ISET Journal of Earthquake Technology, Paper No. 538, Vol. 55, No. 1-4, March-Dec. 2018, pp. 1-20

SEISMIC PERFORMANCE OF OPEN GROUND STOREY REINFORCED CONCRETE BUILDING WITH CHEVRON STEEL BRACING INCORPORATING X-PLATE DAMPER

C.K. Madheswaran**, N. Gopalakrishnan****, J. Prakashvel* and K. Sathishkumar***

*Senior Technical Officer, CSIR-Structural Engineering Research Centre, Chennai, India
**Senior Principal Scientist, CSIR-Structural Engineering Research Centre, Chennai, India
Corresponding author, E-mail: ckm@serc.res.in
***Senior Principal Scientist, CSIR-Structural Engineering Research Centre, Chennai, India
E-mail: ksksercm@gmail.com
****Chief Scientist, CSIR-Structural Engineering Research Centre, Chennai, India

ABSTRACT

A three-storey half scale Reinforced Concrete (RC) open ground storey building is fixed with yielding type X-shaped metallic (elasto-plastic) damper at the ground storey level, to study the seismic response characteristics. Experimental studies are carried out using the 4m x 4m triaxial shake table facility to evaluate the seismic performance. Initially the reinforced concrete building is tested for different earthquake inputs in the shake table. During the test, the cracks and hinges are formed in various locations of beams, columns, beam-column joints and infill walls. During the seismic testing, the plastic failure cracks (plastic hinges) are formed in the columns and beam-column joints of the ground storey. The seismically damaged RC building is retrofitted. Two types of retrofitting techniques have been developed. Type 1 is the local retrofitting of columns and beam-column joints in the ground storey using Geopolymer concretes. Type 2 is the global retrofitting of RC building with Chevron type steel bracing incorporating X-plate damper in the ground storey. The dual functioning of X-plate damper is to improve the global stiffness of building thereby protecting the building during earthquake. In general, earthquake loading induces large displacements in an Open Ground Storey (OGS) structure. During such large displacements, a yielding type elasto-plastic device made of X-shaped metallic dampers performs better. The supporting steel frame of Added Damping and Added Stiffness (ADAS) is of chevron type, serially contributing stiffness to the system. Free vibration tests on OGS RC building with and without yielding type X-shaped metallic damper is carried out. The natural frequencies and mode shapes of the model with and without yielding type X-shaped metallic damper are evaluated.

KEYWORDS: Earthquake Response, Dynamic Characteristics, RC Building, Yielding Type X Shaped Metallic Damper, Natural Frequencies and Mode Shapes

INTRODUCTION

Reinforced concrete frame buildings are built in India which has open ground storey. Owing to the high cost of land and small sizes of plots, parking is often accommodated in the ground floor area of the building. Open ground storey buildings have consistently shown poor performance during past earthquakes across the world. For example during 1999 Turkey, and 2003 Algeria earthquakes, a significant number of them have collapsed. In India, during Gujarat earthquake (2001) many buildings have been damaged that are seismically deficient. It is found from that the Reconnaissance Report of January 26, (2001) Bhuj India Earthquake that large number of open ground storey buildings in Ahmedabad, Bhuj, and other towns in Gujarat suffered severe damage or dramatic collapse. Out of the 130 buildings that collapsed in Ahmedabad, most were of open ground storey configuration. Among those that did not collapse, the damage was confined mostly to the open ground storey columns. The entire lateral deformation is concentrated in the ground storey columns, and the upper stories moved laterally as a rigid block. The reinforced concrete columns at the bottom storey have suffered the maximum damage and the brick in-fill at the top stories has developed sliding cum separation failure. These buildings are normally not designed as per the earthquake resistant design proposed in the Bureau of Indian Standard codes IS:1893 (Part I)-2002. The open ground storey RC building are tested to failure and damaged soft-storey frame is retrofitted with Geopolymer concrete and chevron steel bracing incorporating X-plate damper and subjected to earthquake motions. The RC building is excited with an intensity of earthquake motions as specified in Indian seismic code IS1893:2002. The seismic responses of the soft storey frame such as fundamental frequency, mode shape, base shear, and stiffness are evaluated in this study. The Indian seismic code IS:1893 (Part I)-2002. Criteria for Earthquake resistant design of structures, Part-I-General provisions and buildings, BIS, gives the following technical definition for soft open storey buildings in Table-5-Definition of irregular buildings-Vertical irregularities (Clause 7.1), (a) Stiffness Irregularity (Soft storey); A soft storey is one in which the lateral stiffness is less than 70 percent of that storey above or less than 80 percent of the average lateral stiffness of the three storey above. (b) Stiffness Irregularity (Extreme soft storey). A extreme soft storey is one in which the lateral stiffness is less than 60 percent of the storey above or less than 70 percent of the average stiffness of the three storey above. As per commentary by National Information Centre for Earthquake Engineering at Indian Institute of Technology Kanpur , soft storey is one which the lateral is less than 60 percent of that in the storey above or less than 70% of the average lateral stiffness of the three storeys above. The storey lateral strength is the total strength of all seismic force resisting elements sharing the storey shear in the considered direction.

REVIEW OF LITERATURE ON OPEN GROUND STOREY REINFORCED CONCRETE BUILDING

Arslan and Korkmaz (2001) investigated the failure modes during the earthquake at Turkey. In Turkey, generally, building stock is formed from reinforced concrete structures and during last earthquakes, a large number of these buildings in the epicenter regions, were collapsed leading to widespread destruction and loss of life. The performance of reinforced concrete buildings during recent earthquakes in Turkey is discussed. The failure modes consists of foundation failures, soft stories, strong beams and weak columns, lack of column confinement, poor detailing practice and non-structural damages. Observations from the earthquake damages are discussed. Murthy (2006) reviewed major issues associated with open ground storey building. These open ground storey buildings are highly vulnerable in shear generated during strong earthquakes. It is relatively flexible in the ground storey. The total horizontal displacement of the open ground storey is much larger than the storeys above. Also open ground storey is relatively weak. The total horizontal earthquake force that can be carried by the open ground storey is significantly less than that can be carried by the storeys above. Deshpande and Bhalchandra (2010) investigated the seismic analysis of RC building with soft first storey. The structural action of masonry infills panels of upper stories has been taken into account by modelling them as equivalent diagonals struts. The parameters discussed include fundamental natural periods, stiffness of open first storey in relation to the upper storey, lateral displacements, inter-storey drifts by linear elastic analysis using ETABS analysis package. It is noticed that significant change in stiffness between the soft storey and upper storey is responsible for increasing the strength demand on first storey columns. Arlekar et al., (1997) investigated the importance of recognizing the presence of the open first storey in the analysis of the building. They suggested some measures such as increasing the size of column in the open first storey and introduction of concrete core, to reduce the stiffness irregularity and to provide adequate lateral strength. FEMA 356 (2000) stated as the elastic in-plane stiffness of a solid unreinforced masonry infill panel prior to cracking shall be represented with an equivalent diagonal compression strut of width, Weff. The equivalent strut shall have the same thickness and modulus of elasticity as the infill panel it represents. Kaushik et al., (2009) carried out the studies on effectiveness of some strengthening options for masonry–infilled RC frames with open first storey. The frames with extra columns in the open first storey failed due to flexural failure of the extra columns in the first storey. In addition, plastic hinges were found to develop in several upper storey members of the frames. In the case of the frame strengthened using diagonal bracing and lateral buttresses in the open first storey, flexural failure of the first-storey beams and second storey columns, and compression failure of masonry infills in the second storey are observed to be the cause of failure. Columns, bracings, and lateral buttresses in the first storey did not fail. Performance of all frames strengthened using additional elements in the open first storey is found to be significantly better than that exhibited by the methods in which open first storey members were designed for higher forces. Lateral load performance of the open first storey RC frames cannot be improved by using code – specified strengthening schemes that is by designing the first – storey members for higher forces. Sahoo and Rai (2013) studied the seismic strengthening techniques for reinforced concrete frames with soft ground storey. The first technique, termed as column retrofit (CR), uses only partial steel jacking (or caging) to enhance the lateral strength and plastic rotational capacities of the deficient columns at the ground storey level. The later technique, termed as full retrofit (FR), considers the aluminum shear links as supplemental energy dissipation devices in addition to strengthened ground storey columns. Steel collector beam and chevron braces are used to transfer the lateral load from the RC frame to these dissipating devices. The FR frame effectively controlled the drift response by avoiding the soft storey collapse because of the significant energy dissipation in the shear links. Moreover, the FR frame achieved the desired yield mechanism without exceeding the design target drift level. The main advantage of this technique is that it does not require any modification in the existing RC beams for the installation of shear links, which may otherwise reduce their load carrying capacity. Kelly et al., (1972), were the first to propose the use of XPDs for seismic energy dissipation in structures and this work was extended by Skinner et al., (1975) and Tytler (1978). A sequential procedure was developed by Zhang and Soong (1992) for placing Visco-Elastic damper (VE) to structure, based on the concept of degree of controllability. The optimal placement procedure is experimentally verified using a five-storey steel model structure. Soong and Dargush (1997) studied the Passive devices, such as visco-elastic damper, viscous fluid damper, friction damper, metallic damper, tuned mass damper and tuned liquid damper which can partially absorb structural vibration energy and reduce the seismic response of structures. These passive devices are relatively simple and easy to be used as complementary structural appendages. Symans et al., (2001) and Whittaker et al., (1991) have worked on different types of semi-active devices which are developed to equip passive control devices with actively controlled parameters forming a semi-active yet stable and low-power required damping system. Symans and Constantinou (1997) conducted a series of shaking table experiments on a 3 storey moment resistant frame subjected to seismic excitation and controlled by a semi-active fluid damper control system in the lateral bracing of the structure and the mechanical properties of the dampers are modified according to control algorithms which utilized the measured response of the structure. The response of the structure without dampers was improved with the inclusion of the semi-active damper control system. The response reductions achieved with the semi-active control system were comparable to those obtained with a high damping passive control system (as measured by peak response quantities). Constantinou et al., (2001) conducted experimental and analytical studies on a single storey steel building frame model with three types of bracing configuration such as chevron, diagonal and toggle brace. They have presented three new configurations that utilize toggle-brace mechanisms to substantially magnify the effect of damping devices. Shake table testing of a large scale steel model structure and analysis are performed to demonstrate the utility of these configurations. The experimental results show substantial increase in the damping ratio with small size damping devices, and, hence significant reduction of the seismic response of the tested stiff structure is observed. Sathishkumar et al., (2000) and (2002) carried out studies on seismic response reduction of structures using elasto-plastic passive energy dissipation devices. Design of supporting systems for pipelines carrying highly toxic or radioactive liquids is an important issue in the safety aspect for nuclear power plant installation. It is possible to design a flexible pipeline system and to decrease the seismic response by increasing the damping with passive energy absorbing elements, which dissipate seismic energy. Experimental and analytical studies have been carried out on yielding type elasto-plastic passive energy-absorbing (PEA) device to be used as supporting device for pipeline subjected to large seismic deformations. Hence, such a device is chosen in the present study for retrofitting of model damaged reinforced concrete framed building. The mechanism of dissipating the seismic energy by X-plate damper is more effective during the earthquake by absorbing input energy of the structure. Oinam and Sahoo (2019) have used metallic dampers to improve seismic performance of the soft-story RC frames. The Reinforced concrete building with masonry-infilled walls at all stories except first (ground) storey is called open ground storey (or) soft-storey building. The functional requirement is parking vehicles. This study presents the strengthening techniques for the RC frame with a soft story using metallic dampers. Passive energy dissipation devices are used in a global strengthening strategy to improve the seismic performance of building. Metallic devices posses excellent lateral strength, displacements, and energy dissipation potential under earthquake loading. The effectiveness of metallic dampers based on flexural yielding, and combined yielding (Oinam and Sahoo 2017) of steel and aluminium plates have been investigated in improving the seismic performance of the damaged RC buildings. Metallic devices possess excellent lateral strength, and energy dissipation potential under cyclic loading (Li and Li 2013). Conventional steel braces and buckling restrained braces (BRBs) based on the principle of axial yielding/buckling of metallic plates have been adopted to improve the seismic performance of damaged RC frames (Varum et al., 2013), (Khampanit et al., 2014). Oinam and Sahoo, (2017) et al., Oinam (2017) and Oinam and Sahoo (2015) have conducted Pseudo dynamic, Quasi static cyclic experiments on strengthening technique for the RC frame with a soft story using combined metallic yielding devices. Numerical model in Open Sees has been developed to predict the seismic response of the strengthened RC frame. They have demonstrated that combined metallic yielding damper as a passive device dissipated the inelastic energy due to the plastic deformation of shear plates and flexure plates. They have shown that the pinching effect in the hysteretic response of the RC frame has been reduced due to addition of combined metallic damper. The proposed strengthening scheme has enhanced the lateral strength, stiffness, energy dissipation, and drift capacity of the non-ductile RC frame with a soft first story. Sahoo, et al., (2015). Carried out studies on Cyclic-Behaviour of Shear and Flexural Yielding Metallic Dampers.

RESEARCH SIGNIFICANCE

The retrofitting of seismically damaged RC building may sometimes be more financially viable and less time-consuming as compared to the complete demolition followed by the construction of new building. In general earthquake loading introduces large displacements in an OGS structure, under such large displacements, a yielding type elasto-plastic device made of X-shaped metallic dampers performs better and reduces the response of the structure. This device is also found to be cheaper and relatively easier to fabricate. The supporting steel frame of ADAS element is of chevron type, serially contributing stiffness to the ADAS element. XPD facilitates a constant strain over the height of device, thus ensuring that yielding occurs simultaneously and uniformly over full height of damper.

In this study, global retrofitting of building using passive energy dissipation devices in addition to the local retrofitting of ground storey column and beam-column joints with Geopolymer concrete has been chosen to improve the seismic performance of RC building. The Added Damping and added stiffness devices, based on the flexural yielding of metallic plates, are widely used in the seismic applications. The supporting steel frame of ADAS element is of chevron type, serially contributing stiffness to the RC building. The main objectives of this study are (i) to investigate the seismic performance of the RC building retrofitted with Geopolymer concrete and incorporation of X-shaped metallic damper. (ii) to study the performance of proposed connection of X shaped metallic damper with chevron steel bracing. The novelty of the study is local retrofitting of building with Geopolymer concrete and global strengthening of damaged building by incorporation of steel chevron bracing with X-shaped metallic damper. The dual function of X-shaped metallic damper is (i) To improve global stiffness of damaged building and (ii) To protect the building from earthquake loading.

EXPERIMENTAL INVESTIGATIONS

1 Building Details

A reinforced concrete building of two bays in X-direction, single bay in Y-direction with a height of 4.8m has been constructed for the shake table experiment. A photographic view of the reinforced concrete building is shown in Figure 1. Details of steel reinforcement of RC building are shown in Figure 2. Dimension of the building is 3600 x 2600 x 4950 mm, length of the beam in shorter direction is 2 m, length of the continuous beam in longer direction is 3 m, and length of the column for each storey is 1.6m. The total length of the frame in shorter direction is 2.15 m and the total length of the building in longer direction is 3.15 m. The total height of the building is 4.95 m and the total length of the raft slab is 3.6 m. Each storey is 1.6 m height. The section size of beams and columns are 150mm×150mm. The building is an open ground storey, with second and third floor levels filled fully with the brick infill. The slab thickness is 100 mm and base is a raft foundation, which is used for connecting the model to shake table. The longitudinal beam and transverse beam reinforcement consist of four numbers of 16 mm diameter and four numbers of 10 mm diameter bars respectively. Columns are reinforced with four numbers of 12 mm diameter bars. Lateral ties in the columns and beams are 6 mm diameter two legged stirrups at a spacing of 150 mm c/c. Materials used are M25 grade concrete and Fe415 steel. An additional mass of concrete block of 1200 kg is added on each floor to represent equivalent live load.

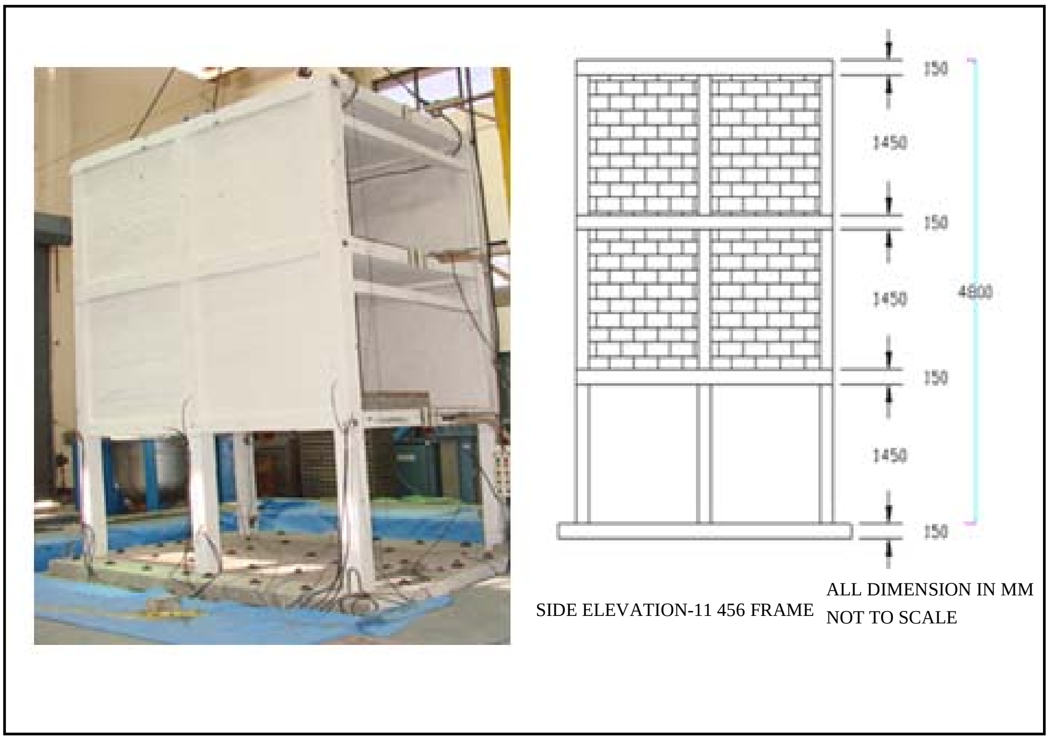


Fig. 1 View of Reinforced concrete building and dimensions

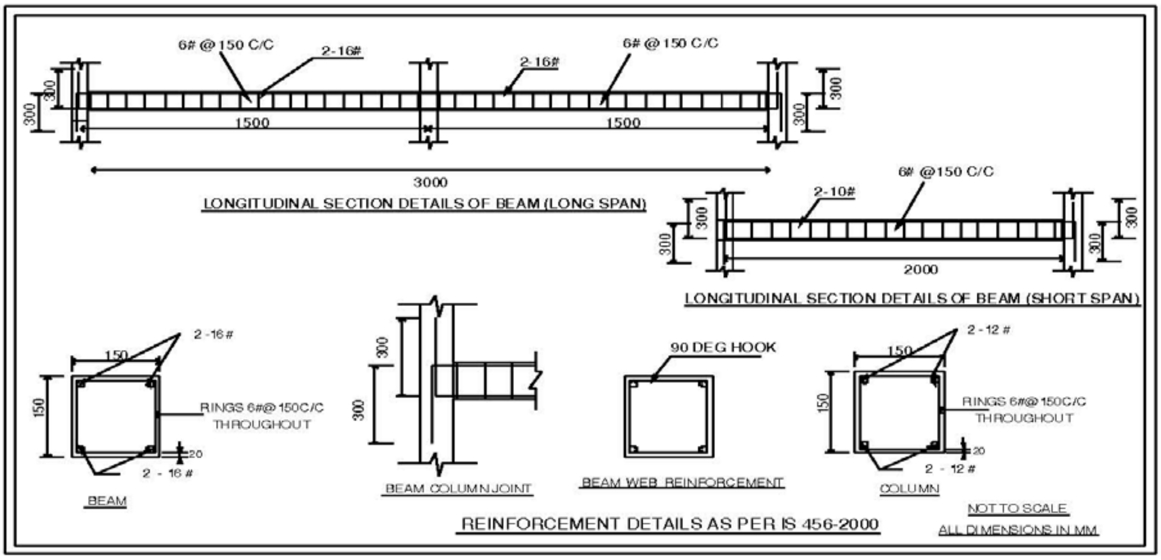


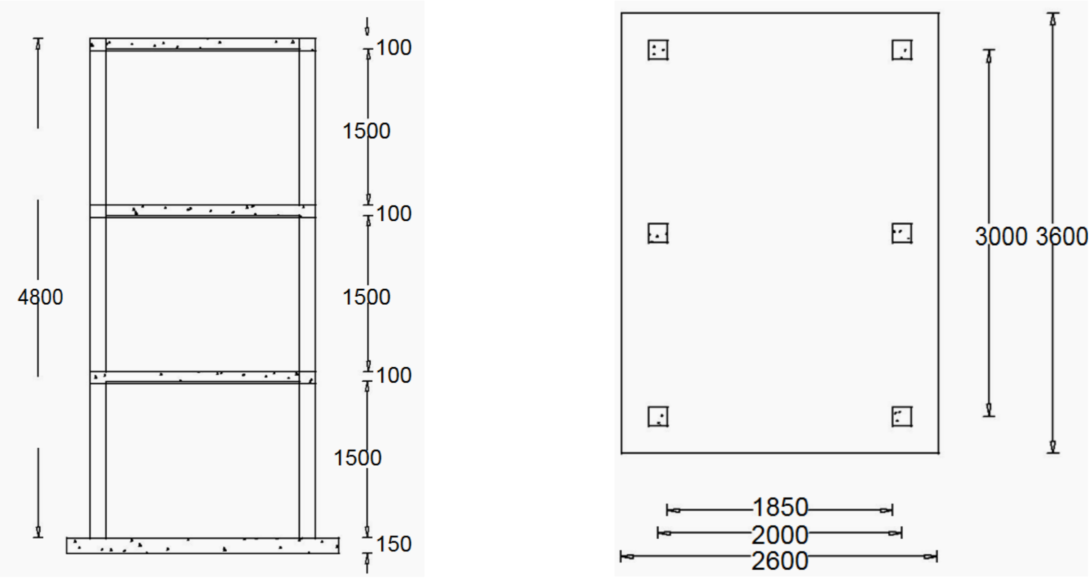
Fig. 2 Reinforcement details of beam and column and dimensions

SHAKE TABLE TEST

The shake table used for the experiment is 4m x 4m size with payload capacity of 30 tonne with servo controller. Required earthquake time history is given to the shake table in the form of displacement values through the multi-directional actuators in the shake table system. Frequency of operation is 0.1Hz–50Hz, maximum acceleration is 1.0g and maximum velocity is 0.8 m/sec.

1 Test Procedure

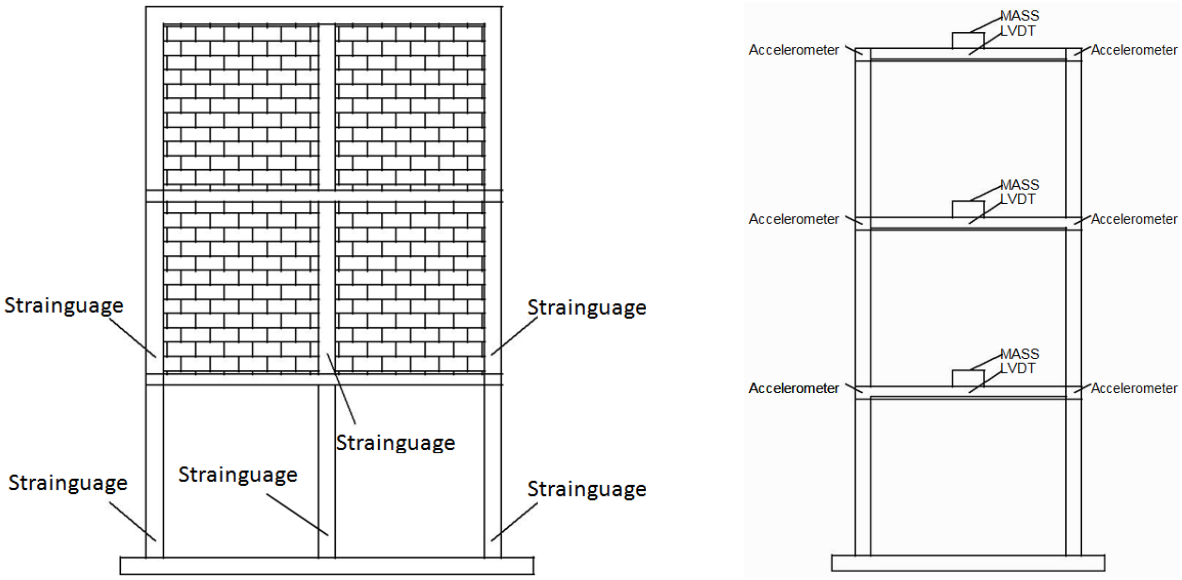
A three storey (Stilt +2) half scale Reinforced concrete building is placed on the shake table at the required position (Prakashvel et al., 2012) and (Jothi Saravanan et al., 2017). Base raft slab of the test specimen is fixed to the shake table with high strength bolts to make it as a fixed end condition. Displacement transducers are connected to the steel fixtures at each floor level to measure the displacement of the frame for every earthquake inputs. Two accelerometers are fixed at each storey level to measure the acceleration responses of the building. The earthquake time history compatible to response spectrum given in IS 1893, for soft soil spectrum for Zone V is modified with frequency scaling of square root of two as per the similitude law for the half scale model of reinforced concrete frame. The earthquake inputs in the form of displacement are given to the shake table actuator with control system software. The magnitude of the earthquake input is increased from 10% to 120% and the response of the reinforced concrete building is noted and measured. The displacements, strains and acceleration responses are measured along the direction of table excitation. Strain gauges are fixed on RC building column steel reinforcement during construction. Responses from all the sensors are recorded. Figure 3 shows the details of RC building. Figure 4 shows the instrumentation set-up. The maximum peak ground acceleration value is 7.99 m/s^2 and peak displacement is 48.75 mm. Maximum base shear of 114.3 kN has been observed during the test. Storey wise plots of the RC model frame displacement and drift for the earthquake input (modified spectrum for soft soil as per IS 1893-1) are shown in Figure 5 and Figure 6 respectively.



(a) ELEVATION (b) PLAN

ALL DIMENSION IN MM

Fig. 3 Details of RC frame building



(a) SIDE ELEVATION STRAIN GAUGE DETAILS (b) FRONT ELEVATION LVDT AND ACCELEROMETER

Fig. 4 Instrumentation setup

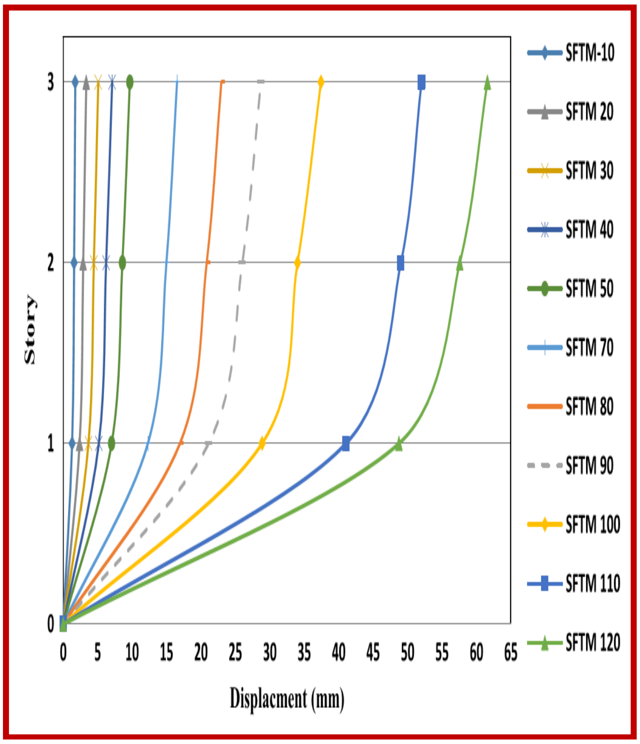


Fig. 5 Peak storey displacement for various seismic inputs

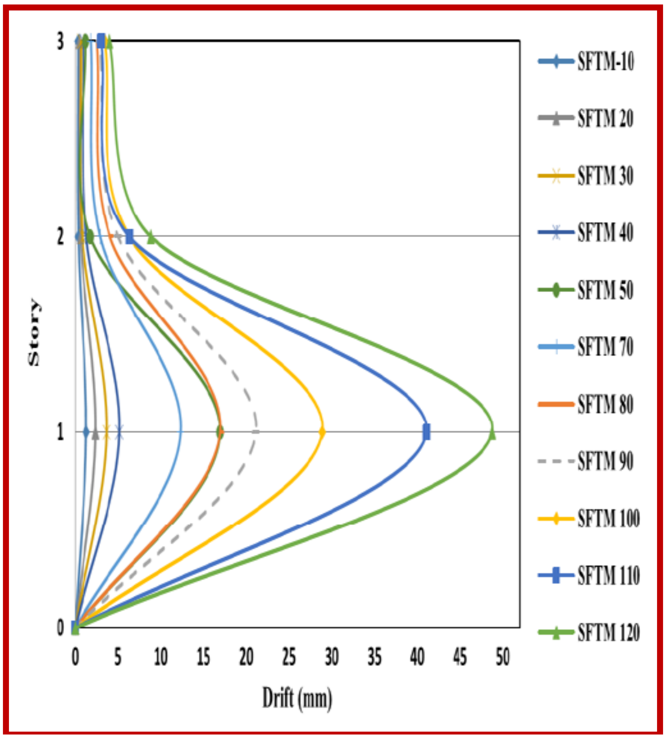


Fig. 6 Peak storey drift for various seismic inputs

YIELDING METALLIC DAMPER

Although a number of devices have been proposed in the literature, the Bechtel's Added Damping and Stiffness device (ADAS) and Triangular-plate Added Damping and Stiffness (TADAS) dampers have been found particularly suitable for the retrofit of existing structures. The devices, schematically represented, are made of X-shaped mild steel plates to deform in double curvature. Because of their shapes, the metal plates in these devices experience uniform flexural strains along their length. Thus when the strain reaches the yield level, yielding occurs over their entire volume. During cyclic deformations, the metal plates are subjected to hysteretic mechanism and the plastification of these plates dissipates a substantial portion of the structural vibration energy. Moreover, the additional stiffness introduced by the metallic elements increase the lateral stiffness of the building, leading to the reduction in deformations and damage in the main structural members.

1 Analytical Modeling of Yielding Metallic Devices

The force-deformation response under arbitrary cyclic loading of the yielding metallic devices has been approximated by discrete multi-linear models, such as the elasto-perfectly-plastic model and the bilinear model. A simple bilinear hysteretic forcing model is used to identify the parameters involved in the design of a typical metallic element. Figure 7(a) represents a structural frame bay with an added hysteretic damper. Herein, the combination of a yielding metallic element and the bracing members that support the device is called as the device-brace assembly. The combined lateral stiffness of this assembly is schematically shown in Figure 7(b). This combined stiffness, denoted as k_{bd}, can be obtained by considering the contribution of stiffness k_d due to the metallic device and the stiffness k_b added by the bracing. Since these stiffnesses are connected in series, as shown in Figure 7(c), it follows that

$$k_{bd} = \frac{1}{\frac{1}{k_b}+\frac{1}{k_d}} = \frac{k_d}{1+\frac{1}{B/D}} \quad (1)$$

Where B/D is the ratio between the bracing and device stiffness

$$\mathrm{B/D} = \frac{\mathrm{k_b}}{\mathrm{k_d}} \quad (2)$$

Another quantity of interest is the stiffness ratio SR defined as the ratio of assembly stiffness to the stiffness of the story $\mathrm{k_s}$ as,

$$\mathrm{SR} = \frac{\mathrm{k_{bd}}}{\mathrm{k_s}} \quad (3)$$

In this study, it is assumed that the bracing members as well as the main structural members are designed to remain elastic during an earthquake and that the stiffness and ratios previously defined correspond only to the initial elastic values of the yielding elements. The yield force of the yielding element, denoted by P_y, is related to the yield displacement of the device Δ_{yd}, and also to the yield displacement experienced by the device-brace assembly Δ_y as:

$$\mathrm{P_y} = \mathrm{k_d}\Delta_{\mathrm{yd}} = \mathrm{k_{bd}}\Delta_{\mathrm{y}} \quad (4)$$

For design purposes, this equation can be expressed in terms of the parameters SR and B/D by considering Equations (1) and (3) in Equation (4) as:

$$\mathrm{P_y} = \mathrm{SRk_s}\left|1 + \frac{1}{\mathrm{B/D}}\right|\Delta_{\mathrm{y_d}} \quad (5)$$

Equation (5) is the basic expression that establishes the relationship between the parameters of the assumed bilinear model. From this equation, it can be observed that in a given structure (i.e. k_s known) the behavior of a metallic yielding element is governed by four key parameters. They are: the yielding load P_y, the yield displacement of the metallic device Δ_{yd}, and the stiffness ratios SR and B/D. However, only three of these variables are independent since the fourth one can be determined from Equation (5).

A bilinear model has been considered in the above discussion to represent the hysteretic behavior of the metallic yielding element. Because of its mathematical simplicity, it provided a convenient tool to establish the relationship between the model parameters.

From the above discussion and considering the relationships given by Equation (3) and (5), it follows that

$$\mathrm{k_o} = \mathrm{SRk_s};\ \Delta_{\mathrm{y}} = \left|1 + \frac{1}{\mathrm{B/D}}\right|\mathrm{yd} \quad (6)$$

Therefore, the yield displacement of the metallic device Δ_{yd}, and the ratios SR and B/D can be selected as the mechanical variables governing the behavior of the device-brace assembly. Once the values of these parameters are selected, the Bouc-Wen's (1967) hysteretic model is completely determined.

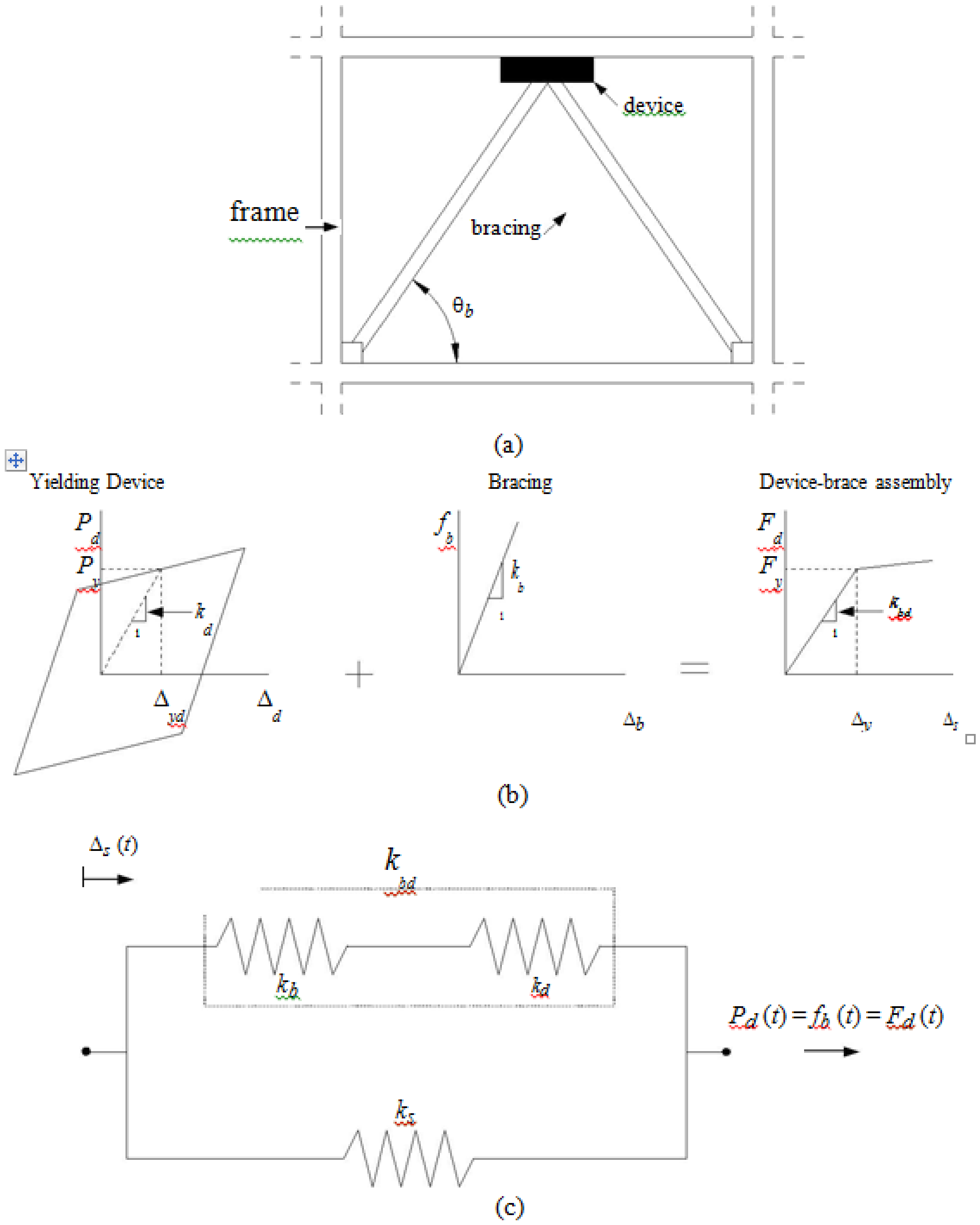


Fig. 7 Yielding metallic damper, (a) typical configuration, (b) yielding metallic device, bracing and yielding element parameters, (c) stiffness properties of device-bracing assembly

2 Performance Indices

Depending on the performance desired different design solutions could be obtained by the search procedure. In this section, a description of the performance indices considered in this study is presented. The improvement in the seismic performance of a building structure obtained with the incorporation of the protective devices can be measured by a number of alternative indices. In particular, inter-story drifts are used as a measure of the deformations and possible damage of structural members and non-structural components. The floor accelerations are alternatively employed to assess the discomfort experienced by the building occupants, as well as a measure of the shear forces and stresses developed in the main structural members. In this regard, it is interesting to examine the effectiveness of the yielding metallic devices in reducing these response quantities. Figure 8 shows the idealized building structure with yielding metallic device.

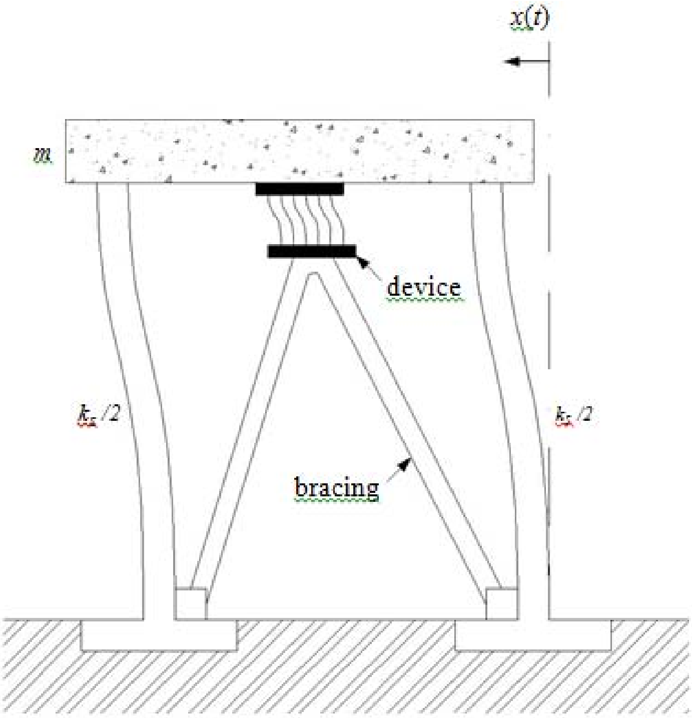


Fig. 8 Idealized building structure with supplemental yielding metallic element

3 Geopolymer Concrete (GPC)

Geopolymer is widely used as a binder to completely replace the Ordinary Portland Cement. In the present study, the brick masonry in-fill wall present in the top two stories have been re-built after dis-lodging damaged in-fill masonry brick walls. The cracked concrete near the beam-column joints is removed and freshly re-laid with Geo-polymer concrete having 75% GGBS and 25% fly-ash designed for a compressive strength of M40, ensuring adequate bond with old concrete surface. 5 Molar ratio (5M) sodium hydroxide alkaline solution is used for preparation of the Geopolymer concrete. The alkaline liquids used for polymerisation are sodium hydroxide and sodium silicate in the ratio of 1:2 respectively. The crack concentration of the damaged building is mainly at the beam column joints and at the bottom of column of ground storey. The concrete at cracked portion is removed completely by chipping of concrete without causing any disturbance to the reinforcement as shown in Figure 9. The chipped column portions and beam-column joints where retrofitting is to be carried out is shuttered using wooden planks with some provisions for pouring the geopolymer concrete. After shuttering, the freshly prepared GPC using 5M alkaline solution is poured into the shuttering. After 24 hours the wooden shutters are de-moulded, and finishing is carried out. The concreted portions are left as such for air curing. The brick masonry with a total thickness of 115 mm using 1:4 PPC mortar mix is reconstructed with 1450 × 450 mm door opening, as shown in Figure 9.

(a) The removal of spelled concrete at column bottom and at beam column joint

(b) Retrofitting with geopolymer concrete

Fig. 9 Retrofitting of Reinforced concrete building with Geopolymer concrete

4 X-Shaped Metallic Damper

The X-shaped metallic damper connection in ground storey is shown in Figure 14. The framed building is retrofitted using X-plate ADAS element at the ground storey. The supporting frame of ADAS element is of Chevron type, serially contributing stiffness to the ADAS element. The thickness, width, length and number of elements have been designed to match with the masonry stiffness at the upper storey. X-plate ADAS elements made of mild steel, with the dimensions 160 mm overall depth× 40 mm width × 12 mm thick are provided in 2 numbers in each bay in the excitation direction at the open ground storey. The properties like yield stress (σ_y), and Elastic modulus (E) for the ADAS element material are 235MPa, 1.94 $\times 10^5$ MPa respectively. In each bay of the ground storey 2 Nos. of X-plates are connected such that the open ground storey stiffness becomes equal to the brick masonry of upper storey in the excitation direction. The X–plate is connected to the building using the angle bracings. The end conditions of XPD are made as both ends fixed. The effectiveness of a XPD depends on the percentage of energy dissipated by the XPD. The energy dissipation increases as the thickness of XPD increases.

As the height decreases and width increases, the energy dissipation by the X-plate increases. Two equal angles of 50 × 50 × 6 mm are connected back to back at 65 inclination with horizontal. The connections of the angles are made by welding of 6mm size. The XPD is connected to the frame using 12 mm size bolt.

The stiffness calculation of retrofitted building having XPD

Stiffness due to inclined angles, $K_a = (AE/l)\cos^2\theta$

Stiffness due to XPD, $K_d = Ebt^3/(12a^3)$

Thus stiffness due to XPD in one bay is $1/Ke_{ff} = 1/K_d + 1/K_a$

Where A = area of angles =4 x area of angle 50×50×6 mm = 2272 mm^2

E = Elastic modulus of steel = 2.1×10^5 N/mm^2, θ = 65°, l = 1300 mm

B = 40 mm, a = 40 mm, t = 12 mm

K_a = 65551.22 N/mm

K_d = 37800 N/mm, so Ke_{ff} = 23975 N/mm

Thus stiffness of ground storey with XPD = $3K_c + 2Ke_{ff}$ = 60404.2 N/mm

Stiffness of second and third storey = $4\times K_{wc} + 3\times K_c$ = 69170.38 N/mm

The ratio of ground storey stiffness to upper storey stiffness = 0.87

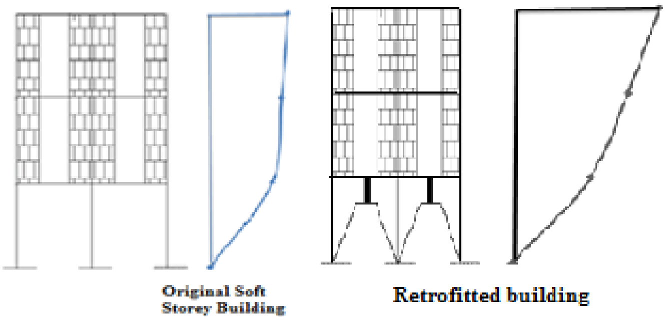
Shear strength of X-plate = neck area×yield stress = 2×12×6×250 = 36000 N

Shear strength of brick masonry = area×0.03 f_m = 2×450 ×115×0.03×7.5 = 23287.5 N

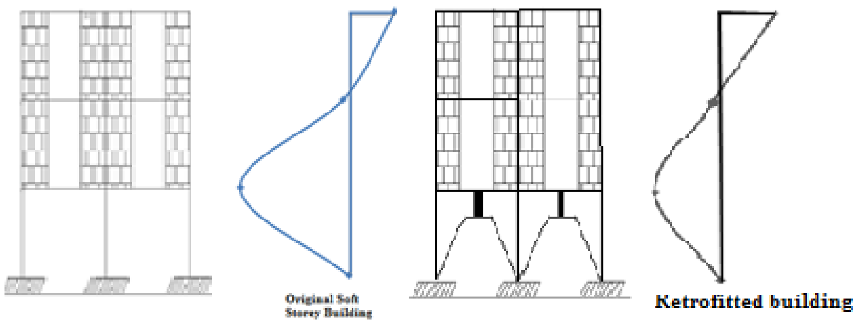
5 Free Vibration Test

Free vibration test on reinforced concrete building model fixed with and without X-plate metallic damper are carried out. The building is excited using the reaction mass shaker. The structural response in the form of acceleration is measured using piezoelectric accelerometer. The acceleration responses from the respective storey level and ground storey level are acquired and fed into a dual channel FFT analyzer. Natural frequencies and mode shapes of the building are evaluated.

For comparison, first the building is tested without X-plate connection and then tested with X-plate. From the acquired and averaged acceleration responses in the dual channel FFT analyser, the frequency response function is obtained for the floor under consideration. Using the FRF curves, the real and imaginary parts of the FRF curves are determined. From the real part of the FRF curve, the natural frequencies and damping values for all the identified modes of the test structures can be arrived. A graph is plotted between acceleration and corresponding output frequencies from FFT analyzer. The first natural frequency is 4Hz and second natural frequency is 18 Hz. The first and second mode shape of building which is locally retrofitted with Geopolymer concrete (GPC) is obtained from the free vibration test, as given in Figure 10.



(a) First mode



(b) Second Mode

Fig. 10 First mode and second mode shapes of RC building with X-shaped metallic damper
(1) Original building (2) Retrofitted building

6 Finite Element Modeling

The natural frequencies of the building at different modes are determined analytically by finite element method. SAP 2000 software is used to analyze the building before and after retrofitting with X-pate damper. The building is modeled with the same dimensions of the test specimen. Beams and columns are modeled as 3D frame elements. The brick infill is modeled as diagonal compression strut element. Rigid joints connect the beams and columns and equivalent struts are connected to beam-column junctions with pin joints. ADAS elements are modeled using link element by applying nonlinearity in the form of multi-linear plastic model, by defining the effective stiffness based on the beam theory. Transient dynamic analysis is performed on two models in the excitation direction. The modal analysis results show that the ADAS element retrofit improved the stiffness. The three dimensional original reinforced concrete frame model in SAP 2000 software is shown in Figure 11. The 3D view of retrofitted reinforced concrete building is shown in Figure 12. The natural frequencies and mode shapes are obtained.

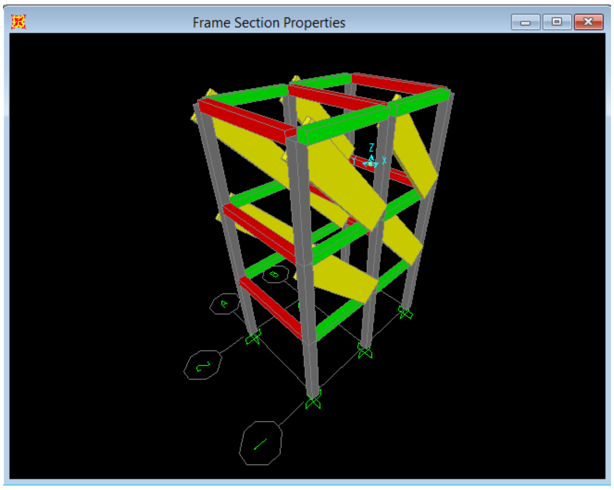


Fig. 11 3D view of original building in SAP2000 before retrofitting

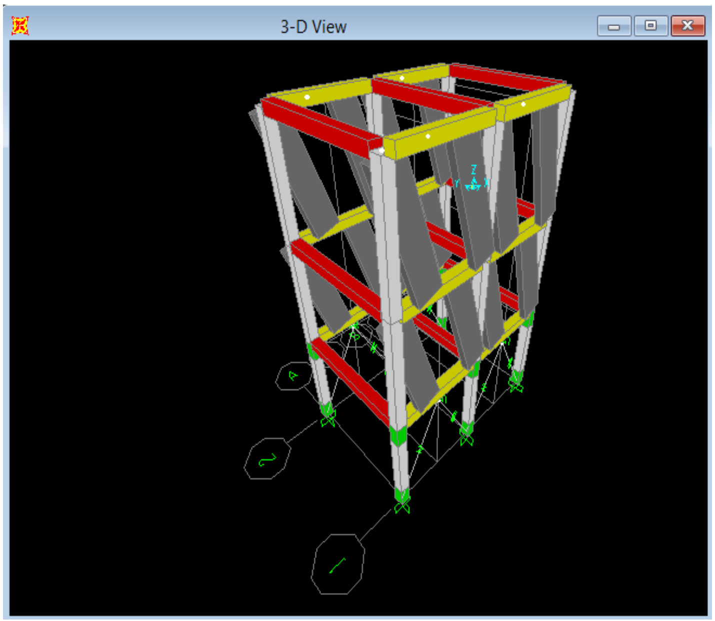


Fig. 12 3D view of original building in SAP2000 after retrofitting

SHAKE TABLE TEST OF RETROFITTED OGS-REINFORCED CONCRETE BUILDING

A three-storey half scale reinforced concrete (RC) building, fixed with X-plate metallic damper at the ground floor level, is designed and fabricated to study its seismic response characteristics (Madheswaran et al., 2017). Experimental studies are carried out using the 4m x 4m tri-axial shake-table facility to evaluate the seismic response of a retrofitted RC frame building with Open Ground Storey (OGS) structure ground storey columns repaired using Geopolymer concrete composites and retrofitted with X-plate metallic dampers.

The thickness, width, length and number of elements have been designed to match with the masonry stiffness at the upper floor. ADAS elements made of mild steel with dimensions 160 mm overall depth x 40 mm width x 12 mm thick are provided in 2 numbers in each bay in the excitation direction in the open ground storey. The yielding type X-shaped elasto-plastic damper (XPD) used for this experiment is shown in Figure 13 and Figure 14. The thickness of X-plate is 12 mm and total height of X-plate is 160 mm. In each bay of the ground storey 2 such X-plates are used so that the stiffness becomes equal to the brick masonry of upper floors only in the excitation direction. The X-plate is connected to the building using the angle bracings. The end conditions of XPD are made as both ends fixed. The test specimen (Retrofitted Reinforced concrete frame model) is placed on the shake table at the required position. The earthquake excitation given for both cases (case 1- without X-plate and case 2- with X-plate) with increasing magnitude of seismic inputs. The displacement, acceleration responses are measured along the direction of shake table excitation.

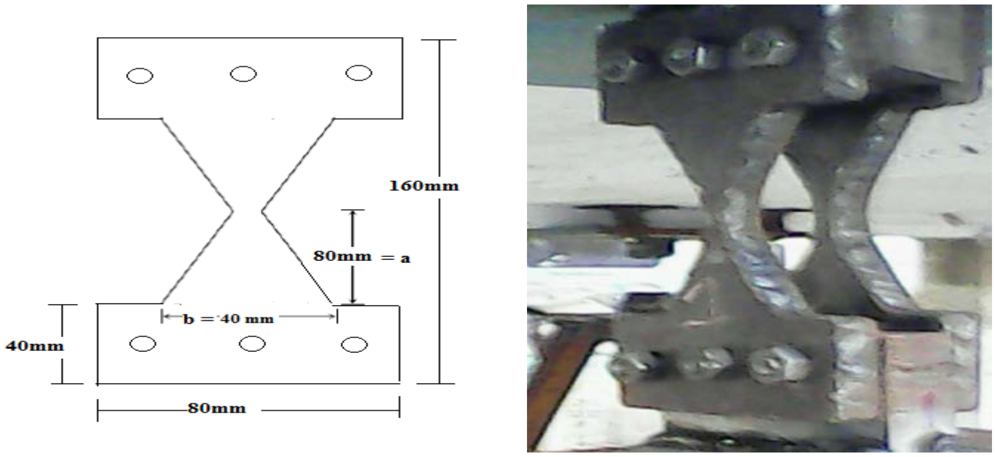


Fig. 13 The yielding X-shaped elasto-Plastic Damper (XPD)

Fig. 14 XPD connections in ground story of RC building

1 Experimental Results

The natural frequencies of building before and after retrofitting are compared for both experimental and theoretical as shown in Table 2. From Table 2, the natural frequencies of retrofitted building is greater than that of original building. The modal analysis results clearly show that the ADAS element retrofit improved the stiffness. The fundamental frequency of OGS building is increased from 4.0 Hz to 6.0 Hz due to addition of ADAS elements and the soft storey deflection profile is eliminated. The average of acceleration obtained at two columns at each floor is compared. From the comparison of acceleration response, the third storey is showing higher acceleration with and without X-plate. When the building is not connected with X-plate, the building behaves as soft storey. The Shake table testing of OGS reinforced concrete building with chevron steel bracing incorporating the X-plate damper is carried out. The modified spectrum compatible time history of IS 1893 soft soil spectrum is used as seismic input. The magnitude of the earthquake input is increased from 0.1 g to 1.1 g. The maximum peak ground acceleration value is 11.15 m/s^2 and the maximum response acceleration at third floor is 18.86 m/s^{2}during the 1.1 g earthquake. The maximum displacement is 44.60 mm at third floor level during 1.1 g seismic input. The maximum base shear is 205 kN for 1.1 g earthquake input. The strain measured on X-plate damper is 1200 micro-strain for 0.3 g and 19000 micro-strains for 1 g earthquake. The strains on the ground storey columns are 1500 micro-strain. It is observed that 19000 micro-strains in the X-plate damper shows the energy dissipation takes place in the plate rather than the structural columns in the OGS building. This can be seen in open ground storey columns as there is no visual cracks/damage in the columns.

The comparison of relative displacement of each floor for building with and without X-plate is shown in Figure 15. From Figure 15, it is observed that when the building is not connected with X-plate the building have relative displacement similar to that of soft storey building i.e., the relative displacement for each floor is almost equal with slight increase in upper stories. But when the building is connected with X-plate damper the relative displacement for each floor increases with height which is a linear variation. The relative displacement of building is less when connected with X-plate damper due to increase in global stiffness of the building. Figure 16 shows the variation of drift values for each storey of the building with and without X-plate damper. The drift values for every storey are compared for the building with and without X-plate damper. And it is observed that the building with open ground storey has maximum drift for first storey, but when the building is connected with X-plate damper the drift values for all stories are equal, even though slight increase in drift value for lower stories.

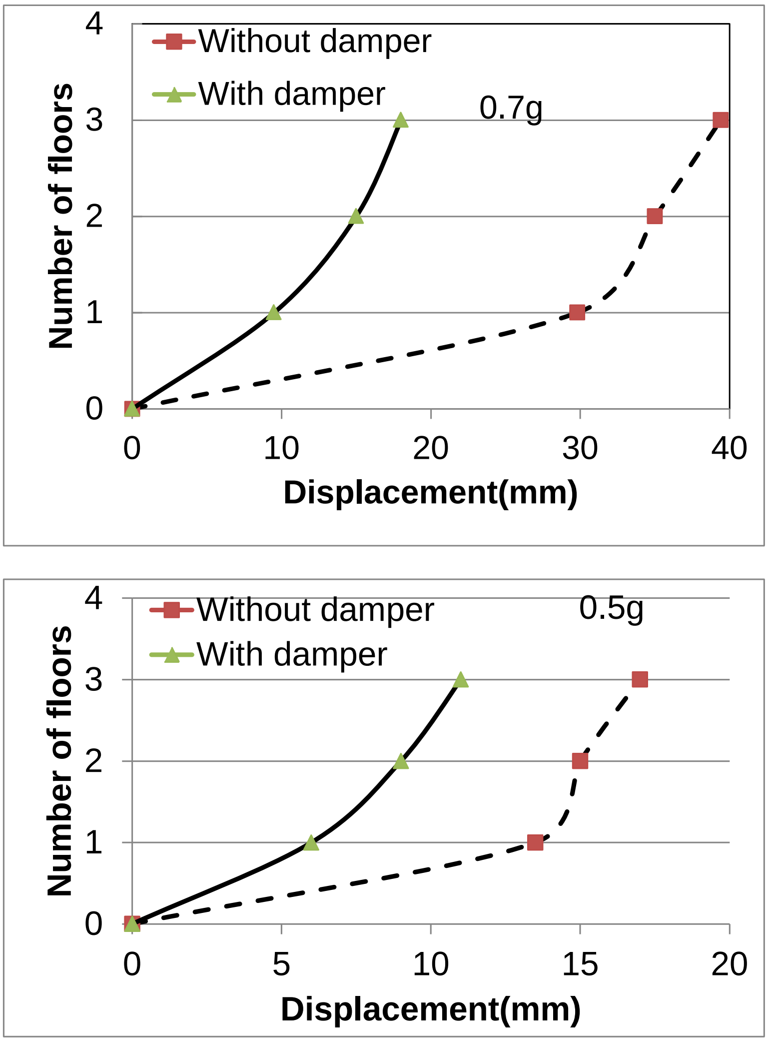
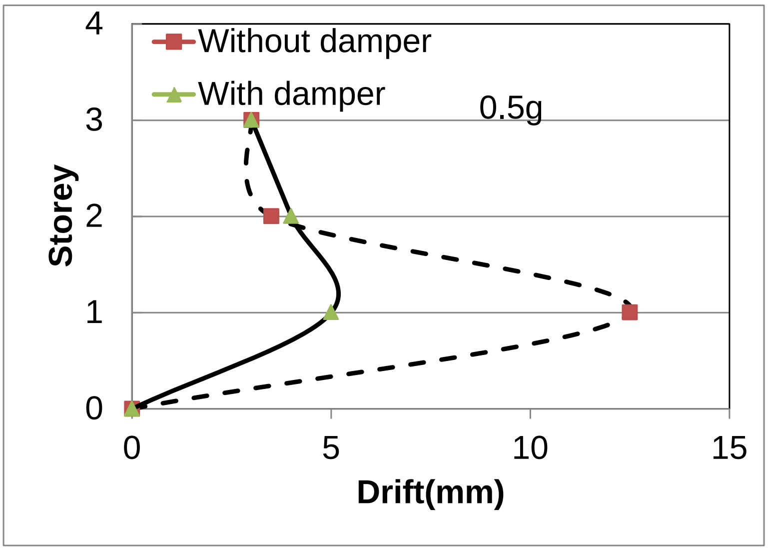


Fig. 15 Comparison of relative displacement of building for different cases of earthquake with and without damper



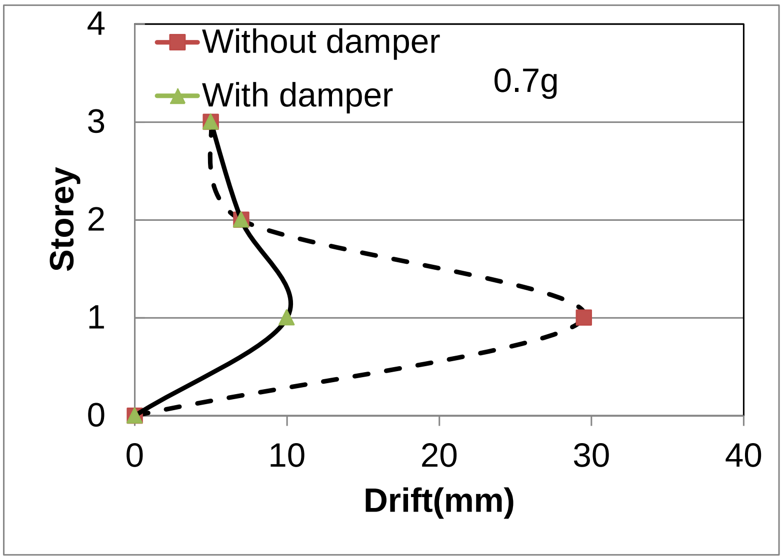


Fig. 16 Comparison of storey drift of building for different cases of earthquake with and without damper

DISCUSSION OF RESULTS

Table 1 shows the properties of Portland Pozzolana Cement concrete and Geopolymer concrete. The natural frequencies of building before and after retrofitting are compared as shown in Table 2. From Table 2, the natural frequencies of retrofitted building is greater than that of original building. It is observed that there exists a good agreement between experimental and SAP analysis. The modal analysis results clearly show that the ADAS element retrofit improved the stiffness of the structure. The fundamental frequency of OGS building has increase from 4 Hz to 6 Hz due to addition of ADAS elements and the soft storey deflection profile is eliminated.

Table 1: Properties of PPC, GPC and masonry infill

Type	Modulus of elasticity E (N/m^2)	Poisson's Ratio (ν)	Density ρ (Kg/m^3)
Portland Pozzolana cement (PPC) concrete	25×10^9	0.2	2500
Geopolymer concrete (GPC)	27.9×10^9	0.27	2500
Masonry infill	4.125×10^9	0.17	1800

Table 2: Natural frequencies of building before and after retrofitting

Natural frequency	Original building experimental Hz	Locally Retrofitted building with GPC experimental Hz	Globally retrofitted building with damper experimental Hz	Original building theoretical Hz	Locally Retrofitted building with GPC theoretical Hz	Globally retrofitted building with damper theoretical Hz
First mode	4.15	4.0	6.0	4.05	4.40	6.159
Second mode	18.8	18.0	21.75	18.08	18.40	22.195
Third mode	-	-	-	31.76	32.24	34.268

a) Earthquake Response of Open Ground Storey Reinforced Concrete Building

During the shake table experiment, various earthquakes are imparted to the open ground storey reinforced concrete building. The maximum peak ground acceleration value is 7.99 m/s^2. Maximum base shear of 116.48 kN has occurred. Reinforced concrete building has undergone a maximum displacement of 48.75 mm at third floor level and corresponding response acceleration value at third storey level is 11.44 m/s^2. It is found that the inter-storey drift is higher in the ground storey (48.74 mm) compared to other storey drifts (9.34 mm & 4.53 mm).From the strain results, it can be observed that the magnitude of strain variation in the ground storey column reinforcement is in the range of 10,000 micro-strains and it is only 700 micro-strains in the second storey column reinforcement during shake table test which demonstrates the open ground storey behaviour. Moreover predominant failure plastic hinges are formed in the open ground storey columns.

b) Earthquake Response of Open Ground Storey Reinforced Concrete Building Retrofitted with Chevron Bracing Incorporating the X-Plate Damper

The retrofitted half-scale open ground storey reinforced concrete building is tested in the shake table with yielding type X-shaped metallic damper. The modified spectrum compatible with time history of IS:1893 soft soil is used for test. The magnitude is increased from 0.1 g to 1.1 g and the response is measured for every earthquake time history. The maximum peak ground acceleration value is 11.15 m/s^2 and the maximum response acceleration at third storey is 18.86 m/s^2 during the 1.1 g earthquake. The maximum measured displacement is 44.70 mm at third storey level during 1.1 g earthquake. The comparison of relative displacement of each floor for locally retrofitted concrete frame building with and without X-plate is shown in Figure 15. From Figure 15, it is observed that when the building is not connected with X-plate damper the profile of relative displacement is similar to that of soft storey building i.e., the relative displacement for each floor is almost equal with slight increase in upper stories. Figure 16 shows the comparison of storey drifts of building for 0.5 g and 0.7 g with and without X-plate damper. The drift values for every storey are compared for the building with and without X-plate damper. And it is observed that the building has maximum drift in the open ground storey, but when the building is connected with X-plate damper the drift values increases linearly similar to bare frame profile. The measured strain on X-plate damper is 1200 micro-strain during 0.3 g earthquake input and 19000 micro-strain during 1 g earthquake input.

SUMMARY AND CONCLUSIONS

A three-storey half scale reinforced concrete open ground storey building is constructed and tested in the shake table to study the seismic response characteristics. After the shake table testing of above building, local retrofitting is carried out with geopolymer concrete and global retrofitting is carried out with X-plate damper in the open ground storey. Experimental investigations are carried out for determining the natural frequencies and mode shapes of the same building retrofitted with and without yielding type X-shaped metallic dampers. Based on the above experimental studies the following conclusions are drawn. The natural frequency of reinforced concrete framed building retrofitted with geopolymer concrete is found to be 4 Hz. After the building is retrofitted with X-shaped metallic damper, the frequency is increased to 6 Hz. Hence it is observed that the global stiffness of the building has increased. From the shake table test, it is found that the acceleration response of the building with X-plate damper has reduced due to increase in stiffness when compared to that of building without X-plate damper for the same earthquake input. The maximum strain magnitude in the OGS column is nearly 10,000 micro-strains, whereas it is only 700 micro-strains in the second storey columns for original OGS RC building. But in the case of globally retrofitted building, the maximum strain measured on X-plate damper is 19,000 micro-strains and strain measured on ground storey column is 1500 micro-strains. Also no visual damage and cracking have been seen in the OGS column and failure is limited to the yielding of X-plate which is preferred failure mechanism. The relative displacement of floor is reduced considerably when the X-shaped metallic damper is connected for all the earthquake time histories. The drift value for the building without X-plate damper is higher for the ground storey. But when the same building retrofitted globally (with X-plate), all the three storeys have almost equal drift (linear profile). The use of steel bracing with passive energy dissipation device significantly reduced the lateral displacement. A shake table testing of OGS building and validates the hypothesis and proves the relationship.

ACKNOWLEDGEMENT

This paper is being published with the permission of the Director, CSIR-Structural Engineering Research Centre, Chennai. The cooperation and guidance received from, Shri S. Harishkumaran and Shri P. Vasudevan of CSIR-SERC, Chennai and the technical staff of Advanced Seismic Testing and Research laboratory of CSIR-SERC are gratefully acknowledged.

REFERENCES

1. Arlekar, Jaswant N., Jain, Sudhir K. and Murty, C.V.R. (1997). “Seismic Response of RC Frame Buildings with Soft First Storeys”, Proceedings of the CBRI Golden Jubilee Conference on Natural Hazards in Urban Habitat, New Delhi.
2. Arslan, M.H. and Korkmaz, H.H. (2001). “What is to be Learned from Damage and Failure of Reinforced Concrete Structures during Recent Earthquake in Turkey”, Journal of Engineering Failure Analysis, Vol. 14, No. 1, pp. 1-22.
3. Bouc, R. (1967). “Forced Vibration of Mechanical System with Hysteresis”, Proceedings of the 4th Conference on Nonlinear Oscillations, Prague, Czechoslovakia, pp. 186-197.
4. Constantinou, M.C., Tsopelas, P., Hammel, W. and Siaher, A.N. (2001). “Toggle-Brace-Damper Seismic Energy Dissipation Systems”, Journal of Structural Engineering, ASCE, Vol. 127, No. 2, pp. 105-112.
5. Deshpande and Bhalchandra, S.A. (2010). “Seismic Analysis of RC Frame Building with Soft First Storey”, Proceedings of the Seventh Structural Engineering Convention (SEC2010), Annamalai University, Annamalainagar, T.N., India, pp. 1075-1084.
6. EERI (2001). “Bhuj, India Earthquake of January 26, 2001”, Reconnaissance Report.
7. IS 1893 (Part I): (2002). “Criteria for Earthquake Resistant Design of Structures”, Part I General Provisions and Buildings, Bureau of Indian Standards, New Delhi.
8. Jothi Saravanan, T., Rama Rao, G.V., Prakashvel, J., Gopalakrishnan, N., Lakshmanan, N. and Murthy, C.V.R (2017). “Dynamic Testing of Open Ground Story Structure and in Situ Evaluation of Displacement Demand Magnifier”, J. Perform. Constr. Facil., Vol. 31, No. 5, pp. 0401-7055.
9. Kaushik, H.B., Rai, D.C. and Jain, S.K. (2009). “Effectiveness of Some Strengthening Options for Masonry Infilled RC Frames with Open First Storey”, Journal of Structural Engineering, Vol. 135, No.8, pp. 925-937.
10. Kelly, J.M., Skinner, R.I. and Heine, A.J. (1972). “Mechanisms of Energy Absorption in Special Devices for Use in Earthquake Resistance Structures”, Bull NZ, National Society for Earthquake Engineering, Vol. 5, No. 3, pp. 63-88.

11. Khampanit, A., Leelavaitwat, S., Kochanin, J. and Warnitachai, P. (2014). “Energy–Based Seismic Strengthening Design of Non-Ductile Reinforced Concrete Frames Using Buckling-Restrained Braces”, Eng. Strut., Vol. 81, pp. 110-122.
12. Li, G. and Li, H.N. (2013). “Experimental Study and Application of Metallic Yielding-Friction Damper”, J. Earthquake Tsunami, Vol. 7, No. 3, pp. 1350012.
13. Madheswaran, C.K., Prakashvel, J., Sathishkumar, K. and Rama Rao, G.V. (2017). “Earthquake Response of Reinforced Concrete Building Retrofitted with Geopolymer Concrete and X-Shaped Metallic Damper”, Journal of Institution of Engineers (India), Series A. Vol. 98, No. 1-2.
14. Murthy, C.V.R. (2006). “Open Ground Storey RC Frame Buildings with 230 mm Columns Unsafe during Earthquakes Published in National Seminar on Seismic Detailing of R.C.C Structures Proceedings”, pp.1-30.
15. Oinam, R.M and Sahoo, D.R. (2017). “Rehabilitation of Damaged RC Frames Using Combined Metallic Yielding Passive Devices”, Structures and Infrastructures Engineering, Vol. 13, No. 6, pp. 816-830.
16. Oinam, R.M. (2017). “Metallic Energy Dissipation Devices for Seismic Strengthening of Reinforced Concrete Frames with Soft-Story”, Ph.D Thesis, Department of Civil Engineering, Indian Institute of Technology Delhi.
17. Oinam, R.M. and Sahoo, D.R. (2015). “Enhancement of Lateral Capacity of Damaged Non-Ductile RC Frame Using Combined Yielding Metallic Damper”, The Indian Concrete Journal, Vol. 89, pp. 80-86.
18. Oinam, R.M. and Sahoo, D.R. (2017). “Numerical Evaluation of Seismic Response of Soft-Story RC Frames Strengthened with Passive Devices”, Bulletin of Earthquake Engineering, Vol. 16, No. 2, pp. 983-1006.
19. Oinam, R.M. and Sahoo, D.R. (2019). “Using Metallic Dampers to Improve Seismic Performance of Softstory RC Frames: Experimental and Numerical Study”, J. Perform. Constr. Facil., Vol. 33, No. 1, pp. 1-18.
20. Prakashvel, J., Umarani, C., Muthumani, K. and Gopalakrishnan, N. (2012). “Earthquake Response of Reinforced Concrete with Open Ground Storey”, Bonfring International Journal of Industrial Engineering and Management Science, Vol. 2, No. 4.
21. Sahoo, D.R. and Rai, D.C. (2013). “Design and Evaluation of Seismic Strengthening Techniques for Reinforced Concrete Frames with Soft Ground Story”, Engineering Structures, Vol. 56, pp. 1933-1944.
22. Sahoo, D.R., Singhal, T., Taraithia, T. and Saini, A. (2015). “Cyclic-Behaviour of Shear and Flexural Yielding Metallic Dampers”, Journal of Construction Steel Research, Vol. 114, pp. 247-257.
23. Sathishkumar, K., Muthumani, K., Gopalakrishnan, N., Sivaramasarma, B., Reddy, G.R. and Parulekar, Y.M. (2002). “Seismic Response Reduction of Structures Using Elasto-Plastic Passive Energy Dissipation Devices”, ISET Journal of Earthquake Technology, Paper No. 421, Vol. 39, No. 3, pp. 121-138.
24. Sathishkumar, K., Muthumani, K., Sivaramansarma, B. and Gopalakrishnan, N. (2000). “Evaluation of X-Type Metal Passive Energy Absorbers”, Technical Report, SERC, Chennai.
25. Skinner, R.J., Kelly, J.M. and Heine, A.J. (1975). “Hysterisis Dampers for Earthquake Resistant Structures”, Earthquake Engineering and Structural Dynamics, Vol. 5, No. 3, pp. 287.
26. Soong, T.T. and Dargush, G.F. (1997). “Passive Energy Dissipation Systems in Structural Engineering”, Wiley & Sons, Chichester, England.
27. Symans, M.D. and Constantinou, M.C. (1997). “Seismic Testing of a Building Structures with a Semi-Active Fluid Damper Control System”, International Journal of Geotechnical Engineering, Vol. 26, No. 7, pp. 759-777.
28. Symans, M.D., Cofer, W.F., Du, Y. and Fridley, K.J. (2001). “Fluid Dampers for Seismic Protection of Wood Frame Structures”, Proc. of the 2001 Structural Congress and Exposition, ASCE, Edited by P. Chang, Washington. D.C.

29. Tytler, R.G. (1978). “Tapered Steel Energy Dissipaters for Earthquake Resistant Structures”, Bull NZ, National Society for Earthquake Engineering, Vol. 11, No. 4, pp. 282-294.
30. Varum, H., Teixeria-Dias, F., Marques, P., Pinto, A.V. and Bhatti, A.Q. (2013). “Performance Evaluation of Retrofitting Strategies for Non-Seismically Designed RC Building Using Steel Braces”, Bulletin Earthquake Eng., Vol. 11, No. 4, pp. 1129-1156.
31. Whittakar, A.S., Bertero,V.V., Thompson. C.I. and Alsonson, L.J. (1991). “Seismic Testing of Steel Plate Energy Dissipation Devices”, Earthquake Spectra, Vol. 7, No. 4, pp. 563-604.
32. Zhang, R.H. and Soong, T.T. (1992). “Seismic Design of Viscoelastic Dampers for Structural Applications”, Journal of Structural Engineering, ASCE, Vol. 118, No. 5, pp. 1375-1392.