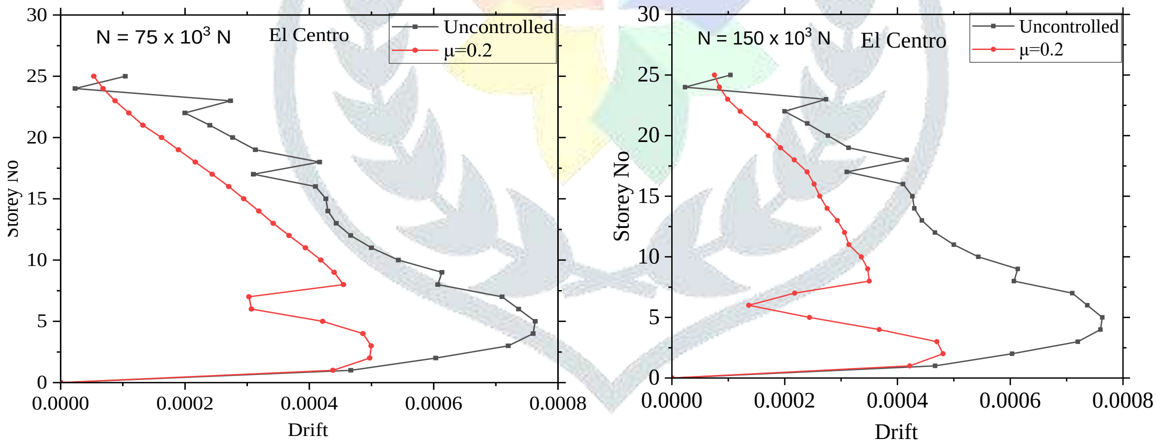

Fig.8. Inter-storey drift response with optimum normal force (N = 75 x 10^3 & 150 x 10^4 N) under El Centro (1940) earthquake

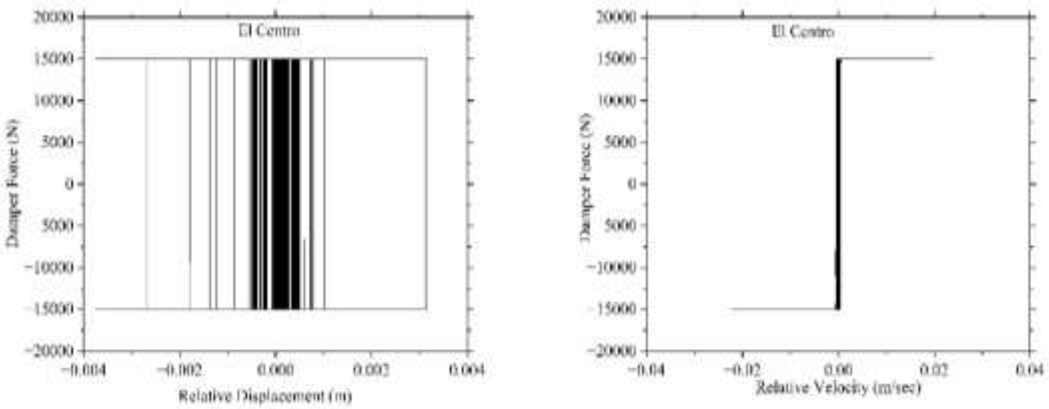

Fig.9. Hysteresis loop for optimum normal force (N = 75 x 10^3) under El Centro (1940) earthquake

Table 2, Fig. 9 indicate that considerable energy is dissipated when the value of normal force is higher at consider coefficient of friction. These trends validate that as frictional resistance is increased, either through higher clamping force or a rougher interface, the energy dissipation capability of the damper is enhanced. However, the choice of parameter values must consider the corresponding increase in force demands, which could impact the structural components connected to the damper. Further, the characteristics of earthquake influenced the peak damper force utilization: under the high-intensity or long duration events, like North Ridge and Bhuj earthquakes, the full damper capacity was more consistently shaking effectively activates the dampers to their maximum potential. As per Table 2, incorporation of friction damper resulted in a consistent increase in base shear across El Centro earthquake records, with values rising in proportional to the damper parameters. While this rise in base shear reflects the effective engagement of the dampers in energy dissipation, it also highlights a potential trade off; enhanced control over displacement and drifts comes at the cost of higher demand on the foundation and lateral load resisting system.

4. CONCLUSIONS

According to the results of the present study, the following conclusions can be drawn:

1. The seismic performance of tall building is significantly influenced by the combined variation of normal force (N) and coefficient of friction (μ) used in friction type dampers. Increasing either parameter enhances energy dissipation, but optimal performance is achieved through balance tuning.
2. Higher values of N combined with μ generally results in better control of displacement and drift, especially under moderate intensity or short duration El Centro earthquake.
3. Earthquake characteristics, particularly intensity, duration and frequency content greatly affect the friction damper effectiveness in tall building. Moderate earthquakes show effective control at lower value of N and μ=0.2.
4. The damper forces increase proportionally with N and μ, with maximum values observed during high demand earthquake motion for the considered tall building. This confirms that full damper engagement may occurs primarily under strong or prolonged ground motions.
5. Friction dampers can enhance the seismic performance of tall buildings by effectively reducing the lateral displacement and inter storey drift, particularly when the normal force (N) and coefficient of friction (μ) are properly optimized.

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