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APPLICATION OF PASSIVE DEVICES FOR THE RETROFITTING OF REINFORCED CONCRETE STRUCTURES

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ABSTRACT

In contrast with previous proposals of using energy dissipation devices in the joints of added bracing, a new redesign technique based on the introduction of passive devices in the vicinity of the expected plastic hinges of the original structure is proposed. Analytical studies of the technique as applied to RC structures are conducted using member and building models. The efficiency of the technique is evaluated by comparing the dynamic performance of the models in terms of deformation capacity and energy dissipation. Results indicate that the technique is effective in reducing the seismic vulnerability of RC framed buildings and may be considered an attractive alternative for the redesign of structures with deficient seismic performance. Limits of applicability of the technique are also highlighted.

KEYWORDS

seismic redesign; passive devices; friction devices; yielding devices; hysteretic damping.

INTRODUCTION

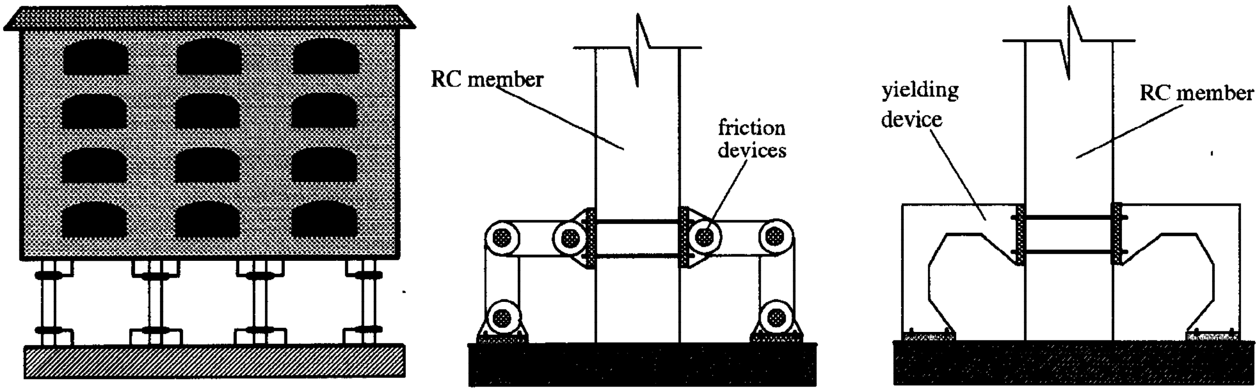
Many buildings designed according to inadequate seismic standards posses deficient ductility supply and poor energy dissipation capacity to withstand a major earthquake. Technical developments as well as socio-economic factors have led to an increasing interest in the development of redesign techniques for buildings with deficient seismic performance. In parallel with this, considerable attention has been given to the development of non-conventional redesign approaches such as the addition of steel bracing with passive energy dissipation devices (Pall and Marsh, 1981; Ciampi and Samuelli, 1990; Whittaker, *et al.* 1991; Grigorian, *et al.* 1992), the addition of post-tensioned steel bracing (Pincheira and Jirsa, 1992) and the incorporation of based isolation systems (Poole and Clendon, 1992). Although traditional and unconventional techniques may be structurally efficient, in some cases significant construction work and severe disturbance to the original function of the building are the side effects of these interventions. In this regard, there is still a need to develop economic redesign techniques that involve minimum disturbance and alteration of the intervened building. This paper describes a redesign technique that involves the addition of energy dissipation devices around the expected plastic hinges of RC framed structures. The main objective of this research work is to evaluate the efficiency and applicability of the proposed technique in terms of deformation capacity and energy dissipation.

PROPOSED NEW TECHNIQUE

A large number of passive devices with high energy dissipation capacity have been developed over the last two decades. In general, devices have been linked to main members of bracing systems and perform as enhanced semi-rigid connections with high hysteretic damping. Devices used in this way protect the main members of the lateral force resisting system (LFRS) by limiting the forces in these members while absorbing most of the hysteretic energy. Additionally, energy dissipation devices are carefully designed to be accessible and easily replaceable or retunable after a major event. In this way, the seismic design philosophy based on the use of energy dissipation devices relays on the explicit detailing and optimisation of the energy dissipation characteristics of the structure.

Although originally developed for new structures, the incorporation of steel bracing with energy dissipation devices has been proposed as a viable alternative for the retrofitting of existing structures. However, in some cases this approach may become structurally invasive and cause significant disturbance to the occupants. Additionally, due to severe disruption of the original functioning of the building the owner may have to face loss of income. Furthermore, due to this drastic intervention in the original LFRS, substantial increase of strength and stiffness may favour a significant increase of seismic forces and may result in costly retrofitting works in the foundation.

In an attempt to provide an alternative solution to the above problems, a new redesign technique based on the application of passive devices has been proposed (Martinez, 1992). As shown in Fig. 1 , the proposed technique incorporates passive devices around member regions with anticipated maximum rotation ductility demand. Under a major event, the main sources of energy dissipation are located in the plastic hinges and hence, the approach of the proposed technique is to deliberately activate complementary sources of energy dissipation around these critical regions. To avoid the use of both sophisticate technology and highly specialised materials, which may preclude the use of the proposed technique in developing countries, yielding and friction devices are considered the most appropriate in this case.



a). soft-storey with added passive devices aroud expected plastic hinges b). assembly of friction devices c). assembly of yielding devices

Fig. 1. Proposed Technique applied to a soft-storey building

ANALYTICAL CONSIDERATIONS FOR THE STUDY OF THE PROPOSED TECHNIQUE

Experimental studies on the hysteretic behaviour of friction and yielding devices have confirmed the adequacy of non-linear analysis techniques to predict the seismic behaviour of structures with friction and yielding devices. In particular, the observed hysteretic behaviour of the devices is stable and virtually elastoplastic, making the modelling of the devices predictable and reliable. In this research work, virgin an upgraded models are studied using a non-linear finite element program (Izzudin, 1990). The program follows a fibre element approach and accounts for geometric and material non-linearities. Elaborate constitutive models for steel (Popov and Peterson, 1978) and concrete (Martinez, 1995) are employed. This allows the explicit characterisation of hysteretic damping and the consideration of important cyclic material properties such as the effects of isotropic and kinematic hardening and the Bauschinger effect in steel, and continuous degradation of strength and stiffness in concrete.

Original RC members and yielding devices are modelled using inelastic elements, which are based on an elastoplastic cubic formulation, accounting for the spread of inelasticity across the transverse section and along the member length. Friction devices are modelled as elastoplastic joint elements in which the rotational behaviour is considered elastic-perfectly plastic, whereas axial and shear behaviour are considered elastic. The steel links of the assemblies of friction devices are designed to remain elastic and hence are modelled using elastic elements. Device strengths are described in terms of the rotational/flexural strength of the device M_d normalised with respect to the flexural capacity of the RC member under pure flexure M_o.

Two types of models are considered in the study. Virgin models represent an existing RC structure and are defined as an assembly of inelastic elements. Upgraded models represent the redesigned structure and are created by adding the corresponding elements representing the passive devices to the virgin models.
The FE program is unable to consider shear deformations. Hence, this study covers only structures in which it is valid to assume that shear deformations are of minor concern. Nevertheless, shear effects on deformation capacity are approximately accounted for in the evaluation of the rotation ductility supply by setting an upper limit to the analytical prediction of plastic hinge length as suggested by Paulay and Priestley (1992).

STUDY OF THE PROPOSED TECHNIQUE AT MEMBER LEVEL

A preliminary evaluation of the proposed technique at member level has been conducted using a simplified model consisting of a cantilever column with a lumped mass at the top (Martinez, 1990; Martinez and Elnashai, 1995). Only friction devices were used in this study. By using different combinations of transverse section and gravity load two virgin models were considered. One model showed critical response to El Centro 1940 NS record whereas the other to Mexico City 1985 SCT EW record. The proposed technique was successfully applied in these two cases corresponding to strong ground motion on stiff soil and soft soil respectively. In particular, the following attributes of the technique were identified:

- the upgraded models show moderate increase of both strength and stiffness and experienced significant response reduction.
- the hysteretic behaviour of the redesigned structure is more stable and presents reduced stiffness degradation.
- a significant amount of energy is dissipated by hysteresis in the passive devices and hence a smaller portion of the total dissipated energy is associated to damage in the original members.
- the main parameter controlling the response of the upgraded models is the device strength.
- to be effective, devices must posses high initial stiffness so that they can perform their task under small displacements, controlling damaging energy from the very beginning of the dynamic response.

Due to the use of a very simple material model for steel (elastic perfectly plastic) the spread of inelasticity along the member length was not properly modelled in the above study. Nevertheless, this study revealed the feasibility of the proposed technique and gave way to more comprehensive studies. The studies reported below have been performed using the multi-surface steel model of Popov and Peterson (1978). This allows a more reliable assessment of the proposed technique.

Detailed study under dynamic excitation

Fig. 2 shows the simplified model used for the study. The model is a cantilever RC column 2.5 m long with square section 0.5 m wide. Material strengths are f_c = 35 MPa for concrete and f_c = 400 MPa for steel. Longitudinal reinforcement is provided by 12 bars Φ 25 mm uniformly distributed. Transverse reinforcement consists of overlapped square and octagonal hoops Φ 10 mm uniformly spaced at 175 mm, providing a confinement factor estimated as 1.15. A concentrated mass of 92.7 Ton is lumped at the top of the column. The mass is equivalent to a vertical load equal to 25% of the column balanced load. Based on monotonic analyses the seismic coefficient and yield period of the virgin model were found to be 0.22 and 0.47 secs respectively. Rayleigh damping proportional to stiffness with damping ratio of 5% was included in the models. Plastic and monotonic analyses showed that for normalised device strengths greater than about 0.06 a plastic hinge no longer occurs at the column base region surrounded by the assembly of devices but right above the assembly. This condition marks the boundary between efficient and inefficient modes of failure of the upgraded models (Fig. 2) and is referred to as the limit of efficient device strength (LEDS).

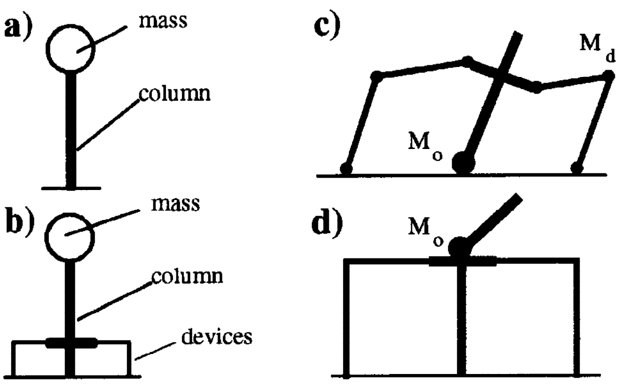


Fig.2. member models of the proposed technique and modes of failure. a) virgin model. b) upgraded model. c) efficient failure mode. d) inefficient failure mode.

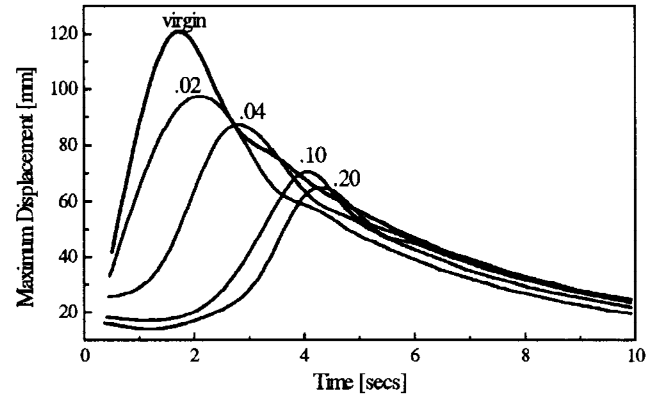


Fig.3. Envelope of lateral displacement under harmonic excitation.

Response under harmonic excitation. Fig. 3 shows envelopes of lateral response of virgin and upgraded models under sinusoidal excitation of constant amplitude (0.30 g) sweeping through a frequency domain of 5-15 Hz. Under this type of excitation pseudo resonance is built up in the models. Despite this critical acceleration time-history, the upgraded models show significant reduction of lateral response. It is also observed that for device strengths exceeding the LEDS, the rate of response reduction drops significantly.

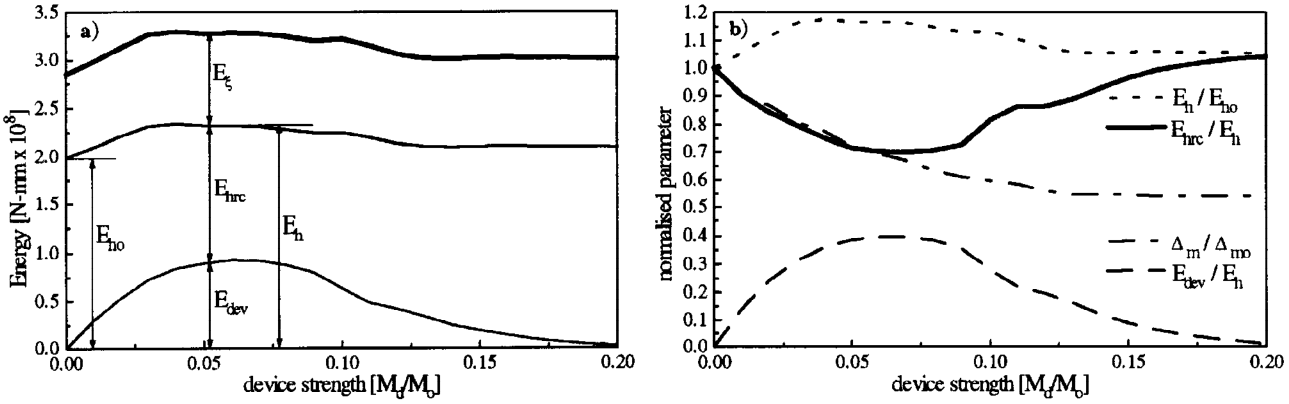


Fig. 4. Response comparison between virgin an upgraded models under harmonic excitation. a) Energy balance. b) Efficiency of proposed technique in terms of hysteretic energies and maximum displacement.

A detailed analysis of the energy balance at the end of the excitation provides insight on the devices participation in dissipating energy and allows a global comparison of performance between virgin and upgraded models. This energy analysis is shown in Fig. 4.a where only the hysteretic energy E_h and the damping energy E_ξ are considered. As confirmed by previous research on the evaluation of seismic energy in structures (Uang and Bertero, 1990), E_h and E_ξ are the major components balancing the energy input E_i. In general, E_h is considered as a good indicator of structural damage; however , for the upgraded models E_h can be decomposed in two components, i.e. the hysteretic energy absorbed by the existing RC members E_{hrc}

and the hysteretic energy dissipated by the added passive devices E_{dev} . As shown in Fig. 4, a significant proportion of E_h can be absorbed by the devices, particularly when these are tuned to a device strength close to the LEDS. Fig. 4.b shows that despite the fact that the introduction of devices results in an increase of E_h , significant reduction in E_{hrc} takes place. It is also evident from this figure that maximum device participation and maximum reduction in E_{hrc} occur when devices are tuned to the LEDS absorbing about 40% of E_h. This point of optimum device participation is also associated to an important reduction of the ratio Δ_m / Δ_{mo} , where Δ_m / Δ_{mo} are the maximum displacements for the upgraded and virgin models respectively. It is important to notice that the region with high device participation is rather flat. Hence, cheaper and more reliable solutions can be achieved tuning the devices to strength levels slightly lower than the LEDS. This gives some allowance for error associated to the estimation of the strength of the virgin structure, as well as, variations in the strength and tuning of the devices.

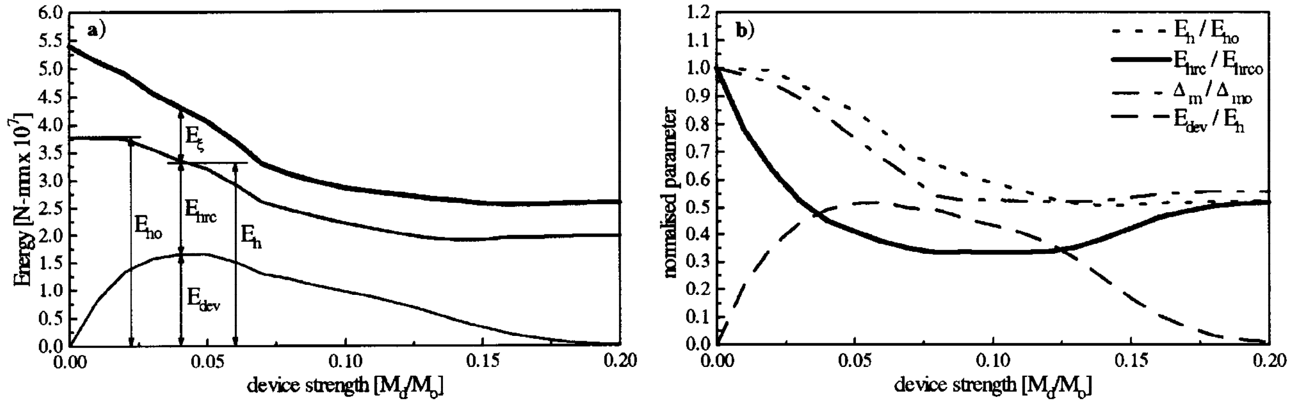


Fig. 5. Response comparison between virgin an upgraded models under seismic excitation. a) Energy balance. b) Efficiency of proposed technique in terms of hysteretic energies and maximum displacement.

Response under seismic excitation. The ground motion used in this case was the first 10 seconds of the record of El Centro 1941 NS, which has a PGA of 0.348 g. Fig. 5 compares the performance of virgin and upgraded models in terms of energy dissipation and maximum displacement. In contrast with the case of harmonic excitation, the energy input is markedly reduced in the upgraded models but the same overall trend in the participation of the devices is observed. In this case, when tuned at the LEDS, devices absorb as much as 50% of E_h. A more drastic reduction of E_{hrc} is observed (about 50% at LEDS condition). This may be attributed to the fact that in general, earthquake ground motions do not posses a frequency content with a distribution in the time-domain as critical as that used in the study under harmonic excitation. Hence, devices in this case are more effective in reducing the response of the upgraded models due to both slight modification of stiffness and added hysteretic damping. The fact that the optimum device strength is more associated to the available strength and ductility of the virgin structure than to the ground motion is advantageous. This implies that the proposed technique can be more easily applied because device tuning is rather simple. On the other hand, the low strength level of the LEDS implies that very low rotation restrain is introduced to the column region enclosed by the assembly of devices. This practically eliminates the risk of a drastic reduction of the shear span at this region which may lead to a more critical mode of failure governed by shear.

STUDY OF THE PROPOSED TECHNIQUE AT STRUCTURE LEVEL

A more comprehensive assessment of the proposed technique can only be performed studying a building model rather than a member model. Due to very limited ductility supply and energy dissipation capacity a soft-storey building posses one of the most critical LFRS under earthquake loading. Hence, a soft-storey building appears to be a critical candidate to validate the applicability and efficiency of the proposed technique. In this section, virgin and upgraded 2D models of a medium-rise soft-storey building are studied in detail. The building model represents a five-storey three-bay RC building which features a soft storey at ground level. The model is able to predict the variation of axial loads in the columns of the soft-storey. The increase in column axial loads due to the overturning moments of the upper storeys have a negative effect in the rotation capacity of the columns. This important feature has not being considered in the above studies at member level.

Parameters of the study

To cover a wide range of building cases, a number of response parameters with direct influence on ductility supply and ductility demand were considered. These included level of confinement provided by column transverse reinforcement, level of gravity loading and level of seismic action.

The confinement levels included are denoted as poor, moderate and high. The provisions for seismic design of the Building Code Requirements for reinforced concrete ACI 318-89 (ACI,1989) were used as a reference to define the high confinement level . Moderate and poor confinement levels were defined by relaxing the hoop separation required by the high confinement level. It should be noted that each level of confinement defines also a level of shear strength.

The gravity load levels considered are denoted as low, moderate and high. These are associated with axial loads in the soft-storey columns equal to 12.5%, 25% and 50% of the column balanced load respectively.

The seismic action levels refer to different degrees of ground motion intensity, and are defined in terms of a localised spectrum intensity evaluated within the range of potential periods of vibration of the structure. The shape of the design spectrum used as reference is the UBC 91 (1991) design spectrum for rock and stiff soils. The PGA values used to define the design spectra for the low, moderate and high levels of seismic action are 0.2g, 0.3g and 0.4g respectively. Several earthquake records were used to carry out the required time-history analyses. Three natural records, including El Centro 1940 NS, Taft 1952 S69E and St Monica 1994 EW in addition to one artificial record compatible with the Newmark-Blume-Kapur design spectra (Filiatrault and Cherry, 1990) were considered in the study.

Results

Different local and global failure criteria were considered for the evaluation of the deformation capacity of the building models. Local failure criteria included rotation ductility and shear demands exceeding inelastic rotation capacity and shear strength respectively. Global failure criteria included a lateral drift in excess of 2% and a drop in the overall lateral strength beyond 15%. To identify a critical record for each of the cases covered in the study, virgin structures were analysed using the four scaled records. The upgraded models were analysed under the same critical records identified for the virgin structures.

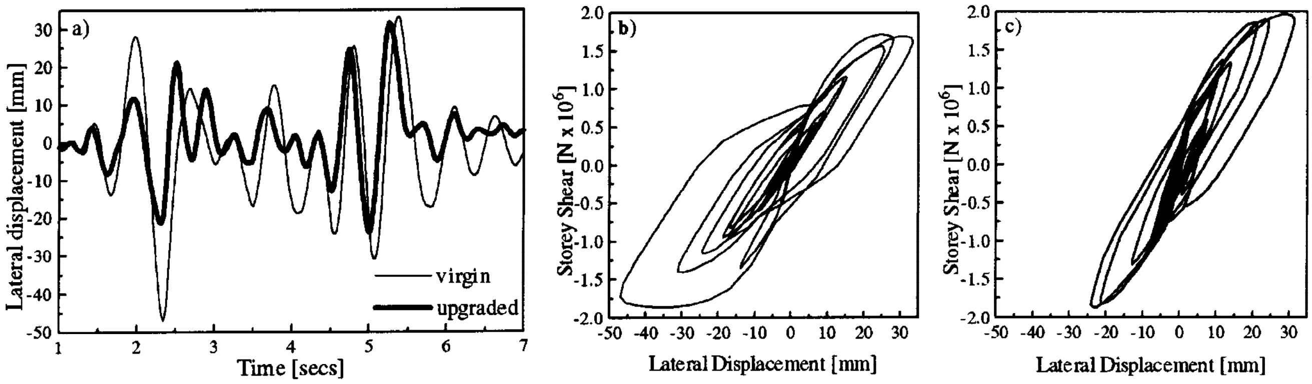


Fig.6. Global comparison for the case of low seismic action, moderate gravity load and moderate confinement. a). displacement comparison. b). hysteretic behaviour of virgin model. c). hysteretic behaviour of upgraded model

In general, the application of the proposed technique lead to a reduction of the displacement ductility demand of the structure. To illustrate the improvement in the performance of the upgraded structures both time-history of lateral displacement and hysteretic behaviour are compared in Fig. 6 for one of the cases considered. This figure shows a significant reduction of response in the upgraded structure. Also, the hysteretic behaviour of the upgraded structure reveals improvements in both stability and energy dissipation capacity. For a given level of reversed displacements, fatter loops and higher peak-to-peak secant stiffness is observed in the upgraded structure.

The root mean square of lateral displacements RMS_d for the soft-storey is shown in Fig. 7. A comparison of RMS_d values between the virgin and upgraded models provides an easy way to evaluate the efficiency of the proposed technique in terms of the overall degree of response. Fig. 7 shows a significant reduction in the overall response of the redesigned structures for all the cases studied. This reduction increases with increasing device strength. Table 1 summarises the applicability of the proposed technique based on local and global failure criteria respectively. In this table, results labelled as 'SUR' indicate that shear upgrading is required. Hence, for this particular cases the proposed technique may be applied only if column shear strength is improved (e.g. by encasing the columns with steel jacketing). In general terms, the evaluation of the proposed technique for the building model is positive. Only in the extreme combination of high gravity load with high seismic action the proposed technique is not applicable at all. More severe interventions are needed to reduce the seismic vulnerability of these structures.

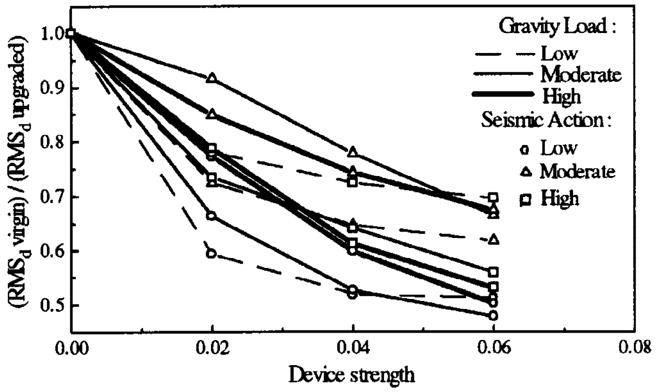


Fig. 7. Efficiency of proposed technique in terms of normalised RMS response of lateral displacement.

Finally, the idea of incorporating passive devices around the expected plastic hinges deserves consideration in the case of general RC framed buildings with distributed ductility demand along the building height. Preliminary studies carried out by the author using a low-rise RC plane frame model show promising results, particularly in the case of frames with deficient detailing for which the bottom longitudinal beam reinforcement is not properly anchored inside the beam-column joint. Also the possibility of exploring the applicability of the proposed technique for the redesign of steel buildings appears to deserve consideration.

CONCLUSIONS

The efficiency of a proposed redesign technique based on the incorporation of passive devices around expected plastic hinges of an existing RC building was assessed. Based on the comparison of dynamic behaviour of original and upgraded models both at member and building levels, it is concluded that the application of the proposed redesign technique results in significant reduction of seismic response. Comparisons made at member level also showed that a significant proportion of the total hysteretic energy is dissipated by yielding/friction in the added passive devices reducing the level of damage in members of the original structure. The proposed technique is considered to be less invasive than conventional techniques with or without the incorporation of passive devices and may be considered as an attractive alternative for the redesign of RC framed structures under tight economic constrains.

Table 1. Applicability of the proposed technique based on local failure criterion.

			local failure criterion			global failure criterion		
			confinement level			confinement level		
Seismic Action	Gravity Load	Critical Record	Low	Mod.	High	Low	Mod.	High
Low	Low	St Monica	Yes	Yes	Yes	Yes	Yes	Yes
Low	Mod.	Taft	Yes	Yes	Yes	Yes	Yes	Yes
Low	High	El Centro	SUR	Yes	Yes	SUR	Yes	Yes
Mod.	Low	St Monica	Yes	Yes	Yes	Yes	Yes	Yes
Mod.	Mod.	Taft	SUR	Yes	Yes	SUR	Yes	Yes
Mod.	High	El Centro	No	No	No	SUR	Yes	Yes
High	Low	St Monica	SUR	Yes	Yes	SUR	Yes	Yes
High	Mod.	El Centro	SUR	Yes	Yes	SUR	Yes	Yes
High	High	El Centro	No	No	No	No	No	No

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