WELLINGTON CENTRAL POLICE STATION

BASE ISOLATION MAINTENANCE

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SUMMARY

Wellington Central Police Station was built in the late 1980s. Its 10-storey tower block featured robust X-bracing around the perimeter and strong floor diaphragms to distribute earthquake actions amongst the perimeter frames, thus making it extremely stiff. To provide the ductility required by the 1984 Loadings Standard, the tower block was supported on a base isolation system that allowed up to 400 millimetres of movement in any horizontal direction.

This paper describes investigations into the continuing serviceability of the base isolation parts, and the remedial maintenance required.

EARTHQUAKE DEFENCE: BASE ISOLATION

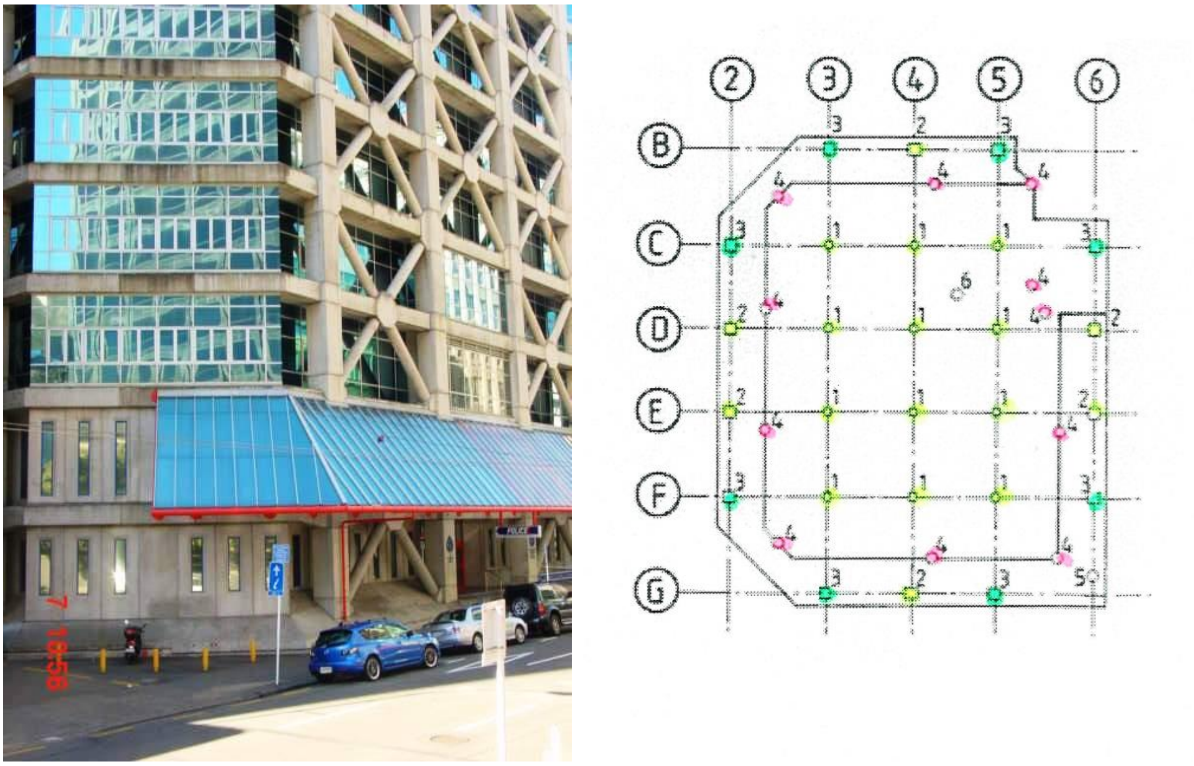

Figure 1: ***Tower block, view from Victoria Street. Pile types 1, 2, and 3 have spherical bearings of slightly different designs near their upper ends. Plan is an excerpt from MOWD drawing 5/1132/1 7002 207/5.***

The tower block features very robust diagonal X braces in the perimeter frame and strong floor diaphragms. Their purpose is to provide great stiffness to the structure, so that in the event of an earthquake the tower block can move as a single unit. In an extreme earthquake, the block is designed to move up to 400 millimetres in any horizontal direction.

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[1] *Waterfront Engineering Ltd., Wellington, NZ.*

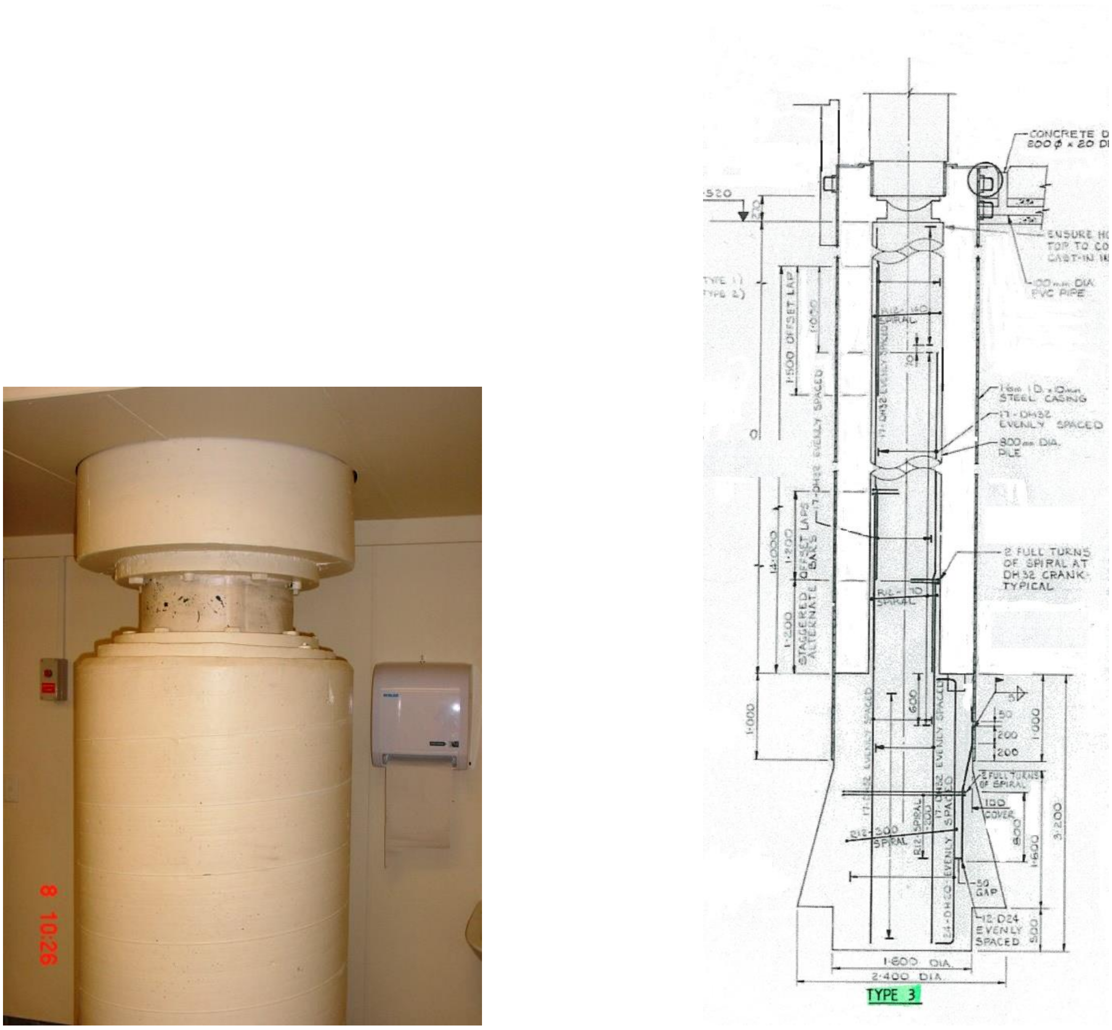

***Figure 2:** Left - type 1 column, showing spherical bearing in painted sleeve; Right - type 3 column in which spherical bearing is located below basement floor level near the top of the hollow casing.*

The movement can occur because the block is supported on reinforced concrete piles which pass down through hollow casings to the bedrock 15 metres below. The piles are founded in and most are rigidly fixed to the bedrock. At their upper ends the piles are free to bend sideways in their casings. The rotation at their upper ends is prevented from being transmitted to the building by spherical bearings as shown in Figure 2. Steel tendons pass through some of the piles to take uplift forces and so prevent the block from "jumping off".

As well as carrying the weight of the building, the piles allow horizontal movements. In the event of a large earthquake, the tower block is designed to move bodily sideways, the piles bending into a banana-like shape under it. Several cycles of oscillating motion are expected to occur.

The piles also act as springs which limit the horizontal movements and provide a restoring force. If the massive tower block were supported on the spring-like piles with no other restraining devices, the effect would be rather like a heavy rubber-tyred digger travelling on a highway: a small bump in the road causes the digger to bounce on its tyres through many cycles of oscillation. Cars and trucks do not bounce because they have energy absorbing devices known as shock absorbers mounted alongside their springs.

In this building, the energy absorbing devices near the springs look rather like the telescopic shock absorbers in a road vehicle. Instead of absorbing energy by forcing oil through holes, those under the tower block absorb the energy generated by earthquake motions by extruding solid lead through a central streamlined orifice.

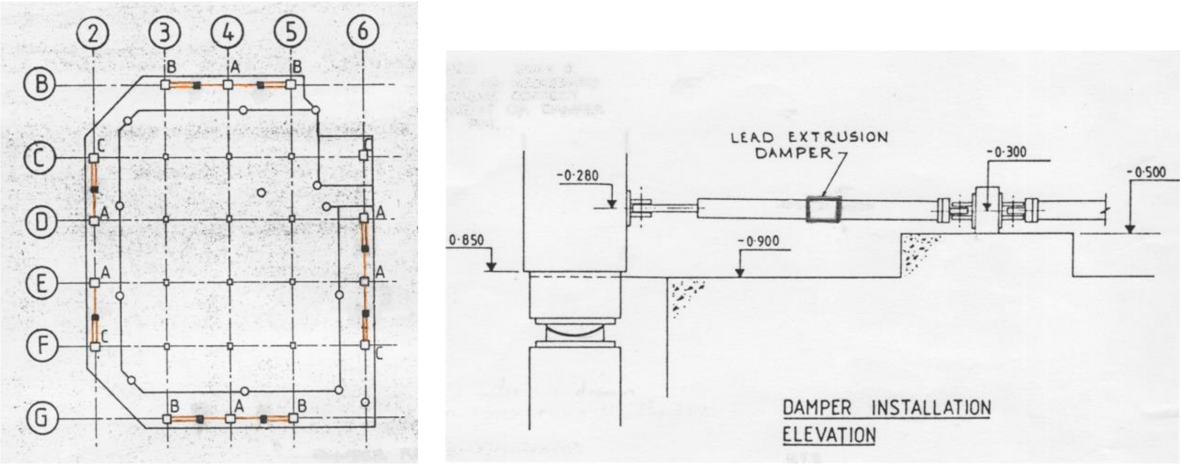

Figure 3: ***Left - plan positions of lead extrusion dampers; right - arrangement in elevation. Details from MOWD drawing 5/1132/1 7002 205/3.***

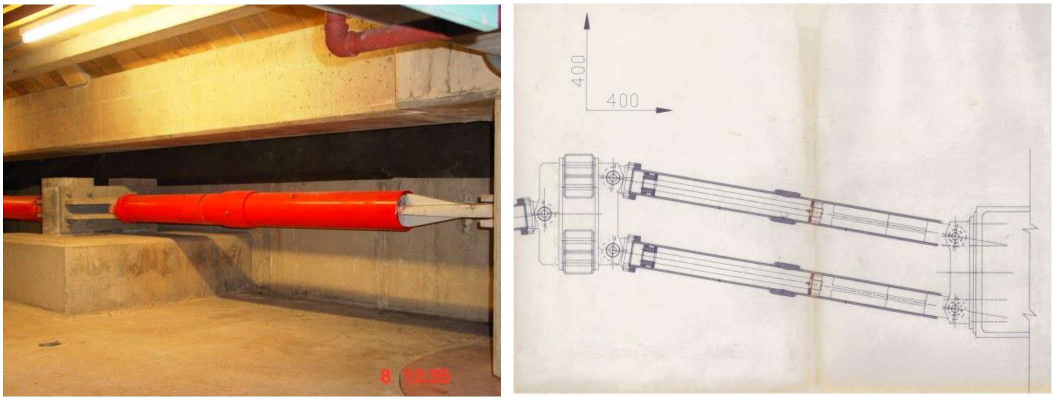

Figure 4: ***Lead extrusion dampers "on guard", and as they would be at their maximum excursion. The pair shown in the drawing at right are compressed to their shortest length, while the one that disappears on the left of the drawing is extended to its greatest length. The abutment shown in the photograph is midway between columns B3 and B4. Image at right from DSIR drawing.***

To summarise, the tower block is designed to move horizontally 300 millimetres during an earthquake with a return period of 450 years, and 355 millimetres for a 1,000-year earthquake. Even more severe earthquakes would cause the tower block to hit its stops at deflections of 400 millimetres. The X braces on the outside together with the floor diaphragms constrain the block to move as a massive rigid unit. The piles in their hollow casings support the weight but allow horizontal movement: they act as horizontal springs in a mass- spring- damper system. The lead extrusion devices absorb the energy of the shaking: they act as dampers. This system of earthquake defence is of the type known as base isolation.

The purpose of base isolation is to give the building “a soft ride” during moderate and major earthquakes. No structural damage leading to collapse is expected even if the oscillations are large. The oscillations are expected to be less violent than would occur with a similarly strong and stiff building rigidly fixed to the ground. Unrestrained furniture and office equipment may topple or slide off desks, but the structure is designed to be operational immediately after the earthquake.

HISTORY

Base isolation as a method of earthquake defence appeared in an American patent in 1930: this illustrated a six-storey building without ductility founded on a tank filled with ball bearings. The idea was revived in more practical form by Dr R. Ivan Skinner at the Physics and Engineering Laboratory of the Department of Scientific and Industrial Research in the late 1960s. During the 1970s several projects presented themselves as candidates for base isolation and the author of this paper took part in the experimental development of several different types of energy-absorbing dampers. PEL’s Dr Bill Robinson became interested in the technology from the materials science viewpoint and invented the “lead-rubber bearing” which provided a simpler and more compact form of base isolation. Lead-rubber bearings are on display in the “Quake Breaker” exhibition at Te Papa. One of PEL’s mechanical workshop technicians was Chris Gannon who helped to build the test rigs that simulated the earthquakes.

Wellington Central Police Station was designed by the Ministry of Works and Development with Andrew Charleson and Peter Wright playing prominent roles. Dr Skinner provided the base isolation expertise. These three presented a paper [1] describing the design to the Pacific Conference on Earthquake Engineering in August 1987. At the time of the Conference the design was not quite finalised, so some of the as-built details differ from those shown in the paper.

Some years later Skinner, Robinson, and their colleague Dr Graeme McVerry published their classic design manual on base isolation [2].

BASE ISOLATION DETAILS: SPHERICAL BEARINGS

Near the upper ends of the base isolation columns are spherical journals (upper part) and bearings (lower part), made as steel castings, shown in Figures 2 and 3. In order to spread the weight of the building as evenly as possible on the bearing surface, the castings were required to fit precisely together with a smooth surface finish. This metal cutting task was accomplished in PEL's mechanical workshop using techniques originally developed for making spherical surfaces of tools used for grinding optical lenses and mirrors.

The task of lubricating the surfaces followed. From other work at PEL, it was known that liquid oil, no matter how viscous, would slowly be squeezed out. This was known from theoretical work and simple demonstrations. Grease, which is an emulsion of oil in soap, would fare no better.

The designers, including the present author, considered a system of grooves into which high pressure oil would be injected at intervals of a few years. The designers rejected this on the grounds that no-one would take seriously a building maintenance instruction to oil the foundations each 29 February. (Since the earthquakes in and around Christchurch, a similar instruction today may have more credence.)

A literature search led the designers to choose a solid lubricant system. The surfaces were to be coated with a tightly-adherent layer of the manganese phosphate crystals well known to military armourers as a preservative and lubricant for gun parts. A layer of molybdenum disulphide, also a solid lubricant, in a greasy vehicle, was to be spread over the phosphate crystals, filling the spaces between them. Finally, a third solid lubricant, graphite, was to be deposited from an aerosol.

The present author arranged to do this work at the army base at Trentham, using the vats of chemicals used by the armourers. The chemistry was found to be out of balance, and the author's colleague Dr Graham McNaughton used his skills to correct the mixture. The army provided the facilities; PEL provided the chemicals and skills; no money changed hands. The author personally put all the journals and bearings through the trichloroethylene cleaning tanks, the phosphating baths, and while the parts were still hot applied the molybdenum disulphide and graphite layers.

The present problem

Late in 2011 the author attended a conference of the Maintenance Engineering Society where solid lubrication was one of many topics discussed. That discussion recalled the work done 22 years earlier, and the author started thinking about the solid lubrication system applied to the bearings at the tops of the piles.

Could the lubrication system have deteriorated so that instead of acting as a lubricant it had become an adhesive?

If the mating surfaces had somehow bonded together, thus "seizing" the bearings solid, what would happen in the event of an earthquake? There was no reason to suspect that this had happened, but nor was there a reason to be confident that it had not.

Preliminary calculations

To get a feel for the magnitude of the problem the author made some preliminary calculations based on the theory of classical elasticity. They are not adequate for structural design, but give an indication of the effect of a lubricant in the bearing turning into an adhesive.

The first point was to calculate the relative movements of each half of the bearing. If a 15 metre cantilever pile moves 400 millimetres at its free end, the bending rotation is 2.3 degrees. As the radius of the spherical surface is 400 millimetres, this angular rotation requires 16 millimetres of sliding movement on the spherical surface. The central stop in the bearing allows a little more than this.

If a spherical bearing seized solid, the effect can be idealised by assuming the cantilever becomes a column of twice the length, built-in at the top as well as the bottom. The central deflection of the double-length column is then taken as 400 millimetres, the same as the cantilever. Elastic beam theory shows that the force required to do this is eight times the force required to deflect the cantilever. This means that the sideways spring stiffness is eight times as great as designed.

The natural frequency at which a building shakes has a strong effect on how much energy it will extract from an earthquake.

The natural frequency is given by

$$\omega_1 = \sqrt{(k_1/m)}$$

If the stiffness increases by eight times, the natural frequency increases to

$$\omega_2 = \sqrt{(8k_1/m)}$$

$$\omega_2 = 2.8\sqrt{(k_1/m)}$$

where ω is the natural frequency in radians per second, k_1 is the lateral stiffness of the cantilever piles in newtons per metre, and m is the mass of the tower block in kilograms.

Hence an eight-fold increase in stiffness gives 2.8 times the natural frequency. In structural engineering it is customary to think in terms of period, the reciprocal of frequency. Hence a factor of 2.8 in frequency means a factor of 1/2.8 = 0.36 on period.

In 1987 the designers estimated the building to have a period of about three seconds. Since 3 *0 .36 = 1.08, the increase in stiffness would reduce the period to about one second.

Inspection of the spectral shape factor curves from NZS 1170.5 [3] shows that reducing the period from three seconds to one second on the soil type now thought to exist at the site [4] would increase the earthquake forces about three-fold.

These preliminary calculations show that if the lubricant in all the spherical bearings turned into an adhesive the tower block would experience earthquake forces about three times as great as it was designed for.

LITERATURE SEARCH

The author consulted materials and surface coatings engineer Willie Mandeno at Opus International Consultants, and structures manager Robert Davey. Opus had inherited the Ministry of Works archives, and Mr Davey arranged for the relevant drawings to be retrieved – most of the figures in this paper are extracts from the MOWD drawings. Mr Mandeno arranged to use the Opus library facilities to search the literature.

Out of 40 papers discovered, none reported deterioration of molybdenum disulphide (MoS_2) solid lubricants with age. Mr Mandeno was not surprised by this, as before starting the search he had noted that molybdenum disulphide was a naturally-occurring mineral that would not be expected to alter with age.

Some reported deterioration with oxidation, but noted that the oxidation products were not abrasive. As air has been excluded from the spherical load-bearing surfaces of the bearings by grease which itself contains MoS_2, as well as a tightly-fitting rubber sleeve, oxidation is unlikely to have occurred.

Deterioration was reported as a result of moisture. The present author was aware of this danger when he applied the MoS_2 layer, and took care to do this work while the steel castings remained at high temperature (about 60 - 70°C) from the phosphating tank, thus ensuring that no moisture would condense on the surfaces. Because of the MoS_2 grease and the rubber sleeve, moisture is unlikely to have reached into the load-bearing surfaces during the period of about 24 years in service. An inspection in October 2012 showed that the basement area was dry, with no sign of leaks from the building services nor rainwater leaking in from the outside.

There were reports of deterioration with temperatures of the order of 300°C. This is important when lubricating machinery, but in the absence of fire such temperatures are inconceivable in this basement.

As a result of the literature search, the present author concluded that:

1. There was no evidence from the literature that suggested the lubricant in the spherical bearings could have deteriorated with age.
2. There was no evidence from the literature that the possibility of the lubricant in the spherical bearings changing into an adhesive had ever been investigated.

The author recommended that a 50 millimetre square be removed from the painted rubber sleeve shown in Figure 2 (or one like it) and a sample of lubricant be removed for examination. Evidence of changes in the lubricant adjacent to the steel surfaces would be looked for. At the time the client declined to accept this recommendation, but since the earthquakes of July and August 2013 has accepted it.

Hence the question of deterioration remained open. The client agreed that the investigation could be publicised in the engineering community with a view to discovering evidence of solid lubricant deterioration in other systems. This has been done through the Maintenance Engineering Society, with no new evidence yet appearing. The present paper serves to notify the Society for Earthquake Engineering of the question.

BASE ISOLATION DETAILS: LEAD EXTRUSION DAMPERS

The dampers are installed in eight sets of three, giving 24 in all, located as shown in Figure 3. Earthquake motions can force them to extend or contract up to 400 millimetres in any horizontal direction, including misalignment as shown in Figure 4. The abutments where three are attached are fixed to the basement and thence to the ground. The ends where one or two are attached are fixed to the underside of the tower block and hence are free to move with the tower but to restrain its movements. A small amount of vertical movement is allowed to occur through SKF plain spherical bearings in the ends of the dampers.

The dampers carry no weight and in the absence of earthquake or wind do nothing. When the wind blows or an earthquake occurs, the dampers resist the horizontal forces applied to the tower block. Sufficient force has to be applied before they will move: the design force required to initiate extension or contraction of one damper is ±250 kilonewtons. At forces below the 250 kN yield force each damper behaves as a near-rigid link, as shown by the central part of the trace in Figure 5.

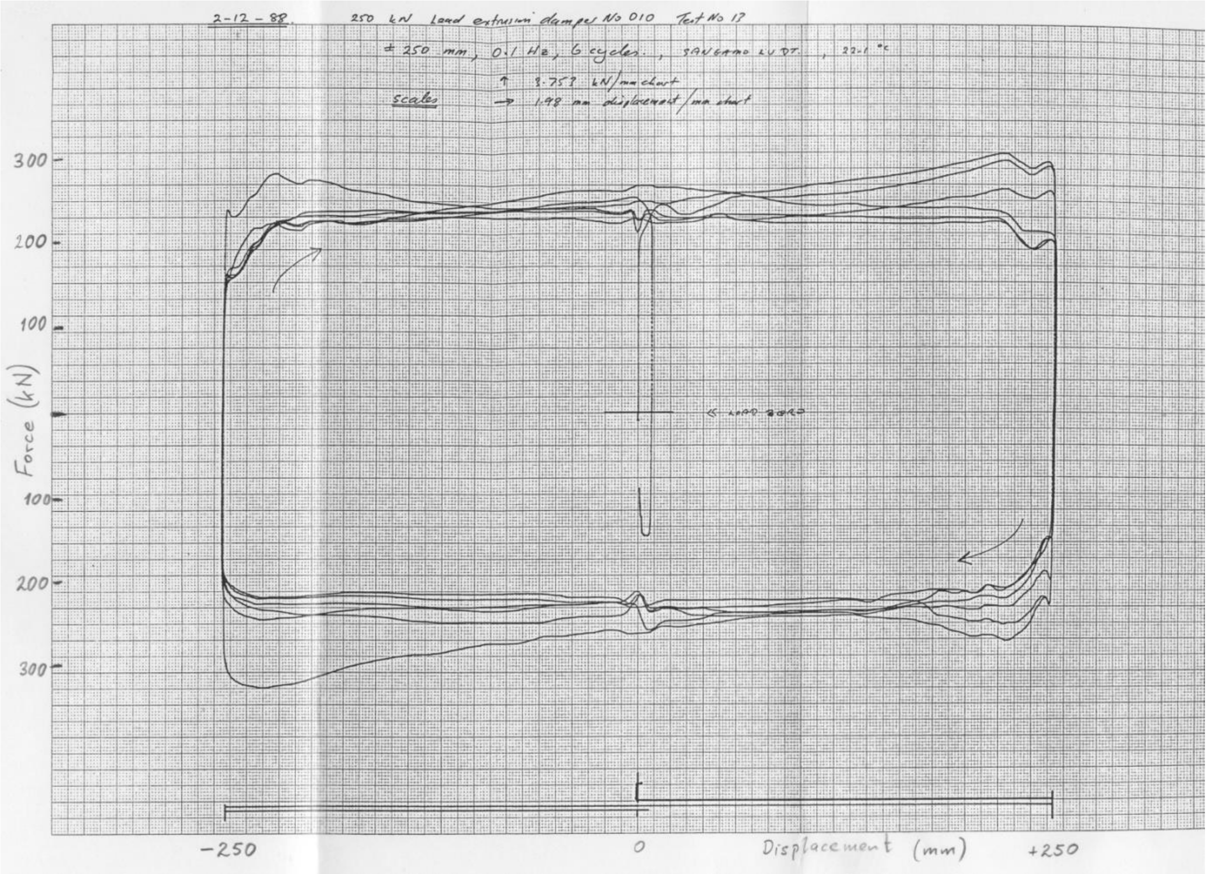

***Figure 5:* Dr Jim Cousins recorded these hysteresis loops for damper Number 10 in 1989. The test rig used at that time could deliver a stroke of ± 250 mm, with the initial force rising to 300 kN before dropping to the design value of 250 kN on subsequent cycles.**

Dr Bill Robinson and his colleague Dr Jim Cousins described several forms of damper at the 1987 Pacific Earthquake Engineering Conference. Their paper included a report of tests done in 1976 and 1986 on one of the smaller 140 kN dampers at ± 120 mm stroke – the ten-year interval resulted in negligible change in performance, the desired result.

The only other occasion on which a retest had been attempted occurred in 2005. Mr Bob Stephenson of Opus Central Laboratories (a successor organisation to Ministry of Works) tested a damper from a bridge. His equipment was able to apply only a "one way" motion, and the result showed resistance without movement to about 40 kN, then a rise to 100 kN at 20 mm deflection.

The present problem

As recounted above, the 2011 conference of the Maintenance Engineering Society discussed solid lubrication. That discussion recalled the work done 22 years earlier, and led to the parallel project on the spherical bearings at the top of the piles. By extension, the author thought about the lead extrusion dampers.

If the lead had somehow become bonded to the steel cylinder, thus "seizing" the damper solid, what would happen in the event of an earthquake? There was no reason to suspect that this had happened, but nor was there a reason to be confident that it had not.

The author approached Mr Gannon of RSL to enquire if the "spare" damper still existed, and if so, could the RSL test equipment be used to conduct a new test. Answers were affirmative, provided the test rig was modified to make it capable of performing the required tests. The author designed suitable parts, and Mr Gannon added a device that would protect his load cell and hydraulics in the event of the damper "seizing" and causing the force to rise catastrophically out of control. The author let a sub-contract to Acme Engineering Limited, Petone, to make the parts.

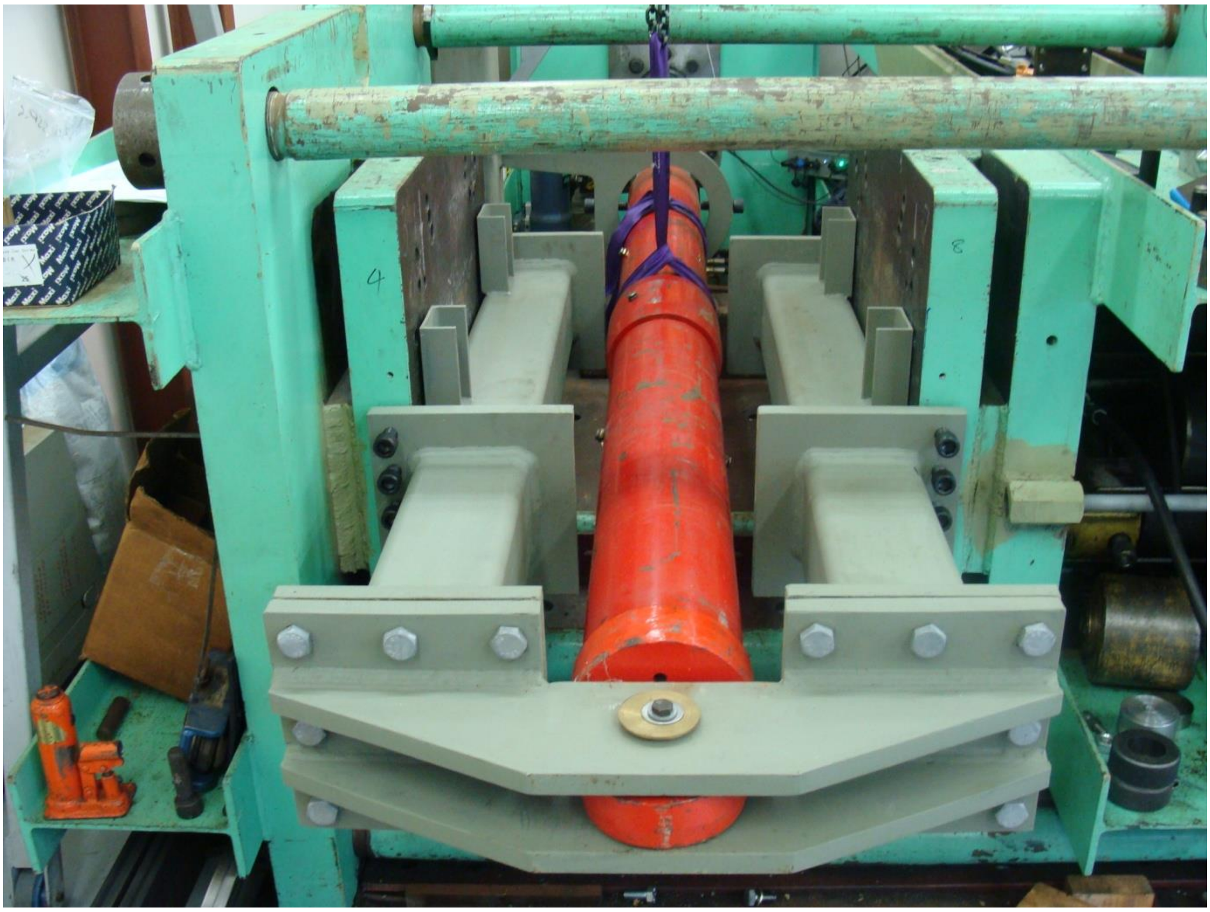

***Figure 6:** U-shaped adaptor frame supported fixed end of damper in the existing test machine at Robinson Seismic Limited.*

Tests on damper No. 10

The load cell was calibrated on a Baldwin test machine at Quest Integrity Ltd. on 10 October 2012. The calibration showed that its error was less than 0.5%, a value acceptable for these tests.

The LVDT (displacement measuring device) built into the hydraulic ram was found to be unreliable, so was replaced with a similar instrument mounted externally between the load cell and the fixed part of the machine frame.

An attempt was made to pump grease containing molybdenum disulphide and graphite into each of the six grease nipples on the test damper. A great effort was required to operate the grease gun, resulting in some grease oozing from the nipple fitting, but little if any getting into the damper. The significance of this is discussed later.

The initial test consisted of six extension and compression cycles each ±150 millimetres with the instruments automatically recording force and movement. The machine cycled less rapidly than would be expected of a large earthquake and corrections for this are discussed later.

At the end of this series of cycles the central portion of the damper, where the energy is absorbed, was warm to the touch.

Figure 7: Maximum extension (left) and maximum compression (right) on first test cycle. Figure 8 shows that the forces just before and after the photograph at left was taken were substantially greater than those designed for.

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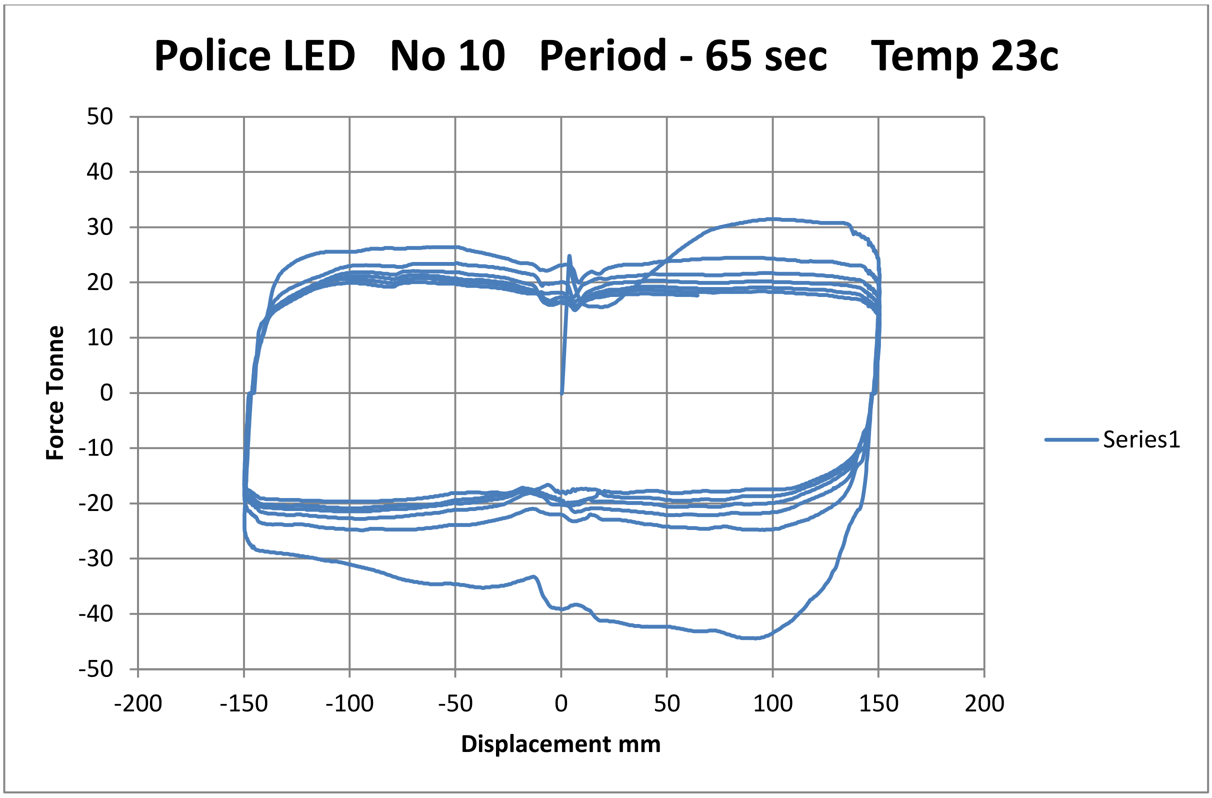

Figure 8: Hysteresis loops for the first six cycles. The trace starts at the zero - zero position and then circulates in a clockwise direction. The first cycle shows larger than design forces (+32 and -44 tonnes) but on the second cycle the forces fall to design (about 25 tonnes). The force decreases on subsequent cycles as the lead increases in temperature and becomes softer. (Note that 25 tonne force is almost identical to 250 kN.)

Twenty four minutes after the first six cycles were completed the test rig was set to give an increased stroke of ± 175 millimetres. The purpose of this was to look for evidence of an undesirable sudden spike in force as the damper moved past its previous limit.

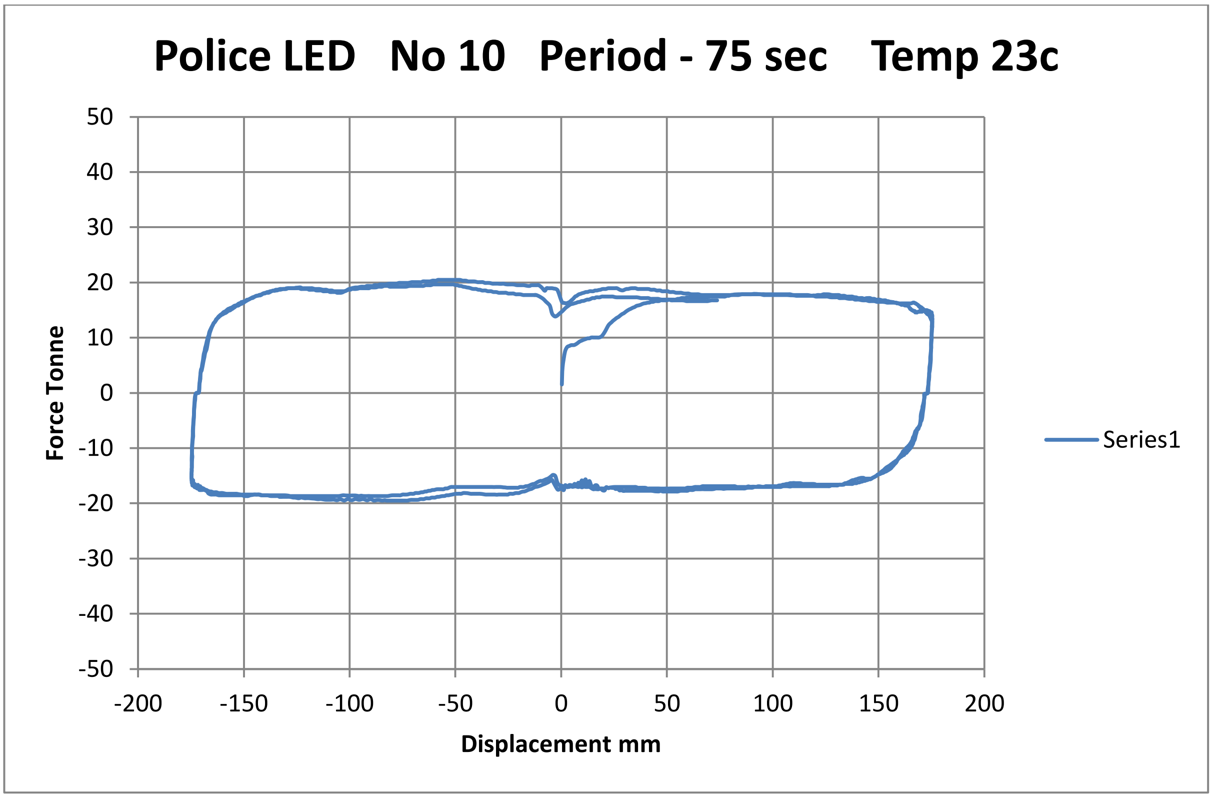

Figure 9: ***Hysteresis loops from a second series of tests. The behaviour shown is excellent, with no spikes in force, but a reduced maximum (20 tonnes) as would be expected from the lead core having a higher initial temperature.***

Significance of rate of test cycles

Although the test rig could exert forces greater than necessary, it had insufficient power to oscillate the damper at rates comparable to those expected in an earthquake. This problem was anticipated during development of the lead extrusion dampers.

The expression for rate dependence is

$$p = av^b$$

Where p is the extrusion pressure (proportional to force), v is the speed of extrusion, and a and b are constants. For speeds in the test and earthquake range, b has a value of 0.03 see reference [5].

With the spherical bearings and dampers working as designed, the tower block is expected to oscillate with a period of approximately 3 seconds. The cycles reported in figure 8 had a period of 65 seconds. The rate dependence formula suggests that the forces at earthquake rates would be about 10% greater than those at the test rate.

Hence the maximum force in the first cycle of earthquake shaking would be expected to increase from about 440 kN to 480 kN.

Significance of failure to inject grease

Dr Cousins' laboratory test records from 1988 show that all the dampers were greased before their initial tests. The retest in 2012 was prompted by the thought that during the intervening 24 years the grease layer may have deteriorated and allowed the lead to form some sort of bond with the surrounding steel cylinder. To break this supposed bond, an attempt was made to inject new grease at high pressure, slightly expand the cylinder, and so allow grease to spread between the lead and the surrounding steel. It is probable that this attempt failed.

Mr Bob Stevenson of Opus Central Laboratories reported somewhat similar problems when he re-tested a smaller lead extrusion damper in 2005. On that occasion he found that lead was protruding through small holes under the grease nipples, and that it was necessary to drill out this lead before grease could be injected – he then managed between 20 and 30 strokes at each nipple [6].

The fact that the initial half cycle required a force substantially greater than that designed was consistent with the idea that some form of bond had formed between the lead and the steel. The second half of the first cycle, and all subsequent cycles, occurred at about the design force, as did the initial tests 24 years earlier.

Significance of high force during first half cycle I

The end fittings of the dampers are made of a material known as spheroidal graphite cast iron. Like all cast irons SG iron includes graphite in its metallurgical structure. In common grey cast iron the graphite is in the form of flakes, sometimes likened to small "cabbage leaves" that make it very brittle. In SG iron the graphite flakes are made to coalesce into tiny spheres that remove the brittleness of grey iron. Hence SG iron possesses some ductility, much more than grey iron but not as much as steel. When the author designed these parts in

1986 he was keen for directional solidification of the castings to occur to minimise the possibility of defects peculiar to castings. To do this he detailed the parts to increase in cross sectional area from one end to the other. To check the design he conducted a finite element stress analysis to predict the behaviour during overload [7].

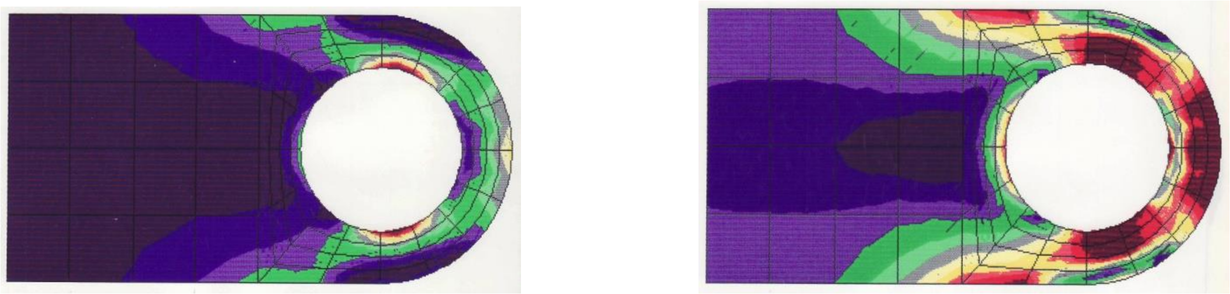

Figure 10: ***Stress analysis of end fitting shown in figure 4. Left image shows stresses at design load of 250 kN; Image at right shows stresses at 492 kN. Darkest areas around eye in both images show material predicted to yield.***

The left image in figure 10 shows the stresses at the design load of 250 kN: the fitting is almost entirely elastic with only tiny areas of material (shown in a dark brown colour) that are required to become ductile. The right image shows the situation that would have occurred if the test had been conducted at earthquake speeds: the substantial dark (brown) areas show material predicted to yield into the ductile state.

This is the situation that concerned the author when he brought the matter to the attention of the Police. When the damper was new the maximum force was a little over 300 kN. During the 24 years of waiting "on guard" some sort of bond had developed between the lead and the steel and this required a force of 440 kN (480 kN predicted at earthquake rates) to break the bond. The stress analysis shown on the right of Figure 10 suggests that only a little more force would be required to yield the remaining elastic material. Fracture would then be expected to occur.

Significance of high force during first half cycle II

The 250 kN design force on each damper keeps the tower block in place during wind storms and small earthquakes. If this threshold force did not exist, the building would move about during wind storms and small earthquakes, an effect that would be disconcerting to passers-by who would see that the building had shifted its position in relation to the footpath, and to occupants who would sense unusual movements. Conversely, if the threshold were too high, the base isolation system would be inactive during moderate earthquakes, thus removing the benefits of the desired "soft ride".

It was likely that the partial bonding demonstrated on the test damper also existed on all 24 installed under the building, and the author assumed that this was the situation. After discussions with the Police, the author agreed to remove, grease, and retest one of the installed dampers to demonstrate the value, or otherwise, of renewing the grease film in all 24.

Damper exchange

Following the tests reported above the Police accepted the following recommendations:

1. The author (trading as Wavefront Engineering) should discover a method of injecting new grease into the test damper then installed in the test rig at Robinson Seismic.
2. Wavefront Engineering, with assistance from Police contractor Transfield Services, should devise a method to remove one of the installed dampers, grease it, repeat the tests described above, and reinstall it in the Wellington Central Police Station.

The remainder of this paper describes how these recommendations were carried out. To save costs, the dampers were exchanged on the same day, and the tests performed later.

Greasing

Each damper is fitted with six grease nipples, designed to allow a molybdenum disulphide grease to be injected into a space created by the injection pressure between the lead and the steel containment cylinder. A greasing operation had been done before the acceptance tests of 1989. An attempt to inject new grease before the 2012 retest almost certainly failed. Three reasons were discovered for this failure:

- The 1989 testing forced lead into the cavity under each grease nipple, preventing new grease from getting in.
- The non-return valve in each grease nipple had become stuck in the closed position during the past 24 years.
- The original coupler that connected the grease gun hose to the nipple was made as a zinc die casting. This was insufficiently robust to take the required pressure, and cracked. Leaking grease obscured the crack.

Remedies for each of these problems were discovered:

- Each nipple was unscrewed in turn, and the passage under it cleared with a 2.5 mm drill. Care had to be taken to prevent the drill advancing too quickly into the soft lead and becoming stuck.
- The non-return valves needed to be pressed inwards a few times against their springs. A pin punch proved to be a good tool. This was best done with the nipples away from the dampers so that free flow

of grease could be checked. Some nipples were found to be incapable of either passing grease inwards or preventing it exuding outwards: these were assumed to be internally corroded and were replaced.

- A new coupler machined from solid brass worked much better, allowing grease to be successfully injected.

Damper Exchange

As each damper weighed 410 kg, too great for manhandling, mechanical handling equipment was necessary. The author and Transfield Services Ltd devised the broad outlines of a plausible scheme and subsequently passed responsibility for the details to L&K Builders Limited. Police allowed the “sally port”, an outer door normally used to transfer prisoners, to be used, thus eliminating the problem of getting the dampers up and down staircases.

Before attempting the exchange, the centre distance between the connection pins was carefully measured with a steel tape, and the No. 10 damper, still in the test rig at Robinson Seismic Limited, was set to this length. The length was then deliberately set about 1 mm short, as it would have been possible to slacken the clevis fittings to get the pins in, and then tighten them again. An overlength error would have been impossible to correct on site.

Entry to the base isolation area was gained through a convenient hatch. A small crane of the type used for lifting engines out of motor vehicles was used to lift the damper up to the height of the hatch.

The exchange, executed on 7 February 2013, is best described pictorially.

Figure 11: ***Left, damper No. 10 being rolled in through hatch. Right, damper turned parallel to installation position. In both pictures the damper is supported on wooden blocks fastened to floor jacks.***

Figure 12: ***Left, damper being transferred to trolley. Right, damper returned to floor jacks ready to be lifted to correct height and rolled into position.***

Figure 13: ***Left, equipment improvised to extract pin at right hand end from No. 21 damper. Right, No. 10 "spare" damper in place previously occupied by No. 21.***

Extracting and inserting the pins was worthy of note. The pins made for the 2012 tests could be tapped in and out with light hammer blows with no load on the damper, but this was not expected to be possible for a damper with 24 years' service history for two reasons:

- Experience suggested light corrosion would have partially bonded the pins to the clevises.
- Small earthquakes known to have occurred may have left the dampers under loads approaching the "trigger" level of 250 kN. These loads may have decreased through creep, but there was no way of knowing.

The author considered building a reaction frame to surround the clevis and a hydraulic jack. Preliminary design showed that this would cost 3,000-4,000 dollars, and would require someone to spend an uncomfortably long time close to the dampers while it was fitted and removed. If the crew were unlucky enough to experience a big earthquake while close to a moving damper (or column), they would be likely to suffer fatal injuries. Hence the author wished to minimise the time dangerously close to the moving parts.

Building Maintenance Officer Jack McAllister suggested that a jack placed between a pin and the beam above would eliminate the need for the reaction frame and would minimise the time in the dangerous position. This appeared to be a good suggestion, and the author decided to adopt it.

At the left hand end this worked very well. An Enerpac RC-55 hydraulic jack had sufficient stroke to remove a pin in one push, a desirable state of affairs as it eliminated the time need to insert packers of successively longer lengths. The pin moved in jerks, each jerk occurring at a force of about 40 kN. With the left pin out, there could be no residual force on the damper, and it was expected the right pin would move easily. This proved not to be the case. At the right hand end the jack had to be on the edge of the beam above, and when a small piece of concrete spalled away the crew found it necessary to improvise the system shown on the left side of Figure 13. A piece of flat steel plate about 10 mm thick protected the concrete edge and provided a small overhang to give a secure position for a truck-type jack. With this arrangement the pin moved in a series of jerks, each requiring 100 - 200 kN, and each accompanied by a loud 'bang' which caused some anxiety to staff on the floor above.

The crew found it impossible to insert the old pins into damper No 10. Hence they substituted the new pins made for the 2012 tests – these featured a taper at their lower ends, and were able to be inserted with light taps of a hammer. Copious quantities of WD 40 penetrating oil helped.

Tests on damper No. 21

The author and Mr Gannon fitted the "service" damper, No. 21, into the test rig at Robinson Seismic in February 2013. The arrangement was identical to that used for "spare" damper No. 10 in 2012.

Three test runs were performed:

- A stroke of ± 150 mm, extension first, with force governed by the damper
- A stroke of ± 175 mm, extension first, with force governed by the damper, thus simulating a severe aftershock
- A stroke of ± 10 mm, with force governed by the damper, thus simulating a small aftershock.

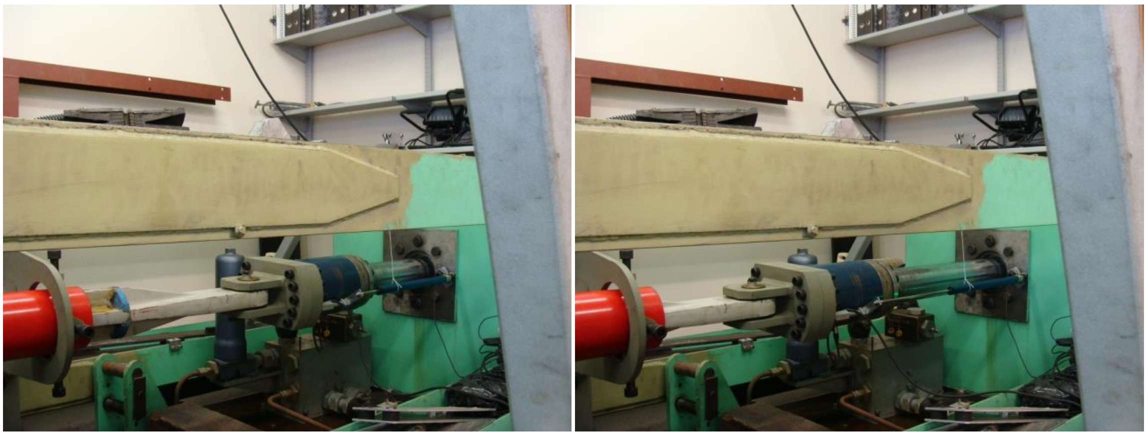

Figure 14: Damper No. 21 on test in 2013. Left: 150 mm extension on first test stroke. Right: 150 mm compression on first test stroke.

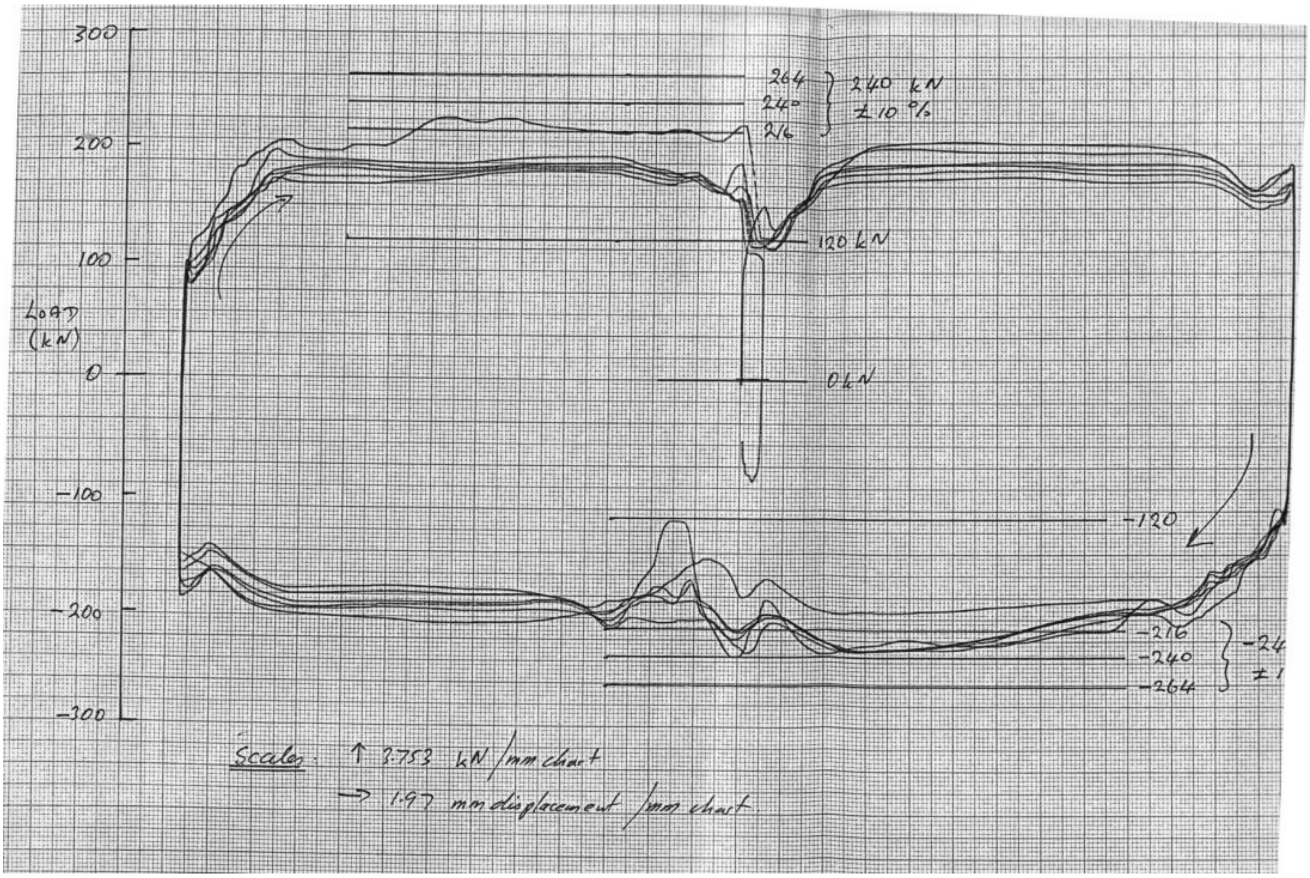

Figure 15: ***Force-displacement hysteresis test loops recorded during acceptance tests on 9 December 1988. Stroke was ± 250 mm.***

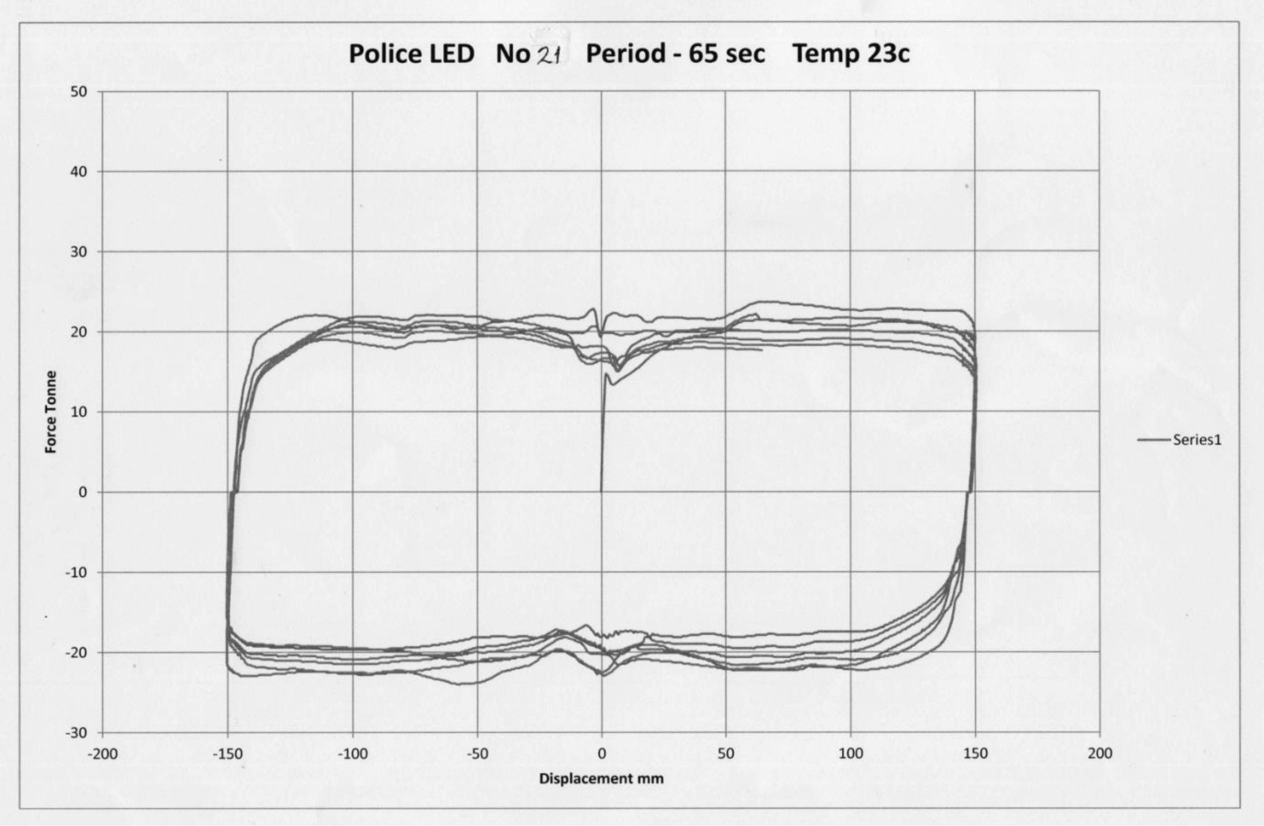

Figure 16: *Force-displacement hysteresis loops from first test in 2013 on damper No. 21, showing "as-new" performance. The damper heats up during cycling, thus softening the lead, and so each successive loop occurs at a slightly lower force.*

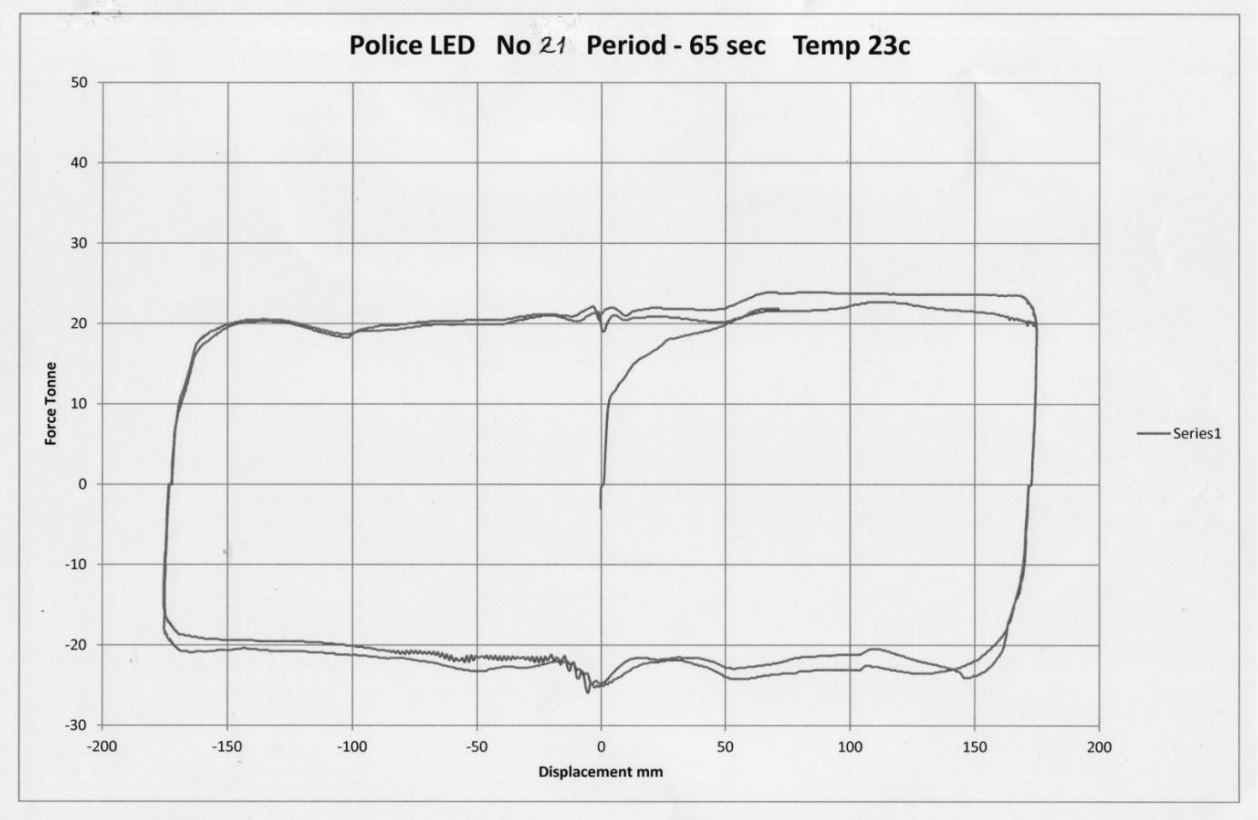

Figure 17: *Force-displacement hysteresis loops from second test on damper No. 21. The test machine was set to change direction at ± 175 mm for this test, thus simulating a severe aftershock.*

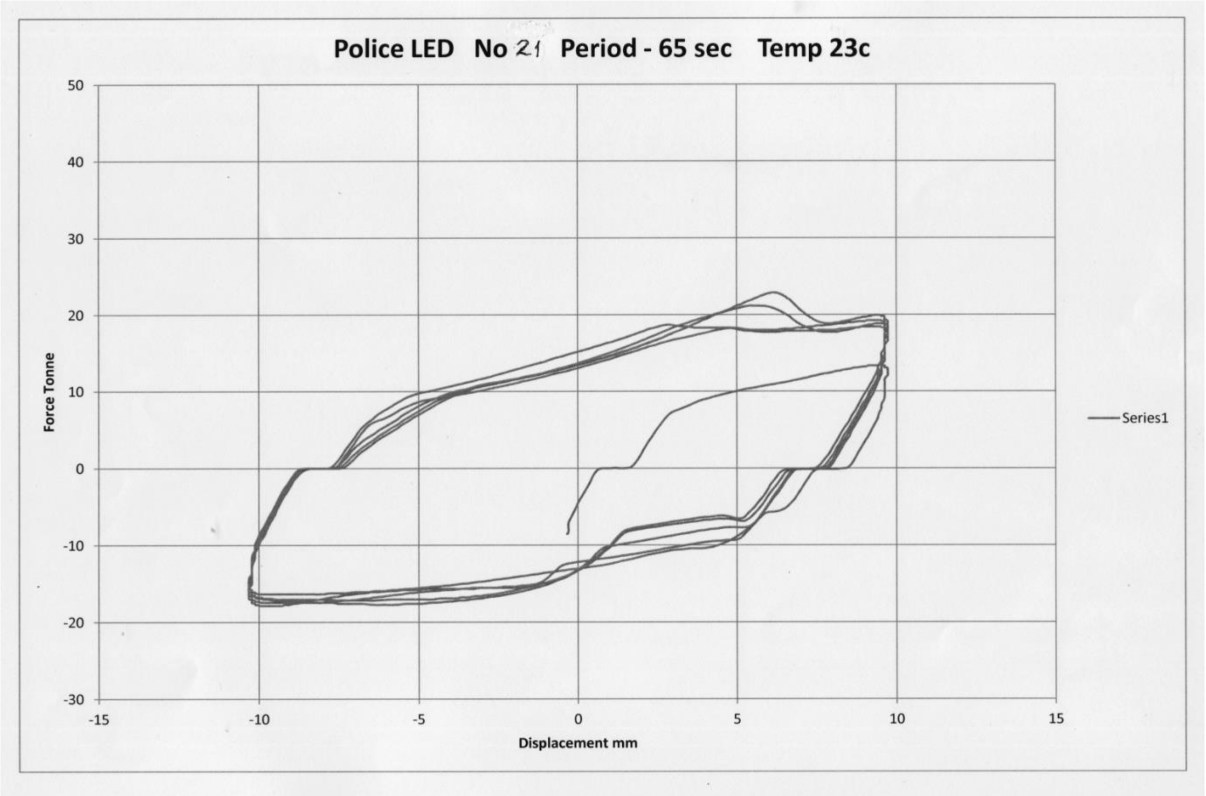

Figure 18: ***Force-displacement hysteresis loops from third test on damper No. 21. The test machine was set to change direction at ± 10 mm but was not "re-zeroed" for this test. This test simulates an early but small aftershock when the building has been left slightly displaced (about ½ mm), thus leaving about 90 kN (~9 tonne) compression in the damper.***

Following the successful demonstration of the efficacy of greasing damper No. 21, the Police accepted the author's recommendation to leave spare damper No. 10 in position, to keep "used" damper No. 21 at Robinson Seismic, and to grease the other 23 dampers whilst they remained in place.

The author wrote a work instruction for L&K Builders Ltd and reiterated the safety precautions needed to work close to the columns and dampers that would move during an earthquake.

L&K Builders performed the greasing task and reported its successful completion, including the previously undiscovered need to replace some of the grease nipples.

The author recommended to the Police that if no earthquake violent enough to move the dampers occurred in the interim, the greasing should be repeated in ten years' time.

Notes on pin fits

The original manufacturing drawing for the end connection pins specified a diameter of 50 mm with tolerance m6. Charts for the International Standards Organisation system of limits and fits show that m6 on a 50 mm diameter allows a maximum diameter of 50.025 and a minimum of 50.009 mm.

These pins go through SKF spherical plain bearings designated GEH 50 ES-2RS. The SKF on-line catalogue gives the deviation of the mean bore diameter Δ_{dmp} as a maximum of 50.000 and a minimum of 49.985 mm.

Hence all pins within tolerance will have interference fits with all bearings within tolerance.

The on-line catalogue gives two choices for pin tolerance:

- m6 for loads of all kinds with an interference fit, with a suggestion of the even tighter interference n6 for very heavy loads
- h6 for loads of all kinds with a clearance or transition fit.

It is clear that the author's 1989 choice of m6 for the pin was influenced by SKF's suggestion of tighter interferences for heavy loads. No records have survived on how the pins were fitted (and the author does not recall), but a technique used at the time was to shrink the pin in liquid nitrogen before dropping it into its hole. As it warmed it expanded to create the interference.

Following the original design, the pins for the 2012 tests on damper No. 10 were dimensioned with the oversize m6 tolerance. The manufacturer of the test equipment (Acme Engineering Ltd) noted that this would require an oversize bar to be machined down to size. They thought this a needless expense, and suggested making the pins from a standard bar which would have a maximum size of 50 mm. The author accepted their suggestion.

The pins extracted with difficulty from damper No. 21 were given a taper and had a very light skim taken off their diameters. They then fitted easily and performed well under test.

If new pins are ever to be made, it would be best to accept SKF's second recommendation and specify an h6 tolerance. This would mean a maximum diameter of 50.000 mm and a minimum of 49.981 mm

POSTSCRIPT

On Sunday 21 July 2013 an earthquake magnitude M_w 6.6 occurred in Cook Strait, off the Marlborough town of Seddon. This caused alarm, a few injuries, and minor damage to some buildings in Wellington.

Inspection of the base isolation system showed that the dampers had moved a few millimetres, probably for the first time in service, and the entire building had rotated clockwise about 10 millimetres at its periphery.

The columns responded elastically, with no evidence that the spherical bearings tilted. It is probable that the movements were insufficient to cause the bearings to break free of their friction, but the possibility remains that a seizure, of the type feared late in 2011, has occurred. Investigation has been recommended.

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