13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 3446

SEISMIC DESIGN OF STRUCTURES USING FRICTION DAMPER BRACINGS

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SUMMARY

A Pall based friction damper located at intersection point of *X* or chevron bracing has been designed concerning Iranian workmanship. Tests have been performed to investigate the energy dissipation capacity of dampers with different types of slipping surface. Efficiency of the system has been investigated through time history nonlinear analysis performed on 2 and 3 story steel structure with a logical range of period under sets of 9 accelerograms matching with *S*2 and *S*3 types of soil.
Due to high performance of the system, damage index of the whole structure has been found to be governed rather by non-structural damage potential or casual p-delta effect leading to potential instability.
The aspect ratio of the friction devices has been judged to be very effective in energy dissipation, so that with aspect ratios near to main frame one, the energy dissipation reached its maximum level. For aspect ratios far from the structure one, rigid body motion of device resulted in reduction of energy dissipation potential.
Keywords: **Friction Damper, Energy Dissipation, Damage Index, Hystersis**

INTRODUCTION

Energy dissipation capacity and capability of structures subjected to severe earthquakes plays a vital role to prevent them from catastrophic instability and failure. Inelastic behavior of structural material is the main source of energy dissipation in conventional structures. Potentially high cost of structural retrofitting, aftermath of a severe earthquake along with the need to predict the actual seismic behavior of structures, are the main causes to localize the energy dissipation capability by devices installed in structures. Viscous dampers (Constantinou [1]), ADAS damper (Kelly [2]), Friction dampers (Filiatrault [3,4]) and Viscoelastic Elastomeric dampers (Mahmoodi [5]) are within this category of structural systems. It seems that the statistical and probabilistic perspective of upcoming earthquakes which may just be judged only doubtfully due to their long return period, can be considered as a source of encouraging implementation of methods with higher efficiency and unlimited capacity of energy absorption.

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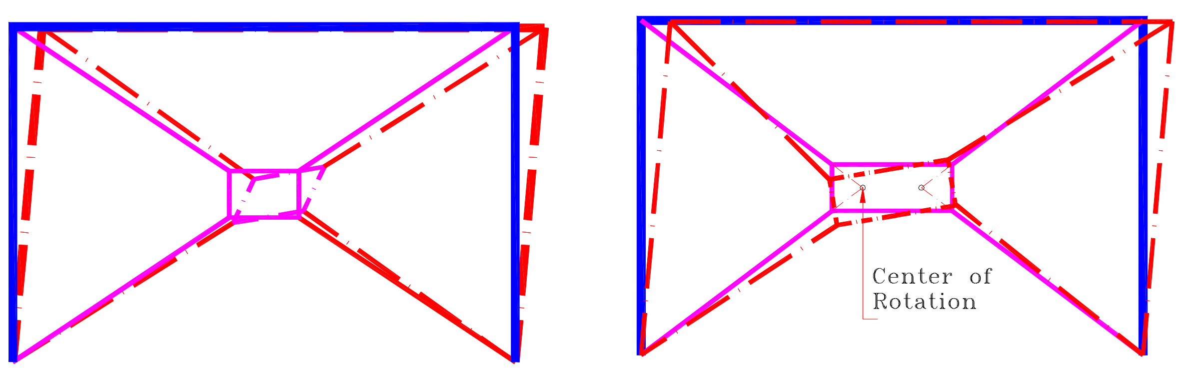
Pall dampers

It has been a common practice among mechanical engineers to apply friction-based brakes to absorb kinetic energy in machines and devices. This has encouraged the development of Pall friction based damper (Chandra [6]). Pall friction dampers have successfully gone through sophisticated experimental studies on shake tables in Canada (Filiatrault [3]) and the United States (Aiken [7]). Pall friction dampers have been very attractive due to their simplicity and low cost of construction. High seismic performance of Pall's damper has been a great motivation to extend its application out of its origin to other countries, specially to United states.
General structure of Pall type dampers is made up of some steel plates layed on each other with high strength bolts pressing them together, generating friction between them. Contrary to Viscoelastic systems, Pall system is not sensitive to environmental temperature and state of loading. Pall system's hysteretic behaviors are almost rectangular and completely similar to ideal elastoplastic behavior. Due to high dissipation energy capacity and stability of hyteresis loops, Pall system seems to show higher seismic performance, than other damping systems.

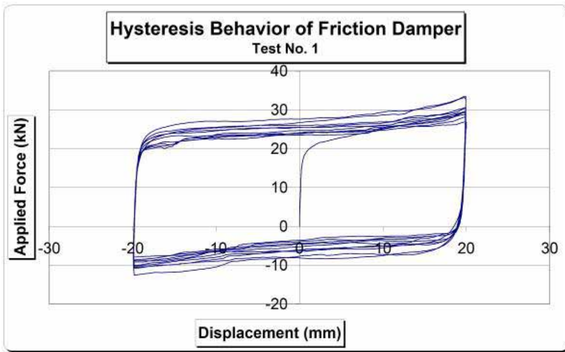
Friction dampers mechanism

As mentioned before, a Pall damper is very popular due to its low cost of construction and its simplicity. Furthermore, considering architectural restrictions, such elements are very easy to be hidden in internal partitions.
Friction based dampers are formed of steel plates tightened together by means of high strength bolts with either axial or rotational deformation mechanism leading to transformation of kinetic energy to thermal one.
Pall friction based bracing has utilized the lever mechanism wisely, to transform relatively low global displacements of braced frames to local high deformations of dampers (figure 1-a). A transformation ratio in order of 10 may be easily reached, leading to high efficiency of the system.
Potential of energy dissipation is affected by damper aspect ratio and its relation with braced frame aspect ratio, so that a maximum potential of energy dissipation may be reached in the case of aspect ratio of damper be equal to the frame one. Formation of 2 instantaneous centers of rotation in the case of different aspect ratios is the source of temporary instability of the system (figure 1-b) and reduction of energy dissipation potential.

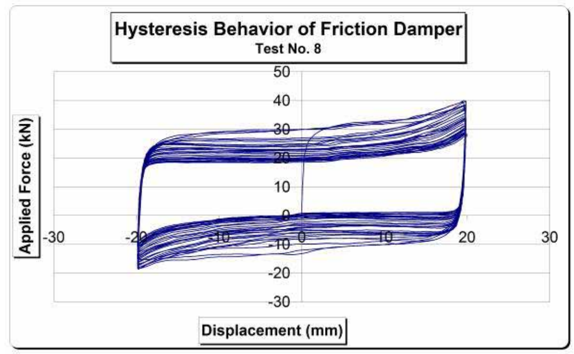


(a) Behavior of damper within structure **(b) Formation of instantaneous centers of rotation**
Figure (1): Performance mechanism of Pall Friction Damper

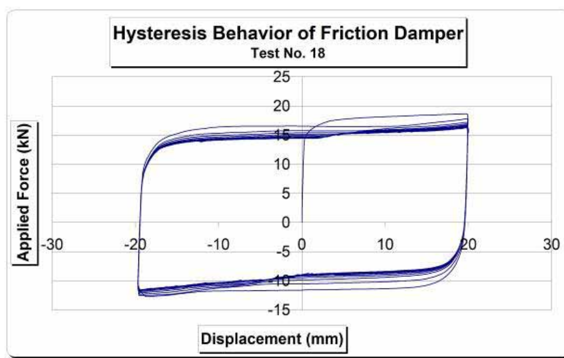
Tests[1] have been performed on 28 samples under 50 loading cycles. 3 types of contact surface, as smooth surface, rough surface and pad sandwiched system have been assessed through displacement controlled cyclic tests with amplitudes of 10 and 20 mm.
All of 3 types of contact surface have shown complete elasto – plastic hysteretic behavior, but it is obvious that the added pad has significant influence on stability of hysteretic loops (figure 2-c).
The pad sandwiched system has been chosen to be studied further in this program.



(a) Smooth surface



(b) Rough surface



(c) Pad sandwiched system
Figure (2): Hysteretic curves drawn out of tests

Case studies

The program consists of structural rehabilitation of 2 schools with 2 and 3 stories, against seismic effects. Due to symmetry of structural plans, only 2 dimensional models of structural systems have been investigated under unidirectional accelerograms with assumption of rigidity of floors. Elevation of structures have been shown in figures (3).

Structural configuration

Structure *(A)* consists of a 2 story steel frame with 5 *m* of span in each direction. Story heights are 4 and 3*m* and floor masses are 360 and 340 tons for first and second floors respectively. Structure B is a 3 story steel structure as structure *A* in which, story heights are 4,3,3 *m* and floor masses are 360, 340, 340 tons for first, seconds and third floors respectively. The structure have been assumed with no lateral strength by itself, in order to make sense in investigation of the pure behavior of friction bracings.

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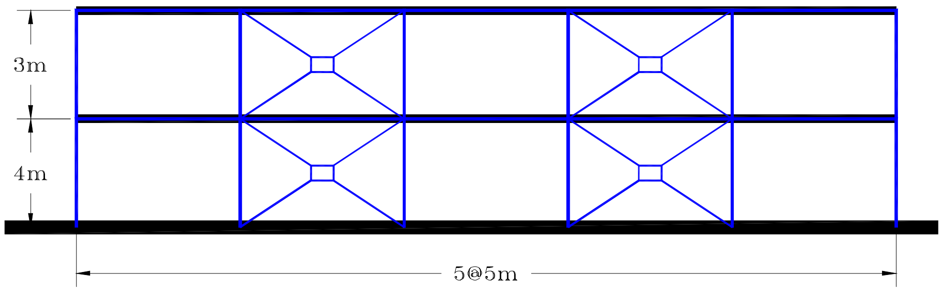
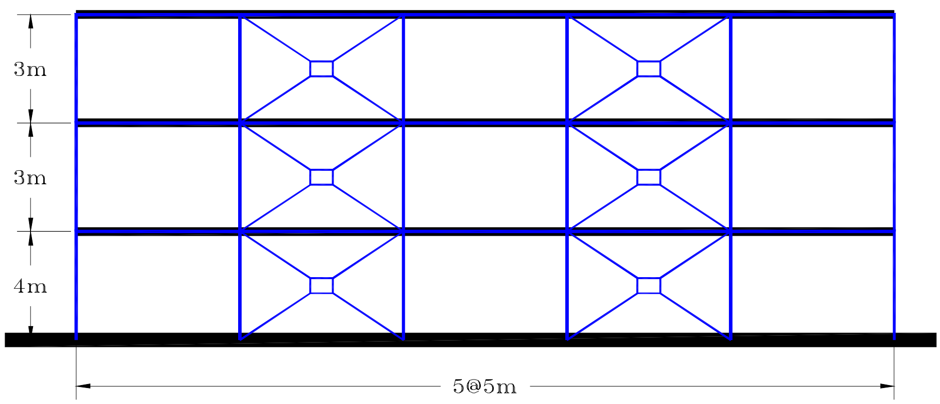


(a): Structure (A)



(b): Structure (B)
Figure (3): Structural elevations

Generalities

A nonlinear time-history analysis have been performed using Sap 2000 software. The θ-Wilson nonlinear time history analysis method has been used and the nonlinear behavior of links which model the friction behavior of interconnected plates, has been assumed to be complete elasto – plastic with 1% of hard straining according to results derived from tests. A damping of 5% of critical damping has been assumed and the following strategy has been chosen as the main discipline to select accelerograms.

Selection of accelerograms

Selection of accelerograms has been subject of discussions in the past (Naeim [8]). No general agreement has been reached about how to select accelerograms to use in time history analysis of structures. This is due to the fact that no absolute logical link may be found between average properties of few selected accelerograms and a specific, developed, modified and smoothed design spectrum. However a general rule of selection may be considered as:

1. To make sure the average response spectra of selected accelerograms matching with design spectrum in the period range under consideration.
2. Selecting of accelerograms with highest energy content in the period range under consideration with due attention to effective period of nonlinear structure. This may be provided by using power spectra of considered accelerograms.

3. Assessment of sensitivity of nonlinear response of structures through either frequency scalling of selected accelerograms or by using artificial accelerograms, with due consideration of the fact that the later may lead to nonlogical high responses of nonlinear structures.

In these studies, the recommendations of UBC 97 have been used in addition to same extra considerations to sweep the whole range of period under consideration. 9 accelerograms (acc1 to acc9) have been selected (table 1) with following procedure to draw out design values from (figure 5):

$$\text{Design quantity= max} \begin{cases} average(acc1 : acc7) \\ acc8 \\ acc9 \end{cases} \quad (1)$$

2 levels of performance objective have been adopted under 2 levels of seismic hazard;

1. Life safety performance objective under 5% probability of exceedence in 100 years earthquake.
2. Serviceability performance objective under 50% probability of exceedence in 50 years earthquake.

Table (1): Accelerograms used in time history analysis

No.	Record Name	Location	Date	Station Name	DEG	HP	LP
1	HOLLISTER CITY HALL	HOLLISTER	4/9/1961	USGS 1028	181	0.25	11
2	HOLLISTER CITY HALL	HOLLISTER	4/9/1961	USGS 1028	271	0.11	11
3	GILROY ARRAY #3	LOMA PRIETA	10/18/1989	CDMG 47381	90	0.1	40
4	GILROY ARRAY #4	LOMA PRIETA	10/18/1989	CDMG 57382	90	0.2	30
5	HOLLISTER CITY HALL	LOMA PRIETA	10/18/1989	USGS 1028	180	0.1	30
6	SALINAS JOHN & WORK	LOMA PRIETA	10/18/1989	CDMG 47179	160	0.1	30
7	SUNNYVAL COLTON AVE	LOMA PRIETA	10/18/1989	USGS 1695	270	0.1	40
8	PARKFIELD-CHOLME 5W	COALINGA	5/2/1983	CDMG 36227	360	0.2	22
9	HOLLISTER CITY HALL	MORGAN HILL	4/24/1984	USGS 1028	1	0.2	19

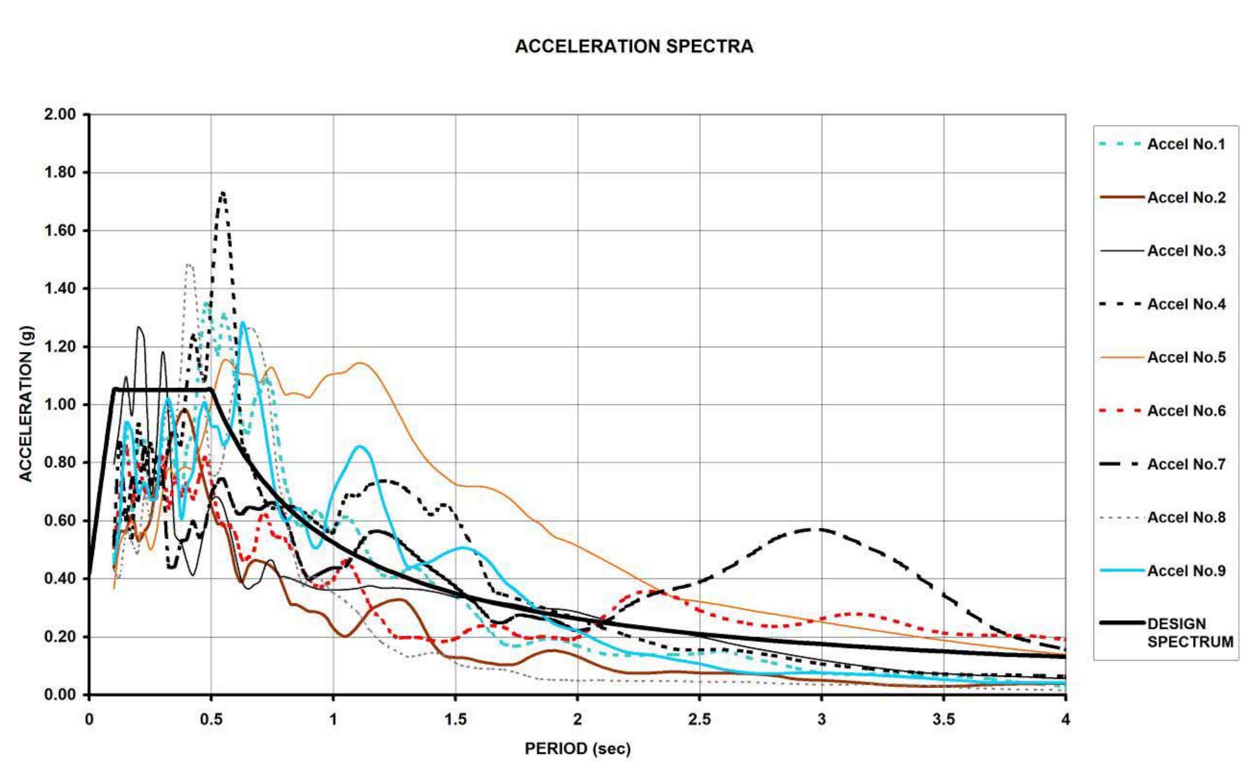


Figure (4): Selected accelerograms acceleration spectra

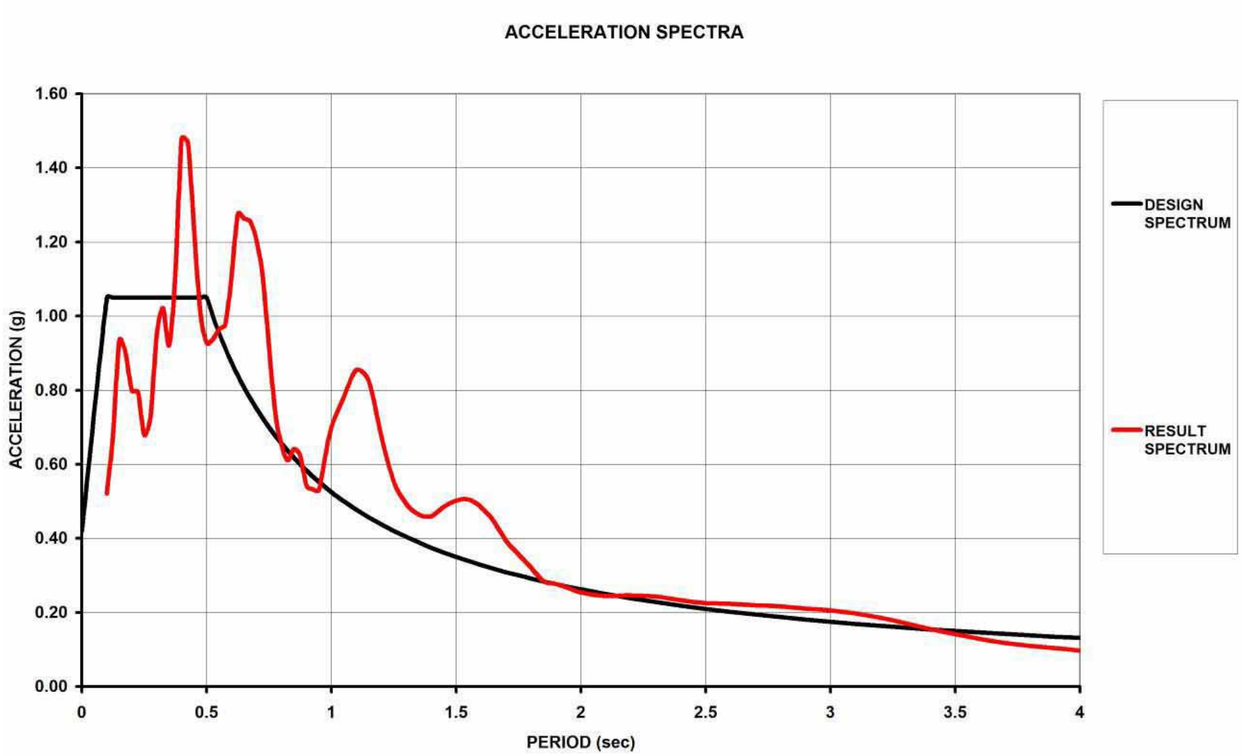


Figure (5): A case of design and resulted spectrum from formula (1)

Preliminary design

Preliminary design of friction dampers has been performed by equivalent linear static method using reduction factor R=12. The value of reduction factor has been chosen according to high performance of friction damper compared to highly ductile structural systems recognized by seismic codes. The following formulation has been developed to estimate the plastic resisting moment of each of friction connections, P_u being resulted from equivalent static method.

$$M_P = \frac{P_u b^2 l}{4\,(b^2 + l^2)} \qquad (2)$$

Parameters in formula (2) are shown in figure (6).

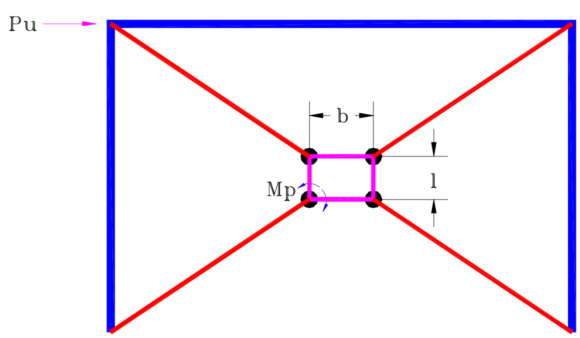
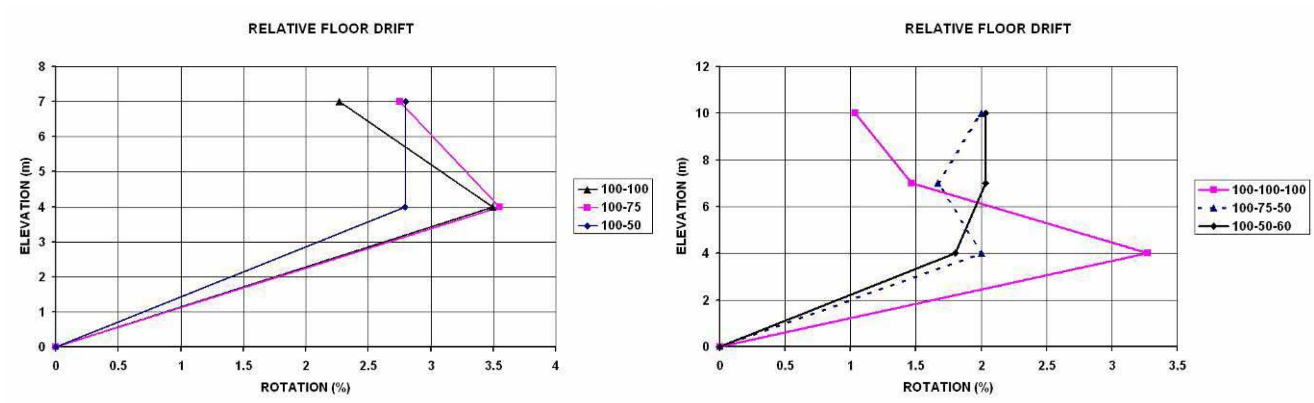


Figure (6): Configuration of friction braced frames and related parameters

Nonlinear time – history analysis results

Analysis of the 2 story structure has been performed considering 2 cases of with / without $P\text{-}\Delta$ (large deformation) effect. According to these studies 26 and 32% of increase in floor displacements have been resulted from $P\text{-}\Delta$ in 1^{st} and 2^{nd} levels respectively. Furthermore a decrease of about 5% in energy dissipation of dampers has been resulted from $P\text{-}\Delta$ effects.

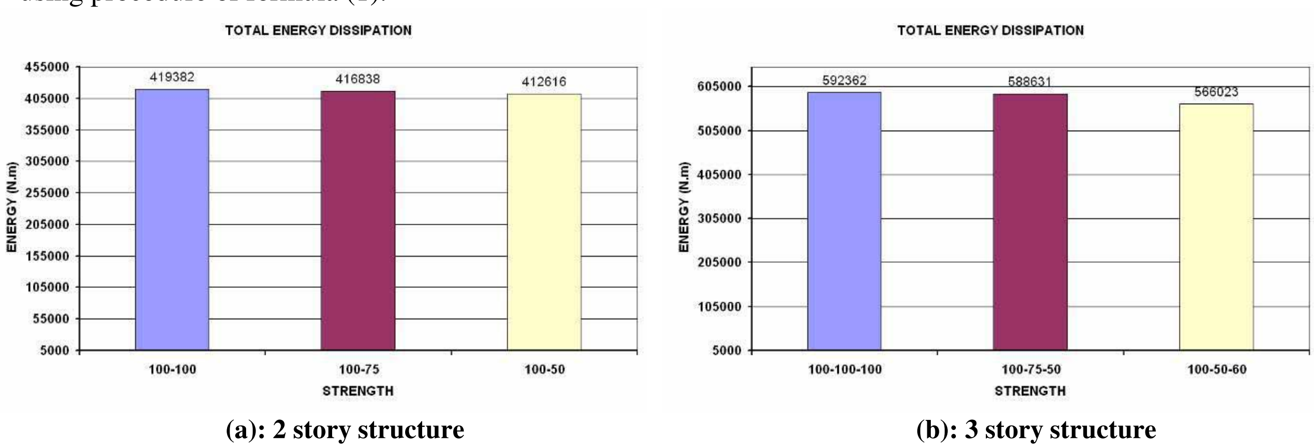
The essential parameter to control the performance of structures under severe earthquake effect scenarios, is the allowable or maximum damage index, modeling the maximum robustness of structures in their post elastic status. Regarding the fact that an unlimited energy absorption capacity may be considered actually for Pall dampers, according to observation of tests, the limitations suggested by Iranian code to control non – structural damages have been accepted as allowable damage index. 3% and 0.5% relative drift $\left(=\dfrac{Interstory\ \ Drift}{Story\ Height}\right)$ have been considered as allowable damage indices for 5% and 50% of probability of exceedence hazard levels respectively. In order to provide the structure with an almost uniform relative drift demand along its' height, a balancing of stories strength has been performed. The stories drift demand, before and after balancing of strengths has been shown in figure (7).



(a): 2 story structure **(b): 3 story structure**

Figure (7): Distribution of relative story drift (indices beside MP are respectively from left to right, indicating the percent of initial strength of 1^{st} and 2^{nd} stories used in balancing process)

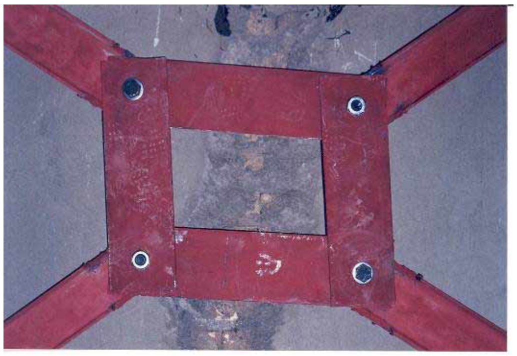
As it is shown in figure (8) the balancing in story strength leads to a balancing in story energy dissipation demand, while the total energy dissipation demand remains almost the same in all strength arrangements. It is notable that all results have been derived using nonlinear analysis under 9 accelerograms processed using procedure of formula (1).



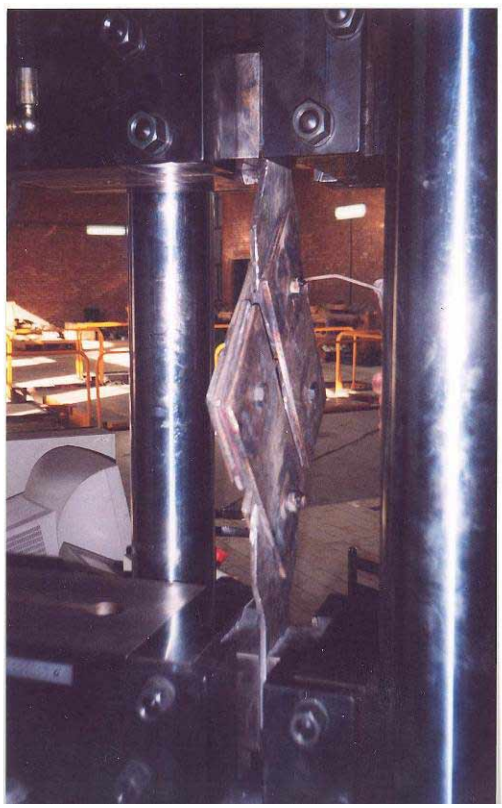
(a): 2 story structure **(b): 3 story structure**

Figure (8): Distribution of energy dissipation demand of stories

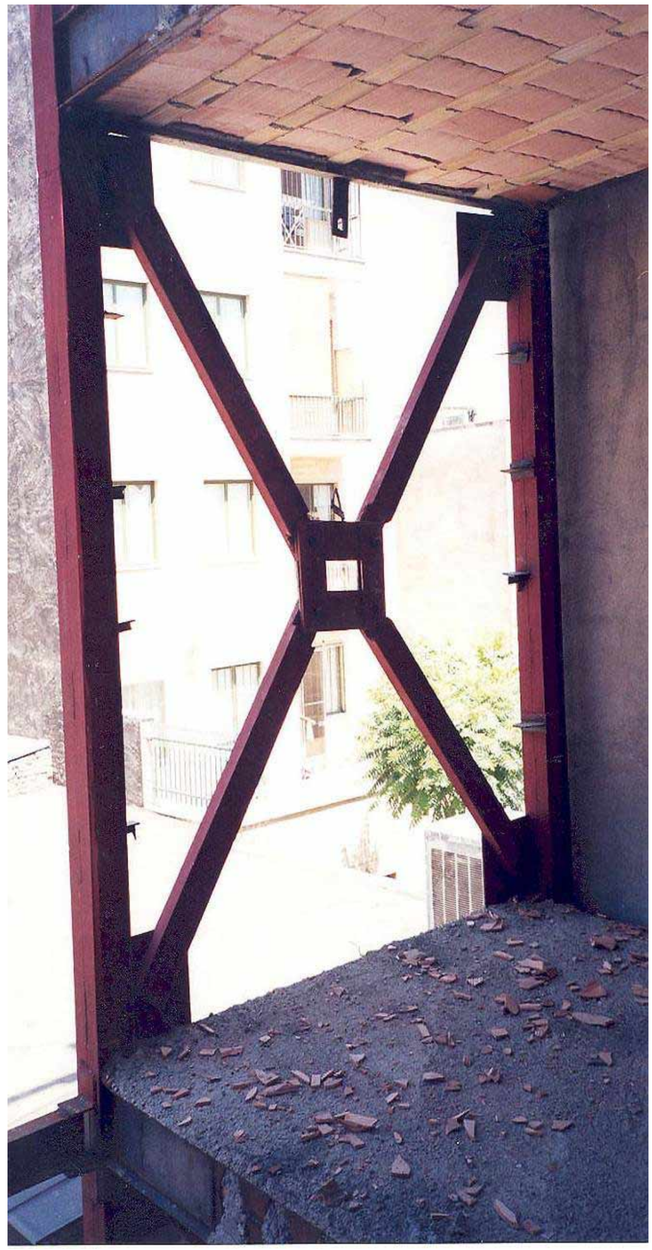
In order to model the variation of energy imparting of accelerograms, due to variation in effective structural period resulted from nonlinear behavior of structures or due to errors of period calculation, $\pm 20\%$ changes in structural period have been performed and analyses have been repeated for each case. Analyses showed variations less than 0.5% and 5% in relative story drifts and dissipation energy demands respectively.



(a): Device front view [9]



(b): Cyclic test of damper



(c): A residential building structure equipped with Friction Damper [9]

Figure (9): Friction damper device application (Iran)

CONCLUSIONS

1. It is obvious that increases in energy dissipation of structural systems is an essential strategy to withstand the effect of probable earthquakes. Due to limited energy dissipation capacity of actual steel material, friction connections with unlimited energy dissipation capacity observed in cyclic tests, maybe considered as a favorite alternative for conventional structural systems.
2. An increase of about 30% in relative drifts has been resulted from large deformation (P- Δ) effects.
3. Decrease in higher story strengths provides them with higher potential of energy dissipation. An optimum arrangement of story strengths provides the structure with an almost uniform relative drift and energy dissipation demands in stories of the structure.
4. The equivalent static method along with a modified distribution of seismic loading resulted from balancing of strengths (in order to reach to a uniform relative drift demand) has been evaluated very effective and accurate, regarding results drawn out of nonlinear time history analyses.
5. A dimensional ratio (aspect ratio) of damper frame (figure 6) proportional to the braced frame one, will lead to highest level of energy dissipation potential. An unproportional aspect ratio will lead to an instantaneous instability and lack of energy dissipation potential.
6. Neither a single nonlinear dynamic method of analysis nor unique parameters of a nonlinear method (like θ in Wilson - θ method) shall be used to analyse the nonlinear behaviors of structures. A try and error strategy shall be used to inquire the closest responses to exact quantities. A balance of costs (i.e. time consumation) and benefits (most accurate responses) shall be provided regarding requirements of projects. Convergence objectives are not sufficient to satisfy the efficiency and accuracy requirements of analysis. In addition, the difficulties and uncertainties of accelerogram selection through different strategies, turn the nonlinear dynamic method to a rather doubtful way of structural analysis than an exact approach.

AKNOWLEDGEMENT

This Research has been conducted at Niroo Research Institute and has been supported by Sarzamin Consulting Engineers.

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