CURVED PLATE ENERGY ABSORBERS FOR EARTHQUAKE RESISTANT STRUCTURES

S.F. Stiemer (1)
F.L. Chow (II)
Presenting Author: S.F. Stiemer

SUMMARY

This paper suggests the use of curved plates and bars of hot rolled mild steel as energy dissipating devices for the design of earthquake-resistant structures. The proposed devices would be used in parallel with isolating systems in buildings or other structures. They are designed to deform elastically under minor loads such as wind and to deform plastically when subjected to major earthquake loadings. The devices have a large energy absorbing capacity at a high number of cycles; they are economical and, once installed, can be easily inspected and replaced. An engineering method is presented for the practical design of the steel energy absorbers and for predicting the number of cycles to failure of the devices. Experimental investigations and practical applications are described in the paper.

INTRODUCTION

Earthquake resistant design in structural engineering is achieved by several methods of which the following have received the highest interest: 1) sufficiently stiffening the buildings and internally absorbing the earthquake forces by inelastic action in beams or columns or, 2) designing a very flexible elastic structure and externally absorbing the energy by additional discrete elements or, 3) uncoupling the building or structure from the exciting ground motion and restricting it from excessive displace-ments by dampers. The latter approach has been readily accepted in theory but it has been viewed as impractical for large civil engineering struc-tures. The lack of acceptance of this method has been caused in part by its complete contrast to the current approach to aseismic design described under 1) structures designed using methods (2) or (3) do not withstand earthquake loadings by the structure's strength or by sacrificing parts of the structure but limit the forces in the structure by elasticity or by uncoupling it from the ground. However, if a structure designed by the elastic system (2), does not include damping devices, there is the obvious danger of it developing resonances during excitation which would cause failure. With a proper design which includes discrete damping devices this problem can be prevented. ·When a building is isolated from the ground measures must be undertaken to prevent the excitation during a severe earthquake from becoming so large and that minor loads could permanently displace the building.

(I) Associate Professor, Department of Civil Engineering, University of British Columbia, Vancouver, Canada
(II) Design and Research Institute of the First Ministry of Machine Building, Luoyang, China, PRC

GENERAL CONSIDERATIONS ON THE DESIGN

The research was aimed at the design of reliable, inexpensive solid-state energy absorbers for (a) a mono-axial action and (b) a multi-directional action.

After considering a large variety of shapes and using results from previous research [1]-[5] a bending element was chosen for further development. Based on successful experiments of one of the authors [4] bending action promised a yield element which is easier to manufacture but possesses similar reserve capacity like a torsion element. All shear, compression, tension, and extrusion action apparently inherited major disadvantages. They were excluded from further design considerations. Simple hot rolled steel plates were used for the yield elements. Complicated machining or welding was avoided. No hinged bearings were required, the devices were rigidly clamped (rotationally fixed) at both ends.

For the one-directional type a shape chosen, which was composed from double tapers forming an X. To avoid stress concentrations at the clamped boundaries or in the middle, rounded transitions were chosen (Fig. 1). When this flat plate of mild steel was loaded in the weak direction the fixed bending stresses at the apex of the tapers became uniform along the length, thus allowing yielding to develop over the full length of both tapered section. The plate deformed in a continuous S-shape. This assured an optimum use of the existing material without stress concentrations at any location of the device and resulted in a high number of cycles far into the ductile range of the material. Because there was always a residual elastic core inside the yielding plate, the energy absorber achieved self-centering after being subjected to random load time-histories with decaying ends, which was a very beneficial behaviour in the case of earthquake loads. Although the fatigue life, work hardening characteristics, and amount of energy absorption varied from steel to steel quality, even from batch to batch, the St 10-20 hot rolled mild steel showed a rather uniform behavior (Fig. 2).

The second type of energy absorbing device consisted of two curved plates in pairs like rings with planes perpendicular to each other (Fig.3). This enables energy absorption in any horizontal and even vertical direction, which was the logical evolution of the one-directional device described above. The main goal was to design an element, which shows a stable behaviour, that is, after having experienced elastic and plastic deformation and being brought back to the initial position, the geometric shape of the device should not have changed. The anticipated bending moment distribution was approximately matched by the moment resistances of the deformed plates. This type of energy absorber was aimed at the application in base isolated structures, where bearing pads like roller bearings undergo lateral parallel displacements or rubber pads where even three-directional displacements had to be accommodated. Following requirements for the design, being the same like those for the one-directional device, were governing: the material should be steel with high a ductility, it should have an adequate fatigue life, temperature independence, and it should be possible not only to predict the yield behaviour but the life span, too.

EXPERIMENTAL TESTS AND DESIGN PROCEDURE

A large number of specimens were tested in order to get reliable results for the yielding region and the fatigue life of the devices. Any length, thickness or width effects due to grain sizes or shape effects were tried to be covered.

In the elastic region the load-displacement relation for the X-shaped device is linear up to the yield point of

$$d = \frac{6P \, (\frac{\ell}{2})^3}{E \, b \, t^3} \quad \text{from [5]} \tag{1}$$

In the inelastic region the proportionality between load and displacement no longer holds. However before strain hardening starts the yield plateau is fairly flat with an upper limit of an ultimate load of 1.5 times the yield load, depending on the thickness/length ratio. But this described only the behaviour of the energy absorber in an undamaged, fully operationable state. In order to establish a relation between the maximum number of cycles to failure N and the maximum strain in the outer fibres ε of the device during each cycle it was found empirically (Fig. 4):

$$\varepsilon \, max = \frac{.22}{\sqrt{N}} \tag{2}$$

This formula is of highest importance for the designer and represents one of the major results of this report. The actual strain of the outer fibres of the device is a function of the maximum end displacement d. Starting with the geometric relation of bending radius ρ and d:

$$\rho = \frac{4(\frac{d}{2})^2 + \ell^2}{4d} \tag{3}$$

The curvature of one section is given by

$$\phi = \frac{1}{\rho} = \frac{\varepsilon}{(t/2)} \tag{4}$$

and then the strain as

$$\varepsilon = \frac{t}{2\rho} = \frac{2 \, d \, t}{d^2 + t^2} \tag{5}$$

This would be true for a double circular deflected shape and ideal boundary conditions. Both could be approximately achieved in the experimental tests and do not apply for practical use. An empirical correction factor is suggested which gave good correlation with experimental measurements:

$$\varepsilon = \frac{2 \, d \, t}{d^2 + t^2} \sqrt[3]{\frac{d}{3}} \tag{6}$$

It can be seen that for most earthquakes a design of an energy absorber

with maximum strain of 2% is quite sufficient because we still cover 100 excitations to the maximum amplitude. For structures of extreme high importance it is suggested that the maximum strain in the energy absorber to be reduced to 1.4 - 1.6% in order to achieve a higher factor of safety.

The second focal point of our investigations was the curved plate energy absorbers, in the following referred as yield rings. Their action was a combined bending-torsion action, while the torsion was kept small by devising high length/thickness ratios. The bending action resulted in the formation of plastic hinges at the boundaries (see Fig. 3). This location is fixed for any magnitude of stroke, that means the plastic hinge shifts from A to B. As it was shown in [1] that for high length/thickness ratios the axial force can be neglected, we were dealing with the simple situation of an ideal plastic hinge for which the amount of rotation was limited. So the maximum strain ε

$$\varepsilon = \frac{t}{2R} \quad \text{with } R = \rho \tag{7}$$

was independent from the stroke d. However, when the vertical stroke was allowed simultaneously, then the radius R was no longer constant and the rings developed plastic hinges at their clamped attachments (see Fig. 5). Tests for the case of boundary separation have shown strain dependence from the stroke:

$$\varepsilon = \frac{\alpha\, t}{\ell(d^2 + 1)} \; \sqrt[3]{\frac{d}{15}} \tag{8}$$

with
$$\alpha = 0.983 - \sin^{-1} \frac{1.5 - \frac{m}{2}}{\sqrt{1 + (1.5 - \frac{m}{2})}} \tag{9}$$

and
$$m = \frac{d}{(R + d_{vert})} \tag{10}$$

The same formula for establishing the maximum number of cycles to failure (Eq. 2) is valid for the yield rings and shows a very good correlation to the experimental results for this type of solid state steel energy absorber (Fig. 5).

CONCLUSIONS

A comprehensive study of all available data of our own test results and from others leads to the following general conslusions:

Solid state steel energy absorbing devices represent an efficient, inexpensive, reliable, and maintenance-free means for providing damping in flexible or base-isolated buildings.

Design formula are now available, which describe the yield load, the

strain level, and the life span simply and accurately enough to be used for engineering purposes.

Both devices under investigation act in the same sequence: elastically up to the yield point, plastically with small amount of elasticity (slightly sloped yield plateau), and finally due to strain hardening and geometrical deformation as a soft stop for excessive deflections.

The one-directional X-shaped energy absorber, which has no hinged connection rods like previous designs, is insensitive to limited torsional action.

The multi-directional double yield rings enable energy absorption in any horizontal and vertical direction.

Earthquake excitation forces can be greatly reduced in buildings or structures when flexible systems with energy absorbers or base-isolated systems with wind restraint and displacement limitations are used (Fig. 6 and Fig. 7).

ACKNOWLEDGEMENTS

REFERENCES

[1] Kelly, J.M., Skinner, R.I., and Heine, A.J.: Mechanisms of Energy Absorption in Special Devices for Use in Earthquake Resistant Structures, in Bulletin of the New Zealand Society for Earthquake Engineering, Vol. 5, No. 3, 63-88, Sept. 1972.

[2] Kelly, J.M., and Skinner M.S.: The Design of Steel Energy Absorbing Restrainers and their Incorporation into Nuclear Power Plants for Enhanced Safety, Vol. 4, A Review of Current Uses of Energy-Absorbing Devices, Report No. UCB/EERC-79/10, Earthquake Engineering Research Center, University of California, Berkeley, February 1979.

[3] Stiemer, S.F., and Godden, W.G.: The Design of Steel Energy Absorbing Restrainers and Their Incorporation into Nuclear Power Plants for Enhanced Safety, Shaking Table Tests of Piping Systems with Energy-Absorbing Restrainers, UCB/EERC-80/33, Earthquake Engineering Research Centre, University of California, Berkeley, Sept. 1980.

[4] Stiemer, S.F., Godden, W.G., and Kelly, J.M.: Experimental Behaviour of a Spatial Piping System with Steel Energy Absorbers Subjected to a Simulated Differential Seismic Input, UCB/EERC-81/09, Earthquake Engineering Research Centre, University of California, Berkeley, July 1981.

[5] Schneider, S., Lee, H.M., and Godden, W.G.: Behaviour of a Piping System Subjected to Seismic and Thermal Loading, in Proceedings of the Fourth Canadain Conference of Earthquake Engineering, p. 140-150, Vancouver, Canada, June 1983.

[6] Zackay, V.F., Kelly, J.M., Penzien, J., Powell, G., Wilson, E.L., Bush, S.H., Finnie, I., and Stiemer, S.F.: The Design of Steel Energy Absorbing Restrainers and Their Incorporation into Nuclear Power Plants for Enhanced Safety, Prepared for the Department of Energy under Contract DE-AS03-76SF00035 PA DE-AT03-ER70296, College of Engineering, University of California, Berkeley, California Progress Report, March 1980.

[7] Barwig, B.B., and Stiemer, S.F.: Base Isolation Design for Earthquake Resistant Steel Buildings, Proceedings of the Fourth Canadian Conference of Earthquake Engineering, p. 382-391, Vancouver, Canada, June 1983.
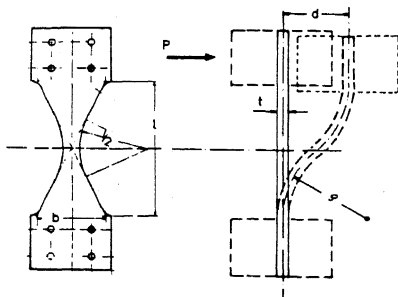
Fig. 1.   One-Directional Energy Absorber, X-Shaped Hot Rolled Steel Plate
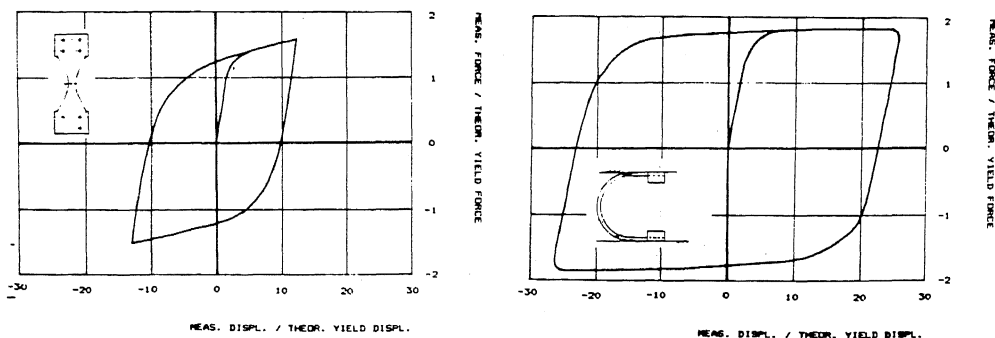

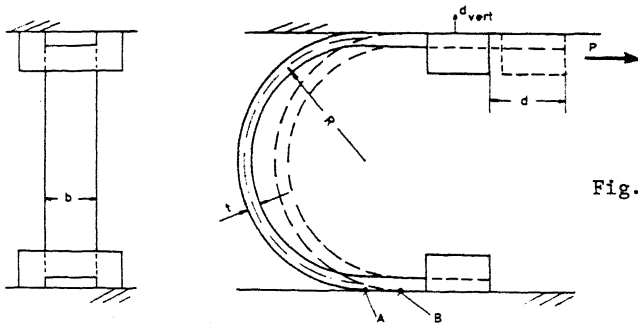Fig. 2.   Load-Displacement Hysteresis Loop for X-Shaped Energy Absorber and Yield Ring

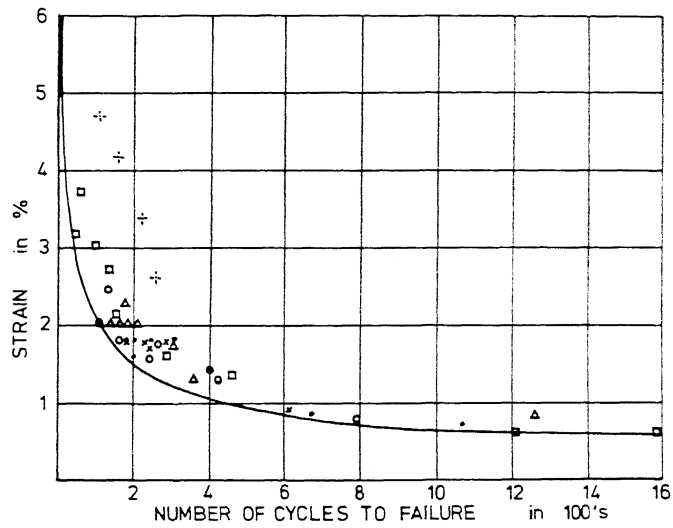Fig. 3.   Quarter Element

of Double Yield Ring

Fig. 4.   Experimental Results for Strain/Number of Cycles to Failure,
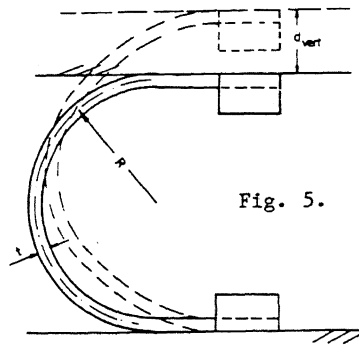Curve Represents Lower Bound (Eq. 2)

Fig. 5.   Yield Ring Element Deflection
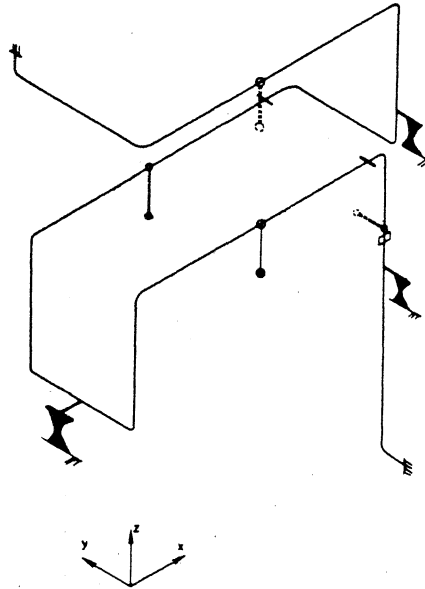
for Vertical Displacement

973

Fig. 6.   X-Shaped Energy Absorber Implemented in Flexible Spatial Piping
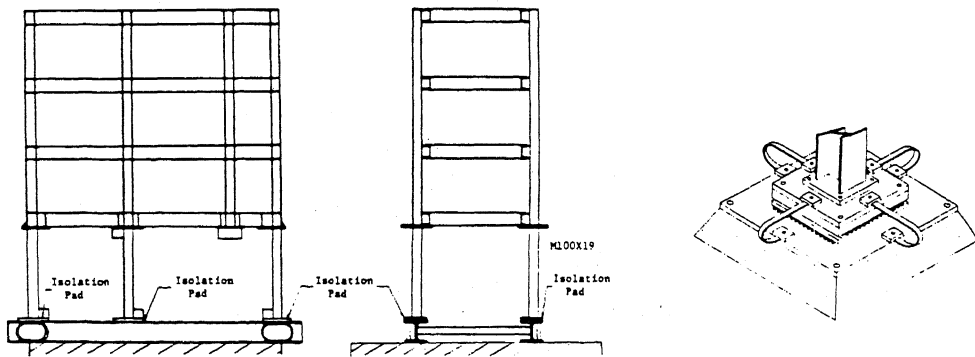System, Schematic from [4]

Fig. 7.   Yield Rings Implemented in Base Isolation System, From [7],
Insert: Proposal for Bi-Directional Use