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RESPONSE MODIFICATION FOR ESSENTIAL FACILITIES HAZARD MITIGATION IN MID AMERICA

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SUMMARY

The majority of earthquake engineering research is focused on problems arising in high-risk seismic areas of the world, and much less attention is directed at hazard mitigation in areas where the recurrence interval is much longer but the inventory of at-risk structures may be greater. Of these, essential emergency, fire, police, medical, and government facilities present some of the greatest vulnerabilities in the central and eastern U.S., especially low rise structures with unreinforced masonry (URM) walls and flexible timber diaphragms. This paper describes research under way in the Mid-America Earthquake Center, one of three major earthquake research centers funded in 1997 by the National Science Foundation, to develop strategies to protect these facilities using response modification approaches. Conceptual models for three passive energy dissipation devices (PED) are presented in this paper and their effectiveness in reducing both displacement and acceleration response of a representative low rise URM structure are compared.

INTRODUCTION

Much of the central and eastern U.S. is vulnerable to a recurrence of the series of large earthquakes such as those that occurred in New Madrid, MO in 1811-1812 [Johnston, et al, 1996]. A significant percentage of the existing inventory of buildings in mid-America is low rise (one or two stories) and these ageing structures have very little capability for resisting seismic loads. Essential facilities, defined as those structures that must remain operable following a destructive earthquake, include police and fire stations, schools designated as potential emergency response centers and shelters and hospitals. Based on an inventory of more than 1100 of these facilities under research Task SE-1, funded by the recently established (1997) and NSF-supported Mid-America Earthquake Center (MAEC), approximately 25% of these facilities (see Table 1) are constructed of unreinforced masonry (URM) and many were built in the 1950's or earlier. Simple and economical retrofit measures are needed to reduce the hazard to the large number of these critical facilities in this region of the U.S. In such situations, passive response modification may represent a cost effective and reliable approach that can be used throughout the entire region.

Continuing research at Georgia Tech and in the Mid-America Earthquake Center (MAEC) are attempting to assess the effectiveness of seismic response modification using passive control devices [Craig, et al, 1998]. Given the long recurrence intervals for mid-America earthquakes, passive response modification systems, especially those utilizing devices that are highly resistant to ageing, are very attractive for hazard mitigation. On-going research related to low rise URM structures is focused on the application of passive control devices to one or two story structures with flexible (wooden) floor diaphragms that are characteristic of a large proportion of low rise essential facility-type structures in mid-America (see Fig. 1). While such structures exhibit relatively high initial linear elastic stiffness, their extreme fragility results in dramatically lower dynamic stiffness after cracking and pier rocking have developed, for example. By incorporating passive damping devices into these structures, particularly devices which take advantage of the relative deformations between flexible floor diaphragms and wall systems, it is possible to significantly reduce the seismic response. Conceptual models for three such passive energy dissipation devices (PED), designated Types A, B and C, are presented in this paper

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and their effectiveness in reducing both displacement and acceleration response of a low rise URM structure are compared.

Table 1: Essential Facilities in Mid-America

Summary: Distribution of Structural Type by Facility for SE-1 Survey										
Structural Type	**School**		**Police**		**Fire**		**Hospital**		**Total**	
Wood	55	8.66%	24	18.32%	26	15.20%	4	2.86%	109	10.12%
Steel	171	26.93%	21	16.03%	50	29.24%	76	54.29%	318	29.53%
Concrete	77	12.13%	26	19.85%	33	19.30%	33	23.57%	169	15.69%
Reinforced Masonry	59	9.29%	9	6.87%	16	9.36%	15	10.71%	99	9.19%
Unreinforced Masonry (URM)	191	30.08%	28	21.37%	41	23.98%	6	4.29%	266	24.70%
Mobile Home	17	2.68%	0	0.00%	0	0.00%	0	0.00%	17	1.58%
Unknown	65	10.24%	23	17.56%	5	2.92%	6	4.29%	99	9.19%
Totals:	**635**	100.00%	**131**	100.00%	**171**	100.00%	**140**	100.00%	**1077**	100.00%

Fig. 1: Low Rise URM Building Typical of Those in Mid-America

LOW RISE BUILDING MODELS

The literature on URM and URM buildings is extensive but recent reports, e.g., [Costley, et al, 1996; Tena-Colunga, et al, 1992], focus on their seismic performance and fragility. While URM structures usually have very stiff structural elements such as the in-plane behavior of load-bearing walls, these studies have pointed out that considerable inelastic behavior can be developed due not only to crack-slip mechanisms but also to pier fracture and subsequent pier rocking in walls with multiple openings. At the same time, the floor diaphragms of these structures are usually wooden and present varying degrees of flexibility depending on age and construction. In addition, diaphragm-wall connections are often questionable and may develop gap opening/closing behavior. The result is a complex and often brittle 3D structure with a great deal of heterogeneity.

In order to assess the feasibility of employing passive response modification to URM structures and particularly to essential facilities, it was decided to examining the behavior of a typical URM firehouse. A URM firehouse in Gilroy, CA (Fig. 1) has been studied extensively following the Loma Prieta earthquake of 1989 (the firehouse experienced no damage) [Costley, et al, 1996] and it was judged to be representative of many URM firehouses in mid-America. As a result it was selected for passive response modification studies to possibly improve seismic performance.

A two-dimensional analysis approach using DRAIN-2dx [Prakash, et al, 1993]was adopted, and the firehouse was modelled in one direction (along plane of symmetry). The structure is 2 story, rectangular in plan and with an interior transverse wall. All of the essential behavioral characteristics of the structure are represented in the conceptual model presented in Figure 2; these include rocking of piers in perforated in-plane walls, significant flexibility of the floor and roof diaphragms, and the effect of foundation compliance. Only the mass of out-of-plane walls was considered. A simplified 3D nonlinear model is currently under development in Task ST-5 and will be modified in the future to include PED conceptual models presented below. Figure 3 illustrates how PED's might be incorporated into wall and diaphragm elements of the 3D low rise building model. However, for computational tractability, a simple lumped parameter, series frame model was constructed for use in this investigation and is shown in Figure 4. The in-plane walls are represented by beam elements with lumped masses while the out-of-plane walls were assumed to contribute mass only (no transverse stiffness). The wooden floor diaphragms were represented in this 2D model as lumped masses supported by connecting springs to each in-plane wall. In this initial model, only linear behavior of the structural elements was considered and both modal and time-history analyses were used to validate the model compared to high fidelity FEM models and responses of the actual structure (Fig. 1) measured during the Loma Prieta earthquake. Due to the comparatively high stiffness of the in-plane walls, the lowest modes are associated with the flexible floor diaphragm coupled to the masses of the out-of-plane walls.

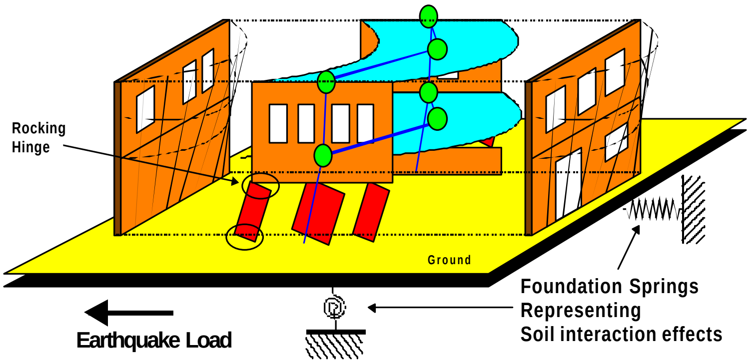


Fig. 2: Conceptual Model of Low Rise URM Building

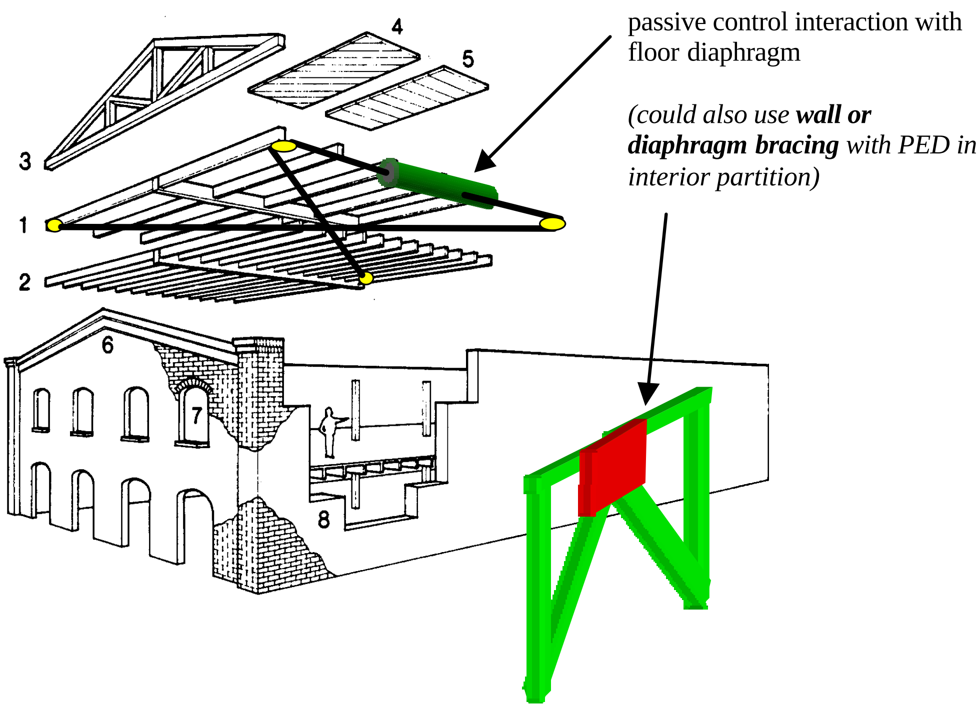


Fig. 3: Applications of PED's Within Low Rise URM Buildings

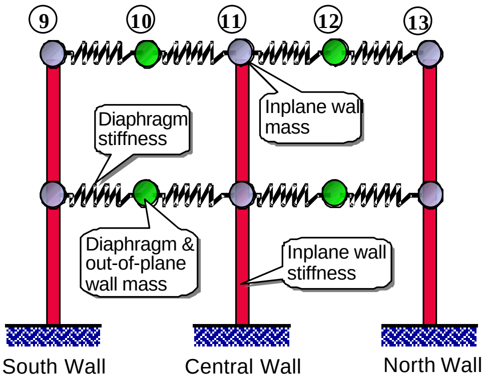


Fig. 4: Plane Frame Model of Low Rise URM Building

RESPONSE MODIFICATION CONCEPTS

Three different passive damping strategies were considered for this URM structure:

1. A damper between the diaphragm mass and the ground (Type A, Fig. 5),

2. A damper between the diaphragm mass and an in-plane wall (Type B, Figs. 6 and 7), and

3. A damper between the in-plane wall mass and the ground (Type C, Fig. 8).

Each of these configurations is modelled by introducing a DRAIN TYPE 04 spring element between the indicated degrees of freedom as shown in the Design Models in Figs. 5-8. The properties of these elements were adjusted to achieve an elasto-plastic behavior representative of hysteretic damping devices tested in the laboratory (e.g., [Pinelli, et al, 1993]). An energy-based design approach was applied to each case and numerical optimization was used to determine optimal damper properties (elastic stiffness, yield force). The optimal properties were determined so as to achieve the best performance for a given design condition. In this case "best performance" was defined in terms of energies as the maximum ratio of energy dissipated in the PED (E_H) to the input seismic energy for the building (E_0) for a given "design" earthquake. The design variables were the initial (elastic) stiffness and the yield force for assumed elasto-perfectly plastic behavior of the PED. This assumed model closely represented test results for ductile steel flexural connectors obtained in lab tests [Goodno, et al, 1998]. In order to reflect practical limits on this approach, limits were placed on (a) the peak (yield) force, (b) the maximum elastic stiffness, and (c) the maximum ductility of the PED [McCabe and Hall, 1989]. Limit (c) was used in order to maintain PED structural integrity and avoid low cycle fatigue fracture.

The Loma Prieta seismic record was used as the design earthquake. Figure 9 shows the optimal design points on objective function contour plots similar to that used earlier. Again, constraints were placed on dynamic ductility but did not come into play for these cases. On the basis of the highest value of the objective function (E_H/E_0), the Type B design provided the best performance. Type C proved ineffective but this was not surprising because it effectively operates in parallel with the in-plane walls which were constrained to elastic behavior only in these studies. As shown in Table 2, the Type B configuration provided a reduction in peak displacements of the floor diaphragms of 64% and 17% for the top wall displacement, compared to the baseline building without response modification devices.

Table 2. Comparison of baseline and Type B passively modified URM buildings

Node (see Fig. 4)	Baseline Building		Modified Building (% reduction)	
	Displacement (in)[a]	Accel. (g)	Displacement (in)[a]	Accel. (g)
10	1.88	1.03	0.68 (-64%)	0.40 (-67%)
11	0.07	0.12	0.058 (-17%)	0.076 (-37%)

[a] 1 in = 2.54 cm

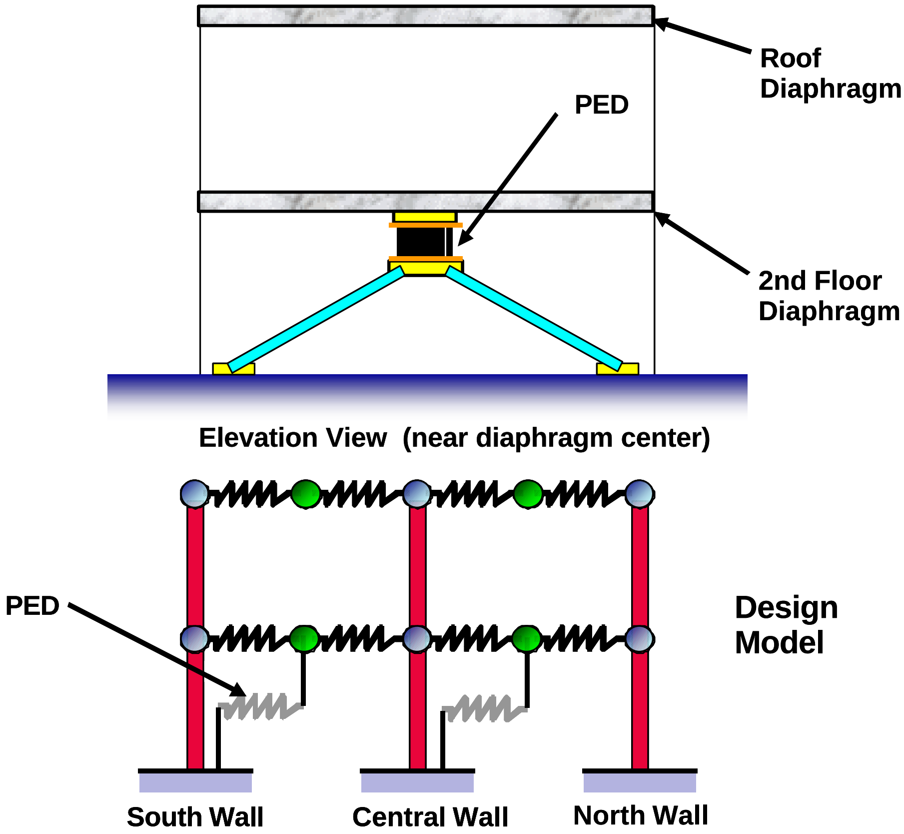


Fig. 5: Type A PED Concept

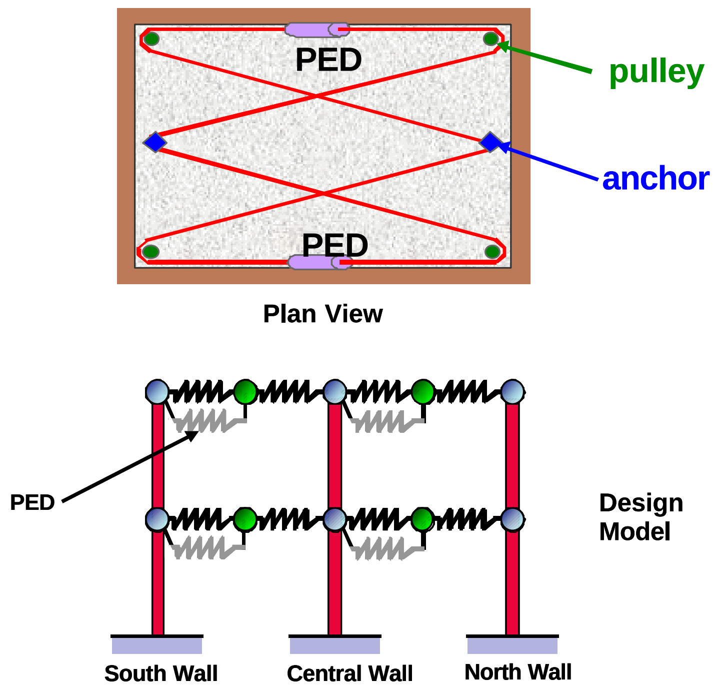


Fig. 6: One Type B PED Concept

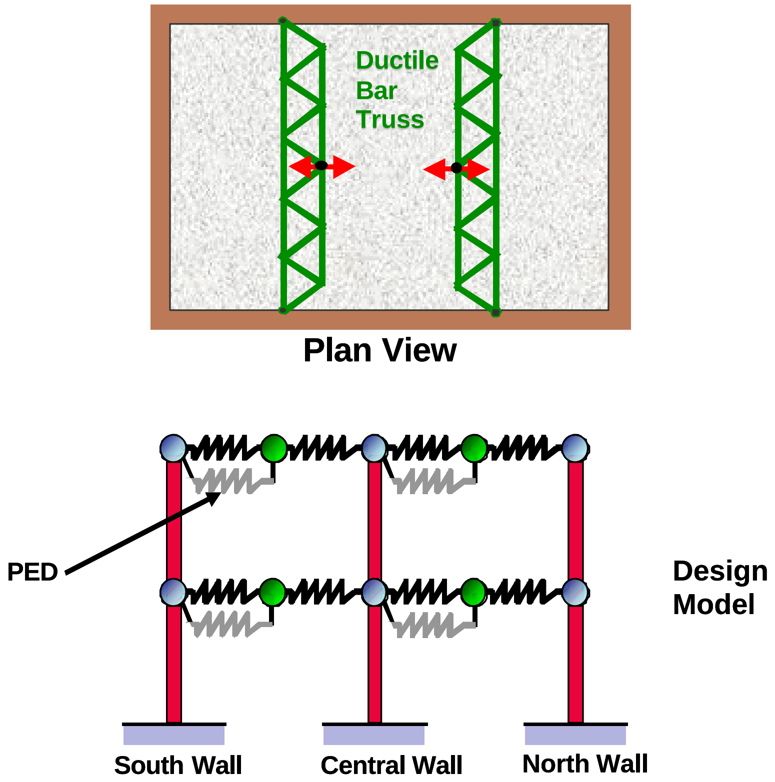


Fig. 7: Another Type B PED

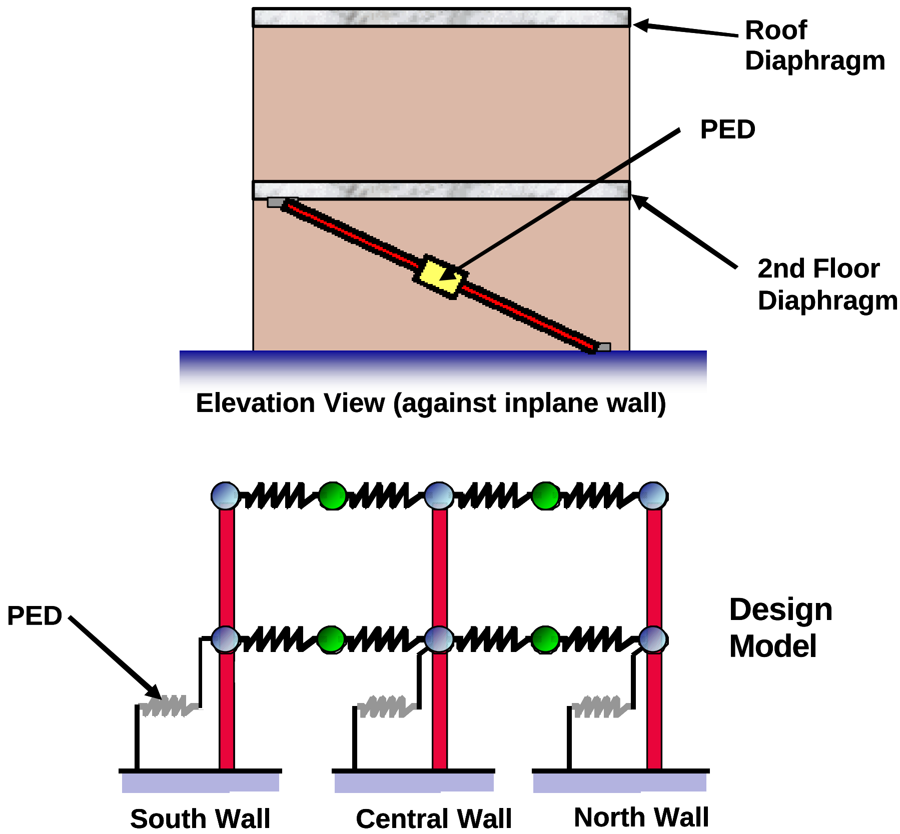
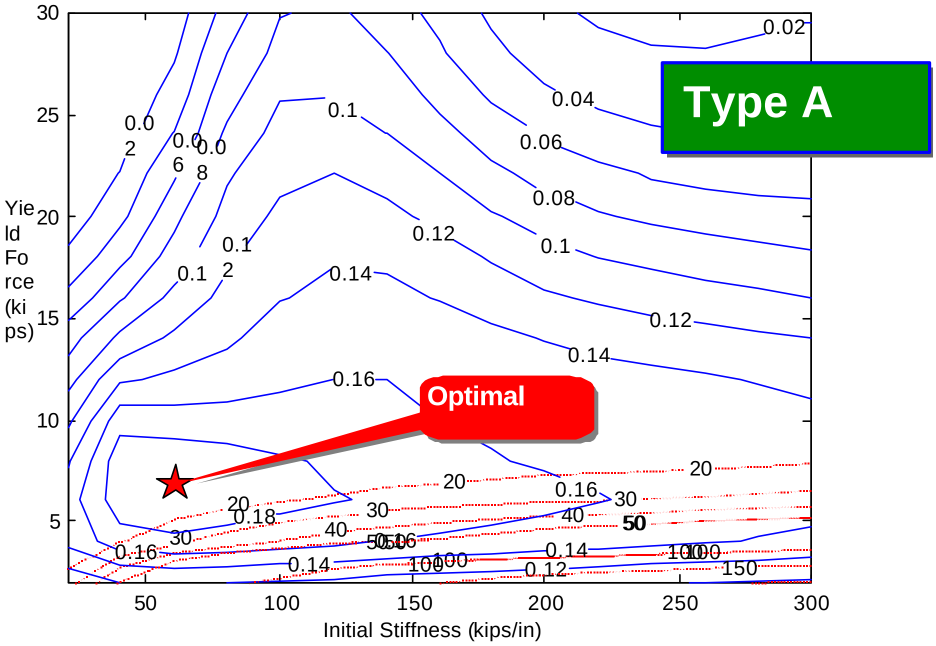


Fig. 8: Type C PED



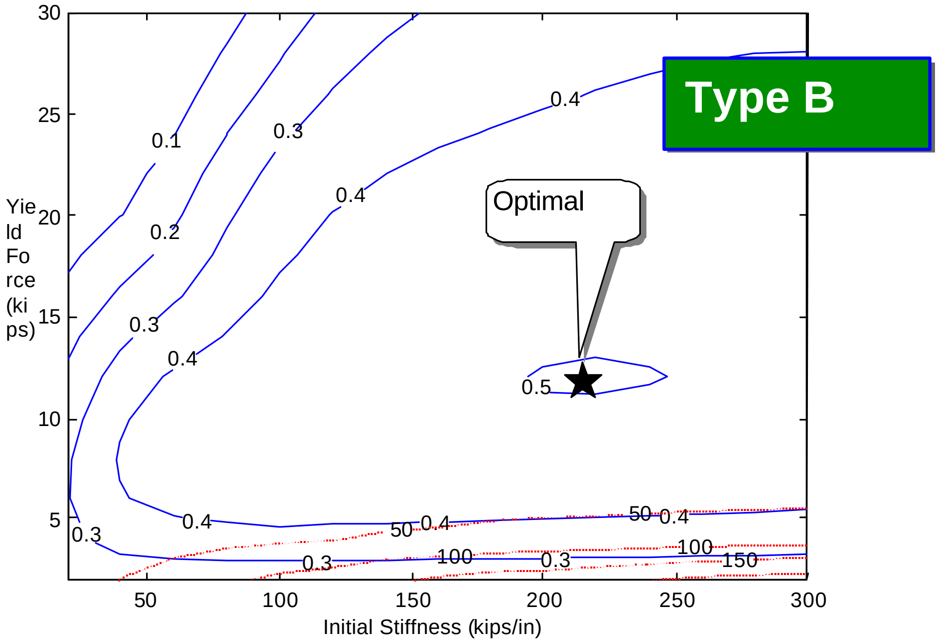


Fig. 9: Design Results for Type A and Type B PED Concepts

CONCLUSIONS

These studies of low rise URM essential facilities in mid-America are under way at present and will be modified to consider nonlinear response of both in-plane walls and floor diaphragms. Particular attention will be given to modelling pier rocking in the URM walls with openings and to modelling diaphragm-wall coupling. The initial 2D models have been utilized for these initial studies but eventually the research will move to full 3D models implemented using the ABAQUS [Users Manual, 1996] structural analysis software. Other MAE Center tasks are developing diaphragm models and these will be incorporated into 3D URM models and passive damping devices will be modelled.

Ultimately, the objective of this work is to assess the impact of added passive damping devices on the fragility of URM structures using methodology similar to that employed in the LAMB study [Abrams, et al, 1997]. This will be accomplished initially using well-known Monte Carlo methods and considering a statistically meaningful suite of ground motions. Initially, the story drift will be used as a measure of damage to the structure. Ultimately, it is anticipated that the Monte Carlo methods will be replaced with direct probability integration methods.

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REFERENCES

ABAQUS User's Manual (1996), Ver. 5.6, Hibbitt, Karlsson & Sorensen, Inc., Pawtucket, RI

Abrams, D. P. and Shinozuka, M (1997) Loss Assessment of Memphis Buildings, *Technical Report NCEER-97-0018*, Multidisciplinary Center for Earthquake Engineering Research (MCEER), SUNY-Buffalo.

Craig, J. I. and Goodno, B. J. (1998) Response Modification Applications for Essential Facilities -Task ST-4, Mid-America Earthquake Center, Georgia Institute of Technology, Atlanta, GA, Jan 1998-Oct 1999.

Costley, A.C., and Abrams, D.P. (1996), "Dynamic Response of Unreinforced Masonry Buildings with Flexible Diaphragms," *Technical Report NCEER-96-0001*, Multidisciplinary Center for Earthquake Engineering Research (MCEER), SUNY Buffalo.

French, S. (1999) SE-1 Task Year 2 Report, Mid America Earthquake Center, Georgia Institute of Technology, Atlanta, GA

Goodno, Barry J., Craig, James I., Towashiraporn, P., and Dogan, T. (1998) Ductile Cladding Connection Systems for Seismic Design, *Report NIST GCR 98-758*, US Dept. of Commerce, National Institute of Standards and Technology (NIST), Building & Fire Research Laboratory.

Johnston, Arch C. and Schweig, Eugene S. (1996) The Enigma of the New Madrid Earthquakes of 1811-1812, *Annual Review of Earth Planetary Science*, 24:339-384.

Kelly, J. M., Skinner, R. I., and Heine, A. J. (1972) Mechanisms of Energy Absorption in Special Devices for Use in Earthquake Resistant Structures, *Bulletin of New Zealand Society for Earthquake Engineering*, 5:3.

Kim, S-C. and White, D. (1999) ST-5 Task Year 2 Report, Mid America Earthquake Center, Georgia Institute of Technology, Atlanta, GA.

McCabe, S. L., and Hall, W. J. (1989) Assessment of Seismic Structural Damage, *Journal of Structural Engineering*, 115(9):2166-2183.

Pinelli, J.-P., Craig, J. I., Goodno, B. J., and Hsu, C. C. (1993) Passive Control of Building Response Using Energy Dissipating Cladding Connections, *Earthquake Spectra*, 9(3):529-546.

Prakash, V., Powell, G. H., and Campbell, S. (1993). "DRAIN-2dx Base Program Description and User Guide," Version 1.10, Dept. of Civil Engineering, University of California Berkeley, November..

Tena-Colunga, A., and Abrams, D. (1992), Response of an Unreinforced Masonry Building During the Loma Prieta Earthquake, *Technical Report No. UILU-ENG-92-2024*, University of Illinois at Urbana-Champaign