0718

PERFORMANCE OF HIERARCHICAL FRICTION DISSIPATING JOINTS IN MOMENT RESISTING STEEL FRAMES

John J W BUTTERWORTH[1] And Charles G C CLIFTON[2]

SUMMARY

Friction dissipating joints with slotted bolt holes have been used in concentrically braced frames (linear sliding) and more recently, in moment resisting frames (rotational sliding). Such joints have the ability to provide many cycles of ductile energy dissipation with little or no primary structural damage and permit the decoupling of the strength and stiffness of connected members. Suggestions are offered on the use of linear sliding joints in K and X-braced frames where they could lead to cheaper, stiffer structures with high levels of ductility. Rotating sliding bolted joints extend the benefits of damage-free energy dissipation to moment-resisting frames. The decoupling of beam stiffness and end moment strength avoids over-sizing columns to deal with beam over-strength moments. The performance of a rotational slotted joint having a hierarchy of two distinct moment levels at which limited rotational slip can occur is discussed. The basic characteristics of the joint are described and some observations made on the seismic response of some sample frames to seismic ground motion.

INTRODUCTION

The design of structures for earthquake resistance typically relies on the provision of adequate ductility and a secure path for gravity loads within a proven, stable structural form. Conventional construction provides ductility by means of hysteretic energy dissipation resulting from inelastic action within members and joints. Such inelastic action causes damage and if continued long enough the cumulative effect may exhaust the ductile capacity leading to fracture. Although this approach has been very successful at preventing collapse, the cost of damage repair can be very high.

Currently, the most widely used system for providing earthquake resistance without significant accompanying damage is that of seismic isolation (base isolation). However, not all structures are suited to this form of protection, for example slender or relatively flexible buildings, and there is an associated cost. Another alternative that is beginning to receive more attention involves the use of passive energy dissipating elements within the structure. Aiken [1993] describes a number of different types of passive device, utilising viscous, visco-elastic or coulomb friction effects. The viscous and visco-elastic devices have no activation threshold and are able to generate damping at very low displacements, but tend to be relatively complex and expensive. The devices considered in more detail in this paper are of the friction-dissipating type, in particular those that employ components bolted together with slotted bolt holes allowing relative sliding movement.

SLIDING BOLTED JOINTS

A sliding bolted joint (SBJ) that is to provide satisfactory performance as an energy-dissipating element in a seismic resistant structure must be capable of repeated cycles of displacement without loss of strength, stability or energy dissipation ability. A testing regime should include at least 50 complete cycles to the displacement corresponding to the structure's design displacement ductility factor and 10 cycles to the device's maximum displacement. Where possible the mean sliding velocity should approximate the in-service velocity under earthquake action. Important factors that influence the satisfactory performance of a sliding bolted joint include:

[1] *Department of Civil & Resource Engineering, The University of Auckland, email: jw.butterworth@auckland.ac.nz*
[2] *New Zealand Heavy Engineering Research Association, Manukau City, email: structural@hera.org.nz*

- Maintenance of contact pressure between the sliding surfaces,
- Maintenance of a more or less constant coefficient of friction between the sliding surfaces,
- Avoidance of brittle failure of any joint components when the joint reaches the limit of its sliding range.
- Simple and cheap construction and maintenance.

A variety of sliding bolted joints have been tried in the past, some using special surface facing materials such as brake lining and others using direct steel-to-steel contact. Direct steel-to-steel contact tends to produce a joint with an undesirably variable friction coefficient, with a high static breakaway level requiring associated components to be sized for the friction over-strength. Brake lining has been found to work satisfactorily although the friction coefficient may be a little low [Pall & Marsh, 1982]. A joint using steel/brass contact surfaces has been found to perform well [Popov et al, 1995], and has subsequently been tested in New Zealand in a slightly different form [Clifton et al, 1998].

Symmetric Linear sliding joint using a steel/brass interface

The basic joint described in [Popov et al, 1995] was intended to provide stable energy dissipation during linear displacement cycles. The details are shown in Fig. 1 below.

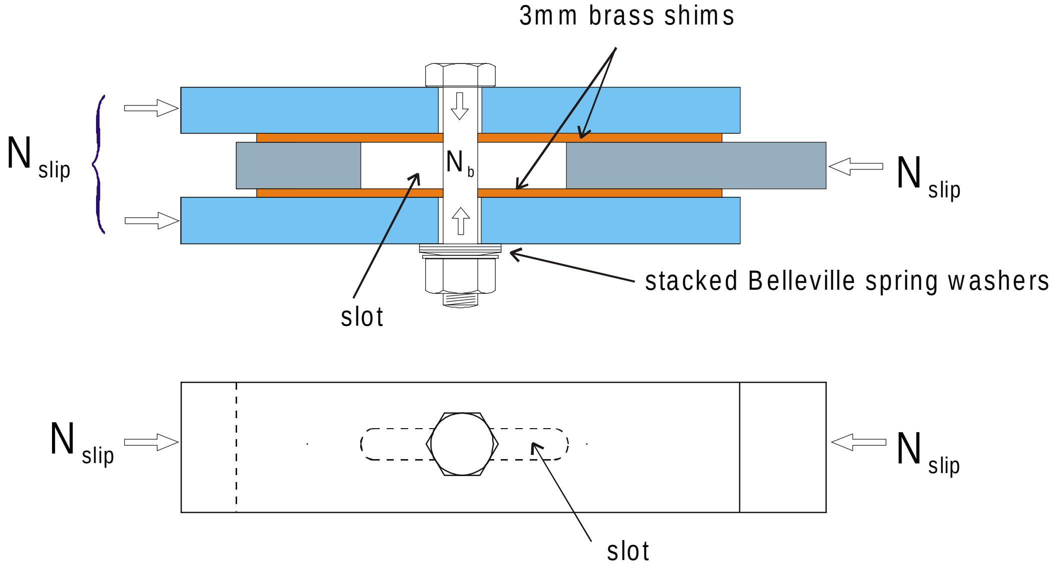


Fig. 1 Basic sliding joint details

Note the use of two clamping plates providing symmetric loading when the joint is subjected to axial loading as shown. Having two friction interfaces also doubles the slip force, N_{slip}, to $N_{slip} = 2nN_b\mu$, where n is the number of bolts, N_b is the tension force in one bolt and μ is the coefficient of friction. The tension in the bolts was maintained during joint deformation by means of the stack of Belleville (spring) washers placed under each nut. Bolt tension was initially set by means of load-indicating washers under the bolt heads. During test the joint was subjected to displacement cycles of increasing amplitude at constant velocity, and simulated earthquake motions. In all cases the hysteresis loops were essentially rectangular with a kinetic friction coefficient in the range 0.27 to 0.31. There appeared to be no upper bound on dissipation of hysteretic energy – i.e. there was no evidence of a cumulative damage effect. Displacement cycles that exceeded the slot length were not reported. The joint load is transferred by friction through the two interfaces until the bolt makes contact with the end of the slot after which the bolt will be subjected to bearing and shear. If the load on the joint continues to increase, then provided the bolt diameter is sufficiently large in relation to the plate thickness, the thinner inner plate will eventually yield causing inelastic deformation and damage

Asymmetric sliding joint

A joint configuration with the driving force applied to one outer plate and the resisting force applied to the inner or central plate allows a greater range of applications. Fig. 2 shows a typical asymmetric joint with the driving force, *F* applied to the top plate. The two friction interfaces, once activated, will each transfer a load of 0.5*F* since they have the same clamping force, N_b and the same coefficient of friction. Additional demand is placed on the bolt in this type of joint, since in order to generate sliding on both interfaces the bolt must transfer half the joint load, 0.5*F*, in shear to the lower plate.

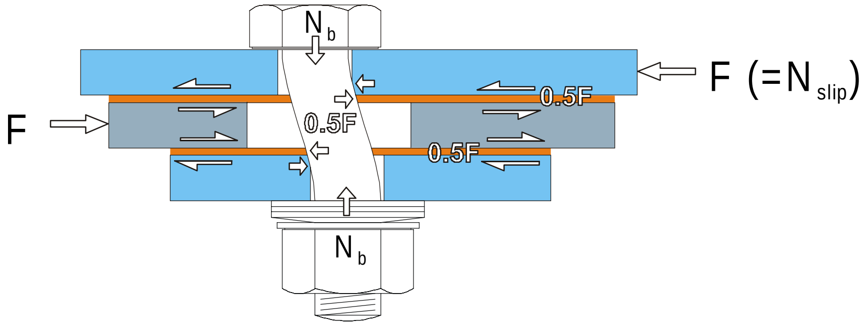


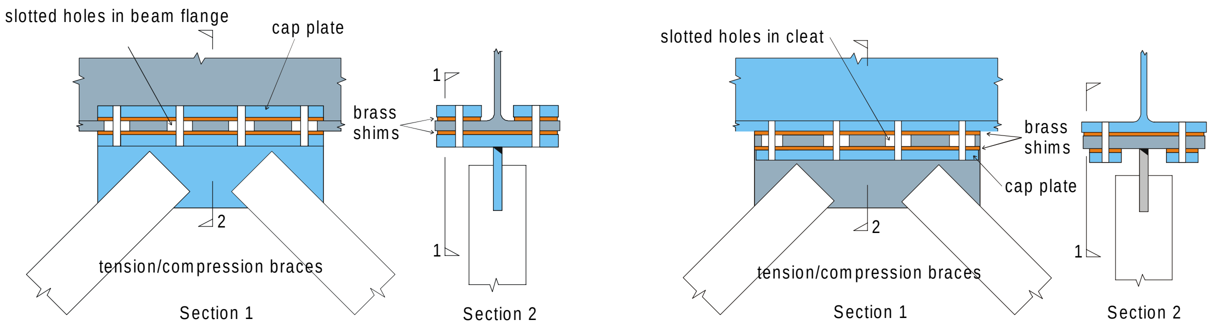
Fig. 2 Asymmetric sliding joint

The behaviour of asymmetric sliding joints is currently being investigated by means of a physical testing programme and finite element modelling. Clifton et al [1998] reported on a beam-column joint incorporating an asymmetric friction configuration in which brass shims were placed between beam flange and column cleat and between beam web and web cleat, with bolts passing through normal clearance holes. Bolts were tightened by the part-turn method against stacked Belleville washers. Stable sliding behaviour was observed, despite the asymmetric loading on the bolt interface. Loading beyond the limited slip range provided by the 2mm clearance holes caused inelastic deformation and finally cracking of the cleat plates. In another study [Murray, Butterworth, 1990] it was noted that the localised yielding around the bolt holes in web side plate connections provided a very ductile and stable energy dissipating mechanism provided the bolts were sized to avoid shear failure prior to plate yielding. In relation to sliding bolted connections the plate yielding mechanism can be expected to furnish extra energy absorption under extreme conditions when the joint displacement exceeds the slot length, provided the bolt diameter to plate thickness ratio is controlled appropriately.

Use in concentrically braced frames

Concentrically braced frames offer one of the most efficient lateral-load-resisting systems available, combining strength, stiffness, low weight and simplicity of construction. Unfortunately, under seismic loading the use of light tension-only bracing tends to lead to poor performance with potential ‘soft storey’ failure due to irrecoverable tensile yielding. The alternative of using braces capable of recoverable yielding in both tension and compression has generally proved unattractive due to the large cross sections required. A better alternative involves the use of sliding joints to protect the braces from damage.

Linear SBJs have most commonly been used in braced frames with the SBJ placed at one end of each diagonal brace and designed to slip prior to yield or buckling of the brace. Single diagonal braces have been used, but the need for a compression capacity in excess of the SBJ slip load results in relatively heavy members. A K-braced configuration, on the other hand still requires compression-capable braces, but they would be shorter and lighter than a full diagonal brace. Both forms have performed well under test [Yang, Popov, 1995]. There appears to be scope for investigating other alternatives for incorporating linear sliding joints into braced frames. Some configurations that are currently under investigation are shown in Figs. 3 and 4.

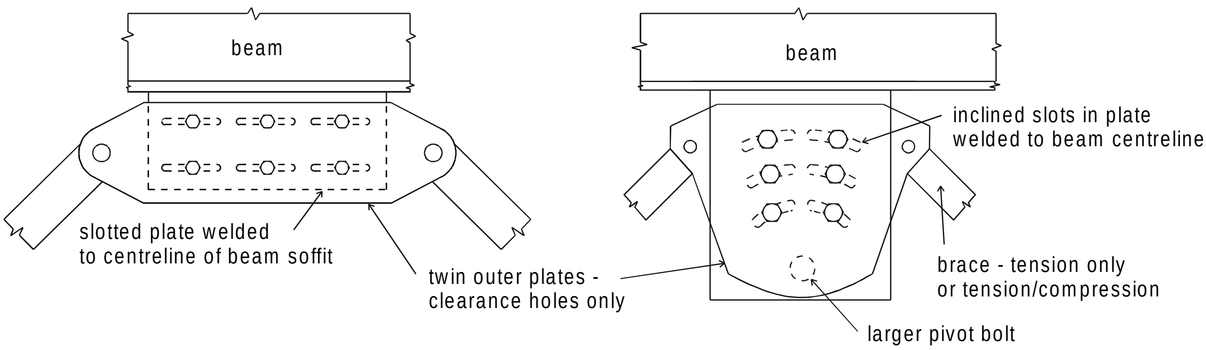


(a) Detail requiring slotted holes in beam flange (b) Detail avoiding slotted holes in beam flange

Figure 3 Sliding connection configurations at junction of a brace and beam

The connection shown in Fig. 3(a) requires slotted holes in the beam flange and has a sliding action that is not symmetric in that the top plate is driven by the bolts from below. There would also be a small moment due to brace eccentricity. Tests on similar asymmetric sliding junctions in beam to column connections have shown promise and further testing is in progress [Clifton et al, 1998]. The braces could be tension-only without prejudice to the reversibility of the sliding, but would introduce a significant vertical force into the beam at mid-span and also cause a significant reduction in overall structure stiffness. Propping action to the beam could be exploited if desired, possibly leading to a smaller beam size. The connection in Fig. 3(b) is similar to the preceding case but avoids the need for slotted holes in the beam flange. The action of both joints is perhaps best visualised by considering the braces to hold the cleat stationary below the beam, with the beam attempting to slide backwards and forwards above.

The version shown in Fig. 4(a) has the sliding plates in the vertical plane and restores some symmetry to the loading on the bolts and sliding plates, but might require sleeves around the bolts to facilitate sliding. Fig. 4(b) shows a prototype rotational dissipator exploiting curved or inclined slots together with a larger reinforced, close tolerance pivot bolt.

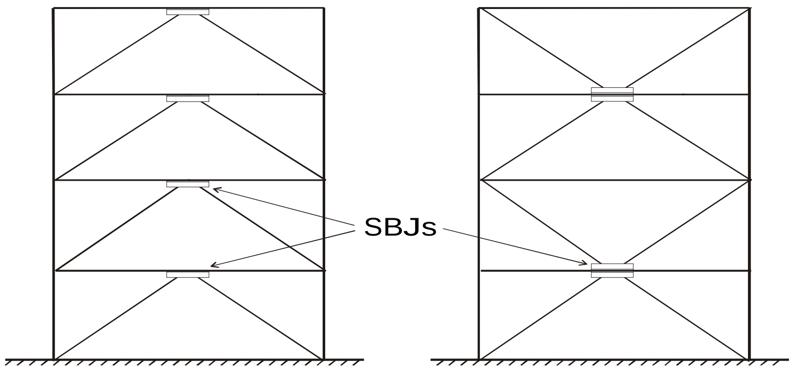


(a) Linear slider (b) Rotational slider

Figure 4 Vertically oriented sliding interfaces for braced frame dissipators

K and X bracing configurations

The K and X bracing configurations shown in Fig 5 appear to be amongst the most suitable for incorporating friction dissipators. As noted earlier, the K configuration requires braces with a compression capacity which when combined with the capacity of the associated tension brace generates a horizontal component in excess of the dissipator slip threshold. By using pairs of dissipators as shown in Fig 5b, an X configuration can be used in which the compression braces can be allowed to buckle (elastically) with the other two members of the 'X' acting in tension. The tension capacity of one brace should exceed the slip threshold of the dissipator (ignoring the post-buckling force in the compression braces) and also the inelastic strength that develops when the joint slip exceeds the slot length. A further margin would be needed to allow for accidental 'overstrength' in the joint components (such as higher bolt clamping forces or higher friction coefficients than expected). The response of braced frames of this type is discussed in more detail elsewhere [Butterworth, 1999].

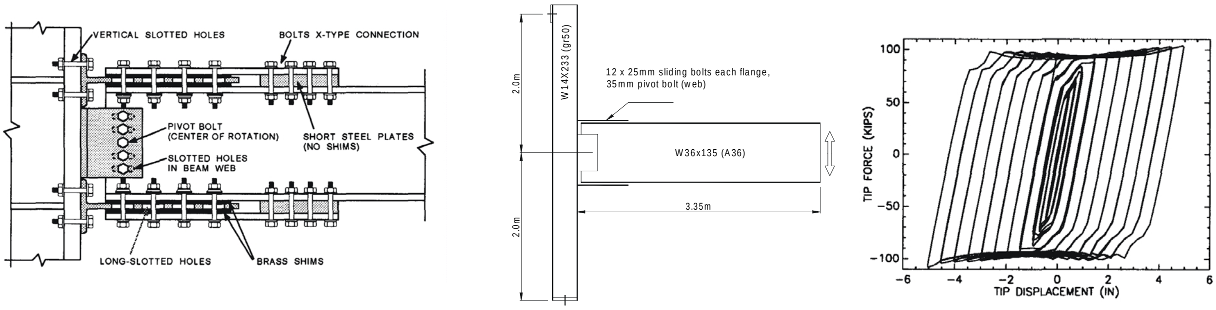


(a) K-braced (b) X-braced

Fig.5 K and X-braced configurations

ROTATIONAL SLIDING JOINTS

Although braced frames appear to offer the best opportunities for exploiting friction dissipators, moment-resisting frames are a popular form of construction relying on flexural action for lateral resistance. An appropriate form of friction dissipator for such structures is one with a rotational action. Fig. 5(a) shows the details of such a joint developed at UC Berkeley [Yang & Popov, 1995]. Tests were carried out on the configuration shown in Fig. 5(b) using cycles of steadily increasing displacement resulting in the near perfect hysteresis loops shown in Fig. 5(c).



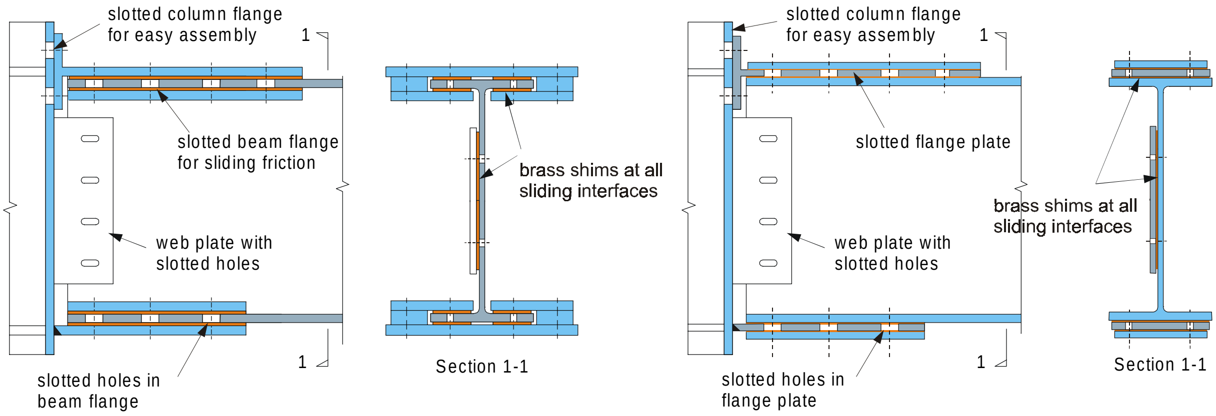
(a) Joint detail (b) Test configuration (c) Hysteresis loops

Fig. 6 Rotational slotted bolted connection (RSBC) [Yang & Popov, 1995]

Under the action of a beam moment the joint behaves like a rigid, elastic connection until the beam flange forces reach the slip level of the sliding connections. The beam then rotates at near constant moment about the larger central (pivot) bolt in the web (which has only a normal clearance hole) until the bolts reach the end of their slots. The threshold moment M_{slip} is given quite closely by $M_{slip} = 2nN_b\mu D$, where n is the number of bolts in one flange, N_b is the clamping force of one bolt, μ is the friction coefficient and D is the beam depth. The factor of 2 results from the number of friction interfaces.

Dual level joint

Fig. 7(a) shows details of a proposed sliding rotating joint in which the beam flanges contain slotted holes and the cover plates are attached to the extra wide flange plates on either side of the beam. A bolted T is used for the top flange to facilitate joint assembly. Clifton et al proposed a similar joint [Clifton et al, 1998] in which only the bottom flange can slide. The top flange is connected conventionally using a single flange plate and normal clearance holes, forcing the centre of rotation close to the top flange and avoiding damage to the reinforced concrete floor slab that is usually present. The simplified version in Fig. 7(b) which exploits a slip interface driven from one side rather than from the centre is currently the subject of detailed modeling with physical testing of some prototype specimens scheduled for the latter half of 1999.

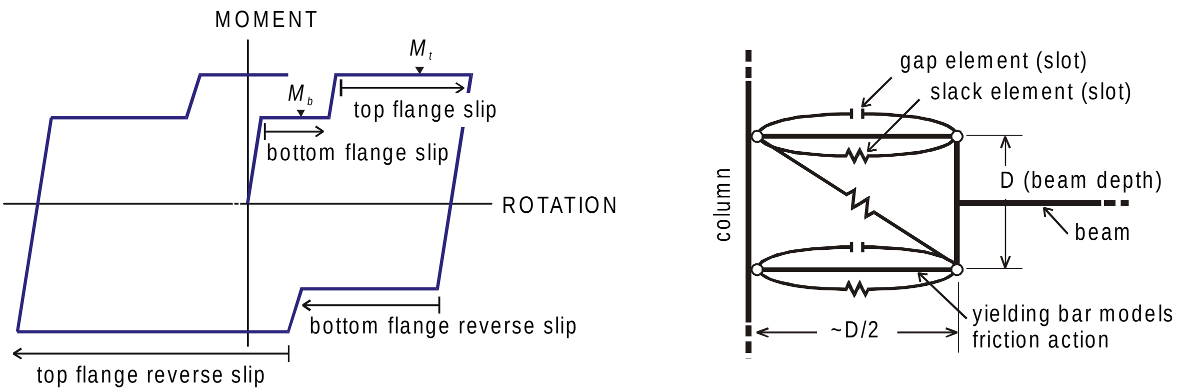


(a) Symmetric slip, driven from central plate (b) Asymmetric slip, driven from non-central plate

Fig. 7 Dual slip level joint details

The dual slip level capability of the joint is achieved by making the top flange slip force higher than that of the bottom flange by means of a higher clamping force. Under increasing beam moment the joint responds elastically until the bottom flange connection starts to slip at the threshold moment M_b causing 'plastic' rotation about the top flange. This continues until the bolts reach the ends of the slots in the bottom flange, after which the moment increases to M_t causing the top flange to start slipping. From this point 'plastic' rotation occurs about the bottom flange until the top flange bolts reach the ends of their slots. Further increase in moment will eventually lead to inelastic deformation of the joint components, concentrated at the slot ends.

Fig. 8(a) shows a moment-rotation cycle in which the slip does not exceed the slot length. Fig. 8(b) shows one of the simple joint models used in the numerical studies referred to below. 'Gap' and 'slack' elements at the beam flange levels simulated the bolt slots and the stiffening that occurred when slot length was exhausted, while elastic-perfectly plastic bar elements simulated the initial elastic joint response and the ensuing frictional sliding. The remaining beam and column elements were modelled as standard 'plastic hinge' beam-column elements.



(a) Moment-rotation response (b) Components of simple finite element model

Fig. 8 Dual level joint - idealised moment-rotation response

The lower slip threshold is intended to meet the strength and ductility demands imposed by the design level earthquake with the upper level providing a reserve of non-damaging inelastic deformation for extreme events, accompanied by an alteration in structure characteristics that may help avoid resonant response. Provided the upper level is not activated, all the slip will occur at the bottom flange, minimising floor slab damage. Slot length L, is related to the beam depth D, and angle of inelastic rotation θ, by $L=D\theta+d$, where d is the bolt diameter. For example, a 450mm deep beam with a maximum expected inelastic rotation of ±0.03rad and 24mm bolts would require slotted holes 51mm long.

Numerical studies

Inelastic time-history analyses of steel, perimeter-frame buildings of 2 and 6 storeys were conducted under a range of scaled earthquake records using the friction dissipator joint model shown in Fig. 6(b) and the nonlinear dynamic analysis program DRAIN-2DX [Allahabadi & Powell, 1988]. The 6-storey building consisted of 4 x 8m bays in each direction with 4 moment-resisting bays in each outer frame and the remaining frames gravity-resisting only. Storey height was 3.5m. Floor loadings were 4.5kPa (dead) and 4.0kPa (live), with 1.0 and 0.5kPa at roof level. The 2-storey frame consisted of 4 x 8m bays with 2 moment-resisting bays in each outer frame and other parameters the same as for the 6-storey model. Mode 1 periods were 1.12sec and 0.57sec respectively. The various earthquake records used were scaled to make their 5% damped spectral ordinate for the mode 1 period match that of the NZ elastic design spectrum (further scaled to the inelastic demand level) for intermediate soils in a region with a zone factor of 1. Earthquake records included Northridge (Santa Monica City Hall), El Centro (1940, N-S), Loma Prieta (Oakland Outer Harbour), Pacoima Dam and San Fernando (Orion Blvd). Rayleigh damping was set at 5% for modes 1 and 2 of the 2-storey building and for modes 1 and 5 of the 6-storey building.

Numerous analyses were conducted with the main parameters varied being the slot lengths, threshold moments, number of levels with dissipators and the seismic ground motion record. Trials were also made in which the top flange sliders were locked in position. Response values monitored included post-earthquake permanent deformation, ductility demand, activation of friction sliders, energy dissipation, member actions and base shear. Space does not permit the inclusion of detailed results, however some general observations based on the results are included in the conclusions below.

COMMENTS AND CONCLUSIONS

Friction-dissipating steel joints utilising slotted holes, brass shims and tension-maintaining bolts show considerable promise as a means of virtually damage-free energy dissipation under seismic loading. Large numbers of virtually identical loading cycles can be achieved. In practice, a residual offset left in a sliding joint after structural loading would be readily repairable by slackening the bolts, re-aligning and re-tightening (possibly replacing) the bolts.

The investigation of asymmetrical sliding joints has not yet been completed and no firm conclusion about their performance can be drawn.

K or X-braced frames probably exploit friction dissipators more effectively than frames and could lead to cheaper, stiffer structures, possibly using tension-only bracing. Such frames could have sufficiently high levels of ductility to make them suitable for seismic zones. Some safety issues relating to the situation when bolts reach the end of their slots require further study.

Rotating sliding bolted joints extend the benefits of damage-free energy dissipation to moment-resisting frames. The decoupling of beam stiffness and end moment strength avoids the possible need for over-sized columns to deal with beam over-strength moments. The joints can readily be made to 'yield' at two distinct threshold moments by varying the slip levels of the top and bottom flange connections. In addition, by varying the lengths of the slotted holes the amount of 'plastic' rotation available at each moment level can be controlled.

Although friction dissipators have no intrinsic self-centring ability, the parts of the frame that remained elastic during earthquake loading, particularly the columns, acted as springs that promoted the return of the structure to its original position.

Limiting the slot length tended to reduce residual offset after seismic loading, but increased the probability of plastic hinge damage as slot lengths became exhausted. Maximum displacements were not significantly affected.

By locking the top flange sliders, comparison could be made between dual level and single level joint behaviour. In most cases there was little difference in performance, and it appears that it may be preferable to avoid top flange sliding and the associated problems of floor slab damage, although setting the *same* slip level top and bottom would provide a useful precaution against inadvertent overstrength or lock-up of one or other flange joint.

It proved to be possible to control drift levels and permanent off-set to within acceptable levels for all the ground acceleration records that were tested.

Issues such as corrosion resistance and long-term retention of bolt tension have yet to be addressed.

REFERENCES

Aiken, I.D., Nims, K., Whittaker, A.S. and Kelly, J.M., "Testing of passive energy dissipation systems", *Earthquake Spectra*, Vol. 9, No. 3, 1993.

Allahabadi, R. and Powell, G.H., "DRAIN-2DX User Guide", *Report No. UCB/EERC-88/06*, University of California, Berkeley, 1988.

Butterworth, J.W., "Seismic response of moment-resisting steel frames containing dual-level friction dissipating joints", *Technical Conference, NZ Society for Earthquake Engineering*, March, 1999, pp. 59-65.

Butterworth, J.W., "Seismic damage limitation in steel frames using friction energy dissipators", *Proc. 6th Int. Conf. on Steel and Space Structures*, Singapore, September, 1999.

Clifton, G.C., Butterworth, J.W. and Weber, J., "Moment-resisting steel framed seismic-resisting systems with semi-rigid connections", *SESOC Journal*, Vol. 11, No. 2, September 1998.

Murray, C.M. and Butterworth, J.W., "Inelastic rotation capacity of ductile web side plate connections", *Report, Heavy Engineering Research Association 88/R6*, Feb 1990.

Pall, A.S. and Marsh, C., "Response of friction damped braced frames", *J. Struct. Div., ASCE*, Vol. 108, No. ST6, June, 1982.

Popov, E.G., Grigorian, C.E. and Yang, T-S., "Developments in seismic structural analysis and design", *Engineering Structures*, Vol. 17, No. 3, 1995.

Yang, T-S. and Popov, E.P., "Experimental and analytical studies of steel connections and energy dissipators", *Report No. UCB/EERC-95/13*, University of California, Berkeley, 1995.