International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:8, No:12, 2014

Performance Based Seismic Retrofit of Masonry Infilled Reinforced Concrete Frames Using Passive Energy Dissipation Devices

Alok Madan, Arshad K. Hashmi

***Abstract*—**The paper presents a plastic analysis procedure based on the energy balance concept for performance based seismic retrofit of multi-story multi-bay masonry infilled reinforced concrete (R/C) frames with a 'soft' ground story using passive energy dissipation (PED) devices with the objective of achieving a target performance level of the retrofitted R/C frame for a given seismic hazard level at the building site. The proposed energy based plastic analysis procedure was employed for developing performance based design (PBD) formulations for PED devices for a simulated application in seismic retrofit of existing frame structures designed in compliance with the prevalent standard codes of practice. The PBD formulations developed for PED devices were implemented for simulated seismic retrofit of a representative code-compliant masonry infilled R/C frame with a 'soft' ground story using friction dampers as the PED device. Non-linear dynamic analyses of the retrofitted masonry infilled R/C frames is performed to investigate the efficacy and accuracy of the proposed energy based plastic analysis procedure in achieving the target performance level under design level earthquakes. Results of non-linear dynamic analyses demonstrate that the maximum inter-story drifts in the masonry infilled R/C frames with a 'soft' ground story that is retrofitted with the friction dampers designed using the proposed PBD formulations are controlled within the target drifts under near-field as well far-field earthquakes.

***Keywords*—**Energy Methods, Masonry Infilled Frame, Near-field Earthquakes, Seismic Protection, Supplemental damping devices.

I. Introduction

THE international standards for earthquake resistant design of buildings are continually evolving over the world with the lessons learnt from experiences of the seismic performance of existing code compliant building structures in recent and past earthquakes. A particular configuration of engineered masonry infilled R/C frame structures that was observed to suffer severe damage and in some cases complete collapse in the Bhuj earthquake (2001) in Gujarat (India) and the Turkey earthquake (1999) in Adapazari (Turkey) was the one in which the masonry infill panels are discontinued above the base for reasons of functionality to create an open story, commonly known as a 'soft' or 'weak' story at the base of the building.

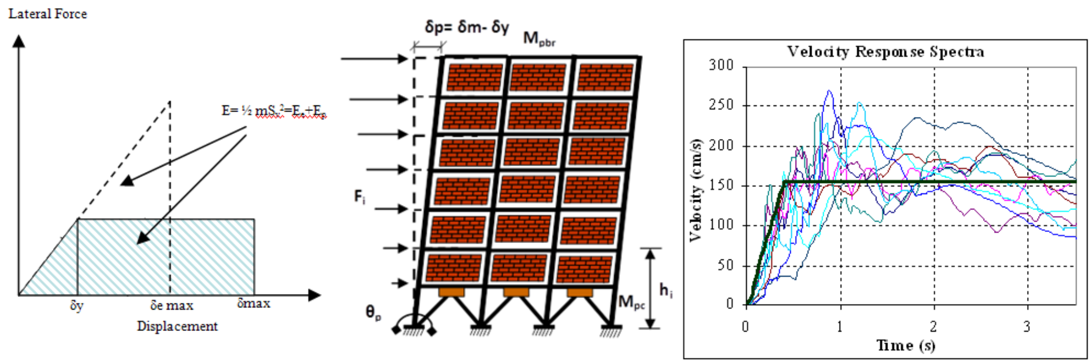
While planning the architecture of these buildings, the masonry panels were omitted at the base for functional purposes such as providing parking spaces at the ground level resulting in a structural configuration wherein the columns at the base act as stilts (stilt columns). The entire building mass is supported on these stilt columns, which therefore are subjected to excessive strength and ductility demands in the event of a seismic event. In 1897, north-eastern Assam in India experienced an earthquake with epicenter at Shillong (north-east India) measuring 8.6 on the Richter scale, one of the strongest ground shaking measured anywhere in the world. The 'Science' magazine in a recent issue reported that there is a substantial evidence to show that one or more of such great Himalayan earthquakes may be overdue in the Himalayan arc threatening millions of people, many of them in the cities, towns and villages of the Indo-Gangetic plains of north and central India [1]. A large proportion of existing masonry infilled R/C framed building structures were constructed in the last decade of 1900s with a 'soft' ground story and are designed in accordance with the revisions of the India seismic design code prior to 2002. Hence, the seismic design of these building structures completely disregards the higher strength and ductility demand on the ground story columns due to the 'soft' story effect. It is, therefore, evident that the existing masonry infilled R/C framed building structures constructed with a 'soft' ground story prior to 2002 are highly vulnerable to 'soft' story failures in the event of a design level earthquake defined by the current seismic design code. In the event of a near-field (near-fault or near-source) earthquake ground motion, the seismic vulnerability of such buildings would be further amplified due to the long period velocity pulses observed in near-field earthquake ground motions. In general, most of the existing masonry infilled R/C frame structures with an irregular distribution of masonry infill panels over the frame elevation that were constructed prior to this century would fail to comply with the more stringent design criteria specified by the current seismic design codes for such structures and thus present an urgent need for seismic retrofit and strengthening.

Alok Madan is a Professor with the Department of Civil Engineering, Indian Institute of Technology, Delhi, Hauz Khas, New Delhi – 110 016 (phone: +91 11 26591237; fax: +91 11 2658 1117; e-mail: madan@civil.iitd.ac.in).

Arshad K. Hashmi was Ph. D. Candidate with the Department of Civil Engineering, Indian Institute of Technology, Delhi, Hauz Khas, New Delhi – 110 016 (e-mail: arshadnnd@yahoo.co.in).

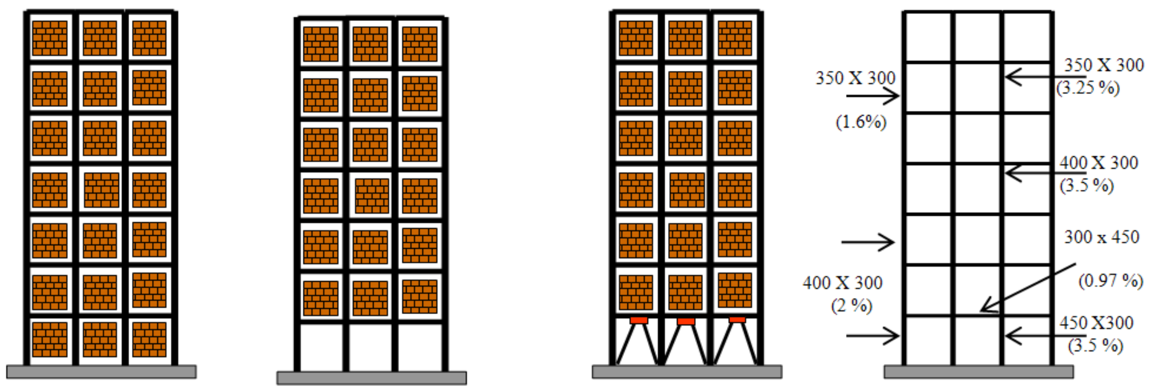
II. Literature Review

Passive energy dissipation (PED) devices have been successfully implemented in buildings around the world to control the structural response under dynamic loads such as wind and earthquake [2]. In North America, PED devices have been implemented in over a hundred buildings for retrofitting of existing buildings as well as in new construction [3]. The basic idea of using a passive energy dissipation device is to concentrate as much of the input energy dissipation as possible into specially designed devices rather than allow the energy to be absorbed by the structural elements thus reducing the seismic damage in the structure. A comprehensive review of the state-of-the-art and practice in application of energy dissipation devices for passive structural control is presented by [3]. A review of the literature published after 2002 presents quite a few subsequent innovative research studies on the application of passive energy dissipation (PED) devices and systems in structural control. Reference [4] proposed an improvised design of the viscous damper with lever arms provided to magnify the drift and drift velocities transferred from the structure to dampers thus effecting larger energy dissipation in smaller devices. Reference [5] presented a new passive structural control technique using sliding friction layers and viscous dampers for dissipating the input seismic energy in existing buildings augmented with additional floors constructed on the rooftop. Reference [6] proposed an improvised design of the original added damping and stiffness (ADAS) device [7] by integrating a rhombic steel plate of low yield strength (LYS) steel with ADAS for enhanced seismic resistance. Reference [8] proposed an application of shape memory alloys (SMAs) for development of PED devices using TiNi SMA rings as passive damping devices. Reference [9] presented an analytical investigation of the seismic performance of PED systems during pulse type near-field earthquake ground motions using pulse response spectra and energy balance analysis. Reference [10] proposed a new friction and homogenous tuned mass damper device for bi-directional passive control of earthquake induced vibrations. Reference [11] present the results of seismic response analysis of structures with velocity-dependent PED devices such as viscous and visco-elastic dampers taking into account the effect of stiffness of the connecting braces.



(a) Energy Balance Concept (b) Multi bay Frame with Selected Global Plastic Mechanism (c) Pseudo-Velocity Response Spectra of the Scaled Earthquake Ground Motion Records

Fig. 1 Methodology for Energy Based Plastic Analysis for Performance Based Design of Multistory Multi-bay Masonry Infilled Reinforced Concrete (R/C) Frame



(a) Completely Infilled Frame (b) Infilled Frame without Infill Panels in First Story (Soft Story) (c) Retrofitted Infilled Frame without Infill Panels in First Story (Soft Story) (d) Dimensions and Reinforcement Details of Code-Compliant R/C Frame with soft ground story

Fig. 2 Practically Relevant Distributions of Masonry Infill Panels along the Elevation of Planar Masonry Infilled Reinforced Concrete (R/C) Frame and Details of Code Compliant Masonry Infilled R/C Frame with soft ground story

A review of the literature on passive energy dissipation (PED) devices and systems for structural control indicates that there is no reported research study on performance based design of PED devices using energy methods for structural control of building structures. Limited research studies have been reported in the literature on performance based seismic design of building structures using energy methods [12]–[15]. However, none of the published research studies on performance based seismic design address the issue of performance based seismic retrofit of existing building structures using energy methods. Moreover, none of the studies consider reinforced concrete (R/C) frames. There is thus a need for a rational methodology for performance based seismic retrofit of existing masonry infilled R/C framed building structures. The present study is based on the application of energy methods for performance based design of passive energy dissipation (PED) devices for the purpose of seismic retrofit of masonry infilled R/C framed building structures, the most common building stock in urban India and many other countries around the world.

III. Energy Based Plastic Analysis Procedure for Performance Based Seismic Retrofit of R/C Frames Using PED Devices

The energy balance concept used in the present study for performance based seismic design is based on the assumption that the energy expended in monotonically pushing a building structure up to a maximum target deformation is equal to the maximum earthquake input energy of an equivalent elastic system [14]. Fig. 1 (a) illustrates the energy balance concept. Considering a multi-story three bay moment resisting frame with a selected global plastic mechanism in Fig. 1 (b), the proposed energy based plastic analysis procedure for performance based design of passive energy dissipation (PED) devices for a seismic retrofit of the frame is based on the following assumptions:

(i) the plastic deformation takes place after the structure reaches its plastic collapse mechanism,
(ii) for the selected yield mechanism of the frame structure shown in Fig. 1 (b), the drift of the frame is uniform over the height of the structure,
(iii) entire input seismic energy is dissipated only in the plastic hinges and the PED devices, if any,
(iv) the hysteretic response of the PED devices used to retrofit the frame is velocity independent and a numerical hysteresis model is available for the device.

Using the above assumptions, the inelastic drift can be related to the plastic rotation θ_p of the frame, i.e., the inelastic story drift approximately equals the plastic rotation of the frame.

Reference [16] showed that the plot of pseudo velocity versus the natural time period of a structural system tends to remain practically constant over a wide range of time periods for typical earthquakes, particularly, for a pseudo velocity spectrum that is obtained by averaging several response spectra of earthquakes with similar intensities. Based on this assumption, Reference [16] showed that the maximum earthquake input energy for a multi degree-of-freedom system on the average can be estimated as

$$E = \frac{1}{2} M S_v^{\,2} = \frac{W g a^2 T^2}{8\pi^2} \qquad (1)$$

where, M = total system mass; S_v = peak relative pseudo velocity from the elastic response spectra, a = peak pseudo acceleration normalized with respect to g (acceleration due to gravity), W = weight and T = fundamental time period.

The energy balance equation (1) provides a rational basis for designing PED devices for performance based seismic retrofit of masonry infilled R/C frames with a 'soft' first (ground) story [Fig. 2] under the action of near-field as well as far-field earthquakes. Another important component of the energy balance equation is the elastic energy E_e. Based on the results of several dynamic analyses, Reference [17] showed that the elastic energy E_e can be predicted with a reasonable accuracy by replacing the multi-degree-of-freedom structure by an equivalent single-degree-of-freedom system thus resulting in the following formulation for the elastic energy:

$$E_e = \frac{1}{2} m \left(\frac{T}{2\pi} \cdot \frac{V_y}{W} \cdot g \right)^2 \qquad (2)$$

where, V_y is the horizontal seismic base shear at which the selected yield mechanism of the frame structure is formed and is termed as the yield base shear in the present study.

The total energy $E_{dissipate}$ that the retrofitted structure needs to dissipate during the earthquake excitation can be found by subtracting the elastic energy from the earthquake input energy. Using (1) and (2):

$$E_{dissipate} = \frac{W T^2 g}{8\pi^2} \left[a^2 - \left(\frac{V_y}{W} \right)^2 \right] \qquad (3)$$

For energy balance, the energy expressed in (3) should be equal to the sum of the energy dissipated in the plastic hinges of the structure and hysteretic energy dissipated by the PED devices if such devices are implemented. For the selected plastic mechanism of the frame shown in Fig. 1 (b), assuming that all the beams at any given level have the same plastic moment capacity and the plastic moment capacities of all columns at the base are equal, the internal energy dissipated in the plastic hinges may be calculated for a target drift level as:

$$E_p = \left(\sum_{i=1}^{n} 2 n_b M_{pbi} + (n_b + 1) M_{pc} \right) \theta_p \qquad (4)$$

where, n is the number of beam levels in the frame, M_{pbi} is the plastic moment capacity of beam at level i, n_b is the number of bays in the frame elevation, M_{pc} is the plastic moment capacity of columns at the base of the structure and θ_p is the plastic drift of the structure obtained by subtracting the elastic drift from the target drift level as:

$$\theta_p = \theta_{target} - \theta_e \quad (5)$$

For the selected yield mechanism of the frame [Fig. 1 (b)], the total internal energy $E_{dissipate}$ dissipated by the retrofitted structure is obtained as the sum of plastic energy dissipated in the plastic hinges of the frame and hysteretic energy dissipated in the PED system as follows:

$$E_{dissipate} = \left(\sum_{i=1}^{n} 2n_b M_{pbi} + (n_b + 1) M_{pc} \right) \theta_p + E_{PED} \quad (6)$$

where, E_{PED} is the hysteretic energy dissipated in the PED system

Equating the total internal work done in the plastic hinges and the PED system to the external work done by the equivalent external inertial forces due to the earthquake excitation:

$$\left(\sum_{i=1}^{n} 2n_b M_{pbi} + (n_b + 1) M_{pc} \right) \theta_p + E_{PED} = \left(\sum_{i=1}^{n} F_i h_i \right) \theta_p \quad (7)$$

in which, F_i is the equivalent inertial force acting at level i due to the earthquake corresponding to the yield base shear of the structure and h_i = height of the beam level i from the ground.

Assuming an inverted triangular (linear) distribution of lateral earthquake forces over the height of the building structure [18], the earthquake inertial forces at level i at the formation of the selected yield mechanism in the frame can be related to the yield base shear by

$$F_i = \frac{w_i h_i}{\sum_{j=1}^{n} w_j h_j} \cdot V_y \quad (8)$$

where, w_i = weight of the i^{th} floor assumed to be lumped at level I and V_y is the yield base shear.

The vertical distribution of lateral earthquake forces recommended by [18] corresponds to the assumed shape of the first mode of vibration for a frame structure with the selected global yield mechanism resulting from a "columns stronger than beams" seismic design philosophy. Using (6), (7) and (8), (3) can be expressed as:

$$\frac{V_y}{W} \left(\frac{\sum_{i=1}^{n} w_i h_i^2}{\sum_{i=1}^{n} w_i h_i} \right) \frac{\theta_p 8\pi^2}{T^2 g} = \left[a^2 - \left(\frac{V_y}{W} \right)^2 \right] \quad (9)$$

Equation (8) is quadratic in terms of $\frac{V_y}{W}$ with the following admissible solution:

$$\frac{V_y}{W} = \frac{-\alpha + \sqrt{\alpha^2 + 4a^2}}{2} \quad (10)$$

in which, α is a non-dimensional parameter which depends on the stiffness, modal parameters and the intended plastic drift level of the structure and may be written as:

$$\alpha = \left(\frac{\sum_{i=1}^{n} w_i h_i^2}{\sum_{i=1}^{n} w_i h_i} \right) \frac{\theta_p 8\pi^2}{T^2 g} \quad (11)$$

Equation (10) provides the target yield base shear for the retrofitted frame, a measure of the seismic strength demand on the frame, based on the fundamental energy balance equation (1) to achieve the target drift level of the frame that is related to the plastic drift θ_p by (5). The hysteretic energy E_{PED} that needs to be dissipated by the PED devices to meet the target performance level of the retrofitted structure may be calculated by subtracting the plastic energy from the total energy that has to be dissipated by the retrofitted structure. Substituting from (3) into (6) and rearranging terms:

$$E_{PED} == \frac{WT^2 g}{8\pi^2} \left[a^2 - \left(\frac{V_y}{W} \right)^2 \right] - \left(\sum_{i=1}^{n} 2n_b M_{pbi} + (n_b + 1) M_{pc} \right) \theta_p \quad (12)$$

Solving for the yield base shear V_y for a selected target drift level using (5), (10) and (11), the required hysteretic energy dissipation by the PED system can be computed using (12). In principle, therefore, for a selected target drift of the retrofitted structure, the design properties of the PED system can be estimated to achieve the required hysteretic energy dissipation by the PED system within the target drift.

IV. Performance Based Design of Friction Dampers Using Energy Method for Seismic Retrofit of Existing R/C Frame Structures

Earthquake engineering experts believe that Performance based Design (PBD) principles will be at the core of the next generation of seismic design codes [19]. The proposed energy based plastic analysis procedure presented in the foregoing section of the paper can be implemented for developing PBD formulations for different types of passive energy dissipation (PED) devices for the purpose of seismic retrofit of existing frame structures. For sake of simplicity, the development of PBD formulations for PED devices is illustrated in the present study using the example of friction dampers as the PED device. The multi-story three bay moment resisting frame shown in Fig. 1 (b) is retrofitted by installing a friction damper in each bay of the ground story of the frame using Chevron braces. The development of PBD formulations presented in this section is based on the following additional assumptions:

(v) The selected plastic yield mechanism of the moment resisting frame does not form until the lateral forces resisted by the friction dampers exceed the frictional slip loads of dampers since the frame is effectively braced against side-sway by the Chevron braces prior to the frictional slip in the dampers. Further, the frictional slip loads of all the friction dampers are assumed to be equal.

(vi) The lateral stiffness and strength of the Chevron brace are sufficiently large to result in negligibly small deformations in the brace for the frictional slip load of the damper.

For the selected plastic yield mechanism of the frame [Fig. 1 (b)], the internal energy dissipated $E_{dissipate}$ in the plastic hinges of the structure and the friction damper may be written as:

$$E_p = \left(\sum_{i=1}^{n} 2 n_b M_{pbi} + (n_b + 1) M_{pc} \right) \theta_p + n_d X h_1 \theta_p \tag{13}$$

in which, X is the unknown required slip load of each friction damper, n_d is the number of dampers, h_1 is the height of the first story of the frame.

Equating the total internal work done in the plastic hinges and the friction damper to the external work done by the equivalent external inertial forces due to the earthquake excitation:

$$\left(\sum_{i=1}^{n} 2 n_b M_{pbi} + (n_b + 1) M_{pc} \right) \theta_p + n_d X h_1 \theta_p = \left(\sum_{i=1}^{n} F_i h_i \right) \theta_p \tag{14}$$

in which, F_i is the equivalent inertial force at level i corresponding to the yield base shear of the structure and h_i = height of the beam level i from the ground.

Rearranging terms in (14), the required frictional slip load of each friction damper may be computed as:

$$X = \frac{\left[\left(\sum_{i=1}^{n} F_i h_i \right) - \left(\sum_{i=1}^{n} 2 n_b M_{pbi} + (n_b + 1) M_{pc} \right) \right] \theta_p}{n_d h_1 \theta_p} \tag{15}$$

Substituting from (8), (15) may be simplified as:

$$X = \frac{\left[\lambda V_y - \left(\sum_{i=1}^{n} 2 n_b M_{pbi} + (n_b + 1) M_{pc} \right) \right]}{n_d h_1} \tag{16}$$

where,

$$\lambda = \frac{\sum_{i=1}^{n} w_i h_i^{2}}{\sum_{i=1}^{n} w_i h_i} \tag{17}$$

It may be noted here that the plastic moment capacities of the beams M_{pbi} and columns M_{pc} in (16) are calculated based on the beam and column sections of the existing building structure that is identified for retrofitting and thus represent the strength capacity of the existing structure without the retrofit measures. On the other hand, the yield base shear V_y in (16) represents the strength demand that the retrofitted structure has to meet for achieving the target performance level (i.e. target drift) and is therefore calculated on the basis of the total energy $E_{dissipate}$ given by (3) that the retrofitted structure has to dissipate during the earthquake excitation. Solving for the yield base shear V_y for a target drift level using (5), (10) and (11), the required frictional slip load X of each friction damper can be computed using (16) and (17). The frictional slip load thus computed should be checked to verify that the total maximum frictional force in the friction dampers at the ground story does not exceed the horizontal seismic base shear required to form the selected plastic collapse mechanism of the frame [Fig. 1 (b)].

A. Performance Based Seismic Retrofit of Existing Multi-Story Multi-Bay Masonry Infilled R/C Frames Implementing Friction Dampers Designed Using the Energy Balance Concept

The performance based design (PBD) formulations developed for friction dampers in the previous section using the energy balance concept were implemented for performance based seismic retrofit of multi-story multi-bay masonry infilled reinforced concrete (R/C) framed structures with one of the seismically most vulnerable distribution of masonry infill panels over the frame elevation in which the infill panels are discontinued at the ground level for functional purposes thus resulting in an open story i.e. 'soft' and / or weak story at that level. The application of the proposed PBD formulations for seismic retrofit of masonry infilled R/C frames using friction dampers is based on the following additional assumptions:

(vii) The plasticity in the R/C frame elements is assumed to be concentrated at the plastic hinges for purposes of arriving at the first trial performance based design.

(viii) The yield mechanism selected in the formulation of the plastic analysis procedure [Fig. 1 (b)] is the dominant failure mode of the masonry infilled R/C frame. The assumption is realistic if the shear reinforcement (stirrups or hoops) in the R/C frame are designed and detailed to prevent shear failure of the R/C frame elements considering the concentrated shear forces due to the infill panels at the frame-infill interface, particularly near the beam-column joints and the increased shear forces due to the friction dampers.

(ix) The local plastic collapse mechanisms such as the beam mechanism are prevented by adopting suitable retrofitting techniques,

(x) The stiffness degradation, strength deterioration and hysteretic energy dissipation in the infill panels under cyclic load reversals may be neglected in the energy based plastic analysis procedure. The assumption should result in conservative design in most cases since the lateral strength of the masonry infills is neglected in the performance based design process while the lateral stiffness and yield deformation of the masonry infilled R/C frame is computed in the proposed methodology considering the structural effect of infills.

For sake of simplicity, the representative frame geometry shown in Fig. 2 is considered to illustrate the application of the proposed energy based plastic analysis procedure for performance based seismic retrofit of existing masonry infilled R/C frames using friction dampers. As shown in Figs. 2 (b) and (c), the seven story three bay masonry infilled R/C frame has an open i.e. 'soft' ground story that is retrofitted with three friction dampers one installed in each bay of the ground story using Chevron braces. The Chevron braces are the preferred choice for installation of the dampers as they allow overhead clearance in the ground story of the frame to serve the intended functional purposes for which the ground story was originally planned to be an open story. The existing masonry infilled R/C frame with the representative geometry and a open i.e. 'soft' ground story is assumed to be designed in compliance with the criteria specified by the latest revision of the Indian seismic design code [20] for such frames. Fig. 2 (d) presents the design dimensions and reinforcement details of the code-compliant masonry infilled R/C frame. For purposes of deriving the design input seismic energy in (1), the design pseudo-velocity can be calculated using the elastic design pseudo-acceleration spectrum provided by the seismic design codes as follows:

$$S_v = \frac{T}{2\pi} ag \tag{18}$$

where, T = fundamental time period, g acceleration due to gravity and a is the peak pseudo acceleration normalized with respect to g that can be obtained from the elastic design pseudo-acceleration spectrum of the Indian seismic design code last revised in 2002 [20].

The proposed PBD methodology formulated on the basis of the energy balance concept for seismic retrofit of masonry infilled R/C frames requires estimates of the yield drifts of the frames, since the yield drift of the frame equals the maximum elastic rotation for the yield mechanism of the frame that is selected for the proposed energy based plastic analysis procedure and needs to be assumed in the PBD process. The yield drifts of the masonry infilled R/C frames were estimated in the present study by performing a non-linear pushover analysis of the code-compliant design of the frame using rational and realistic non-linear macro-element models for the frame elements and masonry infills [21], [22]. The yield drift estimated from the pushover analysis of the code-compliant masonry infilled R/C frame is assumed as the elastic rotation θ_e of the frame in the proposed energy based plastic analysis procedure. Selecting a target drift level θ_{target} for the performance based seismic retrofit; the limiting plastic drift θ_p is obtained using (5). The fundamental period T of the retrofitted frame is estimated considering the lateral stiffness of the damper-brace assemblies. Subsequent to calculating the limiting plastic drift, the peak normalized pseudo acceleration and the fundamental period of retrofitted structure, the target yield base shear V_y for the retrofitted frame is computed using (10) and (11). Finally, the frictional slip load of each friction damper required to achieve the target performance (drift) level of retrofitted frame is computed using (16) and (17).

B. Trial Performance Based Design of Friction Dampers for Seismic Retrofit of Representative Masonry Infilled R/C Frame with a 'Soft' Ground Story

To validate the proposed energy based plastic analysis procedure for performance based seismic retrofit of masonry infilled R/C frames, the performance based design (PBD) formulations developed for friction dampers in the present study were implemented for a simulated trial performance based seismic retrofit of the representative masonry infilled R/C frame with a 'soft' ground story [Fig. 2 (c)] for a target drift level of 2% in the retrofitted frame. It may be mentioned that the selected target drift level conforms to the performance limit state of life safety (LS) in accordance with global acceptance criteria defined by [23] and [24]. Table I summarizes the values of the salient design variables computed in the course of the proposed energy based plastic analysis procedure for performance based design of the friction dampers. Assuming a lateral stiffness of 660 kN / mm for the damper-brace assembly, the required frictional slip load of each damper was calculated using the performance based design methodology described in previous section as 379 kN for specified target drift level of 2% in the retrofitted R/C frame corresponding to performance limit state of life safety (LS). Similarly computed values for specified target drift levels of 1% and 4%, corresponding to performance limit states of immediate occupancy (IO) and collapse prevention (CP), respectively, are also included in table.

V. Displacement Based Seismic Evaluation of Representative Masonry Infilled R/C Frames Retrofitted Using Friction Dampers

In order to evaluate the seismic performance of the masonry infilled reinforced concrete (R/C) frames retrofitted with friction dampers designed using the proposed performance based design methodology, non-linear dynamic analyses of the retrofitted masonry infilled R/C frame was performed using rational and realistic hysteretic models of the R/C frame elements and masonry infill panels [21], [22]. For purposes of comparison, the seismic performance of the corresponding un-retrofitted masonry infilled R/C frame was also assessed by performing non-linear dynamic analyses of the code-compliant design of the frame without friction dampers. The non-linear dynamic analyses were performed using eight recorded earthquake ground acceleration records and one synthetic accelerogram. The recorded earthquake ground motions of Bhuj (India, 2001), Elcentro (1940), SanFernando (1971) and Chile (1985) earthquakes considered in the dynamic analysis are far-field ground motions, while the Northridge (1994), Tabas (Iran, 1978), Erzincan (Turkey, 1992) and Chi Chi (Taiwan, 1999) ground motions are near-field ground motions. All the recorded ground motions used for the dynamic analysis were scaled to achieve the same intensity as that of the ideal design level (design basis) earthquake specified by the revised Indian seismic design code [20]. The method used in the present study for scaling the earthquake records to represent the code-specified design earthquake is based on the definition of spectrum intensity by [25]. Fig. 1 (c) displays the pseudo-velocity response spectra of scaled earthquake ground motion records. The synthetic ground motion was artificially generated to be compatible with the design response spectrum provided by the Indian seismic design code.

A. Results of Nonlinear Dynamic Analysis and Interpretation

Fig. 3 (a) displays the variations of the peak normalized inter-story drifts in percentage terms over the height of the code-compliant R/C frame without any retrofitting devices as predicted by the non-linear dynamic analysis under the influence of the nine earthquake ground excitations. It can be observed from figure that the maximum interstory drifts of the code-compliant masonry infilled R/C frame with a ‘soft’ ground story (without any infill panels in the ground story) range from 2.5% to 6% for the different earthquake ground excitations. Fig. 3 (b) shows similar plots of variation of the peak normalized inter- story drifts in percentage terms over the height of the masonry infilled reinforced concrete (R/C) frame with a ‘soft’ ground story retrofitted with friction dampers for a target drift of 2% as predicted by the non-linear dynamic analyses under the action of the nine earthquake ground excitations. It is evident from Fig. 3 that the maximum inter-story drifts in the masonry infilled R/C frame with a ‘soft’ ground story that is retrofitted using the trial performance based designs of the friction dampers are within the target drift of 2% for all stories for all the earthquake ground motions with the exception of Chi Chi and Tabas earthquakes ground motion for which the inter-story drift at the second level marginally exceeds the target drift. The marginal deviation from the target performance level in case of the Chi Chi and Tabas earthquakes may be neglected for practical applications. The results of maximum inter-story drifts presented in Fig. 3 demonstrate that the first trials of performance based design of the friction dampers meet the target performance level for all practical purposes. Hence, a second trial by increasing the design frictional slip load of the dampers is not required.

Another important interpretation that can be derived from the results presented in Fig. 3 is that the application of the proposed energy based plastic analysis procedure for performance based seismic retrofit of masonry infilled R/C frames using friction dampers is successful in limiting the inter-story drifts within the target drift of 2% under the influence of near-field earthquakes as well far-field earthquakes. Figs. 3 (c) and (d) show plots of variation of the peak normalized inter-story drifts in percentage terms over the height of the masonry infilled reinforced concrete (R/C) frame with a ‘soft’ ground story retrofitted with friction dampers for target drifts of 1% and 4 %, respectively, as predicted by the non-linear dynamic analyses under the action of the nine earthquake ground excitations. While the peak normalized story drifts in the latter case [Fig. 3 (d)] are limited within the target drift level of 4% at all levels of the frame structure, the story drifts in the former case [Fig. 3 (c)] exhibit an interesting trend. The representative masonry infilled R/C frame with a ‘soft’ ground story retrofitted with friction dampers designed for a target drift level of 1% using the proposed energy approach is predicted to display story drifts as large as 1.5 – 3.5% at level 3 of the frame [Fig. 3 (c)] even though the story drift at the ground level is controlled well within the target drift level of 1%. The discrepancy may be attributed to an inherent deficiency in the code-compliant design of the masonry infilled R/C frame due to which the stories of the code-compliant frame above the ‘soft’ ground story do not have adequate lateral strength for limiting the story drifts within the desired 1% drift level. In any case, the excessive story drifts predicted at higher levels by non-linear dynamic analysis may be controlled by retrofitting higher stories also to achieve the desired performance level in entire frame.

VI. Concluding Remarks

The paper presents a plastic analysis procedure based on the energy balance concept for performance based seismic retrofit of multi-story multi-bay masonry infilled reinforced concrete (R/C) frames using passive energy dissipation (PED) devices. The proposed energy based plastic analysis procedure was implemented for developing performance based design (PBD) formulations for friction dampers used for seismic retrofit of existing moment resisting frame structures with a ‘soft’ ground story. The results of the non-linear dynamic analyses demonstrate that the maximum inter-story drifts in the masonry infilled R/C frame with a ‘soft’ ground story that is retrofitted using the trial performance based designs of the friction dampers for target drift levels of 2% and 3% are controlled within the respective target drifts for all stories with a marginal discrepancy in case of one earthquake ground motion. The results thus lead to the conclusion that the first trials of performance based design of friction dampers using the proposed energy based plastic analysis procedure meet the target performance level of life safety for all practical purposes and a second trial by increasing the design frictional slip load of the dampers is therefore not required.

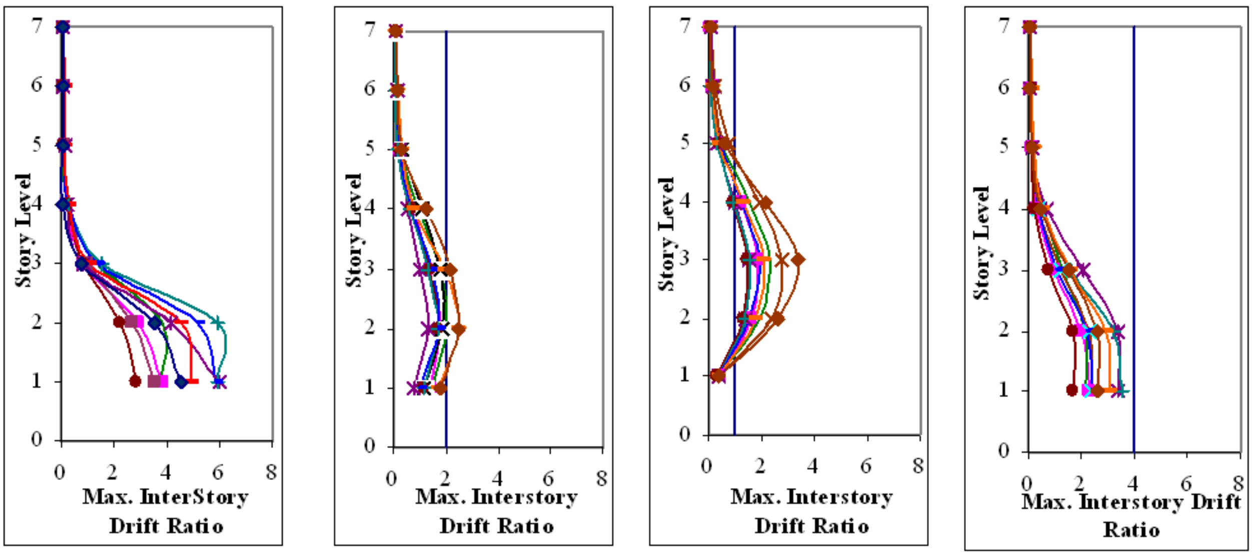
TABLE I
DESIGN VARIABLES COMPUTED FOR PERFORMANCE BASED DESIGN OF PASSIVE ENERGY DISSIPATION DEVICES USING PROPOSED ENERGY BASED PLASTIC ANALYSIS PROCEDURE

(A)

Assumed Yield Drift , Φe%	0.7
Fundamental Period, T (s)	0.4
Weight of Structure at Level i, Wi (kN)	441
Design pseudo-acceleration(g), a	2.4
Plastic moment of column at base of Structure, Mp (kNm)	401
Plastic Moment of Beam First Story Level, Mpbi (kNm)	101
Height of Story Level , h_i (m)	3
Number of Dampers, $n_{d,}$	3
Number of Bays, $n_{b,}$	3

(B)

Design Parameters for PBD of Friction Dampers fr Seismic Retrofit of Soft First (Ground) story of Masonry Infiilled R/C Frame	Infilled Frame Retrofitted at First Story for Target Drift of 2%	Infilled Frame Retrofitted at First Story for Target Drift of 1%	Infilled Frame Retrofitted at First Story for Target Drift of 4%
Target rotation, Φt%	2	1	4
Plastic rotation Φp%	1.3	0.3	3.3
Design Base Shear Parameter, α	11.06	2.54	19.47
Base Shear coeff., V/W	0.294	0.952	0.169
Base Shear, V (kN)	908	2940	522.76
Required Slip Load of each friction Damper, *X* (kN)	379	808	140



(a) Infilled Frame without Infill Panels in First Story

(b) Infilled Frame without Infill Panels in First Story (Target Drift 2%)

(c) Infilled Frame without Infill Panels in First Story (Target Drift 1%)

(d) Infilled Frame without Infill Panels in First Story (Target Drift 4%)

Fig. 3 Variation of Peak Normalized Inter-Story Drifts in percentage terms over height of Unretrofitted and Retrofitted Masonry Infilled R/C frame with 'Soft' Ground Story

A more important conclusion that can be derived from the results of non-linear dynamic analyses is that the application of the proposed energy based plastic analysis procedure for performance based seismic retrofit of masonry infilled R/C frames using friction dampers is as effective in controlling the inter-story drifts of the R/C frame within the specified target drifts under the influence of near-field earthquakes as far-field earthquakes. Non-linear dynamic analysis of the representative code compliant masonry infilled reinforced concrete (R/C) frame with a 'soft' ground story that is retrofitted with friction dampers designed using the proposed performance based design methodology for target drift levels of 1% predicts excessive inter-story drifts in the frame at levels above the retrofitted 'soft' ground story even though the peak normalized story drift in the retrofitted ground story is predicted to be controlled well within the target drift level.

The excessive inter-story drifts point to an inherent deficiency of the prevalent force based design methodology provided by the current generation of seismic design codes that the inelastic displacement demands of the earthquake are disregarded in the force based design formulations provided by current seismic codes. Moreover, the force based design formulations provide by the current seismic design codes do not incorporate any limitation on the maximum plastic drift of the structure. The proposed performance based design methodology using the energy approach offers an engineering solution to the inverse problem of determining the hysteretic energy that needs to be dissipated by PED systems used for retrofitting framed building structures to achieve the specified performance objective by the retrofitted building for a given seismic hazard level. The proposed energy approach is more rational and realistic for performance based design of PED systems for seismic retrofit of existing building structures subjected to near-field as well as far-field earthquakes since the approach is based on the fundamentals of energy balance.

References

[1] Bilham, R., Gaur, V. K., and P. Molnar, P. (2001) "Himalayan Seismic Hazard." Science, 293(5534), 1442-44.
[2] Towashiraporn P., Park J., Goodno B.J. and Craig J.I. (2002). " Passive Control Methods for Seismic Response Modification." Progress in Structural Engineering and Materials, 4(1), 74-86
[3] Soong T.T. and Spencer Jr. B.F. (2002). "Supplemental energy dissipation: state of art and state of practice." Engineering structures, 24(3), 243-59
[4] Ribakov Y. and Reinhorn A.M. (2003). " Design of Amplified Structural Damping using Optimal Consideration." Journal of Structural Engineering, 129(10), 1422-27
[5] Li., H., Wang, S.Y., Song, W. and Liu, G. (2004). "Reduction of Seismic Forces on Existing Buildings with Newly Constructed Additional Stories Including Friction Layer and Damper." Journal of Sound and Vibration , 269(3), 653-67
[6] Shih, M. H. and Sung W.P. (2005). " A Model for Hysteretic Behavior of Rhombic Low Yield Strength Steel Added Damping And Stiffness." Computers and Structures, 83(12), 895-908.
[7] Tsai C.S., Le H.H. (1993). "Application of Viscoelastic Dampers to High-Rise Buildings." Journal of Structural Engineering, 119(4), 1222-33.
[8] Dong Y.S., Xiong J.L., Li A.Q., Lin P.H. (2006). " A Passive Damping Device with TiNi Shape Memory Alloy Rings and its Properties." Material Science and Engineering, A 416, 92-97
[9] Xu, Z., Agrawal, A.K., He, W.L. and Tan, P.(2007). " Performance of Passive Energy Dissipation Systems during Near-Field Ground Motion Type Pluses." Engineering Structures, 29(2), 224-36.
[10] Almazan J.L., Llera J.C.D.L., Inaudi J.A., Garcia, D.L. and Izquierdo L.E. (2007). " A Bidirectional and Homogeneous Tuned Mass Dampers: A New Device for Passive Control of Vibrations." Engineering Structures, 29(7), 1548-1560
[11] Ou, J.P., Long, X. and Li, Q.S.(2007). "Seismic Response Analysis of Structures with Velocity- Dependent Dampers." Journal of Constructional Steel Research, 63(5),628-38
[12] Choi, B.J. and Shen J.H. (2001). "The Establishing Of Performance Level Thresholds for Steel Moment-Resisting Using an Energy Approach." The Structural Design of Tall Buildings, 10(1), 53-67.
[13] Akbas, B. Shen J. and Hao, H. (2001). " Energy Approach in Performance Based Seismic Design of Steel Moment Resisting Frames for Basic Safety Objective." The Structural Design of Tall Buildings, 10(3), 193-217.
[14] Leelataviwat, S., Goel, S.C., and Stojadinovic, B. (2002). " Energy-Based Seismic Design of Structures using Yield Mechanism and Target Drift." Journal of Structural Engineeing, 128(8), 1046-1054.
[15] Surahman, A. (2007). "Earthquake-Resistant Structural Design Through Energy Design and Capacity." Earthquake Engineering and Structural Dynamics, 36(14), 2099-2117.
[16] Housner, G.W.(1956). "Limit Design of Structures to Resist Earthquakes." Proceeding of 1st world conference on earthquake engineering, Earthquake Engineering Research Institute, Oakland, California, 5, 1-13.
[17] Kato, B., and Akiyama, H. (1982). " Seismic Design of Steel Buildings" Journal of Structural Division, ASCE, 108(8), 1709-1721
[18] IBC (2006), International Building Code, ICC.
[19] Kunnath, S. K. (2006), "Performance-based Seismic Based Design and Evaluation of Building Structures." Earthquake Engineering for Structural Design, ed. Chen, W. F. and Lui, E. M., CRC press, © 2006 by Taylor and Francis Group, Oxfordshire, England.
[20] BIS (2002)."IS 1893-2002(Part 1): Indian Standard Criteria for Earthquake Resistant Design of Structures, Part 1-General Provisions and Buildings." Bureau of Indian Standards, New Delhi, India.
[21] Valles, R. E., Reinhorn, A. M., Kunnath, S. K., Li, C., and Madan, A. (1996). "IDARC Version 4.0 - A Program for the Inelastic Damage Analysis of Buildings." Technical Report NCEER-96-0010, SUNY/Buffalo.
[22] Madan, A., Reinhorn, A. M., Mander, J. B., Valles, R. (1997). "Modeling of Masonry Infill Panels for Structural Analysis." Journal of Structural Engineering, 123 (10), 1295 - 1302.
[23] ATC-40 (1996)."Seismic Evaluation and Retrofit of Concrete Buildings." Report SSC 96-01, California Seismic Safety Commission, Applied Technology Council, Redwood, CA, USA.
[24] FEMA-356 (2000), "Prestandard and Commentary for Seismic Rehabilitation of Buildings", Federal Emergency Management Agency (FEMA), Washington D. C., USA.
[25] Housner, G. W. (1959). "Behavior of structures during earthquakes." Journal of Engineering Mechanics, 85(4), 109-129