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Seismic Response of Open Ground Storey with Metallic Damper

Dipankar S. Kamble[1], Mahendra Umare[2]
[1, 2]Department of Civil Engineering, K.D.K. College of Engineering, Nagpur-440009, India

Abstract: In the past it was a common practice to ignore the masonry infill walls in the design of reinforced concrete frame buildings. Many buildings were constructed with open ground storey, resulting in a serious threat when struck by a lateral load like earthquake. Thus, the requirement of seismic strengthening of such buildings was felt all over the world. Various types of energy dissipating devices based on wide range of concepts were explored to seismically strengthen the structures. Metallic damper as an energy dissipating passive device can be very effectively used to address this problem. This paper presents the seismic evaluation of typical ductile designed 5–storey RC building with open ground storey by time history analysis using a computer package SAP2000. A strengthening scheme involving metallic damper is adopted to enhance the performance of the ductile prototype buildings considered in this study.
Keywords: Open ground storey, metallic damper, time history, SAP 2000, RC frame.

I. INTRODUCTION

Buildings resting on ground experience motion at base due to earthquake. According to Newton's law of inertia, even though the base of the building moves with the ground, the roof has a tendency to retain its original position. But the flexible columns will drag the roof along with them. Due to this flexibility of columns, the motion of roof is different from that of the ground. As the ground moves the building is thrown backwards and the roof experience inertia force. Internal forces are developed in the columns as they are forced to bend due to the relative movement between their ends as shown in Fig. 1.

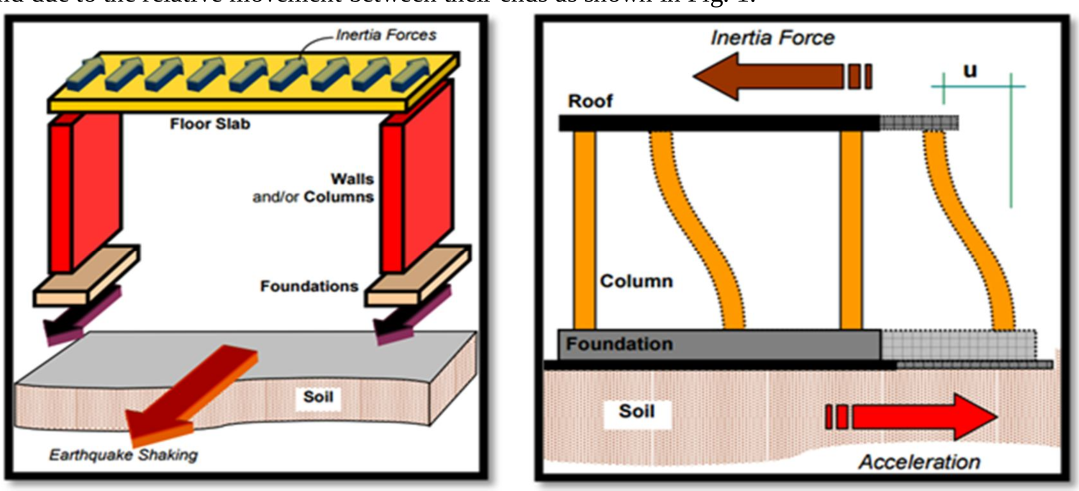

Fig. 1. Effect of Inertia in a building when shaken at its base. (google searched)

Earthquakes are thus a severe structural hazard for structures designed for gravity loads as they may not sustain the horizontal shaking. Structures like buildings, elevated surface reservoir, bridges, towers, etc. may experience extreme vibrations during earthquake.

Reinforced concrete (RC) is the most widely used construction material these days, primarily owning to its low cost, easy availability of materials, simpler execution without requirements of any special machineries or labor. Generally, the RC buildings are analyzed and designed such that, the moment resisting frame actions are developed in each member. The masonry infill wall are normally considered as nonstructural elements used to create partitions or to protect the inside of the building and thus are ignored while analysis and design. Such construction practices are followed in many countries including India. However, under the action of lateral forces like the once due to earthquake and wind, these infill wall panel's stiffness, strength and mass affect the behavior of RC frame building.

At times due to uneven distribution of mass, strength and stiffness in either plan or in elevation, irregularities are introduced in RC frame buildings. If the masonry walls are not symmetrically placed, then in that case, the eccentricity between centre of mass and centre of rigidity may induce torsional effects causing additional stresses. In recent times it has been a common practice to construct RC buildings with open ground storey i.e. the columns in the ground storey do not have any infill walls between them. This provision generally kept for the purpose of parking, garages, and various recreational purposes introduce a vertical irregularity in the structure.

An open ground storey building is one where columns in the ground storey and both partition walls and columns in the upper storey have two distinct characteristics, namely:

(a) It is relatively flexible in the ground storey, i.e., the relative horizontal displacement it undergoes in the ground storey is much larger than what each of the storey above it does.

(b) It is relatively weak in ground storey, i.e., the total horizontal earthquake force it can carry in the ground storey is significantly smaller than what each of the storey above it can carry.

Thus, there is a requirement of seismic strengthening of such open ground storey RC frame buildings. Various types of energy dissipating devices based on wide range of concepts have been explored in the recent past.

Recently, metallic plate dampers have received increasing attention from earthquake engineering community and their implementation in new building design and retrofitting of existing buildings were cited in several comprehensive review articles by many researchers. The idea of utilizing separate metallic dampers within a structure to absorb a large portion of seismic energy began with theoretical and experimental work of Kelly et al.[1972], and this work was extended by Skinner et al. [1995] and Tyler [1978]. During the ensuing years, considerable programs has been made in the development of metallic devices, most of which are made of mild steel and lead, metallic devices such as flexural plate systems, tensional bars dampers, yield ring dampers and extrusion devices Skinner et al. [1980]. Bergman and Goel [1987] and Whittaker et al. [1989] have studied metallic dampers with the help of experiments. Xia et al. [1992] studied the influence of metallic damper parameters on building seismic response as well as proposed design of supplemental steel damping devices, subsequently, employed in seismic retrofit projects discussed by Martinez-Romero [1993] and Perry et al. [1993]. Tena-Colunga [1997] mathematically modeled metallic dampers. Soong and Dargush [1997] was the first to publish a book on passive energy dissipation systems. Later, another book on seismic design with supplemental energy dissipation devices was again published by Hanson and Soong (2001). First study in India on passive energy dissipaters was done by Kumar et al. [2003]. Kokil and Shrikhande [2007] proposed an approach to find the optimal placement supplemental dampers in structure systems. Recently, Seyed et al. [2008], studied the behavior and performance of structures installed with metallic dampers Climent [2011] investigated the energy based method for seismic retrofit of existing frames using hysteretic dampers. Pujari and Bakre [2011] evaluated the seismic response of multistoried buildings by optimum placement of X-plate dampers.

A. Requirement of Retrofitting

As per IS 1893 (Part 1) : 2002, a soft storey is one in which the lateral stiffness of that storey is less than 70 percent of that in the storey above or less than 80 percent of the average lateral stiffness of the three stories above. Whereas, the weak storey is one in which the storey lateral strength is less than 80 percent of that in the storey above, The storey lateral strength is the total strength of all seismic force resisting elements sharing the storey shear in the considered direction. Thus an open-ground storey can behave like a soft storey as well as like a weak storey.

Seismic retrofitting is the modification of existing structures to make them more resistant to the seismic activity, ground motion, or soil failure due to earthquakes. According to IS 13935:2009, many existing buildings do not meet the seismic strength requirements of present earthquake codes due to original structural inadequacies and material degradation over time or alterations carried out during use over the years. Their earthquake resistance can be upgraded to the level of the present day codes by appropriate seismic retrofitting techniques.

Following are the Performance Objectives of Retrofit:

1) Safety of its occupants: - The goal is to protect human life, ensuring that the structure will not collapse upon its occupants or passersby, and that the occupants can safely exit.
2) Primary utility of structures: - A high level of retrofitting should ensure that, he lifeline structures like bridges, hospitals, elevated service reservoirs, etc., are not damaged beyond a limit to be utilized for their primary application just after the earthquake.
3) Historic Significance: - This level of retrofit is preferred for historic structures of high cultural significance.

II. MECHANISM OF XPD IN STRUCTURE

X-plate dampers consist of one or multiple X-shaped steel plates, each plate having a double curvature and arranged in parallel; this number of plate depends upon required amount of energy wants to be dissipates in the given system. Material used for manufacturing of X-plate may possibly be any metal which allow large deformation such as mild steel, although sometimes lead or more exotic metal alloy are employed. In order to reduce the response of structure by dissipating the input seismic energy such damper can be used with an appropriate supporting system, essentially in building structure combination of bracing and XPDs can be used and such an assembly known as device-brace assembly. When such system experiences the lateral forces like earthquake, high winds, etc., then input seismic energy dissipates through their flexural yielding deformation of material. They can sustain many cycles of stable yielding deformation, resulting in high level of energy dissipation or damping. The aim behind the use of X-shape of damper is it will have a constant strain variationover its height, thus ensuring that yielding occur simultaneously and uniformly over the full height of the damper. XPDs allow it to behave nonlinearly but restrict behavior of the structure up to the linear elastic range.A series of experimental tests were conducted at Bhabha Atomic Research Center (BARC) and IIT Bombay to study the behavior of these XPDs by Parulekar et al. (2003) and Bakre et al. (2006) also studied the behavior of XPDs and observed the subsequent results (i) it exhibits smoothly nonlinear hysteretic loops under plastic deformation; (ii) it can sustain a large number of yielding reversals; (iii) there is no significant stiffness or strength degradation and (iv) it can accurately modeled by Wen‘s hysteretic model or as a bilinear elasto-plastic material. A typical XPD with holding device used in the present work as shown in Fig. 2.

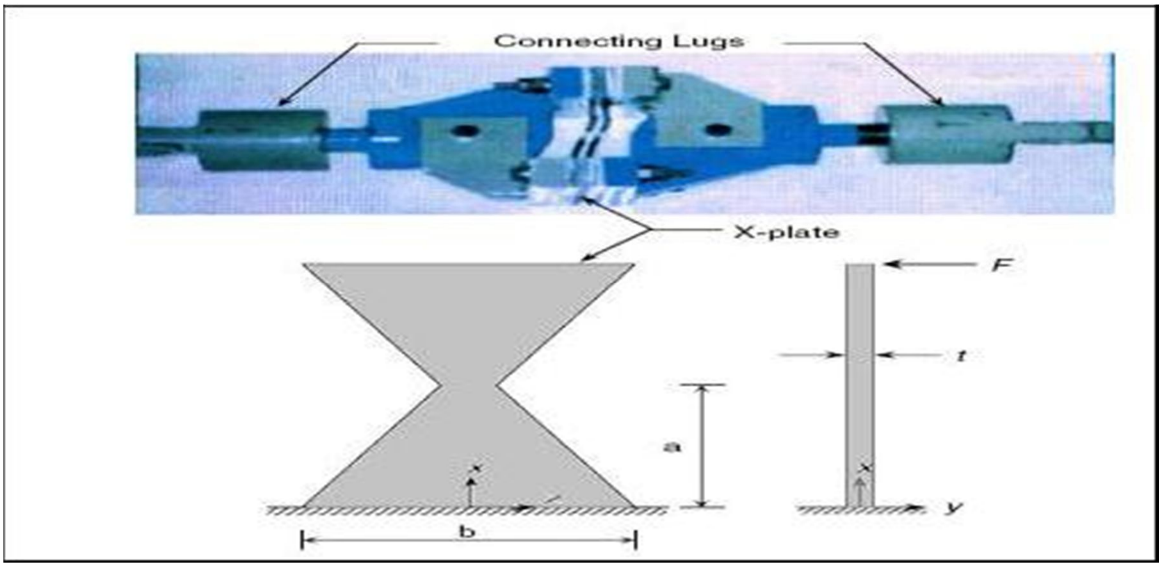

Fig. 2. Typical XPD with holding devices (Bakre et. al., 2006)

Using beam theory the properties of XPD are evaluated using the following equations:

$$F_y = \frac{\sigma_y bt^2}{6a} n \quad (2.1)$$

$$q = \frac{2\sigma_y a^2}{Et} \quad (2.2)$$

$$K_d = \frac{F_y}{q} \quad (2.3) \quad K_d = \frac{Ebt^3}{12a^3} n$$

In the above equations, K_d is the initial stiffness, F_y is the yield load and q is the yield displacement of the XPD. E and σ_y are elastic modulus and yield stress of the damper material, respectively; a, b and t are height, width and thickness of the XPD. The generalized equation of motion for an N-degree of freedom lumped mass system equipped with hysteretic metallic damper subjected to base motion is given by

$$M\ddot{u}(t) + C\dot{u}(t) + ku(t) + F(t) = Mr\ddot{u}_g(t) \quad (2.4)$$

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where M, C and K are the mass matrix, damping matrix and stiffness matrix of the system, of size N x N respectively and F (t) is the restoring force vector for the metallic damper as per **Wen [27]**; u (t) is the column vector of the story displacements relative to the ground, r is a column vector of ones and üg (t) is the ground acceleration.

According to Bouc-Wen's model the restoring force is expressed as:

$$F(t) = \alpha \frac{F_y}{U_y} u(t) + (1-\alpha) F_y z(t) \quad (2.5)$$

$$F(t) = F_e(t) + F_h(t) \quad (2.6)$$

Where,

$$F_e(t) = \alpha \frac{F_y}{U_y} u(t) \quad (2.7)$$

$$F_h(t) = (1-\alpha) F_y z(t) \quad (2.8)$$

$$K_e = \frac{F_y}{U_y} \quad (2.9)$$

$$\alpha = \frac{K_p}{K_e} \quad (2.10)$$

Ke and Kp is initial and post-yielding stiffness of system, Fy and Uy is the yield force and yield displacement of the system and over dots denotes the derivative with respect to time. For small values of 'n' the transition from elastic to the post-elastic branch is smooth, while for large values that transition is abrupt.

Z (t) a non-observable hysteretic parameter (usually called the hysteretic displacement) that obeys following nonlinear differential equation with zero initial condition z (0) = 0.

$$\dot{z}(t) = A\dot{u}(t) - \beta |\dot{u}(t)| |z(t)|^{(n-1)} z(t) - \gamma \dot{u}(t) |z(t)|^{n} \quad (2.11)$$

In the above equation, *A*, □□, □□and *n* are dimensionless quantities controlling the behaviour of model, again □□and □□controls the shape and size of hysteretic loop.

III. DESCRIPTION OF PROTOTYPE BUILDING

Typical five-bay five-storey RC building with open-ground-storey as shown in Fig. 3 and Fig. 4 are considered as the prototype structures in this study. Overall size of the building in plan is 30.0 m x24.0 m with bay width of 6.0 m in each orthogonal direction.

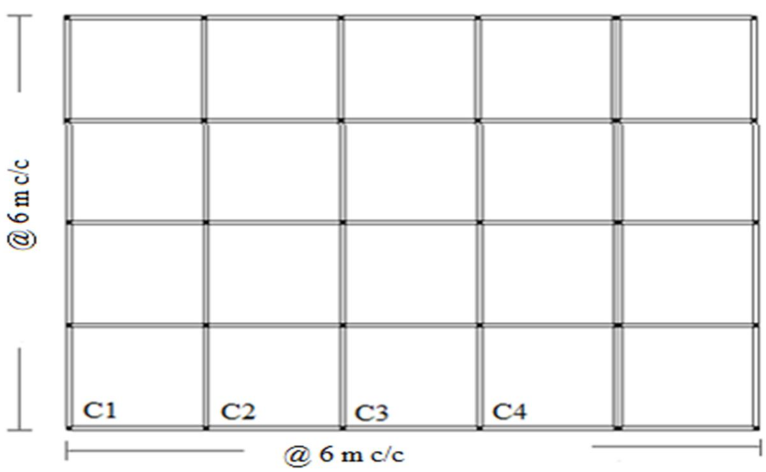

Fig. 3 Plan of the prototype building.

The height of ground storey is considered as 3.6 m, whereas the storey height of upper storey is assumed as 3.0 m. The upper storey of building are fully in filled with unreinforced brick masonry of 250 mm thickness. The thickness of roof and floor slab is taken as 180 mm. The building is founded on a rock site in seismic zone-V, the region of highest seismicity as per IS: 1893 Part 1 [BIS, 2002]. Since the buildings are symmetric in both orthogonal directions in plan, torsional response under pure lateral forces is avoided, and hence, the present study is focused only on the weak and soft storey problem due to open-ground-storey. Unit weights of concrete and masonry infill are considered as 25 kN/m^3 and 20 kN/m^3, respectively. Dead load on the beams consisted of self-weight of beam, slab and masonry infill including floor finish of 1.0 kPa. Live loads on the floors and roof are assumed as 3.0 kN/m^2 and 1.5 kN/m^2, respectively.

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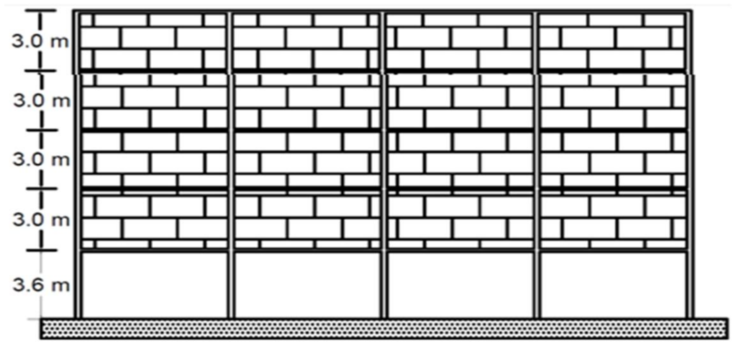
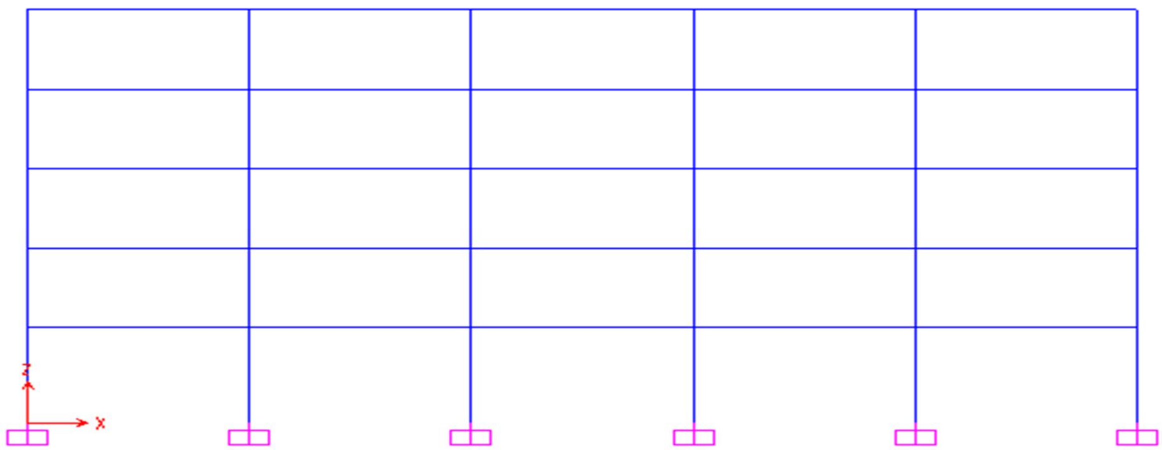
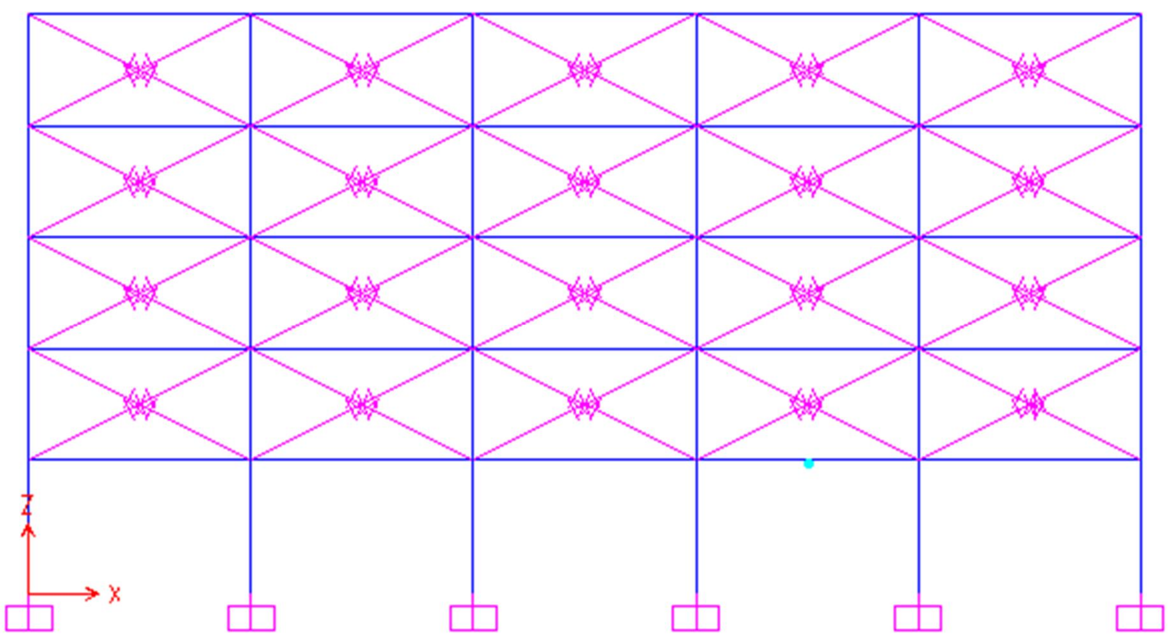


Fig. 4 Elevation of the prototypeofG+4 storey building

Seismic performance of the building was evaluated by linear modal analysis and nonlinear time-history analysis using SAP2000. The properties of frame members, infill masonry, and metallic dampers were used as discussed earlier. Fig. 5 shows the elevation of G + 4 open ground storey RC frame building with different types of metallic dampers modelled in SAP2000 and installed in the selected bays of ground storey.



(a) Bare Frame



(b) Open Ground Storey with infill masonry

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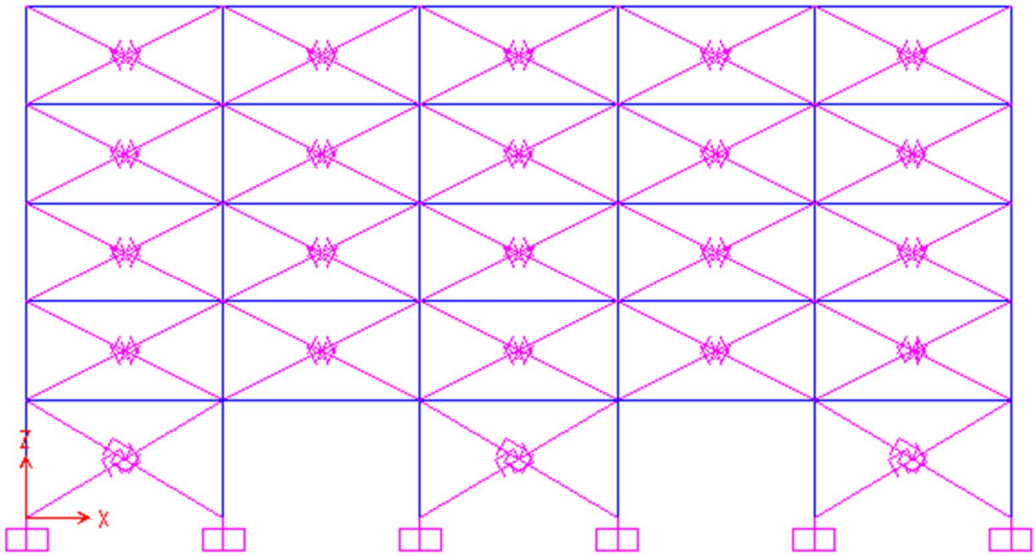
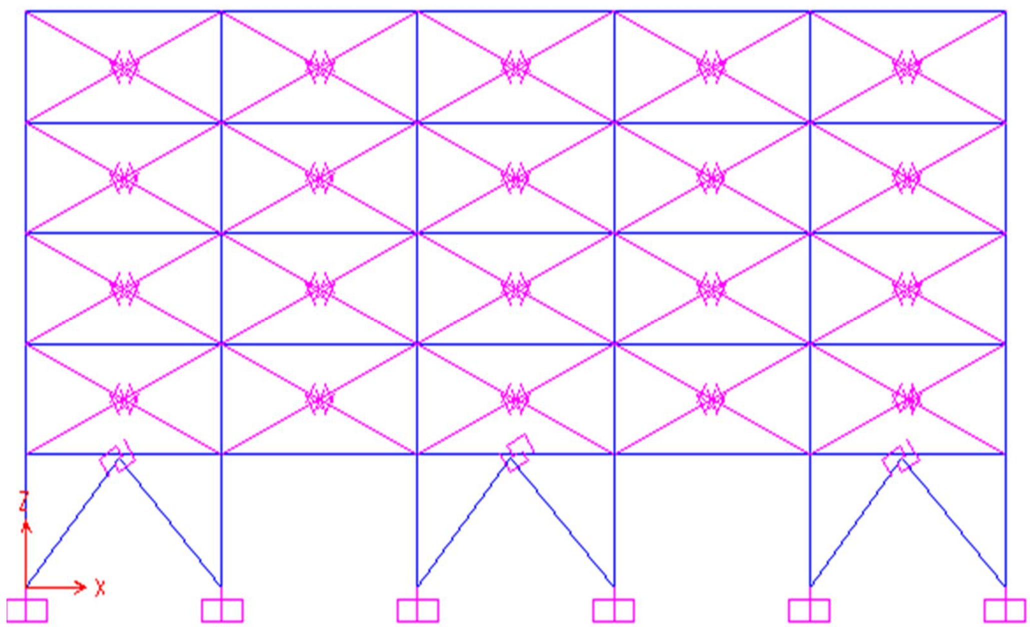


(c) Diagonal Braced Metallic Damper



(d) Inverted V- shaped Metallic Damper

Fig. 5 Elevation of G + 4 open ground storey buildings strengthened with different types of metallic dampers as modeled in SAP2000.

IV. RESULTS AND DISCUSSION

The performance of all strengthened frames under dynamic loading was evaluated by non-linear direct-integration time-history analysis for a set of four recorded ground motions as described earlier. Various parameters of direct integration time history analysis were kept same as in the case of analysis of the RC frame. The frame responses are obtained for different earthquake excitations using non-linear time history analysis. The maximum roof displacement, storey displacement, storey shear force and storey bending moment have been investigated for the considered ground motions as shown in Fig. 6, 7, 8 and 9 respectively. These responses have also been compared with the responses obtained for different cases of installed metallic dampers. It is observed that installation of metallic dampers improves the performance of buildings plagued with open ground storey.

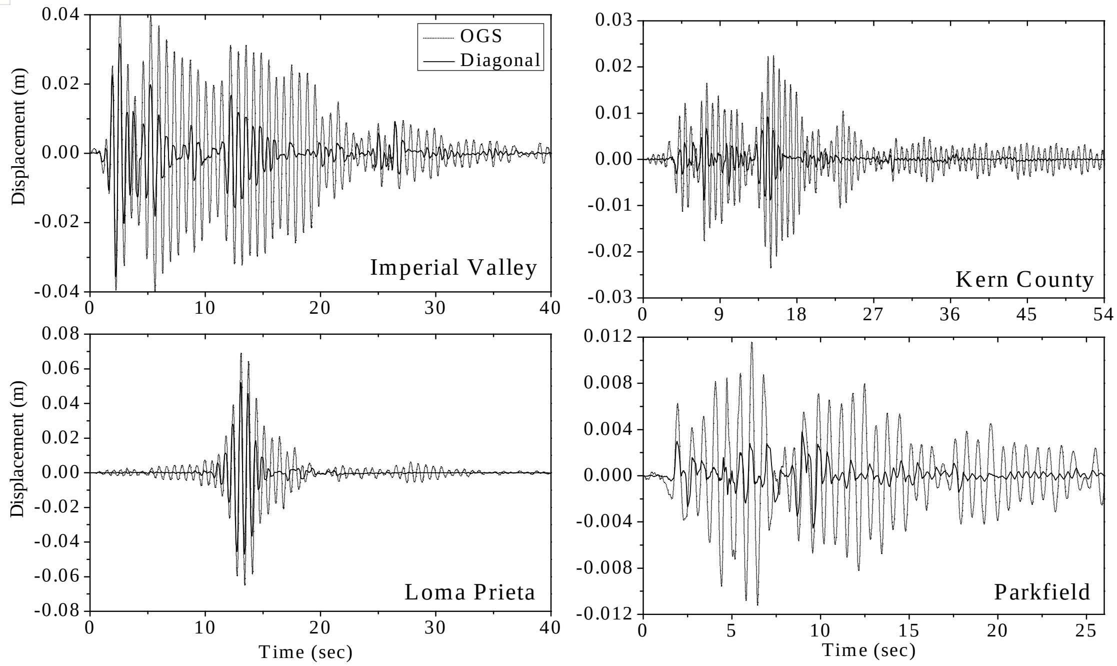


Fig. 6 Time variation response of top storey displacement under selected earthquake ground excitations compared with diagonal braced metallic damper for G+4 building.

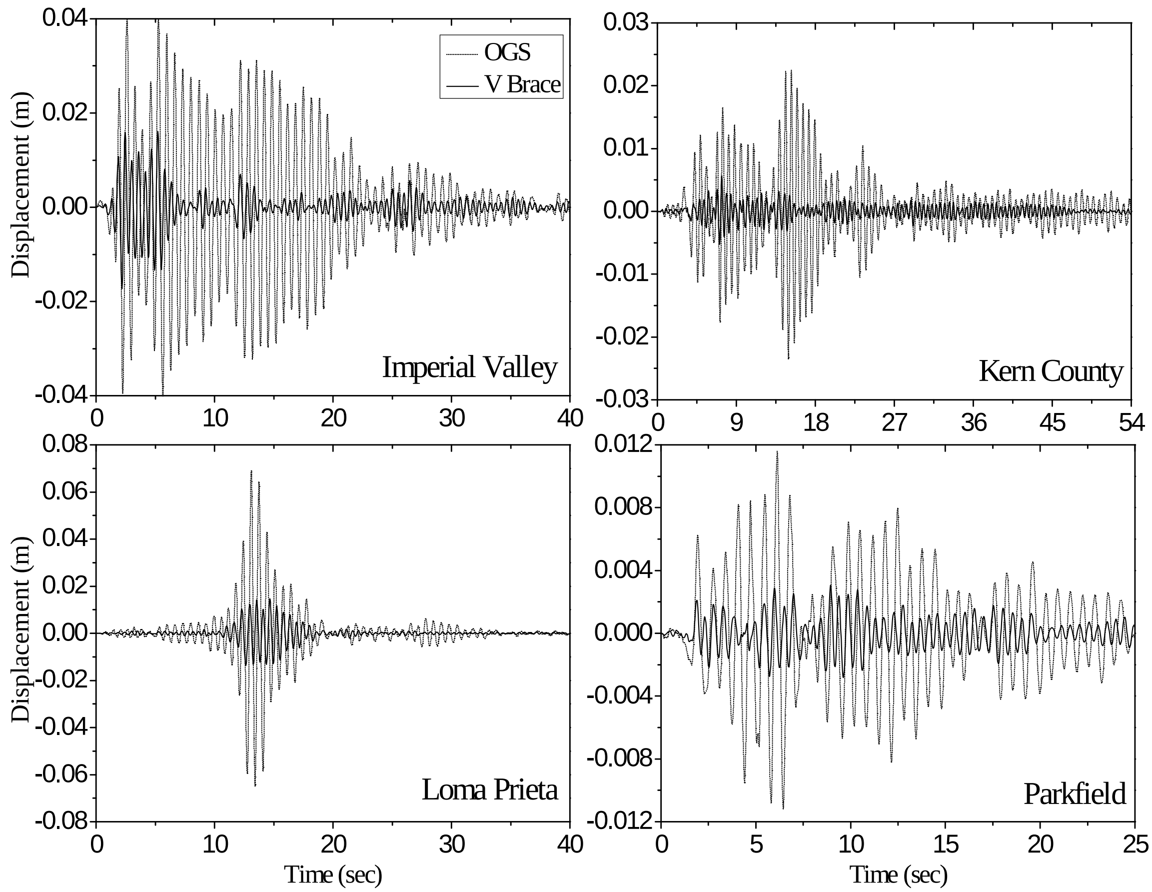


Fig. 7 Time variation response of top storey displacement under selected earthquake ground excitations compared with inverted V-shaped metallic damper for G+4 building.

It is observed from Fig. 6 and 7 that the top storey responses are reduced by installation of two different types of dampers i.e. diagonal braced metallic damper and inverted V-shaped metallic damper under the selected earthquake motions such as Imperial Valley, Kern County, Loma Prieta and Parkfield. The study also compares the performance of the selected dampers with the open ground storey and bare frame case in reducing the storey level displacements under selected earthquake excitations. It is observed from Fig. 8 and Fig 9 that the diagonal and V- shaped dampers are very effective in improving the structural performance of the five storey building when subjected to seismic excitations. Thus the installation of metallic dampers in the selected bays of the buildings is an effective technique to improve the structural performance of the G+4 building. The study also evaluates the forces such as shear force and bending moment incurred on the buildings under seismic ground motions and compares the performance due to installation of metallic dampers. Fig. 10, 11, 12 and 13 shows that the shear force and bending moment at each floor level of G+4 building. The forces are evaluated at the corner column of the building as shown in Fig 5.

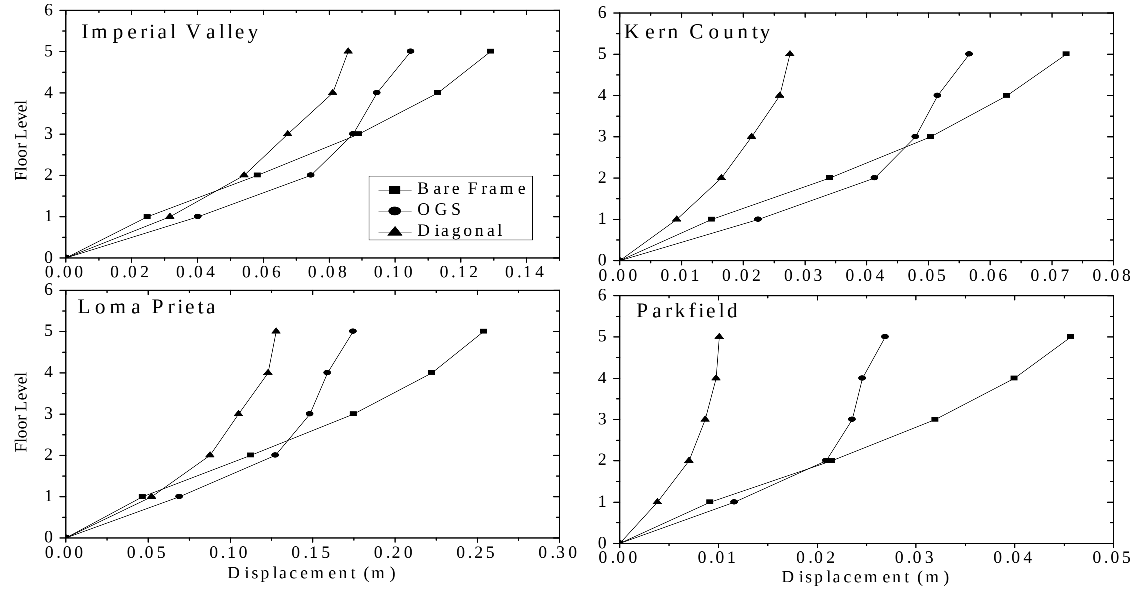


Fig. 8 Floor wise Storey displacement responses compared with diagonal braced damper under selected ground histories (G+4 building).

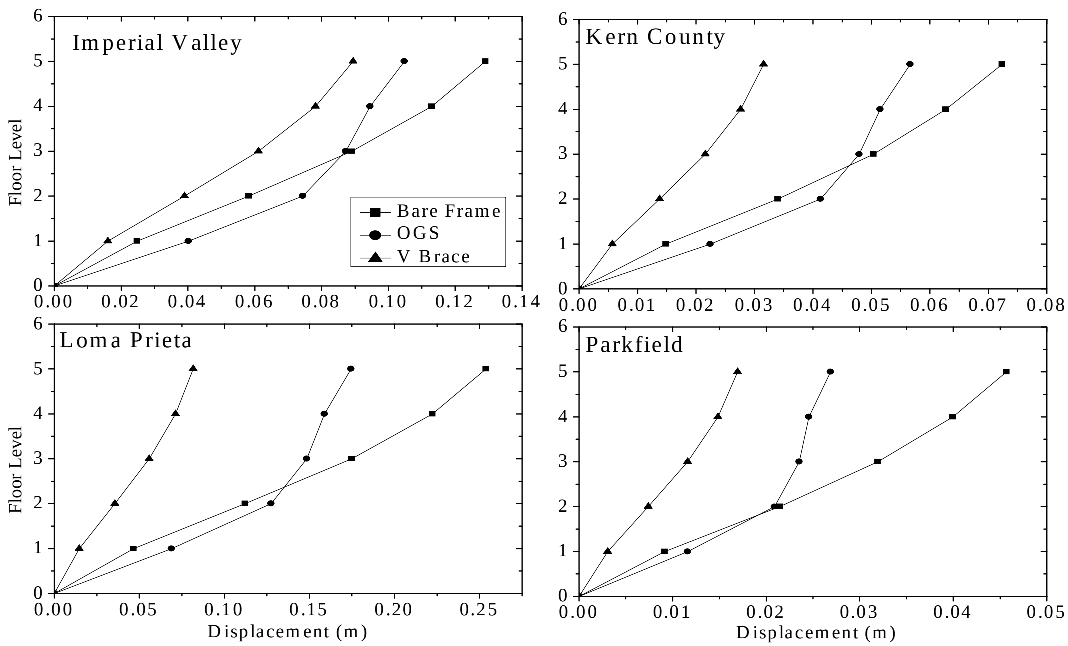


Fig. 9 Floor wise Storey displacement responses compared with inverted V-shaped damper under selected ground histories (G+4 building).

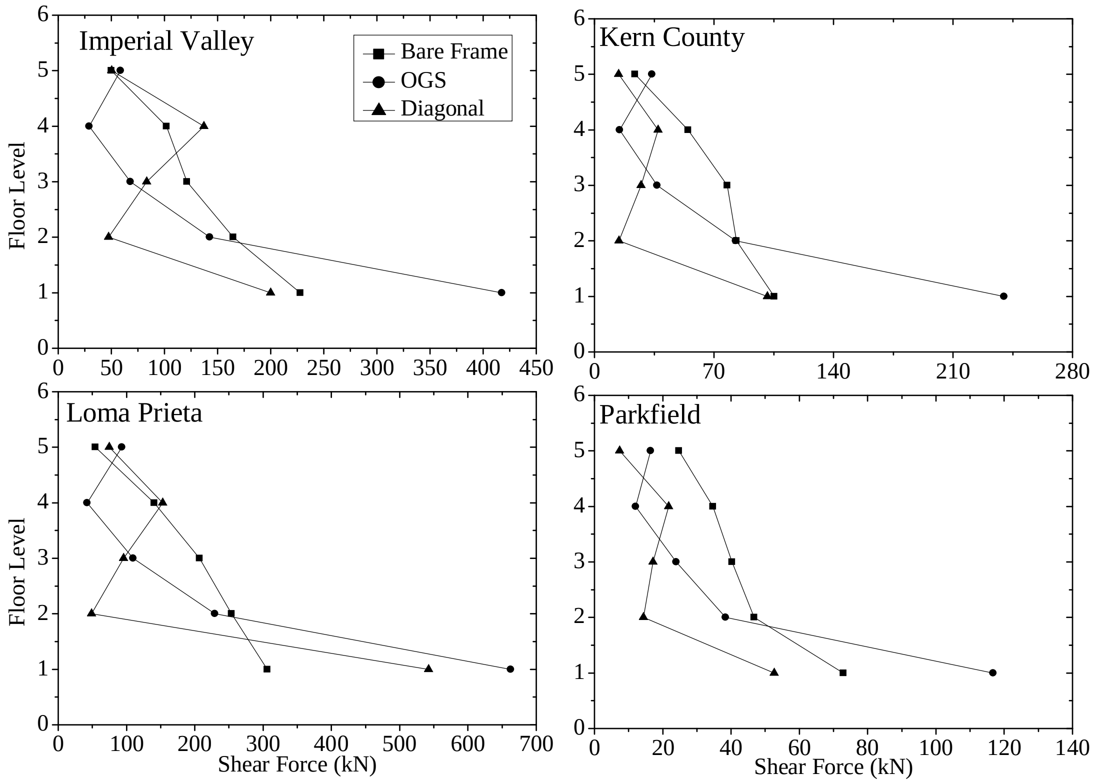


Fig. 10 Floor wise Shear Force responses compared with diagonal braced metallic damper under selected ground histories (G+4 building).

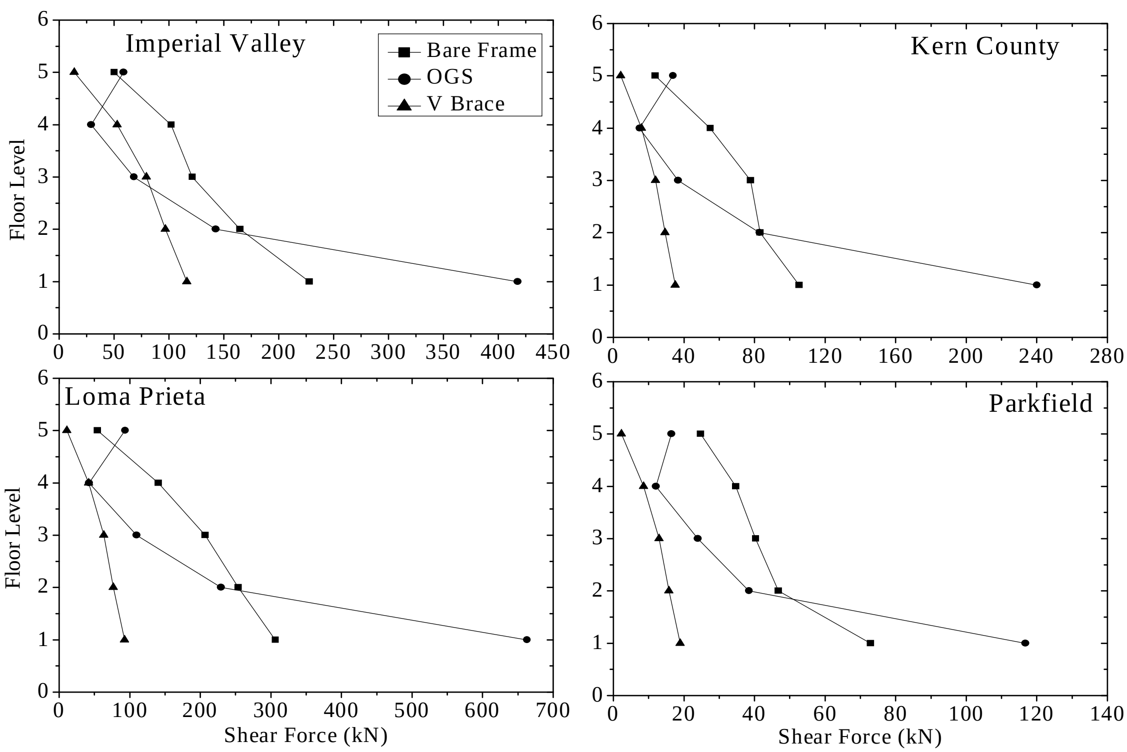


Fig. 11 Floor wise Shear Force responses compared with inverted V-shaped metallic damper under selected ground histories (G+4 building).

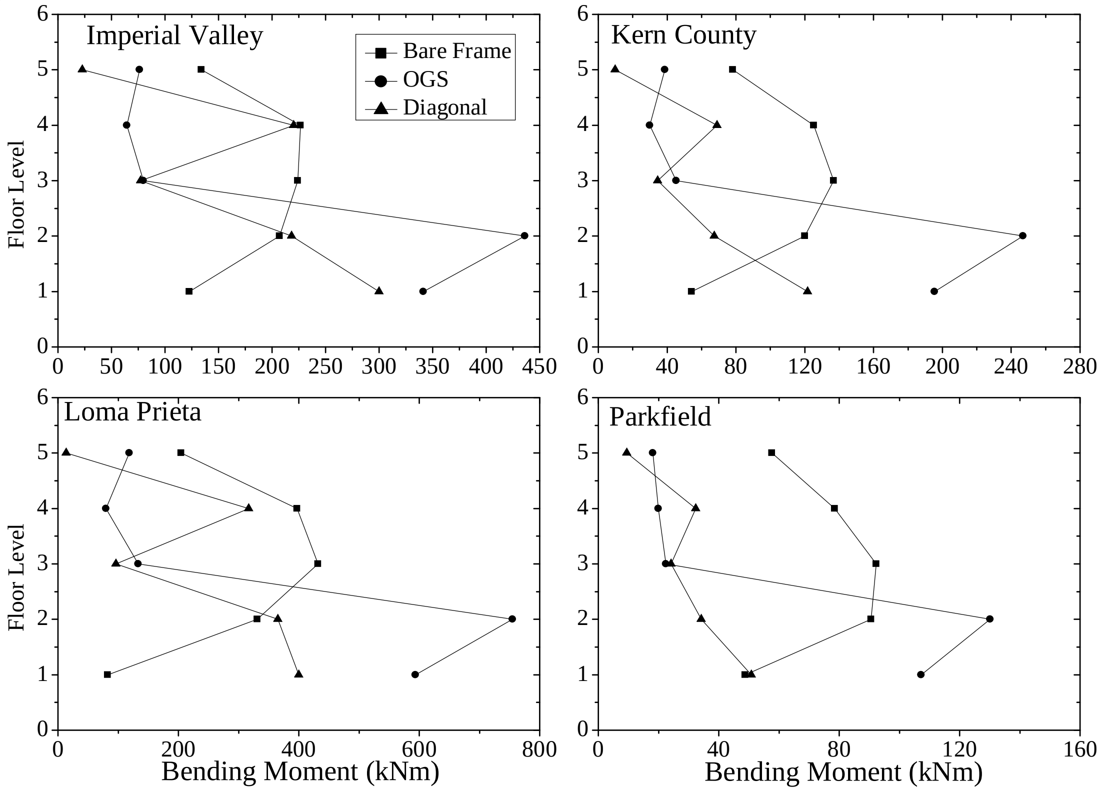


Fig. 12 Floor wise Bending Moment responses compared with diagonal braced metallic damper under selected ground histories (G+4 building).

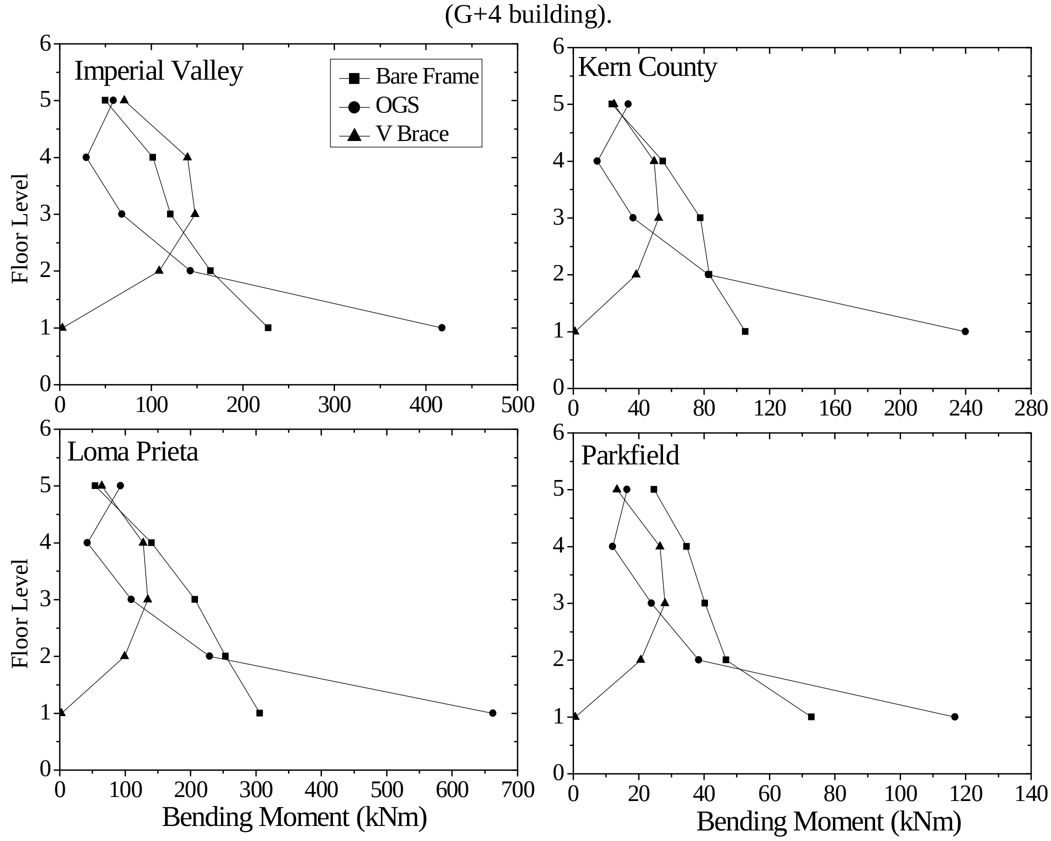


Fig. 13 Floor wise Bending Moment responses compared with inverted V-shaped metallic damper under selected ground histories (G+4 building).

A. Hysteretic Loop

The hysteretic loops for the selected types of metallic dampers installed between column C1 and C2 and between column C3 and C4 (as in Fig. 5) are as obtained below in Fig. 14 and 15 respectively for the considered ground motions.

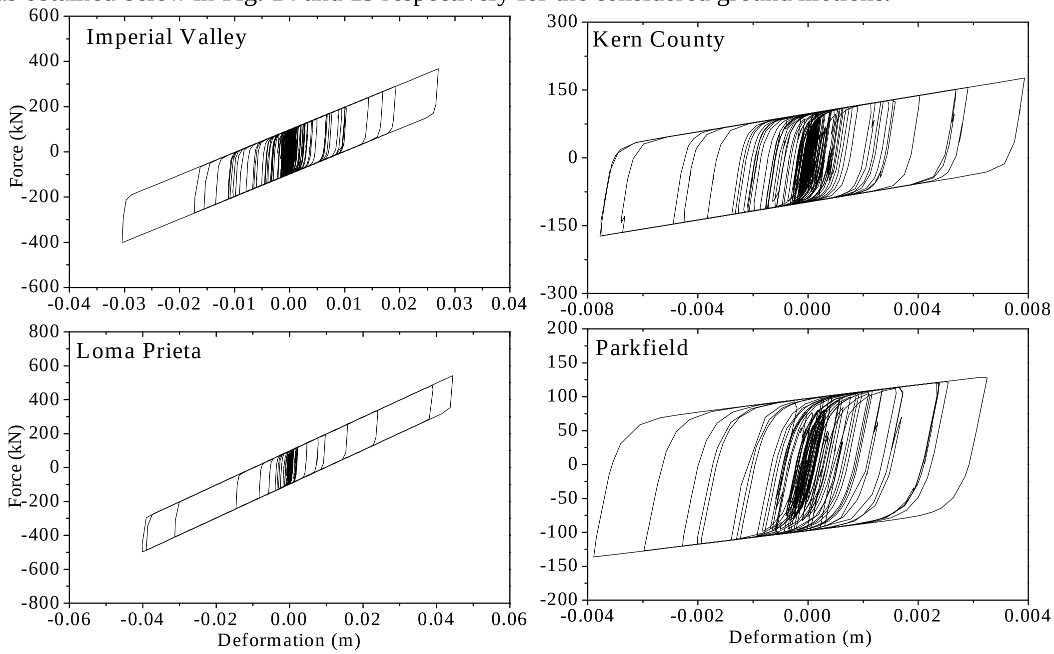


Fig. 14 Time variation response of top storey displacement under selected earthquake ground excitations.

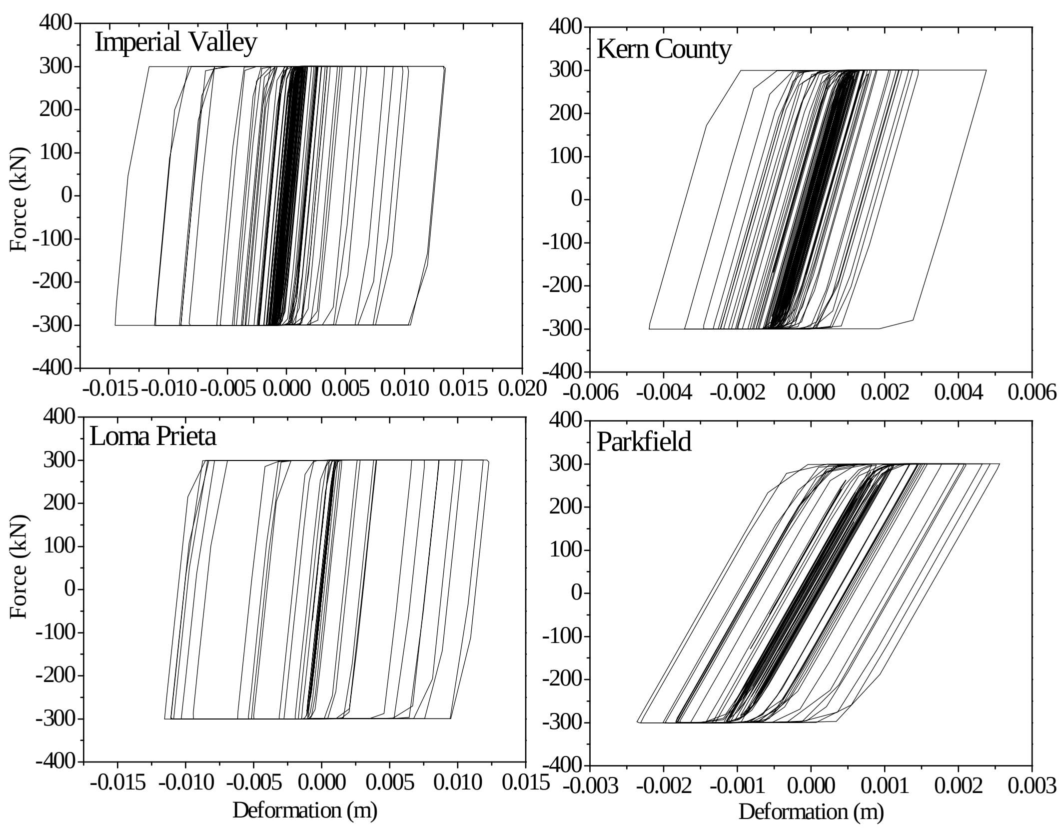


Fig. 15 Plots of axial force in damper – relative displacements between the damper plates for different types of metallic dampers subjected to different types of earthquake

The hysteretic loops obtained are fully stable and perfectly rectangular in shape, thus clearly defining a constant increase in the relative displacement between the plates post yielding i.e. on attainment of slip load. The area under these loops gives the amount of energy dissipated by the damper. Thus, a significant reduction in the lateral load demand on primary members of the ductile open-ground storey RC frame is ensured with the installation of metallic dampers.

V. CONCLUSIONS

The results obtained from the on analytical study using software SAP2000 are observed in this work. The various observations incorporated from the above results are described in this paper. With the installation of metallic dampers considerable reductions was observed in the displacement of ground storey and inter storey drift of the building. With the installation of dampers the lateral-load transfer mechanism of the structure changes from predominant frame action to predominant truss action. The shear force and bending moment in the columns is also found to reduce with the installation of metallic dampers.

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