RESPONSE OF FRICTION DAMPED BUILDINGS

Avtar S. Pall, Ph.D., P. Eng. (I)

SUMMARY

A novel structural system for aseismic design of buildings is proposed. By incorporating simple and inexpensive friction devices at strategic locations in the building joints, their earthquake resistance and damage control potential can be dramatically enhanced. During severe earthquake excitations, the friction devices slip and a large portion of the vibrational energy is dissipated mechanically rather than inelastic yielding or cracking of the main structural components. Results of inelastic time-history dynamic analysis have shown superior performance of the friction device equipped building when compared to computed responses of conventional building systems.

INTRODUCTION

During a major earthquake a large amount of kinetic energy is fed into the structures and buildings sway back and forth with an amplitude proportional to the energy fed-in. The manner in which this kinetic energy is consumed in the structure determines the level of damage.

All building codes, recognize that except for special structures like nuclear reactors, etc., it is economically not feasible to reconcile the seismic energy within the elastic capacity of the materials. In general, all current methods of aseismic design place reliance on the ductility of the structural elements, i.e., ability to dissipate energy while undergoing inelastic deformations causing bending, twisting, and cracking. This assumes some permanent damage, in some cases just short of collapse, but the primary and secondary damage may be as economically significant as the collapse of the structure.

If a major portion of the seismic energy can be dissipated mechanically, the response of the structure can be controlled without structural damage.

PROPOSED MECHANISM

Of all the methods available to extract kinetic energy from a moving body, the most widely adopted is undoubtedly the friction brake. This concept is being extended to building construction, to control their vibratory motion caused by the lateral inertial forces of an earthquake. Several inexpensive and simple friction devices, suitable for different types of construction, have been developed. Basically, these consist of heavy duty brake lining pads trapped between two sliding steel surfaces. These are incorporated at strategic locations in building joints so that the structural integrity of the building during slipping is not jeopardized.

(I) Project Engineer, The SNC Group Inc. Montreal, Que. Canada

These devices are designed not to slip during normal service load conditions, wind storms or moderate earthquakes. During a major earthquake these slip and dissipate excessive seismic energy during building motion. Similar to automobiles, the motion of a vibrating building is slowed down by BRAKING rather than BREAKING.

Several cyclic dynamic laboratory tests have been conducted on the specimen devices (Ref. 1). The performance is reliable, repeatable and possesses rectangular hysteresis loops with negligible fade over several cycles of reversals that are encountered in successive earthquakes (Fig. 1). Much greater quantities of energy can be disposed of in friction than any other method that involved damaging process of yielding of steel or cracking of concrete. Furthermore, these joints are always ready to do their job, regardless of how many times they have performed.

OPTIMUM SLIP LOAD

The seismic response of a structure is determined by the amount of energy fed-in and energy dissipated. The optimum seismic response, therefore, consists of minimizing the difference between the input energy and energy dissipated.

The energy dissipation is proportional to the product of slip load and the slip travel during each excursion. For very high slip loads, the energy dissipation in friction will be zero, as there will be no slippage. If the slip load is very low, the amount of energy dissipation again will be negligible. Between these extremes, there is an intermediate value to give the maximum energy dissipation.

Softening of the structure due to slipping can mean an invitation to higher or lower seismic forces, depending on its relation to the frequency content of the gound motion. The beneficial effects of energy dissipation must be combined with the effect of the altered period of vibration on the energy input which may be positive or negative. By the proper selection of the slip load, it is therefore possible to "tune" the response of the structure to an optimum value.

CONSTRUCTION SYSTEMS

Proposals for dissipating energy by friction have been categorized into three main areas of construction: i) Tall shearwall buildings, ii) Steel framed buildings. iii) Low-rise buildings.

Tall Shearwall Buildings

Generally, stiffer structures such as those which incorporate shearwalls are subjected to high inertial forces caused by earthquakes. In this case, friction devices are incorporated along vertical planes to sectionalize the otherwise rigid wall into two or more laminations. Conceptually, the mechanism proposed is that of a "leafspring", commonly used in automobiles as a shock absorber, which remains elastic while absorbing energy as it deforms. These joints would be preaseembled and placed in forms before pouring the concrete. Some typical details of friction joints for cast-in-place concrete shearwalls are shown in Fig. 2.

A study of shearwalls coupled by vertical sliding friction joints is given in Ref. 3. To compare the improvement in seismic response of friction-jointed wall, the analyses included the other limiting cases of a single monolithic wall and two isolated walls. Nonlinear time history dynamic analysis was carried out using El Centro 1940 (N.S.) earthquake record. Results of analyses for 5 to 20 storey high walls are shown in Table 1. It is seen that friction jointed walls are more suitable for tall structures as differential movement in short walls is not enough to cause sufficient energy dissipation. In case of a 20 story wall, the response of friction jointed wall is considerably improved over two isolated walls and single monolithic wall. The maximum base shear, overturning moment, normal stresses and deflections of the friction jointed wall are about 34, 25, 35 and 65 percent respectively of monolithic wall, and 65, 80, 70 and 60 percent respectively of isolated walls. Typical time-histories for the deflections at the top of 20 story wall are shown in Fig. 3. Experimental results of a friction jointed model shearwall, subjected to simulated seismic excitations on a shake table, confirm the findings of computer studies (Ref. 4).

Friction joints can also be used with advantage in vertical joints of precast concrete large-panel structures wherein natural joints are available (Ref. 1,2).

Steel Framed Buildings

Braced steel frames are known to be economical and are effective in controlling lateral deflections due to wind and moderate earthquakes; but during major earthquakes, these structures do not perform well. Firstly, being stiffer, they tend to invite higher seismic forces, and secondly, their energy dissipation capacity is very much limited due to the pinched hysteretic behavior of the braces. The performance is still poorer when the brace is designed to be effective only in tension. A tension brace stretches during a severe shock and buckles in compression during reversal of load. On the next application of load in the same direction, this elongated brace is not effective even in tension until it is taut again and is being stretched further. As a result, energy dissipation degrades very quickly.

Moment resisting frames are favored for their earthquake resistance capability because they have stable ductile behavior under repeated reversing loads. This preference is reflected in various seismic codes by assigning lower lateral forces. However, these structures are very flexible and it is often economically difficult to develop enough stiffness to control story drifts and deflections to prevent nonstructural damage.

Recent earthquakes have demonstrated the need for stiffer structures, and a strong interest has grown in the past few years to develop structural systems which combine the ductile behavior of the moment resisting frame and the stiffness of a braced frame. In Japan, designers often employ braced moment resisting frames in which the brace is designed to carry only a portion of the lateral load.

An eccentric braced frame (Ref. 5) is another step in this direction. In this method, the brace joints are eccentric, to force the beams into inelastic action to dissipate more energy. After a major earthquake, large inelastic deformations must be expected at all floors of a structure. Although the structure is saved from total collapse, the main beams are sacrificed and an actual structure would need major repair or replacement.

In the proposed structural system, each bracing in the moment resisting frame is provided with a friction device. The device is designed not to slip under normal service loads and moderate earthquakes. During severe seismic excitations, the device slips at a predetermined load, before yielding occurs in the other structural elements of the frame. As the braces then carry a constant load, the remaining loads are carried by the moment resisting frame. In this manner, redistribution of forces takes place between successive stories, forcing all the braces to slip and participate in the process of energy dissipation.

A simple friction joint can be used to slip in tension and compression provided the brace is designed not to buckle in compression. In the case of more commonly used tension bracing system, the cross bracings are connected to a special mechanism as shown in Fig. 4. When tension in one of the brace forces the joint to slip, it activates the four links which force the joint in the other brace to slip simultaneously. Many more variations are possible to suit particular needs.

Furthermore, the device can be conveniently incorporated in existing framed buildings to upgrade their earthquake resistance. Friction joints may also be used with advantage in connecting pre-assembled infill panels or curtain walls, which act as bracing elements to the frame.

To demonstrate the influence of the friction device on the seismic response, and to compare the results with alternate structural systems, a family of three 10 story frames, as shown in Fig. 5, was chosen for the analysis (Ref. 6). Included were (a) moment resisting (MR) frame; (b) braced moment resisting (BMR) frame; and (c) friction damped braced (FDB) frame. Inelastic time-history dynamic analysis was carried out using earthquake record of El Centro 1940 (N.S.). The comparative results show that incorporation of friction device in the bracing system dramatically improves the overall seismic response. At El Centro excitations, the building deflections, moments in beams, moments in columns, and base shears are about 40%, 70% and 70% respectively of other framing systems (Figs. 6, 7). At the level of El Centro, 90% of the beams and 10% of the columns yielded in the MR frame, 60% beams and 90% braces yielded in the BMR frame, while none of the members yielded in the FDB frame.

Low-Rise Buildings

In low-rise structures, where overturning moments are not significant, the slipping joints are located horizontally between foundation and superstructure. Ideally, frictionless joints will allow the ground to move without exerting any force on the building. But, the displacement of the building relative to the ground will be large. A friction force is therefore required, sufficient to react to the wind, but during severe earthquakes the magnitude of the lateral force that the building can experience is limited to this value.

The proposed friction device will partially isolate the superstructure from forcing ground motion. The slip load value is so selected that the stresses in materials do not exceed permissible limits.

In order to provide restraint on the total movement, the steel surfaces on which the friction pads slip are of dished shape. Fig. 8 shows the details of such a joint.

CONCLUSION

The new concept of building construction using friction devices is of particular importance, as:

1) energy is dissipated mechanically rather than the inelastic action of the main structural members;

2) as stresses in the structural members are considerably reduced, the concept offers economy in member sizes;

3) the structure is softened without losing its elasticity and recovers with little or no permanent set;

4) the friction device acts like a structural damper to control the amplitude and as a safety valve to limit the loads exerted;

5) the amplitude of vibrations and accelerations are considerably reduced, hence secondary damage is minimized;

6) the resonance of the structure is difficult to establish.

In short, the application of this concept raises the level of earthquake resistance philosophy from the avoidance of collapse to the control of secondary damage.

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Table 1 — Seismic response of friction-damped concrete shearwall for different heights (0.33g)

Height of wall in stories	Type of response	Response of friction-damped wall as a percentage of that for: Two isolated walls	Single monolithic wall
5	Shear	70	100
	Bending	40	100
	Deflection	30	100
	Overturning	95	115
10	Shear	65	100
	Bending	35	100
	Deflection	20	105
	Overturning	60	75
15	Shear	65	35
	Bending	50	40
	Deflection	45	75
	Overturning	60	35
20	Shear	65	35
	Bending	70	35
	Deflection	60	65
	Overturning	80	25

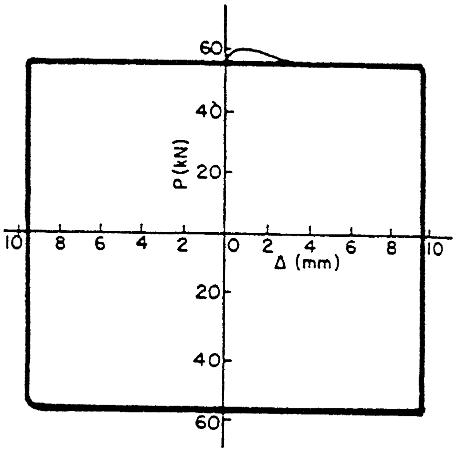
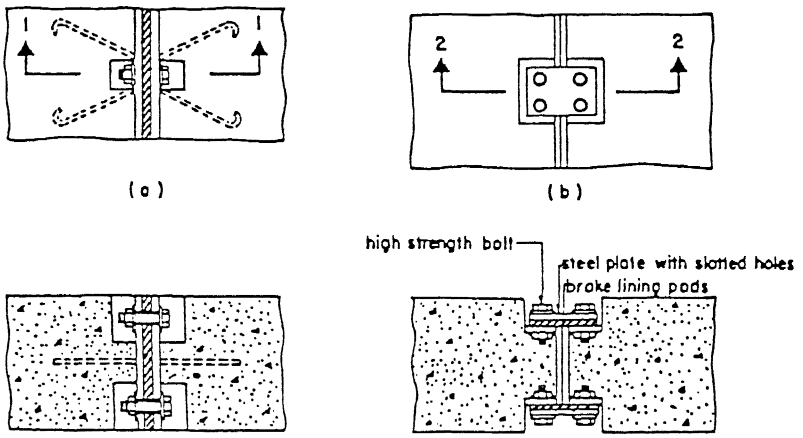
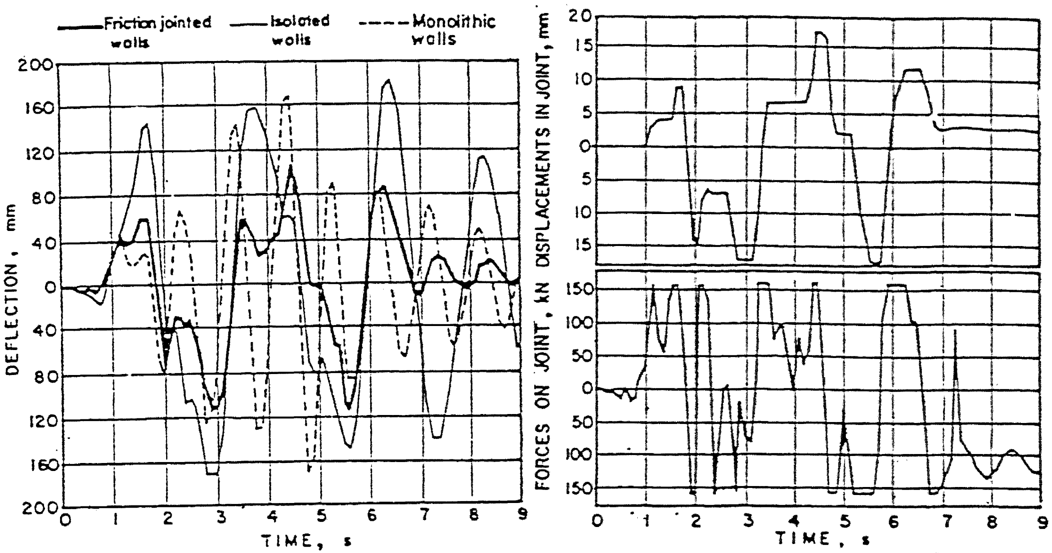


FIG. 1. HYSTERESIS LOOP USING BRAKE LINING PADS



SECTION 1-1 SECTION 2-2

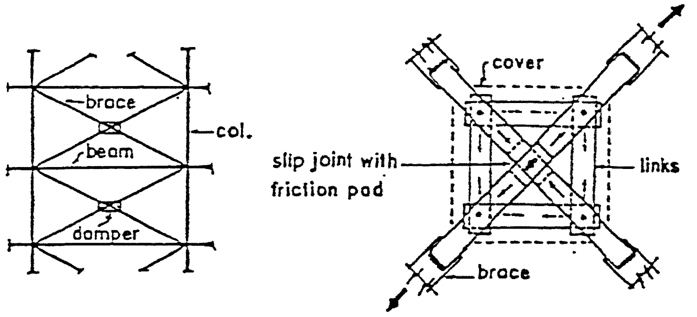
FIG.2. FRICTION JOINTS FOR CONCRETE SHEARWALLS



Building deflection

Joint displacement & forces

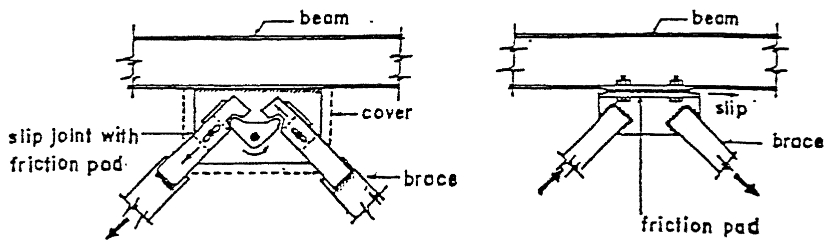
FIG. 3. TIME-HISTORIES AT TOP OF 20 STORY WALL (0.33g)



Location of Friction Device (damper)

Mechanism of Friction Device

X-Bracing

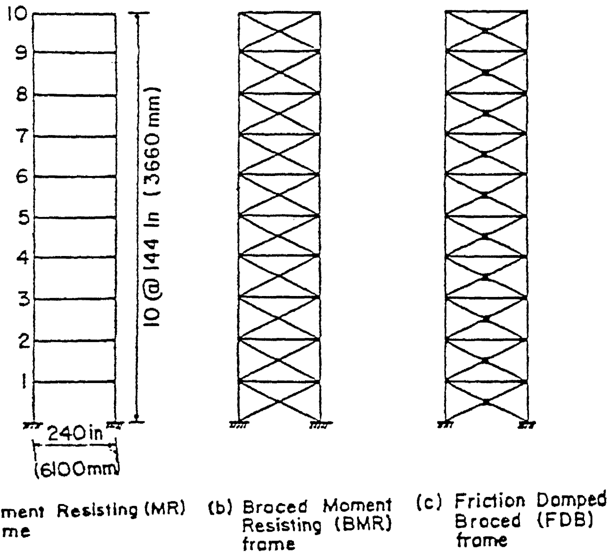


Brace effective in tension, but reverse slip at zero compression

Brace effective in tension and compression

K-Bracing

FIG. 4. TYPICAL FRICTION DEVICES FOR FRAMES



(a) Moment Resisting (MR) frame

(b) Braced Moment Resisting (BMR) frame

(c) Friction Damped Braced (FDB) frame

FIG. 5. TYPICAL FRAMES STUDIED

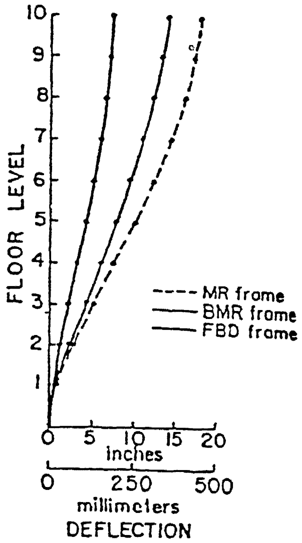
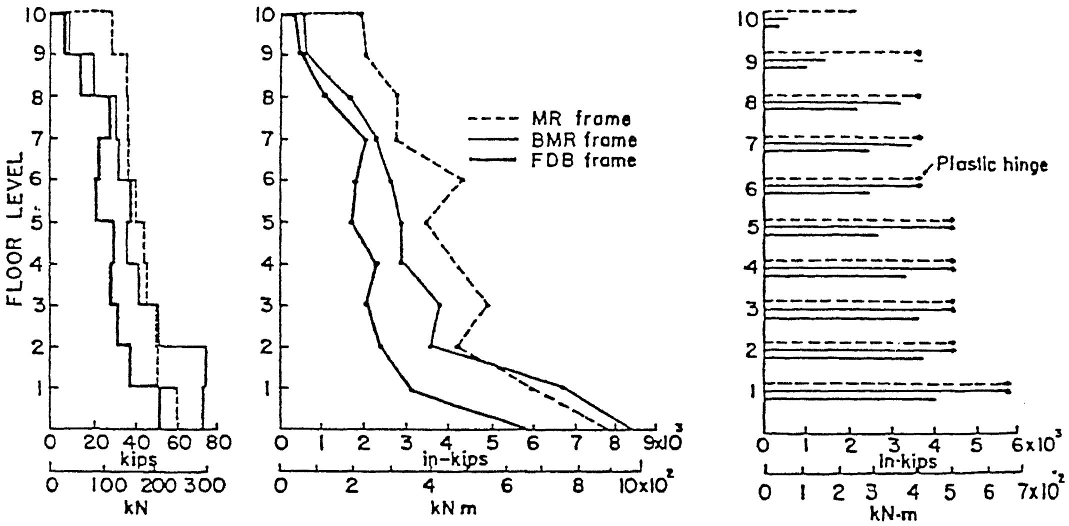


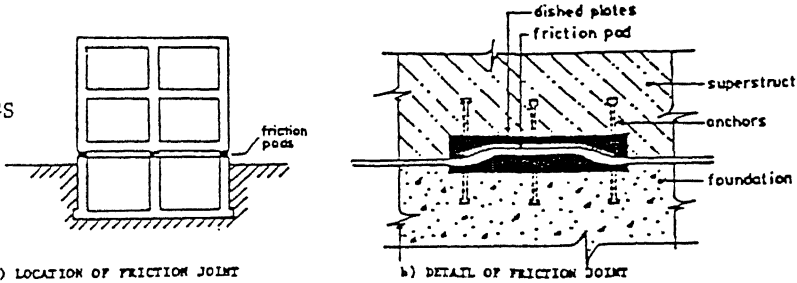
FIG. 6. DEFLECTION ENVELOPE



(a) ENVELOPE OF SHEARS (b) ENVELOPE OF MOMENTS (c) MOMENT

FIG. 7. ENVELOPE OF FORCES IN COLUMNS (a & b) AND BEAMS (c)

FIG. 8
LOW-RISE BUILDINGS



a) LOCATION OF FRICTION JOINT

b) DETAIL OF FRICTION JOINT