DEVELOPMENTS IN ENERGY-ABSORBING DEVICES AT THE PHYSICS AND ENGINEERING LABORATORY, DSIR, NEW ZEALAND

R.G. Tyler (I)

SUMMARY

Recent tests on energy-absorbing devices intended for conventionally designed structures and base-isolated ones are described. For conventional structures the devices include a system for maintaining cross bracings in tension and an axial energy absorber which is supported against buckling effects and can be used in any position. The scope of recent tests on lead-plug rubber bearings for base-isolated buildings and bridges is outlined.

INTRODUCTION

The Physics and Engineering Laboratory, Department of Scientific and Industrial Research, New Zealand, is continuing to take an active interest in the development of energy-absorbing devices for controlling the effect of earthquakes on structures. Work has continued on both steel and lead devices, and many have found application in building and bridge structures. Developments in steel have included torsion beams, bending beams and bending cantilevers, while lead has been used in extrusion and shear dampers (Ref. 1). The most recent application for the steel devices has been in the 11-storey Union House in Auckland where the structure rests on piles free to move ± 150 mm within hollow piles in a horizontal plane at ground level, the movement being controlled by steel taper cantilever devices. For the lead devices the most notable application is in the base-isolated William Clayton Building in Wellington, which has now been in service for some two years, and where a lead plug is employed within laminated rubber bearings (Fig. 1) to control the motions. These structures and other applications are discussed in another paper at this Conference (Ref. 2).

ENERGY ABSORPTION IN CROSS BRACINGS

Cross bracings are often employed in structures to resist in-plane shear forces (Fig. 2). This has the particular advantage that, during horizontal load reversals, one diagonal will always be in tension and buckling of the other can be ignored within the elastic range. Quite slender steel bars may be employed, which will behave quite well until a severe earthquake occurs, when progressive overstrain in tension develops, with slack, and consequent degrading of the structure. On the assumption that the central ring remains elastic, energy absorption only occurs at the end of each cycle of loading (Fig. 3).

A device of rectangular shape within a rectangular frame (Fig. 4) has already been employed in buildings in New Zealand to introduce energy absorption by overstrain in bending at the corners of the inner frame at a, b, c and d; testing was conducted to investigate the behaviour of the system. These tests have already been described in detail (Ref. 3).

(I) Physics and Engineering Laboratory, DSIR, New Zealand.

Tests on a Ring Device

Because a ring is sometimes employed as a means of length adjustment (Fig. 2), tests were first carried out on a ring device of 610 mm diameter within a 4 m square pin-jointed frame, mounted horizontally on the floor, and subjected to an oscillating shear load (Fig. 5). All the bars within the square were 25 mm diameter and there were nuts on the bracings only on the inside of the ring so that the rods could not go into compression. Sufficient pre-tension was introduced into the rods to raise the system above the floor.

Energy absorption was obtained from the device, arising from distortions first as an ellipse in one direction and then in the other, but slack progressively developed as the curved elements straightened so that the nuts on the rods needed to be progressively tightened during the course of the test. Failure occurred in one ring element after about 100 cycles at strokes up to ±140 mm (Fig. 6).

Tests on a Square Device

The square device of 610 mm side illustrated in Fig. 7 performed very much better as no slack developed in the link system. The bars were again 25 mm diameter in bright drawn mild steel and the corners were bent hot, thus producing a normalising effect similar to that in a hot-rolled mild steel with a favourable characteristic from the point of view of repetitive overstrain (Ref. 1). Welds were arranged to occur at points of zero bending moment. Yield in the bars occurred just outside the load points. Again only single nuts were used on the inside of the device so no compression could occur in the diagonals, and some pre-tension was introduced into the rods.

A set of hysteresis loops obtained for increasing shear displacements up to ±142 mm is given in Fig. 8. The loops were repeatable as there was no degradation in the system. A peaking up of the jack loading for displacements above 100 mm is clearly shown, thus indicating a locking-up effect in the device.

One set of bars failed after about 200 cycles, mostly at ±100 mm stroke at frequencies up to 1 Hz. A further set was made up and this survived about 150 cycles at various stroke lengths. A life of 200 cycles suggests that the maximum surface strain in the bars was in the range ±2-3% at ±100 mm stroke (Ref. 3).

Characteristics of Rectangular Device

The square device tested was a particular case of the rectangular one (Fig. 4), which has general application to rectangular frames, the proportions of the inner frame being the same as those of the outer in order that the diagonal elements Aa, cC and Bb, dD are respectively collinear.

Up to the first yield condition, a shear force, such as Q (Fig. 4) produces a tensile force in only one diagonal, BD, AC being unloaded. Corner deformations at a, b, c and d are all equal so that yield occurs simultaneously in all four corners. On reversal of the load, the same amount of yield occurs in the opposite direction, which makes for repeatability in the hysteresis loops.

Calculations indicate that for the square frame tested, first yield occurred at approximately 6 kN, corresponding to the smallest loop of Fig. 8 (Ref. 3). The locking-up effect at strokes above ±100 mm were caused in two ways. On application of the force Q, Fig. 4, tension develops in diagonal BD, and deformation of the inner frame causes the diagonal length ac to shorten more than the overall distance AC on the main frame, with the result that diagonal AC also goes into tension, producing self-straining forces which cause additional load at the jack in excess of that required to cause overstrain at points a, b, c and d. The amount of this load may be calculated by closing an appropriate gap G in a diagonal as shown for the square device in Fig. 9. At the same time the shortening of diagonal ac requires an increasing force in diagonal BD to continue the plastic yielding at points a, b, c and d, which again throws additional load on the jack. As the inner frame is severely deformed, both effects call for large increases in the jacking load giving a resistance similar to a "snubbing" action.

The total calculated locking-up effect (Ref. 3) produced by the two causes is plotted in Fig. 10. Evidently the peaking up is mainly caused by the incompatibility in the diagonal lengths, as, at the maximum stroke of 142 mm, this effect contributes about 7.2 kN, and the other 2.2 kN. The observed increment in peaking up (Fig. 8) is about 7 kN.

Future Work

The performance obtained in the tests suggests that, as continuing frame action is assured, structures incorporating this type of device could be designed to survive a sequence of very large earthquakes. The work needs to be extended to establish the relationship between bar diameter, size of rectangle or square and the frame distortion, for a surface strain of ±3% in the device, which will give about 100 cycles to failure. Performance needs to be checked for models on a shaking table and the design should be such that energy is absorbed while the remainder of the structure remains elastic; it should continue to be absorbed without failure at a ductility factor of, say, 6 in the rest of the structure.

Some work needs to be carried out on devices formed from flat strip of rectangular cross section, perforated by a single hole at each corner to carry the diagonals, as there may be a simple way of reinforcing the holes to give a reasonable fatigue life; welding should again be kept away from the zones of high strain.

Another alternative would be to substitute pins instead of the bents at points a, b, c and d (Fig. 4) and add disc brake pads in such a way that, as the members rotate relative to one another, energy is absorbed by friction on the pads working on stainless steel discs.

The above techniques should find wide application in some humid tropical countries where single occupancy dwelling units are frequently supported some 8-10 feet above the ground using diagonally braced frames of the type shown in Fig. 1.

AXIALLY-LOADED ENERGY ABSORBER FOR BRACINGS

Another way of absorbing energy in braced structures is to include an axially-loaded element in the bracing which operates in push-pull, with buckling restricted by suitable support around the absorber. Such a device has already been installed within concrete members of a building in Wanganui, New Zealand. A feature of these devices is that they develop high energy absorption for much smaller frame deformations than is required by devices of the type shown in Fig. 4.

Tests have been carried out at the Laboratory on the device shown in Fig. 11 which is a round hot-rolled mild steel bar, portions of which are machined down to allow yielding. Such yielding should commence while the rest of the structure is still in the elastic range. At an axial strain of ±3%, with a life of about 80 cycles, the hysteresis loop shown in Fig. 12 was obtained for an axial movement of ±6 mm, demonstrating a favourable energy absorption characteristic. At this stage some local buckling of the yielding portions was observed, as shown in Fig. 11. The device would be designed to remain operative up to a ductility factor of, say, 6 in the remainder of the structure by suitably increasing the length. For this device the restraint against buckling presents a design problem which does not exist for the cross-bracing system described above.

TESTS ON LEAD-PLUG RUBBER BEARINGS USED IN ISOLATION PROJECTS

The lead-plug rubber bearing (Fig. 1) was developed at the Laboratory in the late 1970's as a means of providing both bearing support to a structure and damped lateral movement under earthquake attack (Ref. 4). It has been used in the base-isolated William Clayton Building in Wellington and also in many bridge structures. The concept has a particular applicability for the latter, as laminated rubber bearings are often specified to allow for temperature movement; the addition of a lead plug to provide damping under earthquake attack is quite inexpensive.

One object of the recent tests at the Laboratory, employing the rig shown in Fig. 13, has been to demonstrate performance at very high shear strains in the rubber. A severe earthquake is only likely to occur very rarely at a particular location, say, once every century. For the rest of the time the bearing loading is static, e.g. for the William Clayton Building, the shear movement over the past two years has been ±1 mm, including the effects of high winds. Thus very large excursions should be possible for the few occasions that earthquakes occur without detriment to the bearing, certainly to above 100% strain in the rubber. A potential degradation of high-strain capacity after many years of permanent loading must be tested for in a bearing removed from the structure or kept loaded in a creep rig.

Another object of the tests has been to investigate ways of improving performance when there is very little weight on the bearing, as sometimes happens at the abutment support of a bridge. Tests so far by various workers have indicated that the damping decreases as the vertical load decreases. This is shown up as a diminished area enclosed by the hysteresis loop.

CONCLUSION

Tests on energy absorbing devices at the Laboratory will continue as it is clearly desirable that the concept of ductility through damage of a structure is replaced by one of controlled energy dissipation in special components.

While very large earthquakes are comparatively rare in New Zealand, and it is indeed said that we are in a quiet spell which may last until the beginning of the next century, other parts of the world are more frequently shaken. It is hoped therefore that the use of base-isolation techniques and energy absorbers will spread in order that reliability can be proven in performance.

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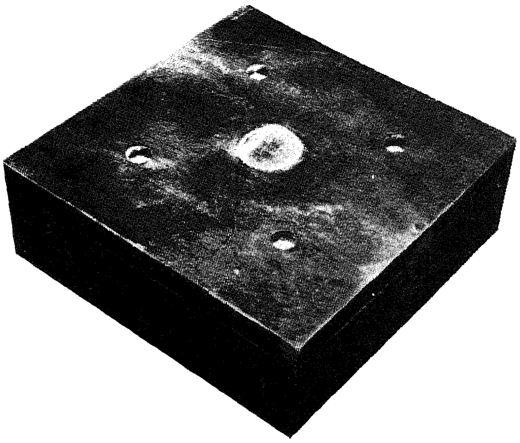

Fig. 1. Lead-plug rubber bearing used for William Clayton Building 610 x 610 x 207 mm

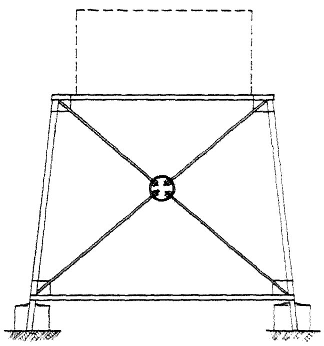

Fig. 2 (right) Typical braced structure with ring adjustment at frame centre.

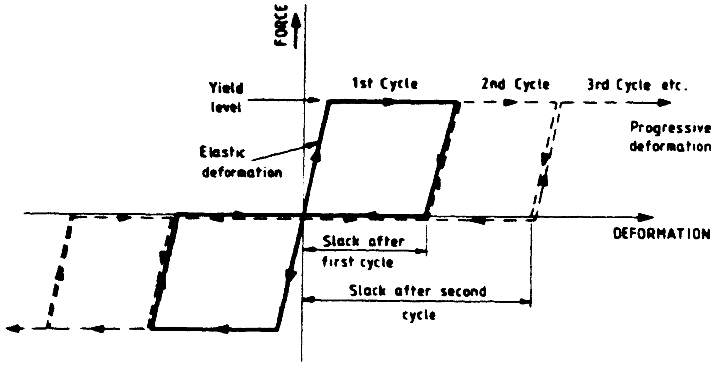

Fig. 3. Degradation of typical cross braced structure under cyclic loading.

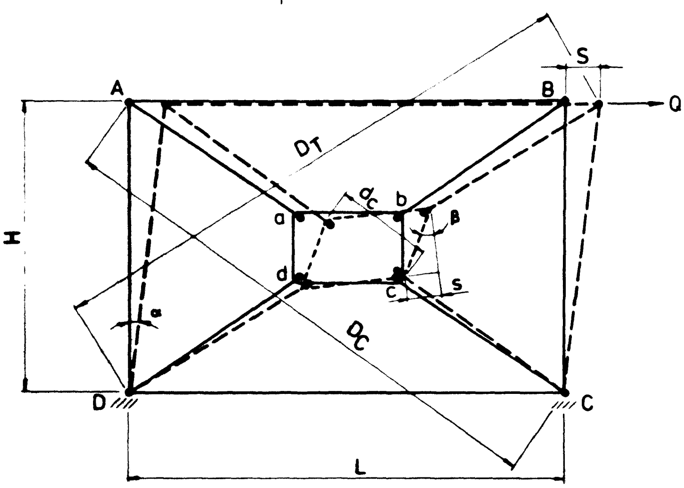

Fig. 4. Rectangular framework with central rectangular energy-absorbing device.

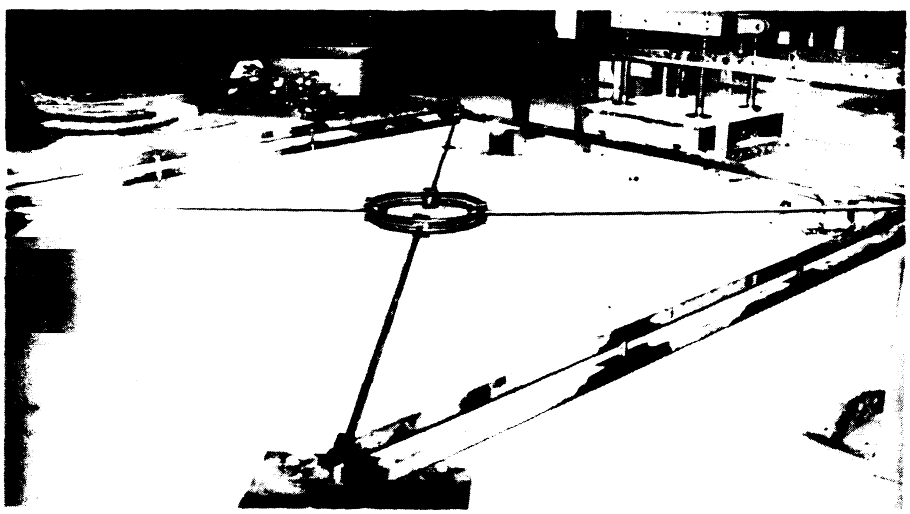

Fig. 5. Ring device tested in 4 m square frame.

Fig. 6. Failed ring device showing straightening between loading points.

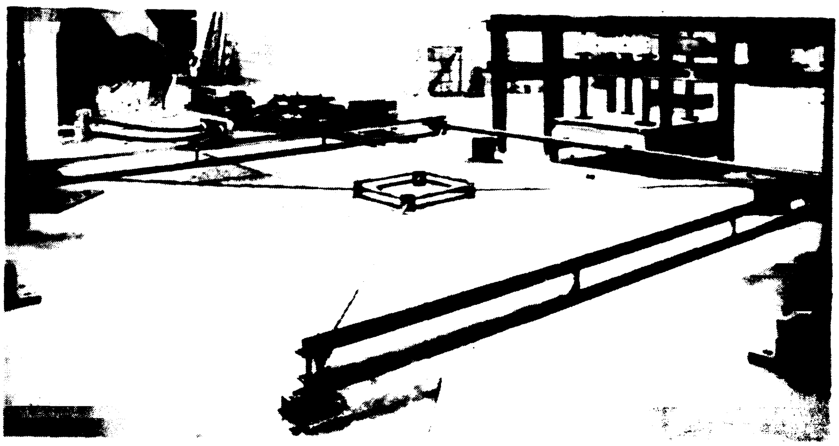

Fig. 7. Square device in 4 m square frame.

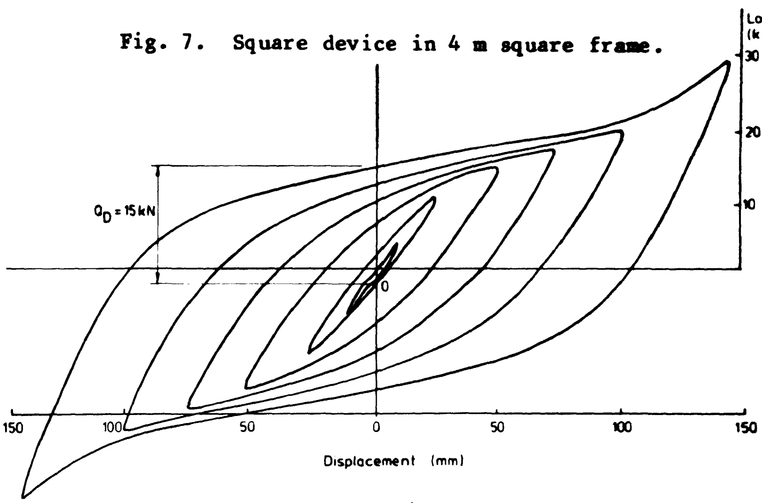

Fig. 8. Frame shear deformation for the square device.

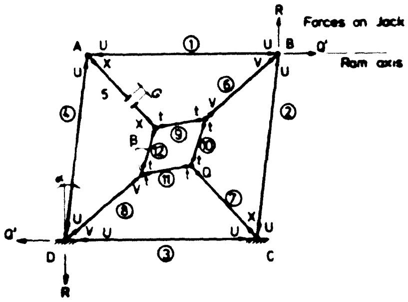

Fig. 9. Frame deformation for calculation of locking up forces.

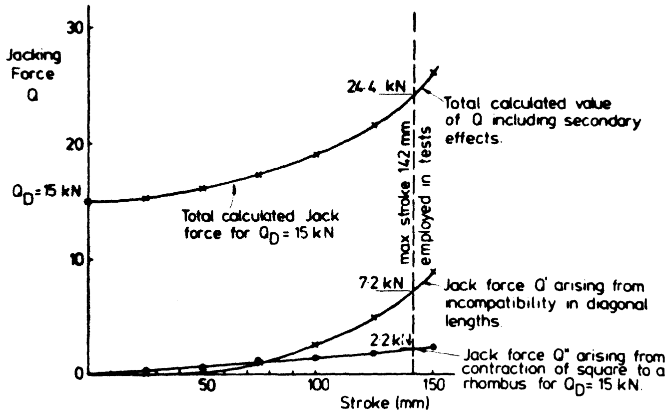

Fig. 10. Locking up forces for square device.

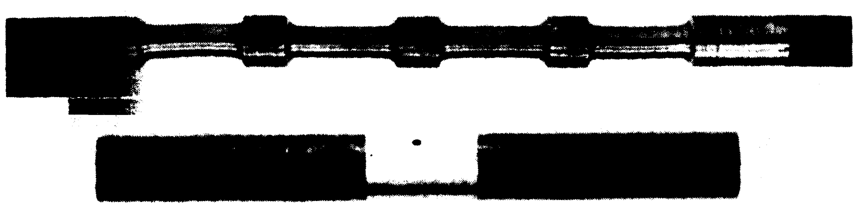

Fig. 11. Push-pull energy absorber with restraining tube to prevent buckling.

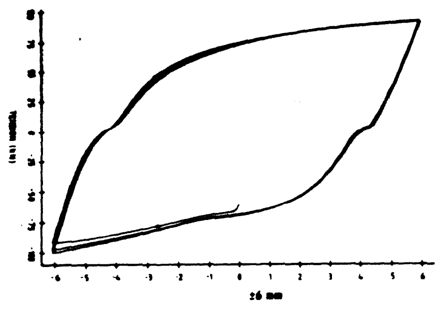

Fig. 12. Load-deformation loop for axial absorber.

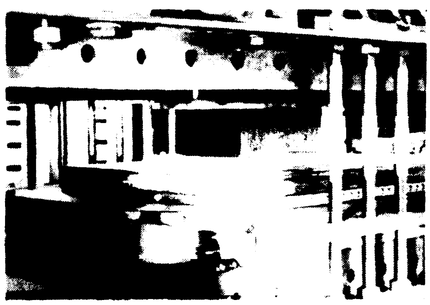

Fig. 13. Rig for testing rubber bearing in cyclic shear, with rollers below central moving plate and jacks below.