

## Full-scale testing of dissipative knee elements for steel frames

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### ABSTRACT

The work presented in the paper is part of a programme to develop the concept of knee bracing in seismic design. Knee elements are tested both individually and in frames using the equipment under development in the new Structural Dynamics Laboratory at Oxford. The part of the programme described here covers the work on individual knee elements. These are being tested at full scale using a rig which reproduces the conditions in the corner of a knee-braced frame. Knee elements are placed in the rig and loaded by a hydraulic actuator to reproduce the diagonal brace forces. The overall load/deflection characteristics of each link are determined under ever increasing cyclic deformation. Load cells measure the end moments and forces applied to the frame by the knee element. The testing is the first major project using the testing facilities under development at Oxford based round an on-line substructure testing facility employing computer feedback to model part of the test structure.

### INTRODUCTION

The effects of recent earthquakes such as Northridge and Kobe highlighted some shortcomings of modern seismic codes and practices. Whilst well-engineered buildings were successful in reducing human fatalities (the primary requirement) a high degree of damage to steel framed buildings was discovered subsequently. In particular, severe cracking in and around the welded beam-column joints of moment-resisting steel frames was widely observed (Bertero et al. 1994, Burdekin, 1996). Many structures had to be either extensively repaired or totally demolished and rebuilt. The secondary aim of seismic design, that of protecting economic investment, was therefore not achieved.

Designers are therefore looking for alternative solutions, in which the desired seismic properties are achieved without the use of what have turned out to be non-ductile connection details. An attractive approach is the use of dissipative systems, in which an additional energy absorbing device is incorporated into the structure to reduce the seismic response at lower levels of excitation than that necessary to excite the main structural mechanism. This additional system acts as a first line of defence, reducing response so as to raise the level of earthquake necessary to cause damage to the main structure. This philosophy fits into the three-tiered hierarchy of seismic design thought. Firstly, that structures have adequate stiffness to withstand the effects of minor earthquakes. Secondly, that for moderate earthquakes some damage to non-structural elements is allowed, whilst structural members remain elastic. Thirdly, that during severe earthquakes the structure should not collapse, thus fulfilling the primary aim of protecting lives. It is also desirable to aim for repairable damage to that retrofitting would be possible in accordance with secondary aim of protecting economic investment.

Knee braced frames (Balendra et al., 1990) are an example of a dissipative system. They represent a further development of the well-known eccentric bracing concept, in which yielding is further concentrated in a short link element. Figure 1 shows a knee-braced frame. For minor earthquakes the system acts similarly to any other bracing method, giving added lateral stiffness to the structure. However, during moderate earthquakes the knee elements form a localised sacrificial ductile mechanism which absorbs energy. Hence the overall response is reduced, and the damage to structures and contents is lessened. Subsequent repair of the elements should prove simple and cost-effective and need not affect the main structural elements.

Current work being carried out in the Oxford University Structural Dynamics Laboratory is investigating the energy-absorbing capabilities of realistic dissipative, disposable knee elements (DKE). This paper reports on the method of investigation, experimental procedure and early findings. This investigation forms the first stage of a three-phase programme sponsored by the UK Engineering and Physical Sciences Research Council, and continues work by the first author and others on scale models using the shaking table at Bristol University.

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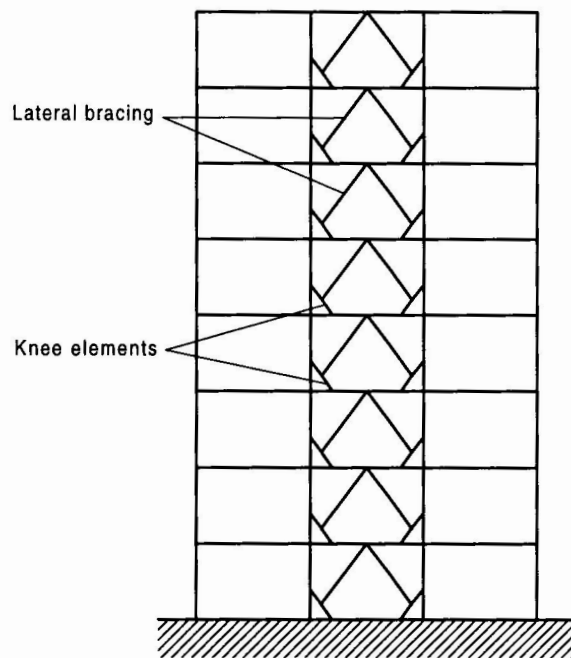


Figure 1. Knee bracing for steel frames

#### DISPOSABLE KNEE ELEMENTS

An effective knee element must sustain its strength under repeated plastic deformation. Several designs of knee element are under investigation in order to determine the most effective in providing strength and stable dissipative cyclic behaviour. One of the main design parameters to be considered is that of orientation of the knee element bending axes. A knee element loaded about a major axis will yield in shear whereas one loaded about its minor axis may yield in bending. Which failure mechanism is more suitable for seismic purposes and modifications to enhance an individual element's performance are being investigated.

The members to be tested in the program and their orientation, are shown in Table 1, these being the largest standard structural sections that can be yielded with the constraints of present equipment. The estimated failure loads were calculated using a yield stress of twice the value of design strength,  $p_y$  given for Grade 43 steel in the British steel design code BS5950, i.e.  $2 \times 275 = 550 \text{ N/mm}^2$ . All knee elements are to be made from Grade 43 steel (for its ductility).

Table 1. Details of test elements

No	Member	Test orientation	Expected failure load in 3-point bending (kN)	Expected failure load in shear (kN)
1	152 × 152 × 30 Universal Column (UC)	X-X	794	337
2	203 × 203 × 71 UC	Y-Y	597	2312
3	203 × 102 × 23 Universal Beam (UB)	X-X	742	342
4	305 × 165 × 54 UB	Y-Y	624	1481
5	Two back-to-back 127 × 64 × 29.8 Channels	X-X	573	286
6	168.3 × 10 Circular Hollow Section	-	659	330
7	160 × 160 × 6 Square Hollow Section	-	678	339
8	200 × 120 × 5 Rectangular Hollow Section	X-X	659	330

Each specimen is 950 mm long, a convenient length for the laboratory and one which fits in with the work of Bourahla (1990), who optimised the geometry of the knee element. Three samples of each knee element are prepared. The prescribed length of 950 mm includes the  $400 \times 200 \times 9$  mm end plates. Each end plate is connected to the member by full-penetration welding. The members are then fixed to the load cells using 8 No. M24 Grade 12.9 caphead screws. The experimental set-up is shown in Figure 2.

Two of the three samples are subjected to an increasing amplitude sine wave load regime in accordance with Park (1989). The third sample is subjected to the displacement history of a knee element derived from a finite element analysis of the response of a building to the El Centro earthquake.

The effect of the rate of loading was considered and judged not be sufficient to have a significant dynamic magnifying effect on the strength of the steelwork, hence static analysis was deemed sufficient for design purposes.

### TEST FRAME

Knee elements are tested in a portal frame rig carrying the test specimen, as shown in Figure 2, together with another identical portal frame used as a bracing structure to prevent out of a plane distortions. This was installed as a result of early commissioning tests which showed lateral displacements up to 50mm at the tops of the columns. Work by Balendra et al. (1997) also noted the requirement for considerable lateral support. Each frame consists of two  $203 \times 203 \times 46$  UC stanchions 3.0 m high. Each frame is braced with a  $203 \times 203 \times 60$  UC. Each stanchion base (25mm plate) is bolted to the Structural Dynamics Laboratory isolation block using four M30 Grade 8.8 bolts. Purpose-built universal load cells measuring axial force, shear force and moments are located at each end of the DKE and rigidly bolted to the columns.

The DKEs are loaded using up to four Instron dynamic actuators, two of 250 kN capacity and two of 100 kN capacity, positioned in a line on a single loading beam ( $203 \times 203 \times 86$  UC). The connection between the loading beam and the test specimen has been designed to transmit a vertical force in the knee element, while providing no restraint to twisting or sideways deflection of the DKE. Such deflections might occur if the element underwent lateral-torsional buckling.

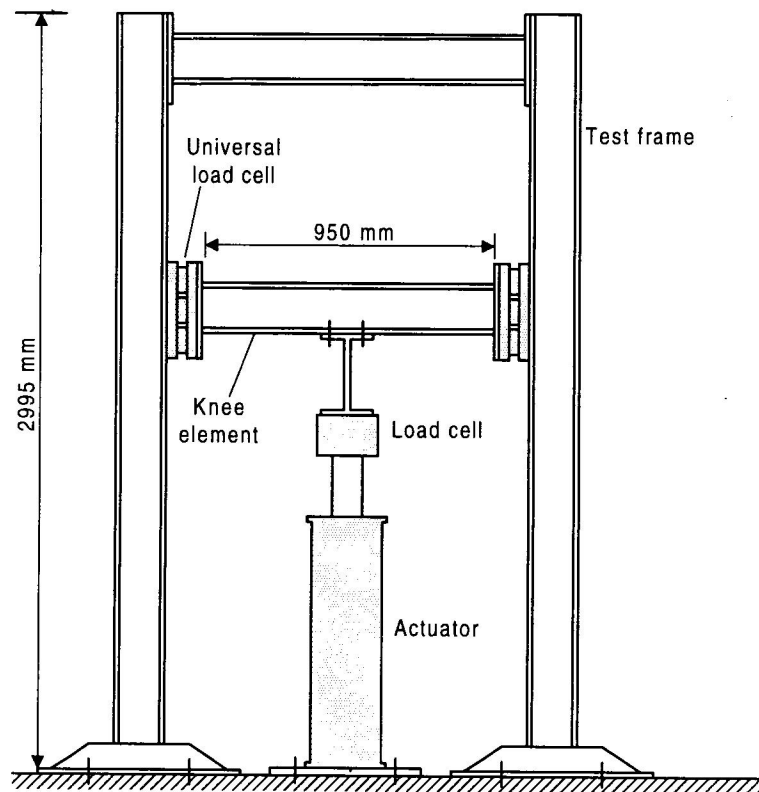


Figure 2. Testing of knee elements

The effective height of the beam can be adjusted so that it can be used for all specimens whilst always starting at the centre point of the actuators' travel.

The test set-up was analysed using the program Prokon (Version 3.01) to determine the axial forces, shear forces and moments. The maximum expected forces induced within a load cell were found to be 770 kN axially, 350 kN in shear and 154 kNm bending. The load cells were modelled as solid blocks of steel for the purpose of this analysis.

### INSTRUMENTATION AND TEST SET-UP

The instrumentation used and data acquired from the tests are as follows:

- (a) universal load cells
- (b) Celesco PT101 cable-extension position transducers attached to the test specimen
- (c) loads and displacements of the four actuators using the Instron 8800 controller.

The load cell and position transducer signals are conditioned using a Data Translation 32 channel programmable signal conditioning system then recorded to PC via an Amplicon A-D board. The actuator loads and displacements are recorded using Instron RS-Plus software (supplied with the actuators) and then stored on a separate PC.

### RESULTS

The results presented here are from a single test performed early in the programme. The test specimen is a  $305 \times 165 \times 54$  Universal Beam loaded about its minor axis. Figure 3 is a view of the test setup for this specimen, showing the welded web stiffeners which were used to provide local strengthening at the point of load application. Also visible are the universal load cells at each end of the element, and the two vertically acting 250 kN actuators which apply the loading.

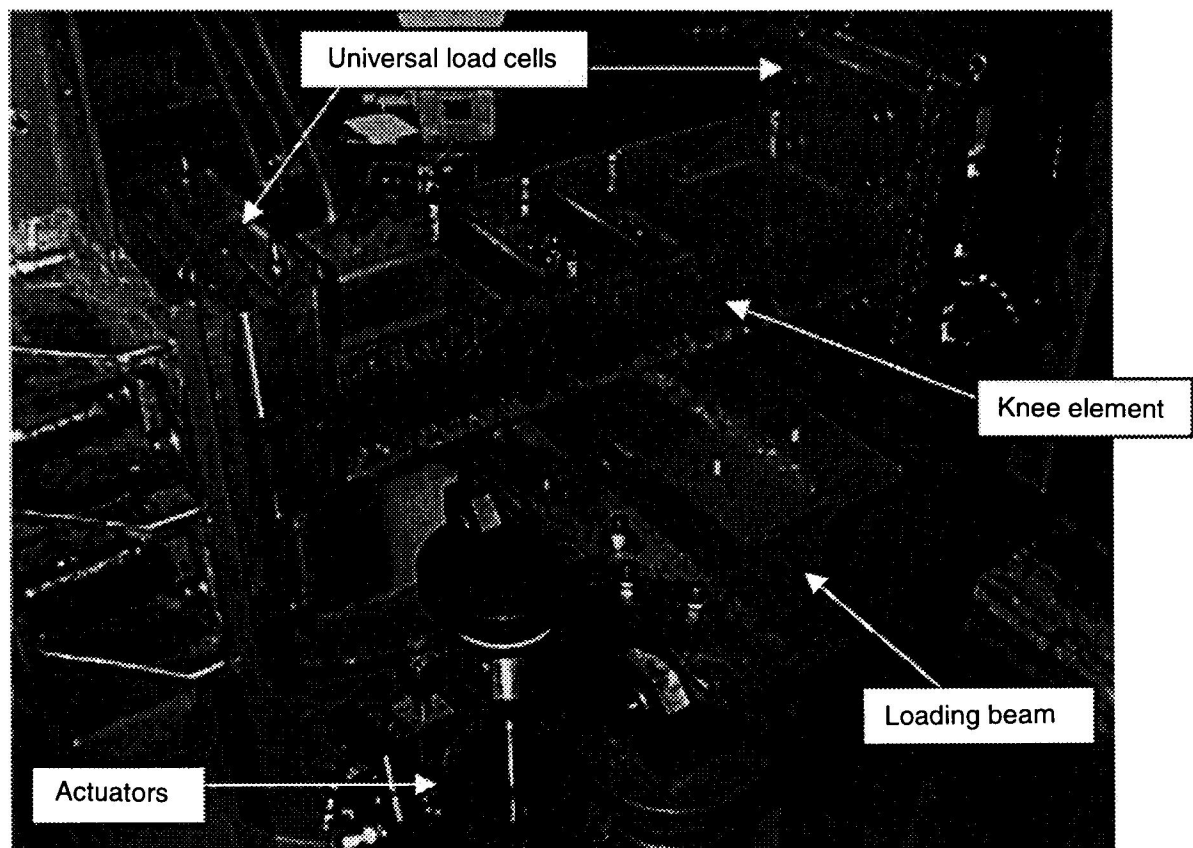


Figure 3. Testing of a  $305 \times 165 \times 54$  UB knee element about its minor axis (viewed from above)

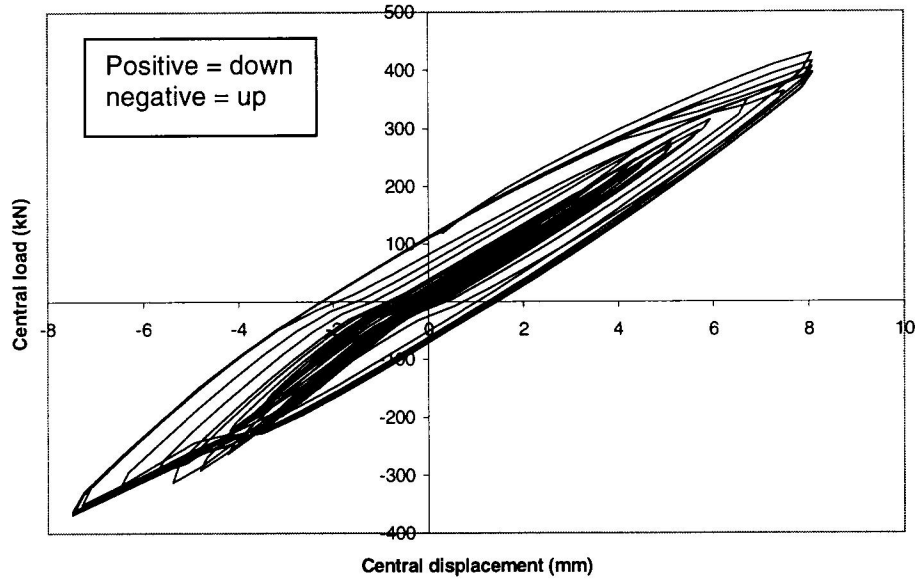


Figure 4. Overall hysteresis response of knee element – cycles up to 8 mm

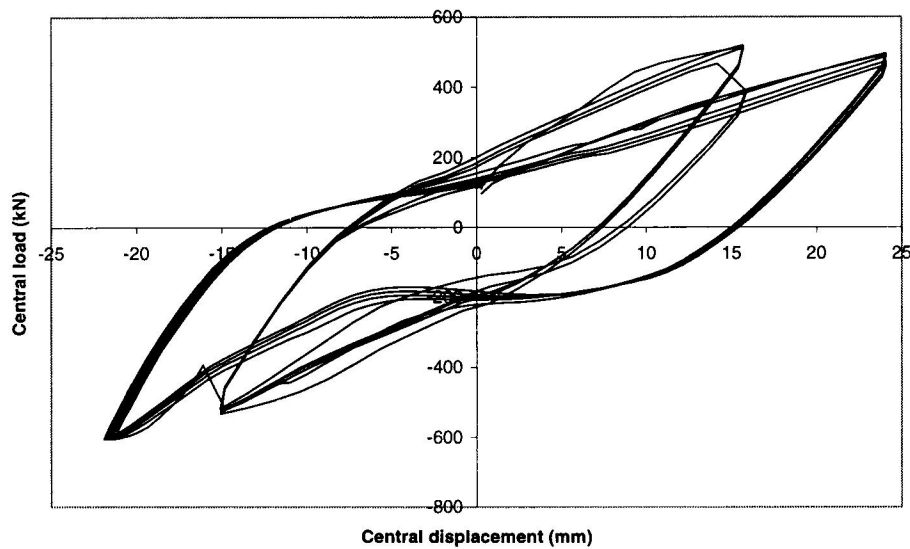


Figure 5. Overall hysteresis response of knee element – cycles at 16 and 24 mm

Figures 4 and 5 show the overall central load versus deflection characteristics. For clarity cycles up to 8 mm are plotted separately and at a different scale to those above 8 mm. It can be seen from Figure 4 that yielding takes place in a gradual and stable fashion, at a displacement amplitude of approximately 6 mm. At the larger amplitudes in Figure 5 large, open hysteresis loops were achieved. However, loading beyond 24 mm (corresponding to a displacement ductility of approximately 4) was not possible due to the complete failure of one of welded stiffeners at the load point. The loops in the negative quadrant of the 24 mm cycles show a sudden increase in stiffness which was caused by the loading beam coming into contact with the bottoms of the flanges of the knee element.

Figure 6 shows the variation of end moment with central displacement for the displacement cycles at 4, 8, 16 and 24 mm. These plots are broadly in agreement with those in Figures 4 and 5. In particular, the significant reduction in load during the 16 mm cycles and the high stiffness of the negative displacement cycles at 24 mm are both clearly visible. The peak moment of approximately 30 kNm is quite small compared to the value of 70 kN that would be expected for an elastic, fixed-ended beam, suggesting that the current test rig has significant rotational flexibility at the ends of the knee element.

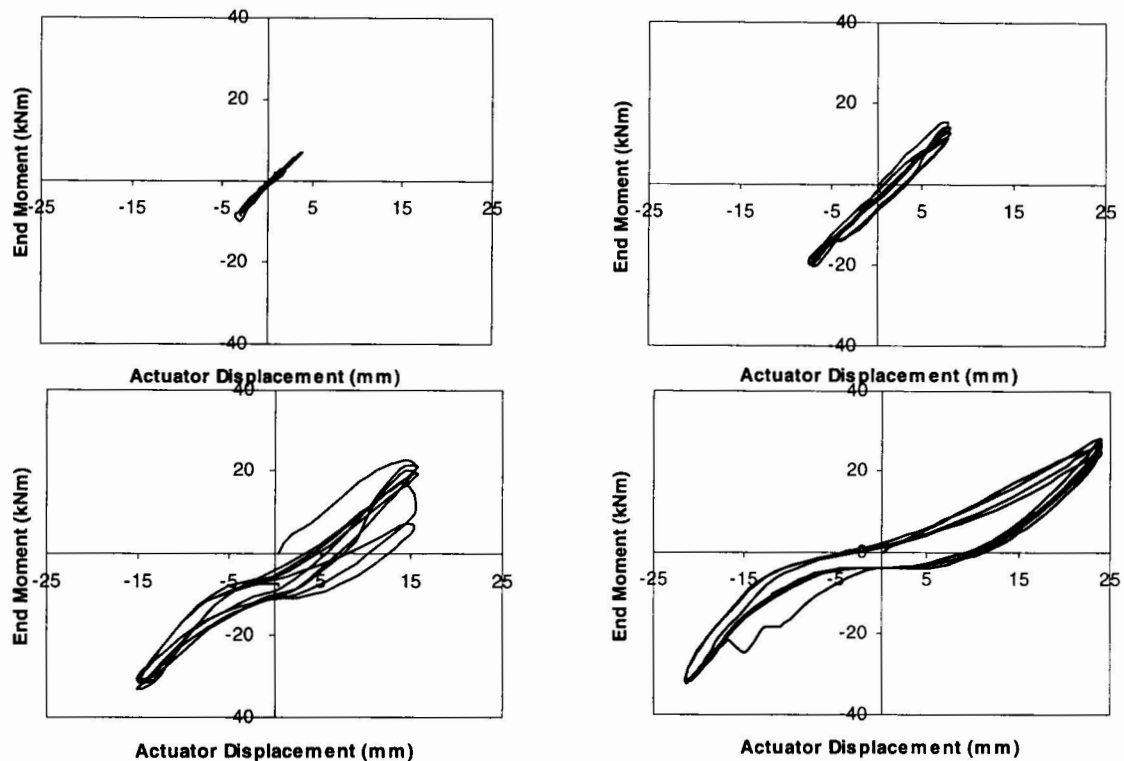


Figure 6. Variation of end moment with central displacement

### CONCLUSIONS

This paper has described the programme of knee element testing currently in progress at Oxford. The results of tests using a Universal Beam section tested about its minor axis showed good, stable hysteresis characteristics at displacement ductilities up to 4, but higher ductilities could not be achieved due to severe damage to the welded stiffeners around the loading point. It is clear that, for elements loaded about their minor axes, the exact way in which they are connected to the load is of vital importance, and considerable attention will be paid to this in subsequent tests.

### ACKNOWLEDGEMENTS

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