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Seismic Response of Steel Framed Hospital Buildings with Self-Centering Systems

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Summary

This paper introduces the concepts of Elasto-Plastic Systems (EPS) and Self-Centering Systems (SCS) for the seismic design of steel-framed hospital buildings. Redesign of the MCEER West Coast Demonstration Hospital with SCS is conducted using this approach. An ensemble of 25 simulated MCEER Ground Motions having a probability of exceedence of 5% in 50 years in Northridge, California is used as earthquake excitations in the seismic analysis of the building. The SCS are achieved by Post-Tensioned Energy-Dissipated (PTED) beam-to-column connections. The redesign procedure is briefly outlined. With a set of optimal design parameters for the SCS, the structural system achieves very good seismic performance. Not only are the maximum displacements reduced, but the floor accelerations are also diminished, which is rarely achieved with other passive hysteretic control systems, such as friction or metallic dampers. Also, residual drifts are largely reduced or eliminated, which will decrease the cost to repair. The improved performance obtained suggests that the implementation of SCS can lead to improved seismic behavior at a reasonable cost.

Introduction

Steel Moment Resisting Frames (SMRF) were widely used in North America and the world until the failures of brittle beam-to-column joints were observed in a large number of SMRF structures as a result of the 1994 Northridge earthquake. Before this seismic event, many practicing engineers believed for years, albeit incorrectly, that steel structures were immune to earthquake-induced damage as a consequence of the material's inherent ductile properties (Bruneau et al. 1998). However, the January 17, 1994 Northridge Earthquake (Los Angeles, CA) changed the thinking of the earthquake engineering community. Approximately 100 SMRF structures experienced beam-to-column connection fractures in the Northridge earthquake (SAC, 1995). Invisible damage to the connections was also found by ultrasonic testing method (Paret, 1999). To avoid that damage in future earthquakes, many research efforts were conducted to upgrade the earthquake codes by SAC joint venture. Other parallel research was initiated by the Federal Emergency Management Agency (FEMA). It is believed that post-Northridge buildings have better seismic performance than pre-Northridge buildings due to the current code. However, the old structures designed with pre-Northridge codes need to be redesigned. Many retrofit methods were studied to get better seismic response than that of the original buildings. The main retrofit method is passive control, including the viscous damper, friction damper, base isolation, tuned-mass damper and self-centering systems.

Concepts of Elasto-Plastic Systems (EPS) and Self-Centering Systems (SCS)

Conventional buildings are designed to have capacities of plastic deformations, ductile inelastic responses and dissipating energy during earthquakes with current codes. Such structural systems are called Elasto-Plastic Systems (EPS). Figure 1(a) indicates the idealized inelastic response of EPS during an excitation of earthquake. The shadow area represents the energy dissipated in structures. Most Steel MRF are EPS and after earthquakes, plastic rotations or local buckling developed at the ends of beams and columns, which led to much damage and cost to repair the structures and recover the normal operations. If a severe residual drift occurred, the cost of repairing the structure may be more than that of building a new one.

The idealized seismic response of Self-Centering Systems (SCS) is shown in Figure 1(b). Such a seismic response of SCS can be achieved by special energy dissipating dampers, control materials (like shape memory alloy) or special connections. The hysteretic loops in Figure 1 are different, which indicates that the energy dissipated in SCS is less than that of EPS. The reduced energy absorbed by SCS "flows" into the special devices rather than the structure itself, so the damage to the structure is diminished or eliminated. The zero residual drift in SCS can save much cost to "return" the structure to the original position compared to the large residual drift in EPS.

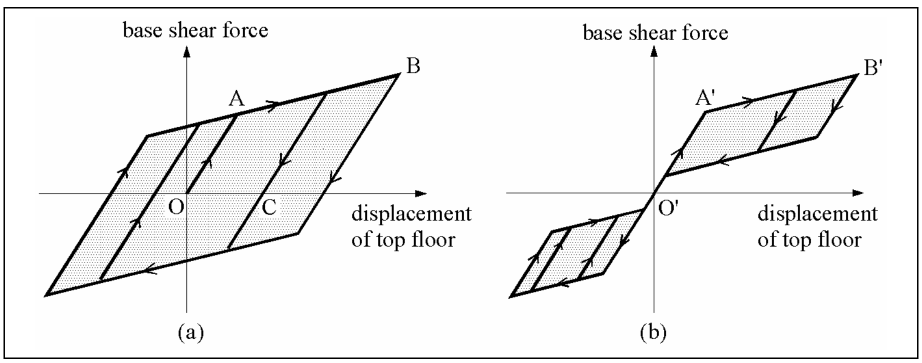

Figure 1. (a) Ideal inelastic seismic response of Elasto-Plastic Systems (EPS); (b) Ideal seismic response of Self-Centering Systems (SCS)

Control Parameters in Self-Centering Systems (SCS)

There are mainly three parameters in Self-Centering Systems: post-yielding factor α, energy dissipating factor β, strength factor η. In Figure 2, k_0 is the elastic stiffness of structures in SCS, which is same as that of EPS. And the factor α in EPS is usually equal to 0.02 which is determined by the yielding properties of structural steel. The factor α in SCS ranged from 0 to 0.35 due to the properties of special connections. The β represents the capacity of dissipating energy by SCS and is normally less than 1. The factor η is equal to the ratio of the yielding force F_Y and the gravity of structure.

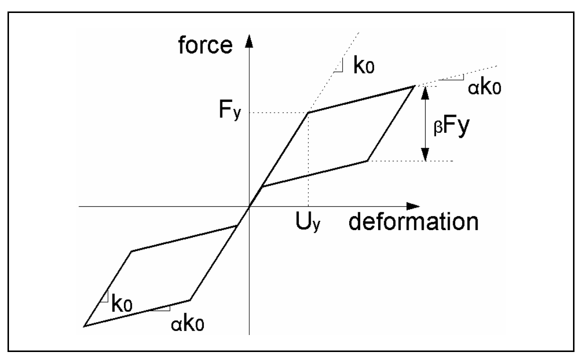

Figure 2. Parameters in Self-Centering Systems

Numerical Models

The MCEER Demonstration Hospital was constructed in early 1970s in California. Figure 3 shows the plan view of this building. More details can be found in the MCEER report by Yang et al. 2002.

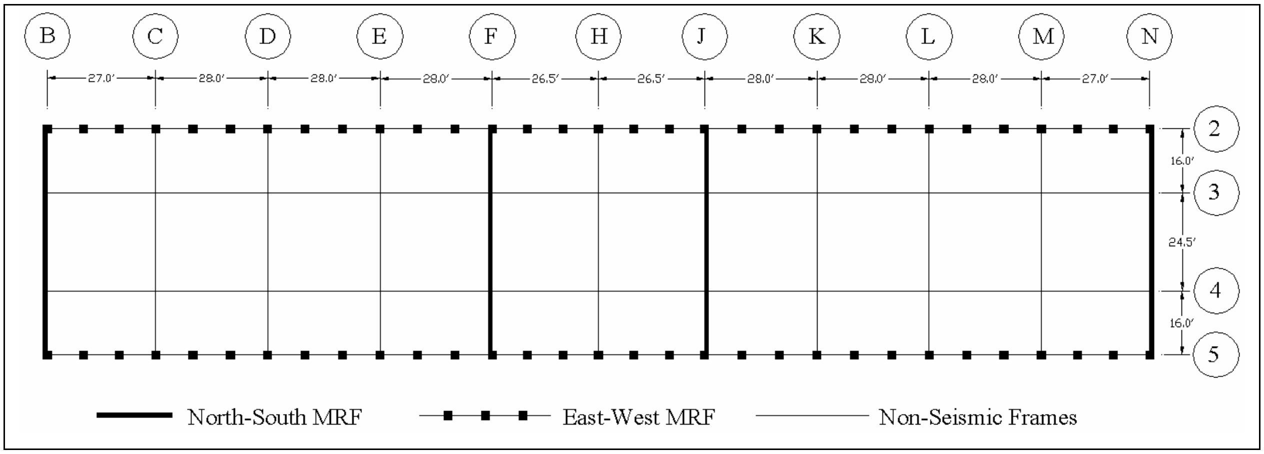

Figure 3. Plan view of MCEER Demonstration Hospital

The moment resisting system is composed by 4 North-South MRF and 2 East-West MRF. Due to the symmetry, a two-dimensional numerical model is used for modeling of the N-S MRF as shown in Figure 4. A frame element is utilized to represent all beams and columns. The inelastic response is assumed to be concentrated in the plastic hinges forming at the end of frame members. A bilinear moment-curvature hysteresis is assigned to all frame numbers. All slab contributions are neglected. The pin-ended gravity column accounts for the P-Δ effect from those non-seismic frames.

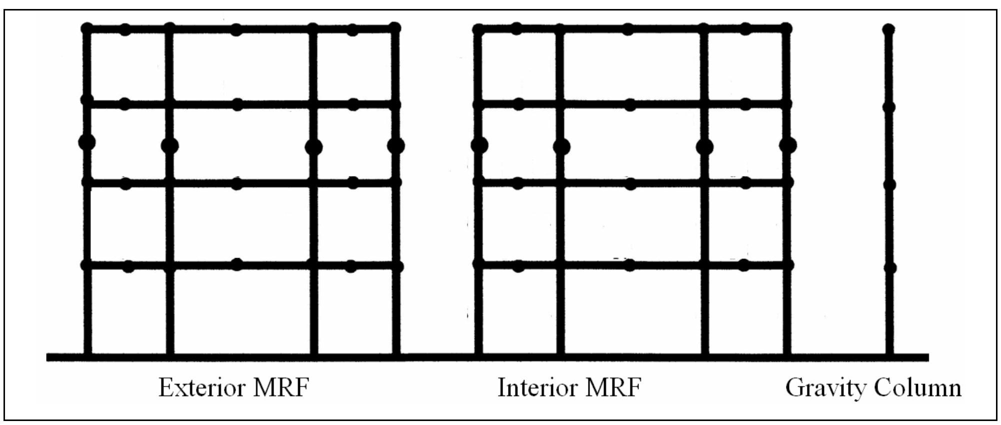

Figure 4. Two-dimensional model of the MCEER Demonstration Hospital

In order to improve the seismic performance of the original building, a Self-Centering System was used to redesign the structure by PTED beam-to-column connections. The PTED connections are shown in Figure 5. This type of connection used the post-tensioned (PT) bar to maintain the contact between beams and columns. Also, the self-centering property is conducted by the PT bar. The energy-dissipating (ED) bar is assigned to absorb the energy and the sections of ED bars determine the shape of hysteretic loop. Shear forces are transferred by the friction between the beams and columns. The beam-to-column connections in the original building were modified by PTED connections to form a new numerical model as a Self-Centering system for seismic analysis.

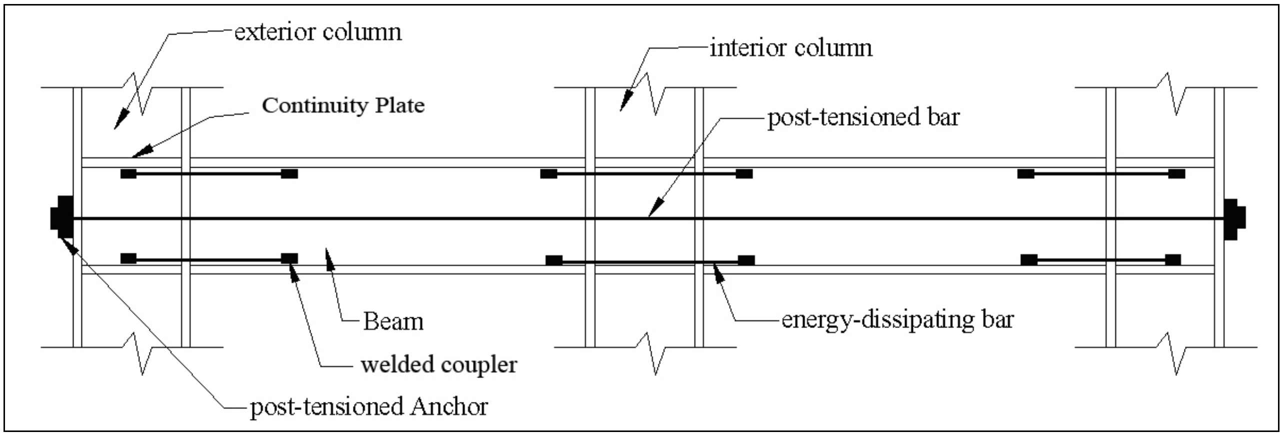

Figure 5. Post-Tensioned Energy-Dissipating (PTED) beam-to-column connections

Redesign Procedure

To redesign this MCEER hospital, the SCS is used and achieved by the Post-Tensioned Energy-Dissipating (PTED) connections (Christopoulos et al. 2002). And the MCEER West Coast Demonstration Hospital is a steel moment resisting frame and also an Elasto-Plastic system. The procedure is briefly outlined:

1) determine the properties of beam-column connections of the hospital
2) select the optimal control parameters of SCS;
3) design the post-tensioned bars and energy-dissipating bars according to selected factors
4) conduct seismic analysis of the original building and the new structure retrofitted by SCS
5) install the new connections and inspect the welded parts

More details can be found in the upcoming MCEER report by Wang, D. and Filiatrault.

Seismic Analysis of the Hospital Retrofitted with Self-Centering Systems (SCS)

Two numerical models (original EPS of the hospital and SCS of the retrofitted hospital were established and computed in RAUMOKO 2D finite element software. An ensemble of 25 simulated MCEER Ground Motions having a probability of exceedence of 5% in 50 years in Northridge, California, was used in this seismic study.

Table 1 shows the seismic responses of the original hospital and the hospital retrofitted with SCS. Comparing the responses of two systems, it is found that the maximum displacement and maximum inter-story drift are reduced in SCS. And the residual displacement and residual inter-story drift are largely decreased. The reduced deformation response and residual drift response show that the SCS achieved better seismic performance than EPS and very small residual drift in SCS means there is much less permanent plastic deformation in structures and less damage to structural elements than EPS. By comparing the maximum absolute floor acceleration of the two systems, it is obvious that the retrofitted hospital with SCS achieved much better acceleration response and reduced the acceleration by 25%. The largely decreased acceleration response will protect the acceleration-sensitive nonstructural components. The maximum ductility of columns in SCS is reduced by approximately 30%, which largely decreased the possibility of collapse because it is known that the ductile deformation of columns is more dangerous than that of beams. The 0 max ductility of beams means the beam remains elastic and the ductile deformation was conducted by the energy-dissipating bars. So after earthquakes, only the ED bars with plastic deformation need to be renewed and the cost is much less than changing a beam with a plastic deformation or local buckling.

Table 1. Responses of seismic analysis of EPS of original hospital and SCS of retrofitted hospital

Mean Value of responses of 25 earthquakes		**Original Hospital (EPS)**		**Retrofitted hospital (SCS) α=0.05 β=0.8 η(original)/ η(retrofit)=0.5**	
	unit	mm	%	Mm	%
Max Displacement	top floor	205.46	1.32	189.14	1.22
Residual Displacement	top floor	42.47	0.27	6.17	0.04
Max Interstory Drift	1st floor	73.52	1.78	59.35	1.44
	2nd	67.14	1.76	58.71	1.54
	3rd	53.66	1.41	47.70	1.25
	4th	34.55	0.91	29.10	0.76
Residual Interstory Drift	1st	16.34	0.40	4.73	0.11
	2nd	14.15	0.37	0.88	0.02
	3rd	10.30	0.27	0.68	0.02
	4th	2.56	0.07	0.04	0.00
Acceleration Unit		g		g	
Max Absolute Floor Acceleration	1st	1.05		0.76	
	2nd	1.01		0.76	
	3rd	1.04		0.82	
	4th	1.41		1.06	
Max Ductility of Beams		5.42		0	
Max Ductility of Columns		5.23		3.69	

Conclusions

The seismic analysis indicates that the seismic performance of the MCEER demonstration hospital redesigned with Self-Centering Systems is much better than that of the original hospital. Both the maximum displacements and absolute floor accelerations are reduced, which is rarely reported in other passive control retrofit methods like viscous damper, tuned-mass damper, base isolation and friction damper. And the largely reduced or eliminated residual drifts will decrease the cost for repairing the post-earthquake building and recovering the normal operations. Through this paper it is proved that the implementation of SCS improves the seismic performance not only from a seismic point of view but also from an economic point of view.

Acknowledgements

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