New Zealand Journal of Science, 1977, Vol. 20, 265 – 71

A hot-water cylinder to survive earthquakes

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The earthquake resistance of polyurethane-insulated domestic hot-water cylinders strapped into place was compared with that of unstrapped cylinders and a strapped union flock-insulated cylinder. The cylinders were mounted in a simulated cupboard and tested against unidirectional sinusoidal vibrations. It is concluded that strapped-in polyurethane insulated cylinders are adequate, union flock-insulated cylinders have good earthquake resistance when strapped in, but unstrapped cylinders are inadequate.

INTRODUCTION

Hot-water cylinders in New Zealand houses are usually installed with no lateral restraint other than that offered by the pipes to the cylinder and the friction between the cylinder and floor or shelf. During a severe earthquake this restraint has proved insufficient and the bottom entry pipe can be sheared off (Shepherd *et al.* 1970). The potable water in the cylinder that could otherwise be available in the first critical days after a major earthquake is lost.

This project was carried out in response to the concern expressed by the water-supply committee of New Zealand Institution of Engineers after the Inangahua earthquake of 1968. It was intended to establish whether it is practical to manufacture and install earthquake-resistant hot-water cylinders.

NATURE OF EARTHQUAKES AND BUILDING RESPONSE

Earthquakes vary from a single shock to a long irregular motion over several minutes. At some sites a prevailing period of vibration may result from the filtering of an earthquake through well defined layers of soft soil or from reflections at interfaces of soft soils. Large-scale permanent ground deformations may occur (Newmark & Rosenbleuth 1971). Accelerations typically occur at varying strengths in all directions, including vertical, and in a mix of frequencies.

Estimates of accelerations during the Inangahua earthquake range up to 0.7 - 0.8*g*. A horizontal scratchplate accelograph recorded a maximum value of 0.35*g* at Reefton. An earthquake of this magnitude may be expected in New Zealand on an average of once every 8 years (Shepherd *et al.* 1970).

The most important frequencies for design purposes usually range between 1 and 10 Hz . The estimated natural frequency at roof level of a timber house is approximately 3 - 6 Hz, but during an earthquake, bracing and nailed joints may be loosened and lower the frequency. At the floor level of a building with a continuous concrete foundation the motion will not be much different from the actual ground motion (R.I. Skinner, pers. comm.).

EARTHQUAKE SIMULATION

Since every earthquake has a unique pattern of vibration there is a problem in choosing a representative simulation procedure. The motions of particular earthquakes might be reproduced, but this does not deal precisely with the response to future earthquakes nor with the modifying influence exerted by undefined buildings. A compromise in accuracy is required.

Earthquake codes for buildings, such as NZS 1900 Chap 8, simply specify a horizontal shear force which varies with resonant frequency but make no allowance for damping.

Testing for a static horizontal acceleration takes no account of the resonant frequencies or damping in the equipment. Static testing may give optimistic results and must therefore be treated with extreme caution.

Pure-tone sinusoidal testing can be used to identify resonant frequencies and low-amplitude damping coefficients, but is conservative. If the test is at the resonant frequency of the equipment, oscillations can build up to very high levels over a number of cycles, whereas in actual earthquakes consecutive cycles will vary in frequency and amplitude, and the peak response will be less.

A refinement of sine-wave testing uses an amplitude-modulated input which has been called "sine-

Received 8 March 1977

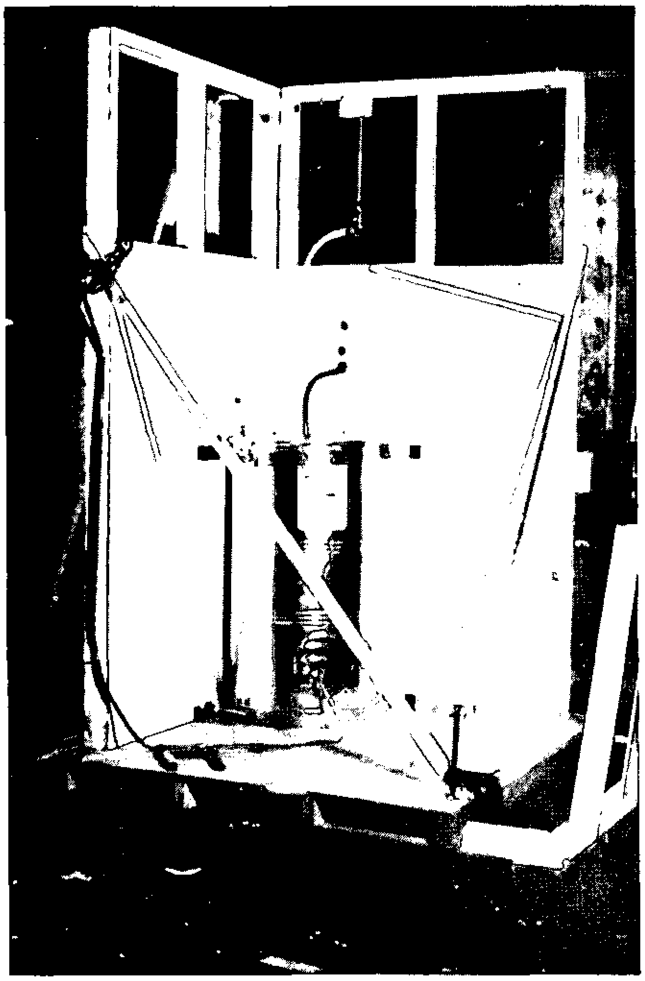

Fig.1 Union flock-insulated hot-water cylinder mounted in simulated cupboard before testing.

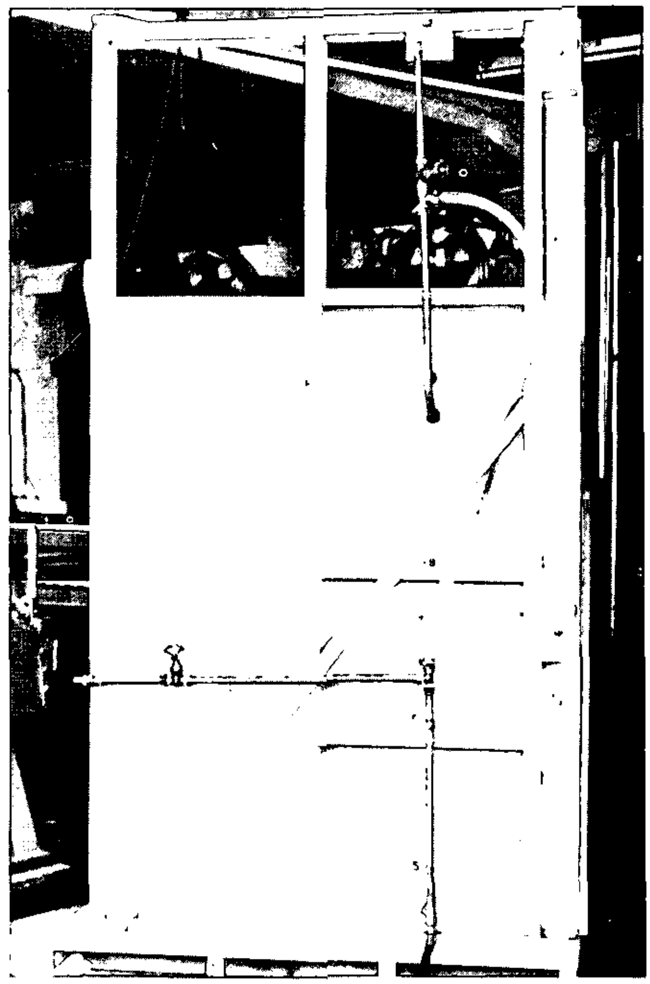

Fig.2 Detail of piping and back wall of simulated cupboard.

beat" (Colaiaco & Albert 1972). This gives a motion more like that from the random sine-wave motions from seismic causes. The method can be further refined by testing in 3 dimensions simultaneously.

However, I used sine-wave testing instead of the more accurate sine-beat testing because (a) available equipment was capable of only pure-tone shaking, and (b) very sophisticated tests were not justified because of variations between earthquakes, buildings, and positions in which cylinders are installed, and the very small increase in cost caused by using conservative results. Sinusoidal vibrations can be applied to the shaking table over the range of frequencies of importance during typical earthquakes.

Although simultaneous application of several frequencies of horizontal acceleration was unlikely to affect the results significantly, the simultaneous application of a vertical acceleration, as during an earthquake, could induce damage at lower amplitudes of horizontal vibration, particularly where the cylinder is not strapped but is able to "walk". Rotational accelerations could not be applied directly with the equipment available and had to be considered separately.

The relative movement between the roof of a house and the floor was not simulated, but this cause of movement at the top of the cylinder was expected to be about the same magnitude as the flexing of the wall of the simulated cupboard.

BASIC APPROACHES TO DESIGN OF EARTHQUAKE-RESISTANT HOT-WATER CYLINDERS

The basic alternatives are to constrain the cylinder to move with the building, and to allow the cylinder to move independently of the building by providing sufficient flexibility in connecting pipework. The first approach was adopted because it was reported (Shepherd *et al.* 1970) that at Inangahua hot-water cylinders were thrown out of the cupboard, so the second apprdach might be unsuccessful. Moreover, an education programme to ensure that all plumbers and plumbing inspectors adopted a recommended practice of routing pipework to avoid restraints on it close to the hot-water cylinder would be a major undertaking, and might be resisted because such a re-routing of pipework would tend to look untidy and "untradesman like".

To restrain the cylinder to move with a building, it must be firmly located within the casing in a manner which does not interfere with the insulation.

A rigid insulation such as foamed polyurethane is particularly suitable. It is a substantially better insulator than the presently used union flock (0.025 W/m°C compared with 0.045 W/m°C). It is also strong and rigid compared with other insulants; the modulus of elasticity depends substantially upon loading rate, but is of the order of 500 kN/m^2.

EQUIPMENT USED

Cylinder construction

Three 135 litre cylinders were tested.

(a) A standard cylinder manufactured to NZS 720. The insulation used was union flock, a mixture of cotton and wool flocks. This cylinder is referred to as 50 F (50 mm thick flock-insulated).

(b) A cylinder insulated with 50 mm of foamed polyurethane; this is the same thickness of insulation as used on standard domestic cylinders, but with foamed polyurethane the insulation level is increased by approximately 80%. This cylinder is referred to as 50 P.

(c) A cylinder insulated with 90 mm of foamed polyurethane. (A study of the economics of hot-water cylinder insulation suggested that increased insulation was desirable for domestic cylinders). This is referred to as 90 P.

The polyurethane-insulated cylinders were standard 135 litre copper internal cylinders with standard casings obtained from a local manufacturer. Rubber grommets were placed around the inlet and outlet pipes where they passed through the casing. The grommets are standard for cylinders from this manufacturer.

Mounting

A simulated cylinder cupboard was constructed with 2 walls braced to a floor and mounted in a shaking frame (Fig.1) made available by the Pottery and Ceramics Research Association Inc. Each wall had 3 studs at 0.6 metre centres and was lined on one side with Gibraltar board. A 100 x 50 mm dwang was nailed in each wall near the top of the cylinders with the 100 mm face against the Gibraltar board. The top plate of the back wall was bolted to the shaking frame.

The cylinder was placed directly on the floor, as is common practice. The bottom entry pipe was taken through the floor by way of a hole of ample size. The movement of the cylinder was monitored to provide information on the hole size required to prevent the piping shearing.

The entry pipe was installed to about 130 mm below floor level (the distance required to clear the 100 x 50 mm floor joist) then bent in the direction of motion and taken to the wall and a short distance up it, where it was fastened to simulate typical installation (Fig.2). Also as in normal practice the top delivery pipe was taken through the wall lining but not fastened until some distance up the wall in approximately the position of the top dwang in a conventional wall.

The cylinder was strapped to the wall with 2 straps of galvanised steel 50 mm wide and 0.8 mm thick, fastened with two 10 mm diam. bolts to brackets of 50 x 50 x 3 mm angle iron. These brackets were placed over the Gibraltar board and screwed to the dwang or bottom plate with two 50 mm wood screws each. Each strap was equipped with a turnbuckle; this was tightened on the top strap to deflect the wall 2-3 mm, and a similar tension was applied to the lower strap.

For the shaking tests, 2 strain-gauge deflectometers were mounted to monitor the movement of the internal cylinder, the lower one being attached to the bottom plate, and the upper one partly to the dwang and partly to the Gibraltar board lining.

Shaking table

The shaking table consisted of a rigid steel frame which held the floor directly under the back wall and under the front edge of the floor 1.3 metres from the back wall. The top plate of the back wall was bolted to the frame.

Compared to the flexibility of the timber walls the frame can be considered rigid. It was hydraulically actuated to follow a sinusoidal displacement command. The motion was horizontal and unidirectional. The maximum shaking amplitude available declined with increasing frequency.

METHODS

All shaking tests were with cylinders completely full of water.

Static Tests

Each cylinder was strapped in the simulated cupboard, which was then turned on its side so that the cylinder was suspended from the back wall, and the cylinder was filled with water. Measurements (to an accuracy of 0.5 mm) of the cylinder movement in its casing were made with a ruler and probe.

Low-amplitude frequency sweep

The strapped cylinder and simulated cupboard were shaken sinusoidally at low amplitudes at varying frequencies from 1 to 12 Hz to determine any reson-

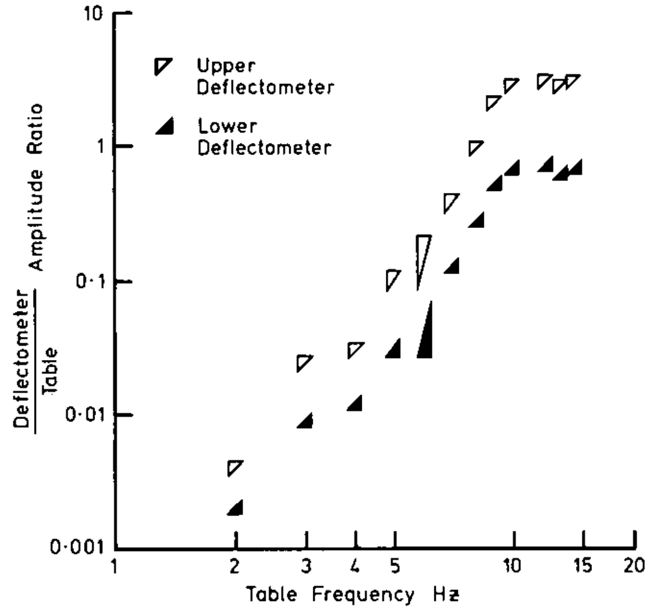

Fig.3 Frequency response for cylinder 50 F.

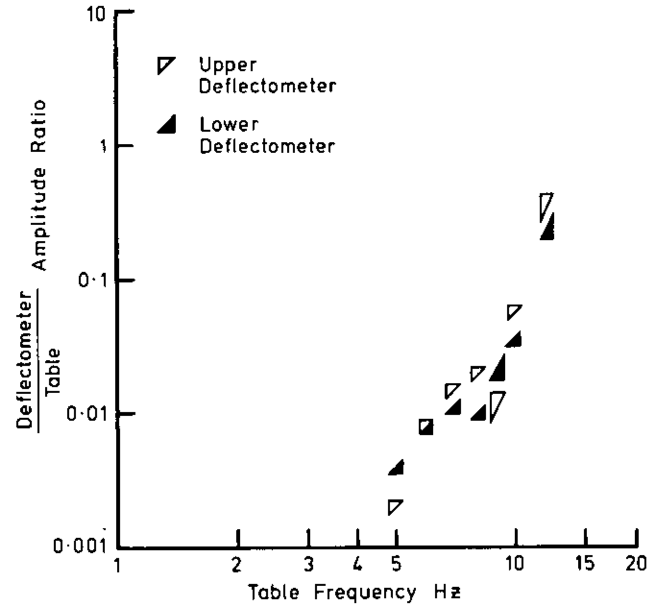

Fig.4 Frequency response for cylinder 50 P.

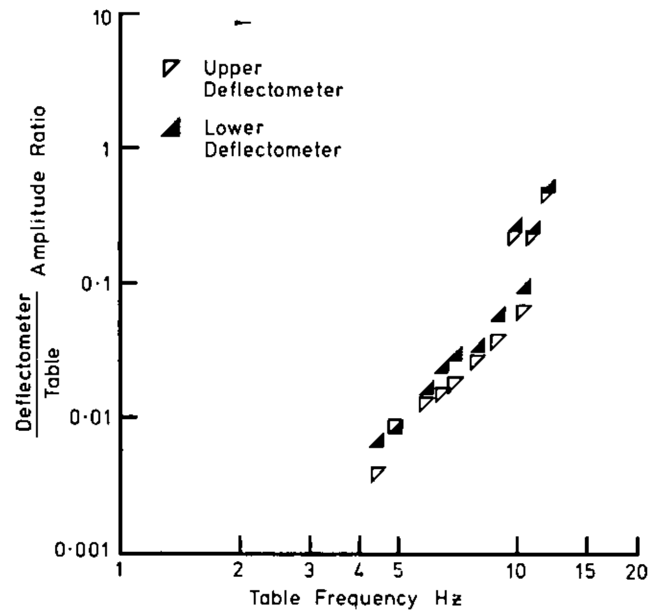

Fig.5 Frequency response for cylinder 90 P.

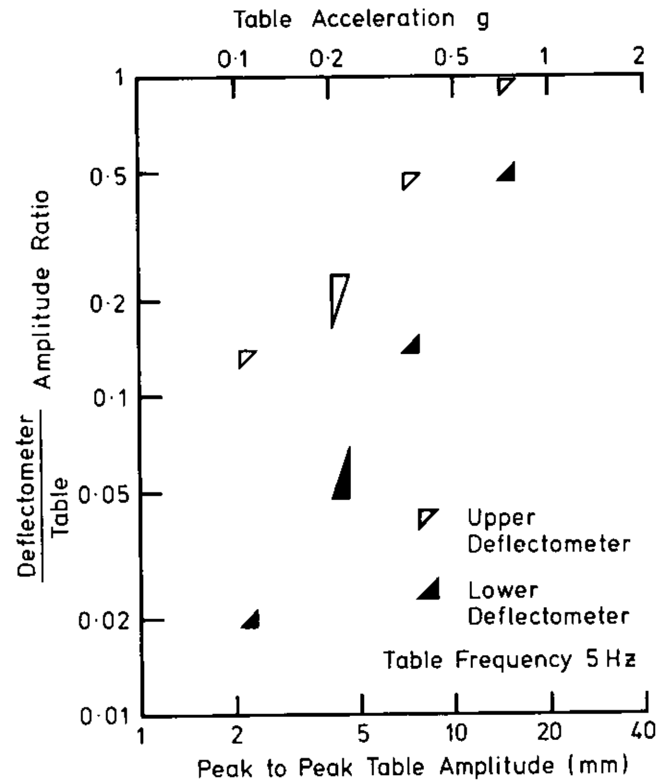

Fig.6 Amplitude response for cylinder 50 F.

ant frequencies and to aid the selection of a frequency for higher-amplitude tests. 100 cycles were given at each of the selected frequencies. The as-damped resonant frequency between cylinders and wall was estimated from the decay of the movement recorded by the deflectometers.

The fraction of critical damping was estimated from the ratio:

1/(2 × amplification ratio).

The results of the ratio of deflectometer amplitude: table motion amplitude are plotted against frequency in Figs 3-5.

High-amplitude shaking tests

High-amplitude sinusoidal shakes were given at 5 Hz. This frequency is higher (i.e., closer to tested system resonance) than the expected resonance frequency of typical single-storey dwellings, and maximum earthquake accelerations are commonly at frequencies less than 5 Hz. The natural frequencies of a

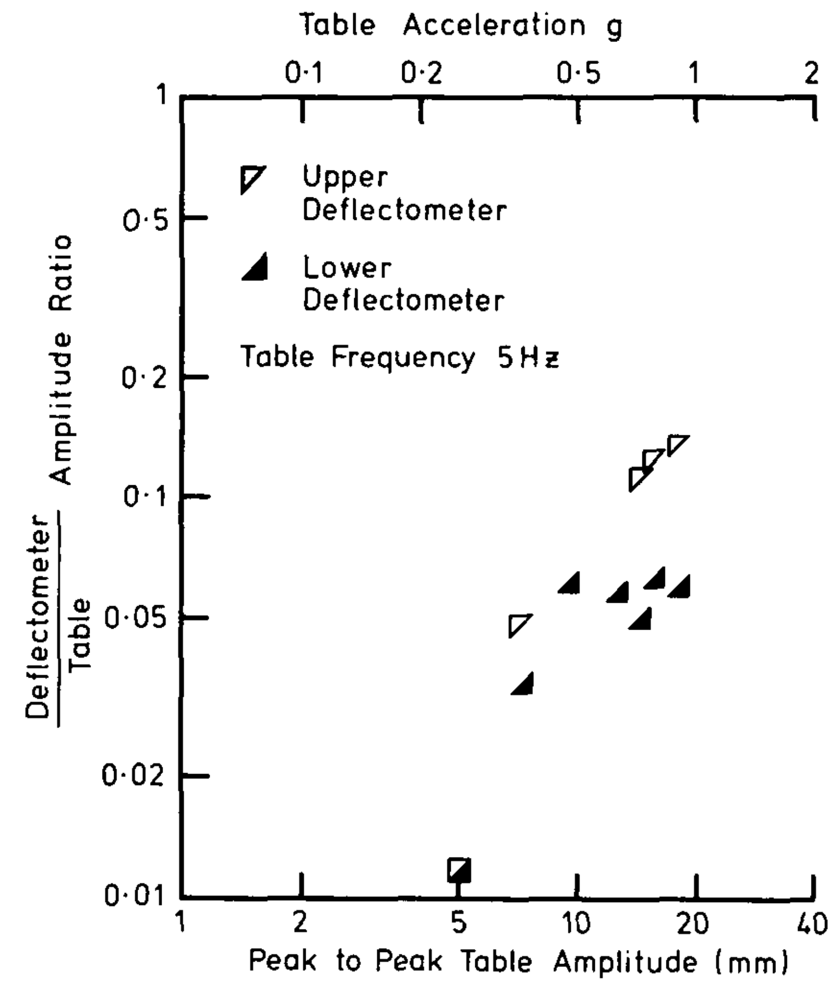

Fig.7 Amplitude response for cylinder 50 P.

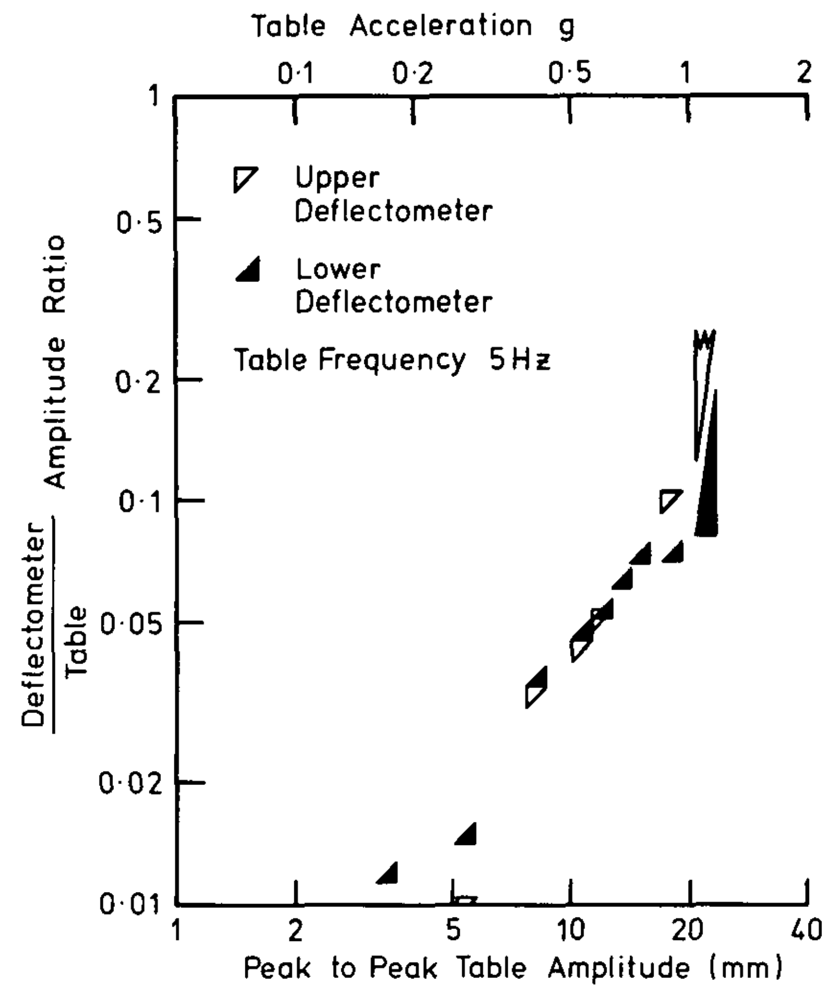

Fig.8 Amplitude response for cylinder 90 P.

typical ground floor will be high and consequently the floor motion will tend to conform to ground motions.

The ratio of deflectometer amplitude : table motion amplitude was graphed against table acceleration (Figs 6-8).

Shaking tests were also conducted on cylinder 90 P unstrapped, and cylinder 50 P with only a top strap, to determine the consequences of the lack of strapping.

Cylinder		Fraction of critical damping
50 F	Top	12%
	Bottom	29%
50 P	Top	36%
	Bottom	40%
90 P	Top	32%
	Bottom	34%

RESULTS

Static test

The polyurethane-insulated cylinders (50 P and 90 P) moved in the casing approximately 0.5 mm compared with 2.5 mm for cylinder 50 F. The rubber grommets around the inlet and outlet pipes on the cylinder 50 F were clearly supporting a significant (but not measured) proportion of the cylinder weight. No cylinder damage was observed during this test.

Low-amplitude frequency sweep

Over the range of interest, the cylinder-cupboard combination had natural frequencies estimated from the decay of the movement recorded by the deflectometers in the approximate range 10-13 Hz. Calculations and observation of the wall movement indicated that this could correspond to the resonant frequency of the wall as modified by the attachment of the cylinder.

High-amplitude shaking tests

There was no significant difference in performance between the strapped polyurethane-insulated cylinders. Both survived the test programme without detectable damage, although they twisted a small amount within the straps; 50 P had the greater movement with a twist of about 8°. This twist caused no leaks. The first observation of slewing of the cylinder was at 0.7*g* (5 Hz), and the cylinder slewed approximately 1° during 100 cycles at this acceleration. Relative movement between the cylinder casing and the floor was observed at 0.36*g*. At accelerations over 0.8*g* the pipe leading from the top connection of the cylinder was seen to oscillate relative to the wall about ± 10 mm, but no damage was caused. At the maximum amplitude, relative movement (rubbing between the side wall and cylinder) of approximately 20 mm was seen.

The strapped cylinder 50 F did not survive the high-amplitude shaking tests and a description of important events follows (approximately 100 cycles were applied at each acceleration):

At 0.4*g* the cylinder started rotating within the straps. At 0.5g a gap was observed to be opening and closing between the cylinder casing and the back wall and at 0.5 - 0.6*g* a small steady leak developed from the crox fitting at the lower connection to the cylinder. At 0.7*g* the internal cylinder was observed to be rotating within the casing in addition to the casing rotating within the straps. At 0.8*g* the internal rotating of the inner cylinder relative to the outer was approximately 8° over 100 cycles. At 1.1*g* the lid of the casing came loose and punctured the Gibraltar board. Severe slewing of the cylinder (approx.120° total) caused the element boss on the casing to puncture the Gibraltar board and damage the hose used for filling and draining the cylinder. At this stage the internal cylinder had rotated, so that the element was no longer in front of the opening in the casing and the leak in a crox fitting in the lower pipe to the cylinder which had developed earlier became a trickle. At the end of the test, a rubber grommet between the top pipe and the casing was found to be cut through by the sharp edge on the casing.

When the casing was removed from the internal cylinder, dents in both domed ends indicated that the pipes had been working the copper outside the elastic region. It is likely that with increasing accelerations, cylinder failure would have soon occurred.

An unstrapped cylinder 90 P remained relatively stable to 0.3*g* at 5 Hz. Small increases in acceleration above 0.3g caused substantial increases in cylinder movement.

A cylinder 50 P with one strap at the top of the cylinder only started sliding about at the bottom above 0.6*g* at 5 Hz.

DISCUSSION

Static test

As expected the polyurethane foam gave much more support to the inner cylinder, but the movement of the flock cylinder was much less than expected because of the support given by the seals around the inlet and outlet pipes.

Low-amplitude frequency sweep

The elongated triangles on Figs 3-5 indicate the range of each deflectometer reading, which increased during the test. This indicates that damage to the installation may have occurred, although none was visible. It may simply be due to a slight movement of the cylinder, loosening the straps.

As the frequency increased the acceleration also increased. Figs 6-8 indicate that

$$\frac{\text{deflectometer amplitude}}{\text{table amplitude}}$$

increases with increasing acceleration and therefore this effect should be considered when interpreting Figs 3-5. The acceleration increased from 0.02*g* to 0.25*g* between 2 Hz and 10 Hz.

High-amplitude shaking tests

Although the damage from acceleration during the complex motion of an earthquake may differ from that from similar acceleration under the test conditions, the results indicate that a polyurethane-insulated cylinder can have an adequate performance. The slight twisting of the cylinder within the straps occurred over a much larger number of cycles at higher accelerations than would be expected during a typical earthquake, and would be insignificant in a real earthquake. The rotational accelerations during an earthquake are not consistently in any one direction and are unlikely to have as much effect as those resulting from the asymmetric design of the simulated cupboard.

For cylinders with rigid insulation there is little advantage in further limiting this rotational movement if the straps are sufficiently tight.

A standard flock-insulated cylinder when strapped has considerably greater resistance than an unstrapped cylinder and it is expected that the earthquake resistance will be satisfactory. However, these tests indicate a performance limit of about 0.5*g*, after which slewing may cause joints to leak. Minor improvements in detail between the grommets and casing and pop rivetting the straps to the casing to prevent it twisting will give improved performance at insignificant cost.

It is not known to what degree the resistance to movement between the inner cylinder and casing is shared between the flock and the rubber grommets. Although the grommets were cut through during the extensive testing, they may not be seriously damaged during the much shorter duration of an earthquake.

Polyurethane insulation is economic compared with the conventional union flock insulation (Elkis 1976). Although the initial cost for 50 mm of polyurethane insulation was estimated to be $7 higher (approx. 10% of cylinder cost) than for 50 mm of union flock, this was more than outweighed by the value of the energy saved through the improved insulation. The study indicated that 90 mm of polyurethane was a conservative level of insulation.

A standard flock cylinder requires the largest clearance where the outlet pipe passes through the floor or shelf. At 0.7*g*, 7.4 mm movement peak-to-peak was recorded by the lower deflectometer. Therefore 10 mm clearance in addition to working tolerances should be ample.

CONCLUSION

An earthquake resistant cylinder can be made and installed at little greater cost than current cylinder installations.

A polyurethane-insulated cylinder properly secured into place has a high probability of surviving a very severe earthquake provided that the house remains intact. The additional cost of polyurethane insulation is small and outweighed by the value of the extra energy it saved. The cost of strapping the cylinder into place is also small.

Strapping standard union flock-insulated cylinders into place results in an improvement in earthquake performance, which although below that of the polyurethane-insulated cylinder, can be expected to be adequate. The seals around the inlet and outlet pipes probably provide a substantial part of the earthquake resistance of the installation. Provided that these seals are capable of transmitting loads from the pipes to the casing, as in the tested cylinder, a strapped flock-insulated cylinder should have a satisfactory resistance to earthquake damage.

ACKNOWLEDGMENTS

Dr R.I. Skinner, Physics and Engineering Laboratory, DSIR; Zip Water Heaters, Lower Hutt; the Director, N.Z. Pottery and Ceramics Research Association Inc.

REFERENCES

COLAIACO, A.P.; ALBERT, W.S. 1972: Seismic testing of metal clad metal enclosed switchgear using sine beat variations. *I.E.E.E. Transactions on Power Apparatus and Systems 91* : 2032-41.

ELKIS, W.J. 1976 : Economics of domestic hot-water cylinder insulation. *Report R26* Building Research Association of New Zealand.

NEWMARK, N.M.; ROSENBLEUTH, E. 1971: *Fundamentals of earthquake engineering.* Englewood Cliffs, N.J. Prentice-Hall, p.225, 226.

SHEPHERD, R. *et al.* 1970 : The 1968 Inangahua earthquake. *Canterbury Engineering Journal, (1)* June 1970: p.3, 23, 53.

SKINNER, R.I. 1964 : Earthquake-generated forces and movements in tall buildings: a handbook for architects and engineers. *Physics and Engineering, Laboratory Bulletin 166*.