13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 1889

STATIC AND REAL-TIME DYNAMIC TESTING OF PASSIVE DISSIPATION DEVICES

Martin S. Williams[1], Anthony Blakeborough[2] and Bin Wu[3]

SUMMARY

A wide variety of dissipative devices has been proposed for the seismic protection of structures – these include yielding/hysteretic elements, fluid viscous dampers and friction devices. While extensive testing has been performed on such devices, there remain gaps in our understanding of how they affect overall structural response. This paper summarises a series of tests aimed at rectifying this situation. Tests have been performed on two types of yielding steel element and a Pall-type frictional device. Test methods included slow cyclic testing of devices and of simple frames incorporating the devices, and real-time substructure tests, in which the device is loaded by actuators controlled by a real-time feedback loop which includes a numerical model of the surrounding structure. In general, the results demonstrate the ability of energy dissipators to give substantial reductions in seismic structural response, however they do also highlight some areas of concern. For example, some hysteretic elements can suffer premature failure by low cycle fatigue or localised plastic buckling if not designed with care, and brace forces in Pall friction-damped frames can be severely underestimated if geometric non-linearities are not taken into account. On the basis of the test results, some recommendations are offered on the detailed design of hysteretic elements, and on design procedures for structures incorporating passive dissipation systems.

INTRODUCTION

Passive dissipative devices have the potential to provide significant improvements to the seismic performance of structures without the need for the sophisticated technology and cost associated with active control systems. In recent year numerous different dissipative systems have been proposed and some structures have been built or retrofitted with such devices. Most devices dissipate energy through one of three mechanisms – hysteresis, friction or viscous damping. he behaviour is highly non-linear and often rate-dependent.

A very wide range of passive dissipative devices exists or has been proposed. Substantial reviews have been published by Constantinou et al [1] and Soong and Spencer [2]. The major categories of device are:

[1] Lecturer, University of Oxford, Dept of Engineering Science, Oxford, UK. martin.williams@eng.ox.ac.uk
[2] Lecturer, University of Oxford, Dept of Engineering Science, Oxford, UK.
[3] Associate Professor, Harbin Institute of Technology, Dept of Civil Engineering, Harbin, China.

- Hysteretic devices based on metallic yielding – examples include the ADAS (Added Damping And Stiffness) device proposed by Aiken and Kelly [3] and the knee element – see Aristazabal-Ochoa [4] and Williams et al. [5]. Obviously these elements are elastic up to yield and then generally display a typical steel hysteresis loop, often with significant strain hardening.

- Frictional systems such as the well-known Pall damper developed by Pall and Marsh [6], which comprises a series of clamped plates surfaced with brake lining material. These are generally taken to be rigid up to their slip load, then to slip at constant load.

- Solid visco-elastic dampers such as those proposed by Xu and Zhang [7], in which materials such as acrylic copolymers are bonded between steel plates and dissipate energy through shear deformation as the plates move. These materials have no activation level and exhibit elliptical hysteresis loops.

- Fluid viscous dampers, such as those marketing by Taylor Devices in North America and the French company Jarret Devices. These generally comprise non-linear stiffness and damping components.

This paper describes tests on two types of hysteretic device and a frictional system, with the aim of providing detailed design recommendations both for the devices themselves and for frames incorporating dissipators.

KNEE ELEMENTS

Knee elements are sacrificial, hysteretic dissipators. In a knee braced frame the main cross-braces are connected to short knee elements which span diagonally across the beam-column joints, Figure 1. The knee elements are designed to remain elastic during small earthquakes. During a moderate event, all energy dissipation takes place within the knee elements, protecting the main frame from any damage.

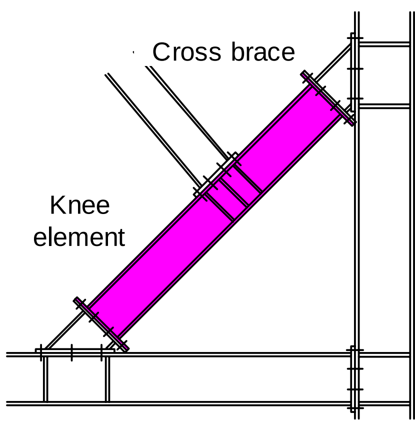

Figure 1. Knee element spanning a beam-column joint

The detailed design of the knee element is crucial to the success of this strategy. The element must yield early and over as wide an area as possible so as to maximise energy dissipation, it must be resistant to plastic web buckling and to low cycle fatigue failure under repeated large-amplitude plastic cycling. Since many aspects of this behaviour are not amenable to theoretical modelling, a large experimental program has been undertaken.

Figure 2 shows the test set-up. Full-scale knee elements were mounted horizontally in a test frame and loaded by vertical, servo-hydraulic actuators. Custom-designed load cells mounted between the specimen and the test frame measured the axial force, shear force and moment at each end of the knee element.

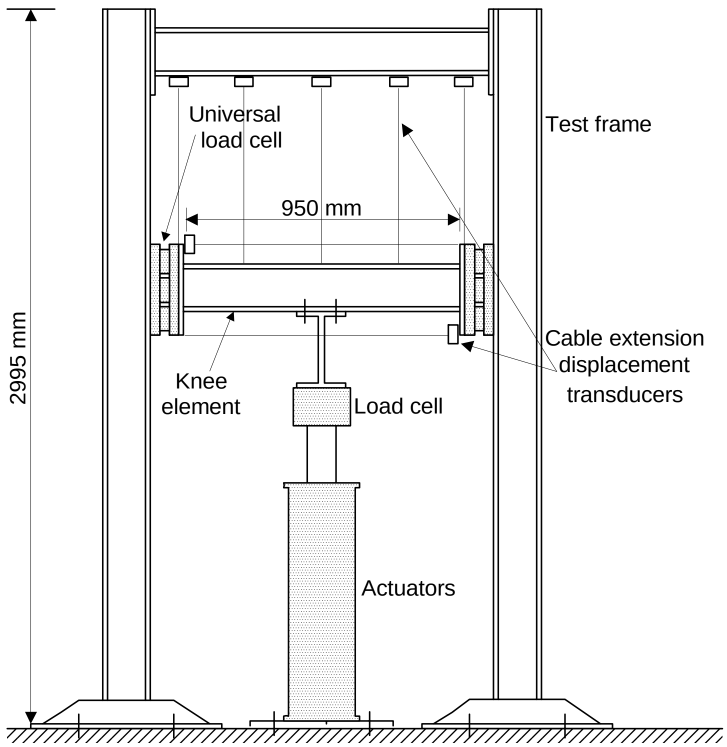

Figure 2. Testing of knee elements

Two types of test were performed – slow, reverse-cyclic loading under displacement control at steadily increasing amplitude, and real-time substructure testing, in which the test element was embedded in a real-time control loop so as to simulate its behaviour as part of a full structure subjected to an earthquake. See Blakeborough et al [8] for a more detailed explanation of the real-time substructuring technique. Tests were performed on a variety of different knee element designs based on standard UK beam and column sections, including attempts to deliberately weaken the section by reducing the web area. However, only one series of tests is considered here, comprising tests on solid-web sections loaded about their major axes, with the webs strengthened by a variety of different stiffener patterns. The results of this test series are summarised in Table 1, and the key findings were as follows:

a) Energy dissipation can be maximised by ensuring that the web of the section yields in shear before the flanges yield in bending. This is optimal because the shear is roughly constant over the length of the knee element, giving a very large volume of yielded material.
b) Rate of loading has little effect on element performance.
c) With inadequate stiffeners, premature failure occurs by plastic web buckling, as shown in Figure 3.
d) With well-spaced stiffeners (5 in a 950 mm long element) very high ductilities were achieved. Failure, when it occurred, was by weld fracture promoted by low cycle fatigue, or occasionally flange buckling, Figure 4.
e) For the sections tested, with well-spaced stiffeners, a central deflection of up to 22.5 mm can be sustained repeatedly, without risk of low cycle fatigue failure.

f) All sections were able to sustain substantial increases in load beyond yield before failing, up to as much as twice the yield load and typically around 1.7 times the yield load. Braces therefore need to be designed to withstand at least double the knee element yield load.

Table 1. Summary of knee element test results

Section	Number of stiffeners	Test type	Tested to failure?	Steel grade (MPa)	Yield Load (kN)	Yield defl (mm)	Max Load (kN)	Max defl. (mm)	Max Ductility	F_{max}/F_y
152x152x30 UC	1	Cyclic	yes	340	335	2.1	599	34.5	16	1.8
152x152x30 UC	1	Cyclic	yes	340	360	2.4	597	39.7	17	1.7
152x152x30 UC	1	Real-time	no	340	350	2.4	542	17.8	7	1.5
152x152x30 UC	1	Real-time	no	300	310	2.25	500	18.3	8	1.6
152x152x30 UC	5	Cyclic	no	340	350	1.8	615	14.6	8	1.8
152x152x23 UC	1	Cyclic	no	340	330	1.7	575	15.6	9	1.7
152x152x23 UC	3	Cyclic	yes	340	340	2.0	642	28.8	14	1.9
152x152x23 UC	5	Cyclic	yes	340	340	1.8	690	25.7	14	2.0
152x152x23 UC	5*	Cyclic	yes	340	335	1.7	601	23.2	14	1.8
203x102x23 UB	1	Cyclic	yes	340	365	1.8	614	17.8	10	1.7
203x102x23 UB	1	Real-time	no	340	365	2.1	563	18.7	9	1.5
203x102x23 UB	5	Cyclic	yes	340	350	1.7	708	26.6	16	2.0

* *Stiffeners welded to web only*

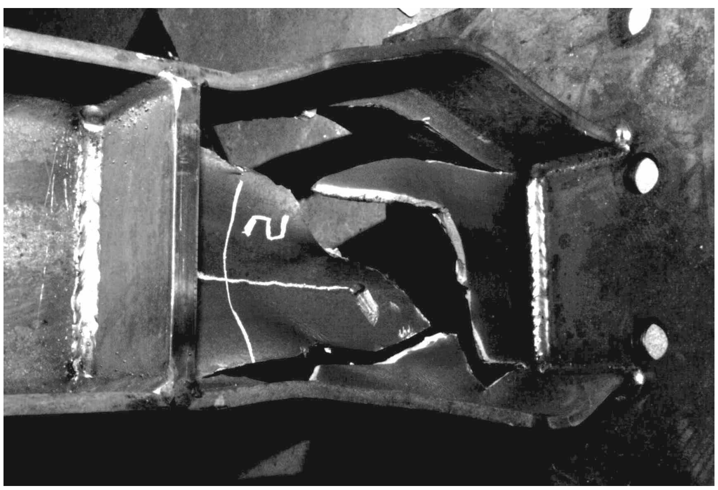

Figure 3. Tearing of buckled web under repeated cycling

Figure 4. Flange buckling

SHEAR PANEL DEVICES

Schmidt and Dorka [9] have proposed a simple yielding shear panel device, consisting of a short length of square hollow section (SHS) with a diaphragm plate welded inside it. The device is positioned between the braces and the main members of a braced frame, with the diaphragm lying in the plane of the frame, so that it is loaded in pure shear as the frame undergoes lateral deformation. Energy is dissipated through shear yielding of the diaphragm, which is restrained from buckling by the surrounding SHS.

Tests have been performed on devices based on a 100 × 100 × 4 mm thick square hollow section, with diaphragm plates between 1 and 4 mm thick. The devices were mounted in a single-storey planar K-braced frame (Figure 5) which was loaded laterally along the centreline of the cap beam. Three loading regimes were used: monotonic, reverse-cyclic (single cycle at each displacement amplitude) and reverse- cyclic (three cycles at each displacement amplitude).

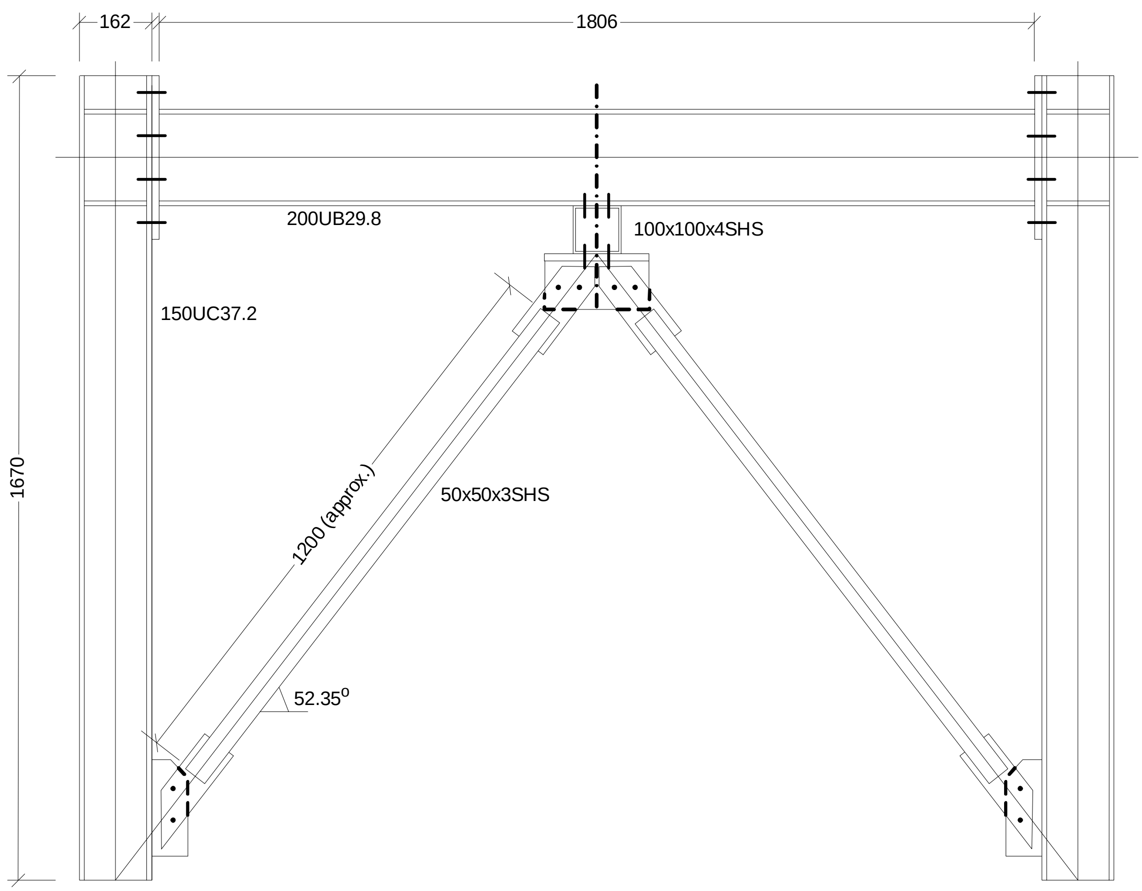

Figure 5. Shear panel device test frame

In monotonic and single-cycle tests all devices tested showed an ability to withstand large deformations without failure and absorb significant amounts of energy. Devices with thin diaphragms (2 mm or less) buckled as shown in Figure 6, and under repeated cycling this eventually led to a tearing failure. Those with thicker plates did not fail. Figure 7 shows the cyclic response of a device with a 2 mm diaphragm, showing that, even after diaphragm buckling, reasonably stable hysteresis loops could be obtained at very large deformations. Like the knee elements, the devices strain hardened significantly and so carried substantial additional load after first yield – up to double the yield load in one case. Any design approach that treats the device as elastic-perfectly plastic is likely to underestimate the loads on the structure by a large amount. The thinner diaphragms sustained ductilities of the order of 20, while for thicker ones the maximum ductility was 10-15. Shear strains were in the range 12–24%. In all cases the overall ductility of the frame (i.e. the ratio of peak cap beam displacement to the value at first yield) was around 8.

Figures 8 and 9 show energy absorptions achieved in cyclic tests, plotted as functions of diaphragm thickness and cap beam displacement respectively. These appear to show that a 2 mm diaphragm offers the best energy absorption capacity, though a 3 mm diaphragm is only slightly less effective. Thinner diaphragms buckle too easily and simply do not have as much material to deform, thicker ones are more resistant to yielding and so undergo less plastic deformation. Since the 3 mm diaphragm did not buckle or fracture even under the most severe test regime, and since its energy absorption performance is close to that of the 2 mm device, the 3 mm device is considered to offer the best combination of energy dissipation and stability. This represents a ratio of plate thickness to breadth of 0.03, a figure which may be transferable to other devices.

Figure 6. Diaphragm buckling

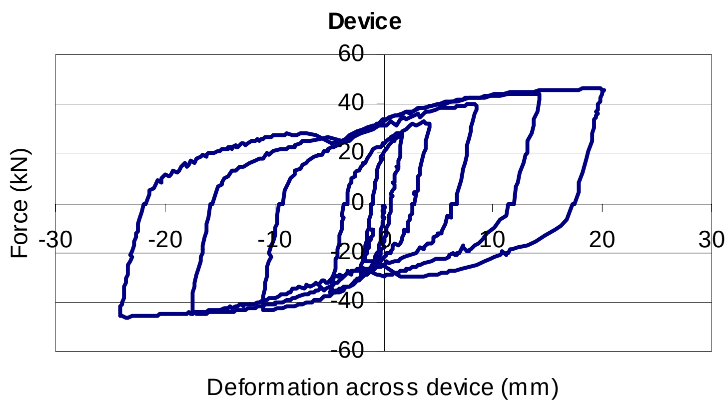

Figure 7. Hysteresis loop for device with 2 mm diaphragm

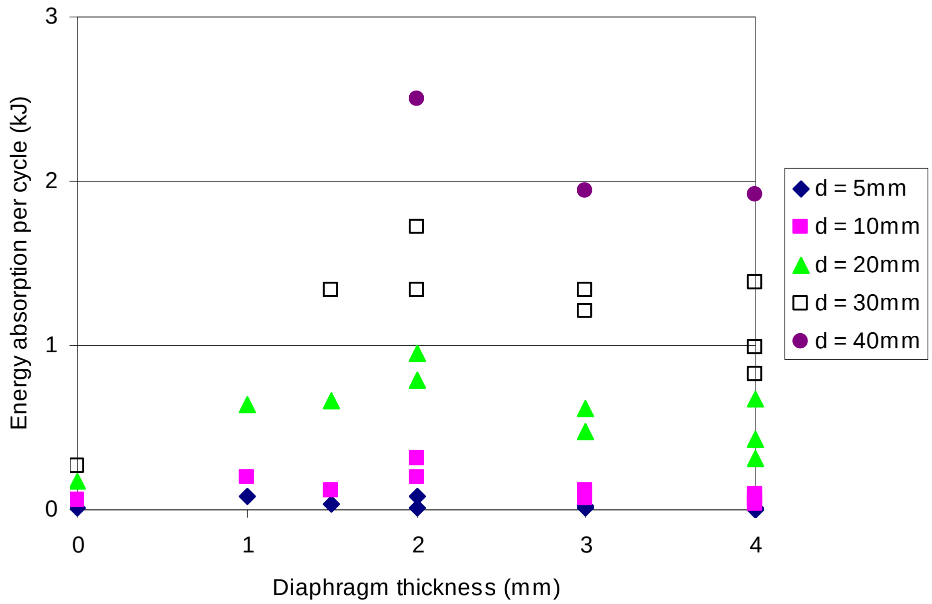

Figure 8. Energy absorption at different cap beam displacement amplitudes

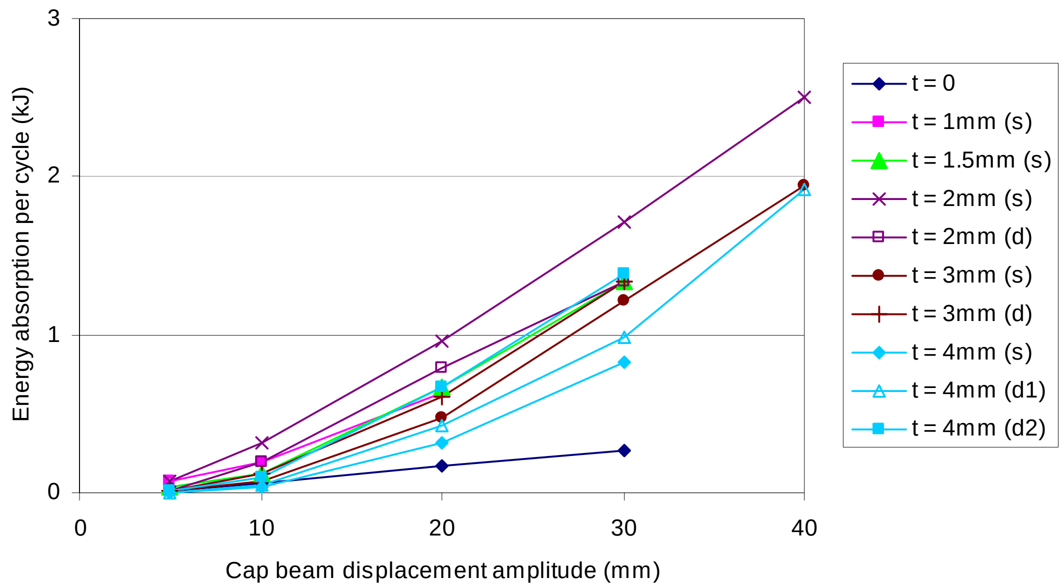

Figure 9. Energy absorption as a function of cap beam displacement amplitude
(t = total plate thickness, s = single plate, d = double plate)

FRICTION DAMPERS

Tests have been performed on a modified form of the well-known Pall friction dampers. The system tested, known as the T-plate friction damper (TFD), uses an inverted T-shaped plate (labelled 3 in the figure) in place of the normal X-configuration. This offers some practical advantages over the more conventional system. A damper is shown in Figure 10. Dampers with clip moments of 20, 40 and 80 Nm were tested in an X-braced frame as shown in Figure 11. In addition to measuring the hysteresis performance of the damper, the braces were strain gauged so that brace forces could be deduced.

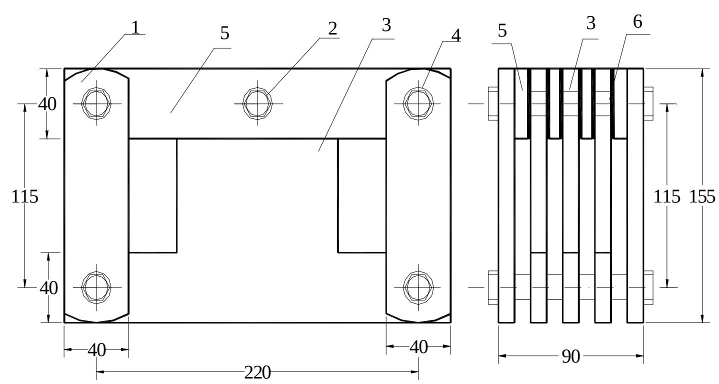

Figure 10. Elevation and section of TFD

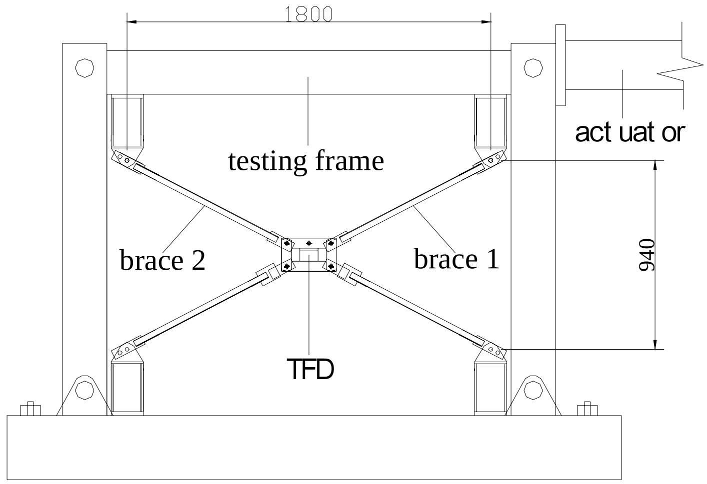

Figure 11. TFD test setup

Figures 12 and 13 show hysteresis loops for a damper with a clip moment of 40 Nm, in terms of the damper and brace forces respectively. From Figure 12, we see that the damper forces are approximately constant during sliding. The hysteresis loops are similar to previously reported experimental research on conventional Pall friction dampers. However, as shown in Figure 13, the brace force after damper slipping does not remain constant, but increases significantly with increasing displacement. The maximum brace forces with the clip moment of 20Nm, 40Nm and 80Nm are, respectively, 1.9, 1.6 and 1.4 times those at the onset of slipping.

In the process of the testing, it was found that the increase of the brace force is sensitive to the fabrication tolerance of the four bearings. Initially, they had such large fabrication tolerances that the movement of one bearing was observed as high as 2 mm and no increase of brace force was found. The presented results were obtained after the bearings were treated and the movements of the bearings reduced to 0.2 mm. It can be predicted that the increase in the brace force will be larger when the dampers are installed in real structures, where the joints are usually rigid.

The high increase in the brace force is due to a significant geometric non-linearity in the damper response. It is likely that this will reduce the safety of structures incorporating friction dampers if it is ignored. This effect has never been reported as no experimental or rigorous numerical work on brace force has previously been reported. As a result, in all the references related to the practical design of structures incorporating Pall dampers, the increase of the brace force has never been considered. There is therefore some uncertainty as to whether braces can be expected to remain elastic, and whether adjacent columns are safe.

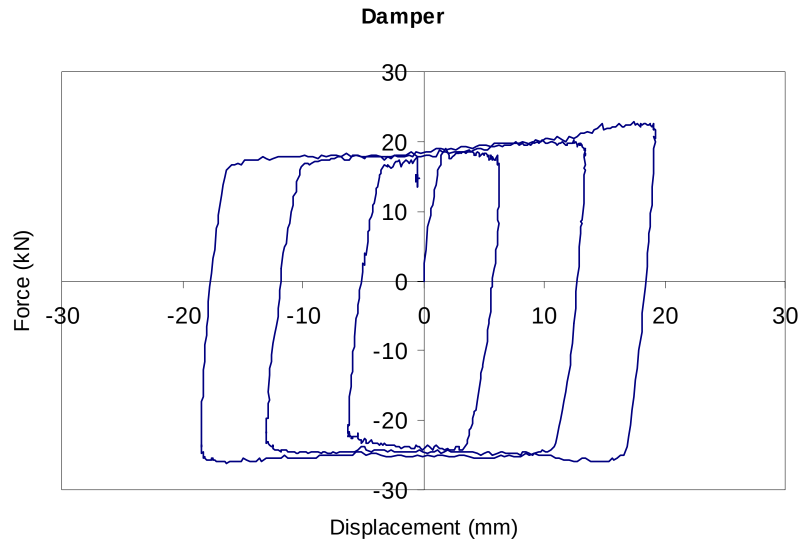

Figure 12. Hysteresis loop for damper, clip moment = 40 Nm

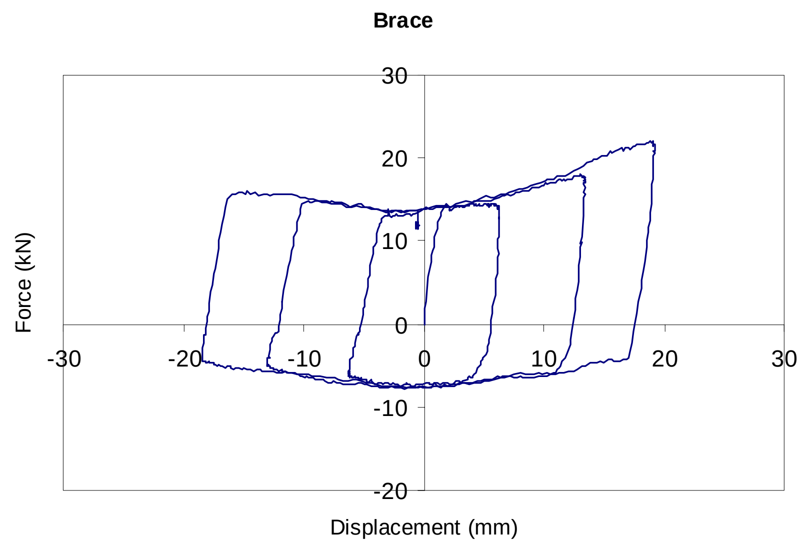

Figure 13. Hysteresis loop for brace, clip moment = 40 Nm

CONCLUSIONS

Tests have been reported on plane frames incorporating a variety of passive dissipative systems – two steel hysteretic systems (knee elements and shear panel elements) and a frictional system.

For the hysteretic systems, it was shown that force increases after first yield can be as high as 100% due to strain hardening, while for the frictional device studied a similar proportionate increase in load could be achieved through the geometric non-linearity of the device after slip. It is therefore necessary to design adjacent elements to withstand loads of around twice the device slip or yield load.

For the knee elements, optimal performance can be achieved by designing the section to yield in shear, and reinforcing it with web stiffeners at a spacing equal to the section depth. For appropriately designed sections, a central deflection of up to 22.5 mm in a 950 mm long knee element can be sustained without risk of low cycle fatigue failure.

For shear panel elements an optimum diaphragm thickness to plan dimension ratio of 0.03 was determined. For these dimensions, very large deformations corresponding to ductilities of around 15 could achieved without diaphragm buckling or fracture.

ACKNOWLEDGEMENTS

Part of this work was performed while the first author was a visiting academic at the University of Queensland, Brisbane, Australia, supported by a grant from the Royal Academy of Engineering's Global Research Awards scheme.

REFERENCES

1. Constantinou MC, Soong TT, Dargush GF. "Passive energy dissipation systems for structural design and retrofit." MCEER Monograph No. 1, Multidisciplinary Center for Earthquake Engineering Research, Buffalo, 1998.
2. Soong TT, Spencer BF. "Supplemental energy dissipation: state-of-the-art and state-of-the-practice." Engineering Structures, 2002, 24: 243-259.
3. Aiken ID, Kelly JM. "Comparative study of four passive energy dissipation systems." Bulletin of New Zealand Society of Earthquake Engineering, 1992, 25(3): 175-192.
4. Aristazabal-Ochoa JD. "Disposable knee bracing: improvement in seismic design of steel frames." J. Struct. Engng, Amer. Soc. Civ. Engrs, 1986, 112: 1544-1553.
5. Williams MS, Blakeborough A, Clement D, Bourahla N. "Seismic behaviour of knee braced frames." Proc. Instn Civ. Engrs: Structs & Bldgs, 2002, 152: 147-155.
6. Pall AS, Marsh C. "Response of friction damped braced frames." J. Struct. Engng, Amer. Soc. Civ. Engrs, 1982, 108(6): 1313-1323.
7. Xu TL, Zhang WS. "Modal analysis and seismic response of steel frames with connection dampers." Engineering Structures, 2001, 23: 385-396.
8. Blakeborough A, Williams MS, Darby AP, Williams DM. "The development of real-time substructure testing." Philosophical Transactions of the Royal Society of London, 2001, A359: 1869-1892.
9. Schmidt K, Dorka U. "Experimental Verification of Hyde-System." Proceedings of the 13th World Conference on Earthquake Engineering, Vancouver, Canada, 2004.