INCORPORATION OF HYSTERETIC DEVICES ON BRACING SYSTEMS OF LOW INVASIVITY: A NEW APPROACH FOR THE SEISMIC REDESIGN OF FRAMED STRUCTURES

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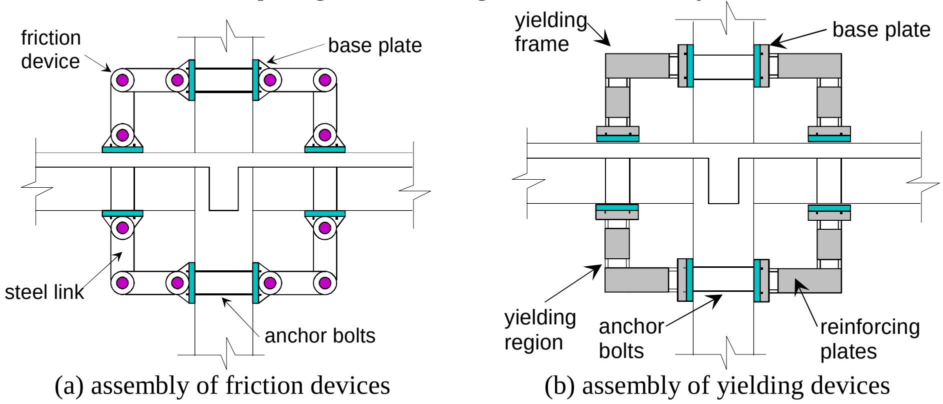
SUMMARY

As an alternative solution to the severe structural invasion of bracing systems for seismic redesign, this paper presents new configurations of dissipative bracing systems with characteristics of low invasivity. The geometry of the proposed systems is either a smooth arch or a poligonal arch of 4 members. Each bracing arch contains six hysteretic devices and the geometry of the arch is such that favours device activation.

The proposed bracing system combines the benefits of the passive control of the initial period of the structure (before devices are activated) with that of a bracing system with stable inelastic response and high energy dissipation capacity. A series of inelastic nonlinear time-history analyses of original and redesigned models under the action of damaging earthquake records confirm the efficiency of the proposed dissipative bracing system

INTRODUCTION

A large number of existing structures may exhibit inadequate deformation capacity under earthquakes of moderate to high intensity. As a result of this, a large number of seismic redesign techniques have been proposed. Many conventional and innovative redesign techniques have proved effective in reducing the vulnerability of existing structures with anticipated deficient seismic behaviour. However, it is not uncommon that the application of these techniques give place to undesired 'side-effects' such as significant amount of construction work, large increments in building weight and base shear, critical alterations to building layout and severe disturbance to the building occupants. In some cases, the redesign scheme may even become structurally invasive with extreme cases even requiring the retrofitting of the foundation system.



(a) assembly of friction devices (b) assembly of yielding devices

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Figure 1. Local incorporation of hysteretic devices around expected plastic hinge regions

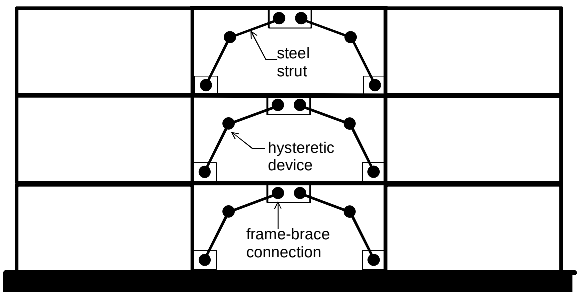
In an attempt to provide an alternative solution to the above problems, the author has proposed a redesign technique based on the local incorporation of energy dissipation devices(Martinez-Rueda,1997,1998a,b,c). As shown in Figure 1, the technique incorporates hysteretic devices around expected plastic hinge regions. Devices used in this way introduce significant hysteretic damping as the structure responds to seismic excitation.

Although the above approach has proved effective from the conceptual and economical view points, it is visualised that in some cases the technique may require the installation of a large number of devices. In order to develop further the ideas on non-invasive redesign techniques this paper explores a technique based on the incorporation of a dissipative bracing system of low invasivity.

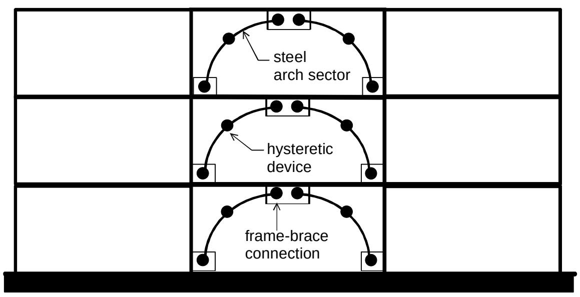
PROPOSED DISSIPATIVE BRACING SYSTEM

Along the years, a number of succesful innovative methods to protect tension-compresion K braces from yielding or buckling have been proposed. Pioneering work by Hisatoku et al. (1974) have now evolved into modern K bracing systems (Pall, 1983; Whittaker et al., 1991; Ciampi et al., 1993) that include a hysteretic energy dissipation device as a connection between the beam and the braces. These systems have in common an enhanced seismic response where inelastic deformations and hysteretic energy dissipation is confined to the devices while the braces remain elastic and stable.

Figure 2 shows a new way of incorporating hysteretic devices into a bracing system both in new or existing structures. This bracing system is referred here as a 'bracing system of low invasivity' and was originally conceived, at conceptual level, as a redesign technique for concrete framed buildings (Martinez-Rueda, 1998b). The bracing systems shown in Figure 2 combine the benefits of imposing a passive control of the initial structural period (before devices are activated) with that of a brace with stable hysteretic response and high energy dissipation capacity (when devices are activated).



(a) polygonal bracing arch



(b) bracing arch

Figure 2. Some alternatives for bracing systems of low invasivity incorporating hysteretic devices

The proposed bracing system deliberately adopts a geometry that favours the activation of rotational hysteretic devices at discrete locations of the braces. Yielding or friction devices can be used to work as joints with enhanced elastoplastic rotational response located at the ends and midway of individual braces.

It is important to recall that the inelastic cyclic response of conventional bracing systems designed to work both in tension and compression is rather poor. Damage to these systems is dominated by the inelastic buckling of the braces with severe degradation of strength, stiffness and energy dissipation capacity. In contrast, the behaviour of the braces shown in Figure 2 may be controlled in a passive way to achieve a stable energy dissipation mechanism. For a given rotational (moment) strength of the devices, the steel struts or the arch sectors must be designed to remain elastic and stable at full device activation. In this way, devices take care of the bulk of energy dissipation demands by introducing large amounts of hysteretic damping into the structure. This results in significant reductions of damage accumulation and displacements.

DESIGN CONSIDERATIONS

The adopted inclination angle of the struts or the geometry of the bracing arch must be decided in accordance with the client requirements for aesthetics and space. Particularly, in the case of redesign applications this decision is important in terms of the interference to the useful that was available prior to the intervention.

As in any successful application of energy dissipation devices, these must be carefully designed to be easily inspected, rehabilitated or replaced after a major seismic event or during programmed maintenance inspections. Additionally, devices must be calibrated or tuned to guarantee device activation and optimise seismic response.

For a redesign application, it is not enough to calibrate devices for a rotational strength that guarantees a stable and elastic response of the steel struts or arch sectors. To enforce beneficial device activation very large device strengths must be avoided. Large device strengths may result in excessive gain in lateral strength incompatible with the strength of the frame members or the existing foundation. For the redesign of concrete structures the application of simple fastening techniques to connect the braces to the existing building must be feasible. In order to achieve this, device strength must be kept as low as possible. Also, the intervention using the proposed dissipative braces modifies the flexural and shear demands of surrounding regions of the beam-brace connection. In fact, during full device activation at large displacements more severe shear-moment interaction and rotation ductility demands are expected at the beams that connect to the bracing. Therefore, beam regions in the vicinity of the beam-brace connection must be strengthen when needed. The installation of either post-tensioned stirrups (Khan ,1980; UN Industrial Development Organization ,1983) or local still jackets (Aboutaha and Jirsa, 1996) are examples of effective techniques to achieve this purpose.

NUMERICAL STUDY OF THE PROPOSED DISSIPATIVE BRACING SYSTEM

To study the effectiveness of the proposed bracing system, an RC frame was studied both under the action of monotonic storey displacements and seismic excitation. A series of inelastic nonlinear analyses were conducted on the frame in its original (without dissipative bracing) and its redesigned condition (with dissipative bracing). The FE formulations adopted in the analyses are similar to those described elsewhere (Martinez-Rueda, 1998). A full parametric study of the system covering a family of structures with different degrees of seismic vulnerability, and the development of a calibration procedure to optimise seismic response are beyond the scope of this work.

Description of original and redesigned structures

The structure under study shown in Figure 3 is a gravity-load-designed (GLD) RC frame. Overall frame dimensions and section properties were adopted from those utilised in a study of GLD frames with deficient seismic response (Hoffman et al., 1990). Member dimensions are indicated in Figure 3(a) and material strengths are $f'c = 28$ MPa and $fy = 275$ MPa for the reinforced concrete. Column reinforcement consists of 4 bars of 19mm of diameter (4 Φ = 19mm) with square hoops Φ = 9.5 mm spaced at 200 mm. Beam reinforcement consists of continuous 2 Φ = 16 mm at top and 2Φ = 19 mm at bottom and stirrups Φ = 9.5 mm spaced at 200 mm. The centred region possess 2Φ = 16 mm as additional reinforcement for positive bending. Each strut consists of two rolled channel sections with a total depth of 152 mm, flange width of 48.8 mm, and thickness of 8.7 and 5.1 mm for the flange and web, respectively. Steel sections are made of mild steel with fy = 250 MPa.

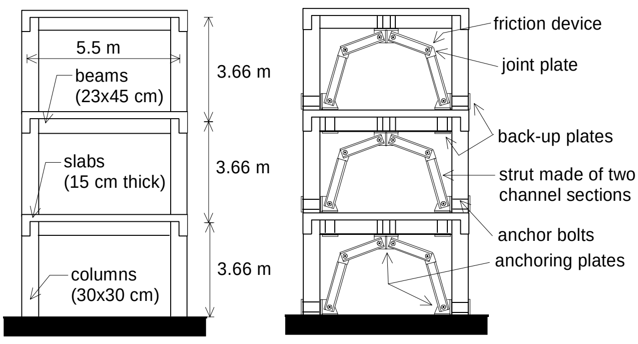


Figure 3. RC frame used in numerical study

As shown in Figure 3(b), in the redesigned structure the dissipative bracing is formed by the assembly of channel sections, rotational energy dissipation devices of frictional type and anchoring plates that connect the braces to the structure through postensioned anchoring bolts. The inclination angle of the struts in this example is 20 degrees and it is assumed that this was a value agreed with the client to meet architectural considerations. As illustrated by Figure 4, the friction devices consist of annular brass plates and steel plates jointed by high strength bolts. The rotational strength of the device is provided by the friction developed between the brass and steel plates and the web of the channel sections. Further details on friction devices similar to those shown in Figures 3 and 4 are given elsewhere (Martinez Rueda, 1997, 1998c).

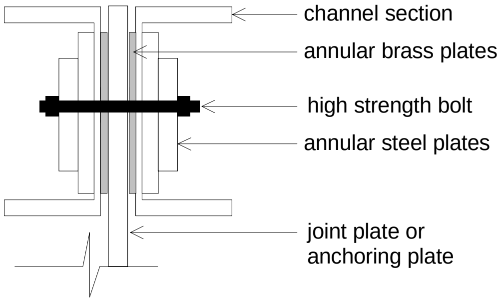


Figure 4. Detail of rotational frictional joint working as energy dissipation device

Although the solution for the dissipative bracing in this example makes use of friction devices, it is clear that several types of yielding devices can give place to an equivalent yielding solution. Also, the struts can have other type of transverse section. However, for the friction devices shown in Figures 3 and 4, the adopted channel sections are convenient as they favour an easy installation of the devices and the braces.

Monotonic Response

Monotonic analyses on original and redesigned models were conducted applying an interstorey displacement equivalent to a drift of about 2.5% while restraining the horizontal displacements of the bottom storey level and lower levels. Therefore, three analyses were required per frame model and allowed the estimation of the complete inelastic behaviour of individual storeys including post-peak response, accounting for the P-Delta effect associated to the gravity loads of storeys above the one under study.

Two levels of braced strength were considered for the study of redesigned structures under monotonic loading. These are labelled as RD-y and RD-u and correspond to structures with devices calibrated so that the contribution of the braces to the lateral strength matched the yield and ultimate storey strength of the original frames respectively. Maximum device strength required to achieve strength level RD-u occurs at first storey and is about 36% of column flexural strength under pure bending.

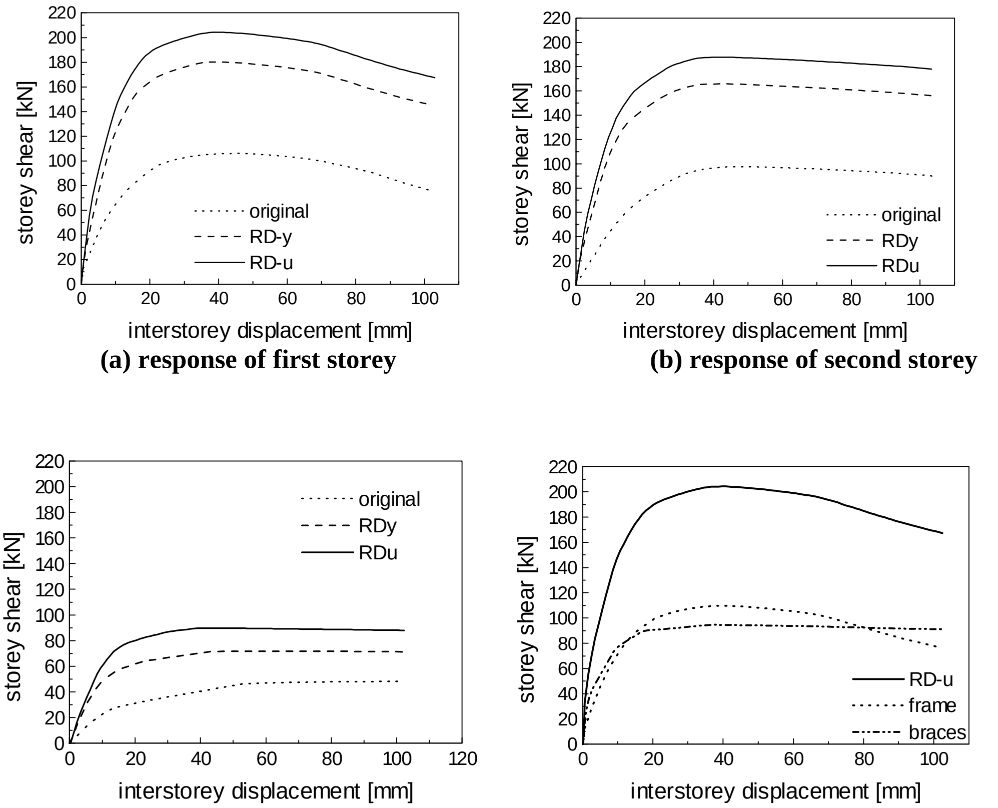
Figure 5 compares the response of original and redesigned structures. In all cases the failure of the storey is controlled by high flexibility rather than by strength drop. The most critical response is that of the original structure in its first storey where strength drops 15% for a displacement of 83 mm; however, this displacement is well beyond a drift of 2% (73 mm), i.e. a displacement commonly assumed as failure criteria based on excessive displacements.

Table 1. Summary of monotonic response parameters

Parameter	Model		
	Original	Redesigned	
		RD-y	RD-u
Δ_y of 1st storey [mm]	16.0	12.6	11.5
Δ_y of 2nd storey [mm]	19.2	12.7	12.7
Δ_y of 3rd storey [mm]	13.9	12.5	12.5
T_y [sec]	1.34	0.84	0.76
C_y	0.086	0.141	0.163

Table 1 summarises the global deformation capacity and dynamic properties estimated for the models. Yield displacement Δy was considered as that corresponding to the point of 75% of the maximum storey strength or the point of commencement of significant nonlinearity, when this was clearly evident in the response. The yield period of vibration Ty was estimated using the secant storey stiffnesses of at the onset of the yield displacement. The yield seismic coefficient Cy was computed as the ratio between the lateral strength at yield displacement of the first storey and the total building weight.

Figure 5 and Table 1 indicate that redesigned structures exhibit a maximum increment of strength of about 100% and shortening of yield period of the order of 60%. These changes in dynamic properties are not that drastic when compared to those imposed by conventional redesign techniques such as the addition of new structural or cross bracing. The added mass due to the installation of the dissipative bracing in the redesigned structure is just 1.4 % of the self-weight mass of the original structure.



(a) response of first storey

(b) response of second storey

(c) response of third storey

(d) brace and frame contribution at 1st storey

Figure 5. Monotonic response of original and redesigned frames

Figure 5(d) shows the composition of response RD-u for the 1st storey in terms of bracing and frame contributions. The response shown is typical of all storeys in the structure. The figure shows that the response of the redesigned frame departs significantly from that observed in conventional bracing systems. Firstly, there is not a large difference between the stiffness at yield between the braces and the frame. Secondly, because buckling cannot occur in the braces, the bracing system maintains its strength after all devices have yielded. This improves the overall ductility and energy dissipation capacity of the structure.

Seismic response

In order to estimate the effectiveness of the proposed redesign technique, original and redesigned frames with strength RD-u were studied under the action of the records summarised in Table 2. As indicated by Table 3, in all cases, redesigned frames experienced substantial reductions of ductility demands. In this table, the symbols $\mu\Delta oi$ and $\mu\Delta ri$ refer to the displacement ductility demand of storey i in its original and redesigned condition respectively. The average ratio $\mu\Delta ri$ / $\mu\Delta oi$ turned out to be 0.28.

Table 2. Characteristics of natural earthquake records used in time-history analyses

Earthquake	Station	Component	Ms	PGA [g]	Epicentral dist.	soil
Imperial Valley, USA 1942	El Centro	NS	7.1	0.343	8	stiff
Michoacan, Mexico 1985	SCT	N00E	8.1	0.171	400	soft
Loma Prieta, USA 1989	Emeryville	N10W	7.1	0.255	90	soft

Table 3. Summary of storey displacement ductility demands of original and redesigned frames

Record	original			redesigned		
	μΔo1	μΔo2	μΔo3	μΔr1	μΔr2	μΔr3
El Centro	3.20	4.08	6.52	1.32	1.71	2.49
Emeryville	23.62	15.90	15.92	5.97	6.30	5.50
SCT	21.75	9.56	10.70	1.37	1.23	0.95

As expected, the characteristics of the frame under study are such that it is vulnerable to collapse under the action of strong ground motion on soft soil. In fact, under the action of the soft-soil records the original frame collapses by loosing completely its lateral strength as exemplified in Figure 7(b). Beneficial changes in response were more noticeable in the case of the SCT record when compared to that of the Emeryville record. This might be attributed to the constrastingly different seismic scenarios associated to the records. In fact, the SCT record has a narrow frequency band content and long duration characteristic of soil resonance and large source distance. On the other hand, the Emeryville record is characterised by fewer acceleration pulses of low frequency and large amplitude. In consequence, the response of the redesigned frame is more sensitive to changes in the dynamic properties of the structure associated with the reduction of period elongation and building-up of resonance.

In general, the redesigned frame showed considerable reductions of ductility demand, strength decay, dissipated hysteretic energy and residual displacements. This is particularly appreciated in the response comparison shown in Figure 7 for the SCT record.

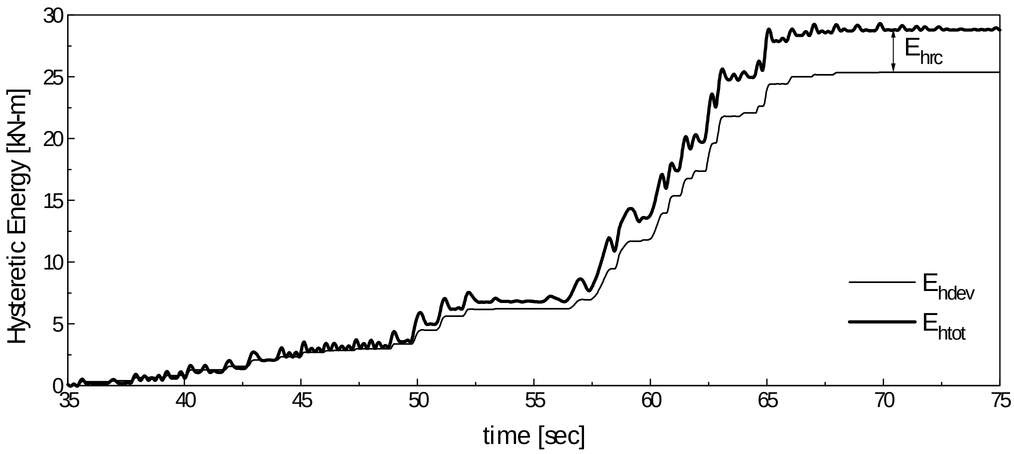


Figure 6. Time-history of the energy balance of the redesigned frame under the Mexico City SCT record

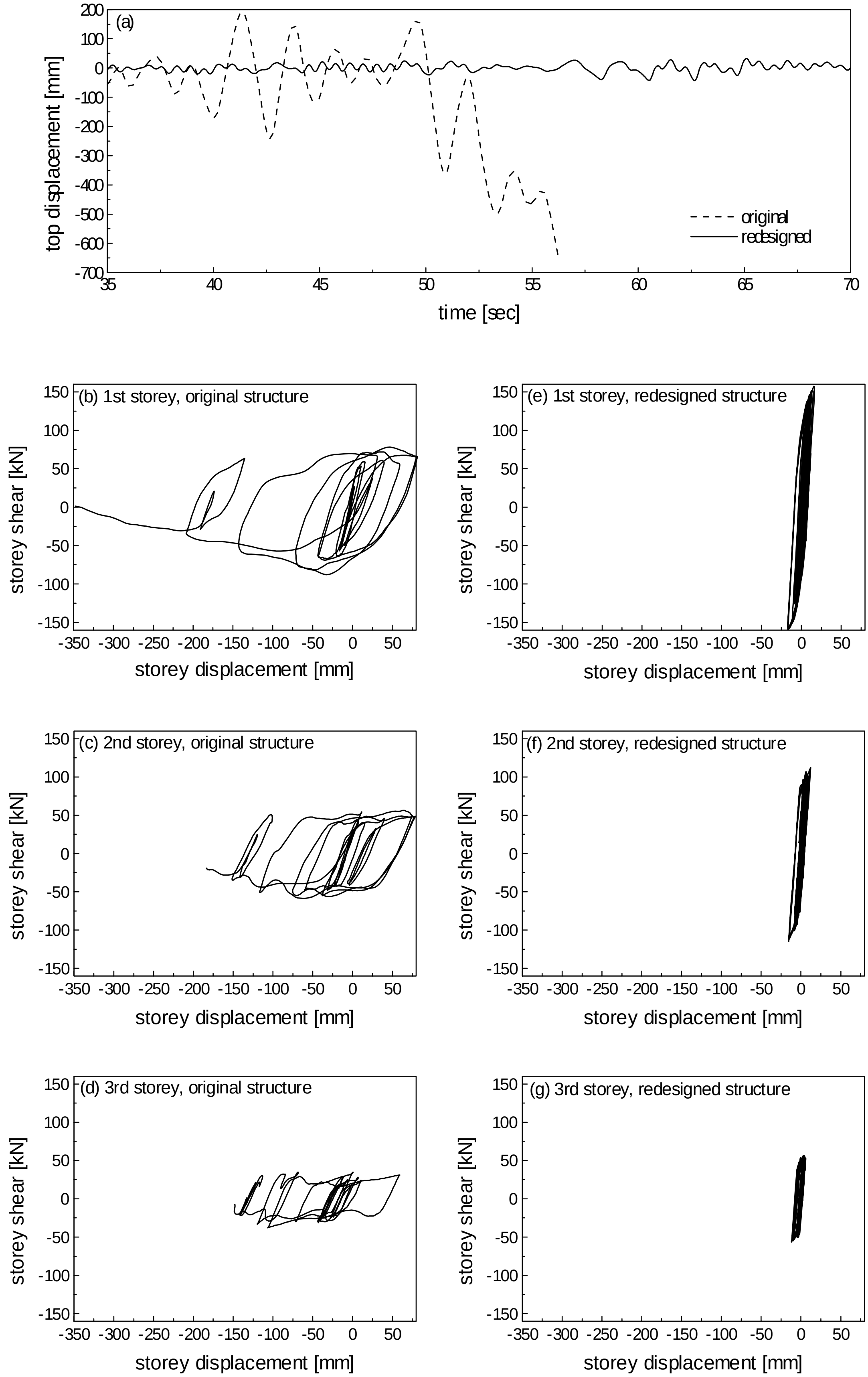


Figure 7. Comparison of seismic response between original and redesigned frame under the acceleration record SCTN90W of the Michoacan Earthquake, Mexico 1985

An example of the evolution of the balance of hysteretic energy is given in Figure 6. It is observed that the major component of the total hysteretic energy Ehtot is the hysteretic energy dissipated by the devices Ehdev. In fact, at the end of the excitation the hysteretic energy associated to frame member damage Ehrc is about 12% of Ehtot. The evaluation of the hysteretic energy of the corresponding original frame revealed that at the time of collapse this frame dissipates by hysteresis about 4.3 and 36.1 times the values Ehtot and Ehrc of the redesigned structure, respectively. These observations show that the application of the proposed redesign technique results not only in a dramatic reduction to damage accumulation in the RC members but a in significant reduction of the seismic input as well.

CONCLUSIONS

In this paper a new type of dissipative bracing applicable to the design of new structures and the redesign of existing ones was introduced. Although the proposed bracing is applicable to both concrete and steel structures, the must challenging application is that of the redesign of an existing RC framed structure.

The feasibility of the proposed bracing system was demonstrated for the case of the redesign of an existing RC structure. Based on the analyses conducted on framed models, it is concluded that a dissipative bracing system of low invasivity reduces significantly the seismic demands of framed structures in terms of damage and maximum and residual displacements.

Further studies of the proposed bracing systems applied to bridges, steel frames, precast RC buildings and flat plate structures are currently under study by the author.

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