Strong-motion instrumentation of buildings in New Zealand

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ABSTRACT: The best way of confirming the adequacy of structural design codes is to record the responses of real buildings during earthquakes. Good acceleration records are available for the response of overseas buildings, but the construction details of those buildings are usually substantially different from those used in New Zealand. The New Zealand GeoNet Project includes provision to extend the existing building monitoring programme to cover a wider range of New Zealand buildings than at present. Also, modern instrumentation and acquisition equipment allow for a much greater range of measurements than just the traditional set of triaxial accelerographs located at 3 levels in the building. A strategy is being developed by the authors to select suitable buildings, types of measurement and instruments for the GeoNet Project. The strategy is based on similar work currently being developed in the United States.

1 INTRODUCTION

There are many ways of evaluating the adequacy of structural design codes. One of the best is to record the responses of real buildings during earthquakes. Major earthquakes in the last two decades have enabled overseas engineers to observe how their buildings have responded to damaging levels of shaking and thence have guided improvements in their building codes. Their construction methods and design codes are different to ours in many aspects, and, while we like to think that our codes are good, we have not had any strong earthquakes in a densely populated region to confirm this belief. Although there are several sets of strong-motion data from New Zealand buildings none have been associated with damage.

The Institute of Geological and Nuclear Sciences (GNS) has, over the years, instrumented a number of New Zealand buildings. Most of the 19 buildings (Cousins 1993) belonged to the government at the time of installation. The instruments are now old and expensive to maintain and so will be replaced as part of the GeoNet project, a collaborative project between the New Zealand Earthquake Commission (EQC), the Foundation for Research Science & Technology and GNS. The GeoNet project will also instrument additional buildings, with the first instruments scheduled to be installed in 2003. Guidelines are being developed by the authors for the selection of suitable buildings, types of measurement and instruments.

In a parallel project, the United States Advanced National Seismic System (ANSS) was recently allocated funding for 6000 new strong-motion instruments. ANSS is currently developing a strategy for deploying 3000 of those instruments for the strong motion instrumentation of buildings. A workshop was held in California in November 2001 (COSMOS, 2001) to obtain input from a broad range of earthquake engineering professionals, with the principle aims of developing guidelines for i) establishing national and regional priorities, ii) establishing building type and instrumentation priorities, iii) use of new instrument technologies and iv) encouraging private participation in the programme. State-of-the-art papers were presented on current instrumentation programs and guidelines, instrumentation needs and developments in instrumentation technologies. Under the NZ GeoNet project a total of c.450 sites, including buildings throughout NZ will be instrumented for strong motion, of which approximately half will be high fidelity instruments. This is quite modest by modern international standards. For example, Reno, Nevada - a city the size of Wellington with a similar perceived seismic risk - will alone accommodate 300 telemetered strong motion recorders under the ANSS project (USGS 1999). The main purpose of our paper is to provide a summary of the outcomes from the ANSS workshop, from a New Zealand perspective, which will be used as a starting point for the development of a set of guidelines for the GeoNet project. A secondary intention is to inform a wider audience. Readers are encouraged to obtain more up-to-date information from the project web sites (www.geonet.org.nz and www.civil.canterbury.ac.nz/deam/GNBuildings).

The two most significant decisions that need to be made are i) the objectives of the monitoring and ii) the buildings to be monitored to best meet those objectives.

2 BUILDING INSTRUMENTATION OBJECTIVES

There are multiple and sometimes-conflicting objectives for a building instrumentation program because there is a wide range of types and uses for the data (and, as a processed product, information). A non-exhaustive list of uses for the information includes:

- Provision of information to support improved building design and construction;
- Advising occupants about whether a building is habitable after an earthquake;
- Advising emergency response services about the level of damage in the structure;
- Advising the building owner about where the structure is damaged and needs repairing;
- Supporting quantitative damage estimates for government, insurance companies and the public; and
- Contribution to a regional accelerograph network.

Each information user has different needs in terms of the type, the level of detail and the timeliness of information. Also, several parties may use the same information and different types of information may be used for the same purposes. This is summarized in Table 1, based on four possible categories of sensors that can be employed in a building.

Table 1 Building Instrumentation information requirements

Phenomenon	User	Use	Required
Basement or free-field acceleration	Emergency management	Establish extent of strong shaking, so resources can be focused on worst problems, and provide information to media and public	Immediately
	Territorial authority	Establish extent of damage to infrastructure and prepare demolition and reconstruction strategy	Hours
	Government and Insurers	Estimate cost of repair	Hours
	Seismologists	Understand and model earthquake propagation	Months
Roof acceleration	Occupants	Assess building habitability	Immediately
	Engineers	Understand and model building behaviour	Months
Interstorey drifts	Occupants	Assess building habitability	Immediately
	Rescue Workers	Assess whether people are trapped or injured Assess safety of rescue workers	Minutes
	Building Owner	Assess whether inspection is required	Hours
	Engineer	Assess where further inspection and repair are required	Days
	Engineers	Understand and model building behaviour	Months
Structural integrity	Occupants	Assess building habitability	Immediately
	Building Owner	Assess whether repair is required	Hours
	Engineer	Assess where the building needs repairing	Days
	Engineers	Understand and model building behaviour	Months

Objectives for the monitoring of structures were debated at length at the ANSS conference with the consensus being that the prime reason for strong-motion monitoring of structures is to

"improve understanding of the behaviour of representative buildings so as to allow the development of adequate general predictive models"

The general predictive models can then be used to

- calibrate specific performance models,
- calibrate design rules, and
- assist with post-earthquake evaluation of buildings.

The need for ***representative*** buildings to be instrumented, rather than one-off designs, was emphasised, as was the need for ***general*** predictive models.

Acceleration has been the traditionally measured phenomenon, mostly because there were no sensors for other parameters in the past. Acquisition equipment and the data transmission and processing software have accordingly been geared toward recording accelerations. Also, with some exceptions, the scientists have predominantly been seismologists and so the other quantities have simply not been needed. It could be added that there has been a greater priority (and funding) for reducing the uncertainties in establishing the ground motions at the base of the building than there has been on refining our understanding of structural engineering. This has changed now that building owners want a structure operational after the earthquake rather than just paying the designer to provide a structure that protects the occupants as they (unknowingly) did in the past!

Inter-storey drift, the second phenomenon, is considered to be one of the most useful indicators of structural damage. It is a 'global' rather than a 'local' phenomena, which makes it less costly to measure than the final category which encompasses the integrity of the individual joints using indicators such as concrete spalling, steel fracture, joint rotation, etc. Also, it has less variation within the building than the joints do, and so it requires only three or four sensors to completely capture the response for each building floor. (Because one storey in a building usually becomes more damaged than the others, the integrity of the whole building can almost directly be assessed from the storey that suffers the most damage.)

3 INSTRUMENTATION

There are two categories of instrumentation, namely *indicators* and *sensors*. Indicators are primarily used to detect whether something has happened, and possibly how much, whereas sensors are used to measure the quantity and store its variation with time using a data acquisition system. Some examples of indicators and sensors are listed in Table 2 for the four phenomena described in the previous section. The instruments are described more fully below.

Table 2 Types of instrumentation

Phenomenon	Indicator	Sensor
Low frequency acceleration	Scratch-plate	Accelerograph
Interstorey drift	Non-structural walls	New sensor
Structural integrity	Alarm tapes	Linear potentiometer
High frequency acceleration	Signature analyser	Accelerograph

3.1 *Indicators*

Indicators usually provide less information and are less expensive than sensors. They are more suited to providing information for the occupants (i.e., advising them that the building is either damaged or undamaged) and the building owner. By their nature most indicators are not able to transmit the information electronically, which makes them simpler to install and possibly also simpler to maintain, but makes it expensive to collect the information after an earthquake.

Most engineers have probably heard of the early scratch-plate seismometers that recorded accelerations using a pendulum to scratch the surface of a spherical dome during an earthquake. This doesn't provide a complete record of accelerations, but gives a good indication of the peak accelerations (and their directions). This information could be useful for recording peak floor accelerations for use in designing parts and portions. There are still some scratch-plate acceleroscopes in use in New Zealand's strong-motion network, but they are gradually being phased out.

In a similar manner, non-structural walls could be used to indicate maximum interstorey deformations in a building when their top and bottom plates are attached to the floor slabs above and below. The maximum deformation is approximately related to the amount of damage in nails around the perimeter of plasterboard sheets. Minor damage (up to say 1 mm lateral deformation per 300 mm wall height) is usually hidden beneath architectural features such as skirting and cornices, but beyond about 1 mm per 100 mm height, the damage is usually obvious elsewhere in the wall. A form of *telltale* interstorey deformation indicator could be useful for warning occupants that the building has been severely damaged.

Structural integrity could be indicated remotely by wrapping critical structural connections with 'alarm tapes' similar to those once used to detect window breakage in intruder alarms. The circuit breaks when the tape is stretched too far (e.g., at a concrete crack or a bolted joint), giving an indication that the monitored joint could have failed. A number of joints could be included in each circuit to minimise installation and monitoring costs. This form of indicator would be useful for alerting the occupants and owners that the building has been damaged. Further enhancements could include i) identifying the location of the failed joint, by including a resistance between the ends of each tape in the circuit, and ii) recording the failure times.

There has been a considerable amount of overseas investment in the area of structural health monitoring, which places a number of sensors (such as accelerometers) in the building. A reference signature is recorded when the building is excited either by ambient wind and occupant vibrations or by impacting the structure using a special device. (The signature essentially identifies the natural frequencies and modes of vibration.) Subsequently recorded signatures are compared with the reference in order to infer where damage has occurred. This method has however proven to be of dubious value as an indicator of seismic damage because i) it is relatively insensitive to small changes in the structure such as the failure of a single joint, ii) it is difficult to establish the correspondence between changes in the signature and the type of failure and iii) it still requires a reasonable number of instruments placed at strategic locations.

3.2 *Sensors*

Sensors form the first of the components in a data acquisition system that is used to record the variation of the physical quantity with time. They convert the physical quantity into an electrical signal, which is then amplified and filtered before being converted into digital data, stored and transmitted to a central repository (database).

A significant amount of effort is required to calibrate each sensor's output against a reference sensor at a number of points over its working range. Sensors also require regular maintenance and periodic recalibration to maintain their accuracy over a long time. Many sensors also need to be corrected for temperature and other environmental fluctuations. They are therefore expensive to construct, calibrate and maintain, although the cost of some sensors, such as accelerometers, has reduced recently because they are in mass production for other industries (i.e. air-bag inflation sensors for motor vehicles).

Accelerographs are used to record low-frequency accelerations (below 100 Hz), and normally have a sampling frequency of 200 Hz. Some models are able to record higher frequency transients, such as those caused by structural impacting or fracturing within the structure (which have accelerations in the range of (say) 1 to 10 kHz) but this is not done routinely because of the great volume of data.

High precision accelerometers are required to monitor buildings because a primary use of the data is to obtain a displacement history by double-integrating the record. This becomes even more important when differences are used to calculate the relative deformations between two storeys. Because it is often the inter-storey deflections that are of prime interest, it would be sensible to record them directly, the difficulty being that currently there is no suitable sensor. An advantage of using a purpose-built sensor is that both the frequency range and the resolution could be lower than for equivalent accelerometers.

A possibility, being tested experimentally overseas, is to use GPS (Global Positioning Satellite) receivers to measure lateral building movements. This currently only gives a resolution of 10 mm, which is more suited to monitoring the movement of the roof of a skyscraper than a typical New Zealand building.

Structural integrity could be measured using strategically placed measuring instruments, such as potentiometers, but this is more appropriate for laboratory experiments than for a general instrumentation plan such as that required for GeoNet. A thoroughly instrumented building could be the basis of a long term, one-off research project.

3.3 *Installation and Maintenance*

A key aspect of instrument installation is neither how to install the instrument correctly nor where it is installed, but the quality of the record keeping. The other two aspects are important, but complete and thorough documentation is vital because there is often a long time between installation, maintenance and record retrieval. The time interval also means that staff changes can influence this. Photographs of the installation site, prior to as well as after the instrument is installed, provide an essential record for later tracking. This is almost essential if the instrument has poor access. Maintenance records are also an invaluable clue to adjustments to the instrument which subtly influence the recorded data.

3.4 *Networking Instruments*

The two primary reasons for networking instruments in the past were transmitting the data back to a central database without having to visit the installation, and synchronising the instrument clock with a reference clock. Many modern instruments can be controlled and their operations can be checked via the network as well. The advent of relatively inexpensive GPS equipment has eclipsed the dependence upon the network for time synchronisation, although only seismological studies require the start time to be highly accurate.

With that as a basis, there are many other issues that need to be decided in order to select the most desirable networking option. These include:

- The physical network connection. Possibilities now include connection to a building's internal Internet, through a telephone line shared with the building's occupants or through a cell phone.
- Network availability. An earthquake might disrupt access to the network. Instruments should always be capable of storing the data and not be dependent on immediate transmission to the database. Recent events have shown that telecommunications are probably as reliable as the reticulated power supply system. The whole transmission chain must be checked and maintained (there is no point connecting to the building internet if there is no power backup system). Cell phone technology appears to have an advantage, particularly because phone lines can be more readily broken, but there is no guarantee that the radio network will be available either immediately after an earthquake (due to overloading) or in the long term (e.g., Australia phasing out the analogue cellular network).
- The connection use. Continuous connection (an internet appliance) allows data to be sent to the central repository for near real-time access by other agencies. Only connecting to the network when there are data to be transmitted, or when off-peak charge rates may be utilised, can significantly reduce operating costs. Unfortunately, this factor is likely to require continuous reassessment throughout the life of the instrument.

It almost goes without saying that the instruments need to be networked within a building itself. It makes sense to have only one interface with the outside world (to reduce the risk of network security breaches). The internal network connections between instruments, however, could be either by wire or by radio. Wires are attractive because they provide complete ownership of the communications channel, and are therefore not affected by governmental or commercial decisions, however they are a significant portion of the total installation cost and need to be carefully considered.

3.5 *Aiming at the mass market*

Whilst the primary aim of GeoNet is scientific, synergy with the commercial sector could provide benefits for both the science and commerce communities. There are two aspects of the commercial operations that could be of direct benefit to GeoNet. The first is to use mass-produced equipment where the development costs are reduced by spreading them over a much greater number of instruments (or components). Also, having the scientific component as an add-on to systems already required to make the building operate should reduce the cost to the scientific fund as well as presenting the supplier with an attractive selling point if the system can be used to advise the owner that the building has not been damaged.

A second benefit could be achieved by engaging building services companies (e.g. security, lifts, computer networking etc.) to supply data transmission services. They could possibly maintain the instruments at lower cost too. There would be additional costs, in the form of staff training, but staff are likely to be more competent at handling sensitive electronic equipment than was the case a decade ago

4 **BUILDING SELECTION**

Building selection should be relatively straightforward once objectives of the instrumentation have been established. However, there are many trade-offs involved, and so there needs to be careful consideration of the different aspects described herein.

4.1 *Existing Systems*

The majority of instruments currently fitted in buildings are accelerometers. New Zealand has a small number of instrumented buildings, most of which predate the current code and belonged to the government at the time of construction. In contrast, California currently has 170 instrumented buildings, in part because legislation requires tall buildings to have accelerographs installed and in part because the installation reduces the requirements for post-earthquake damage inspections.

There is a conflict between the number of buildings that have instruments installed and the number of instruments that are required to give meaningful information about a building's response to an earthquake. The primary reason for this is the instrument costs (the US Geological Survey estimates $US10 000 for installation and $US500 annual maintenance for a three-component accelerograph).

4.2 *Instrument spread*

The first task is to decide how the fixed quantity of instruments should be spread amongst the target buildings. It is possible, at one extreme, to fit all instruments to one building, however this runs the risk that there will be no strong earthquakes that affect the building. Nor would it give information about a wide range of types of building.

Six models for instrument placement are suggested for the California Strong Motion Instrumentation Program (CSMIP) (Huang & Shakal 2001) (Figure 1) as a means of resolving this conflict. These range from a single three-component instrument at the base of the building to a series of three, two and one component instruments distributed throughout the building.

The absolute minimum configuration is a three-component instrument at the base of the building, but this is only useful for recording slightly modified ground motions and so is seldom used. A more common configuration has three-component instruments at the base and roof. This configuration gives some information about the first mode response but the mode shapes are not recorded. Adding a third instrument somewhere else in the building (for the third configuration) gives a slightly better picture of the mode shapes or it can be added in the free-field (for the fourth configuration) to fill in details of the soil-structure interaction. The last two configurations utilise a mixture of 1, 2 and 3 component instruments to record the rotational responses of the floors as well as the horizontal translations (and all assume that the vertical responses are mostly similar to that at the base).

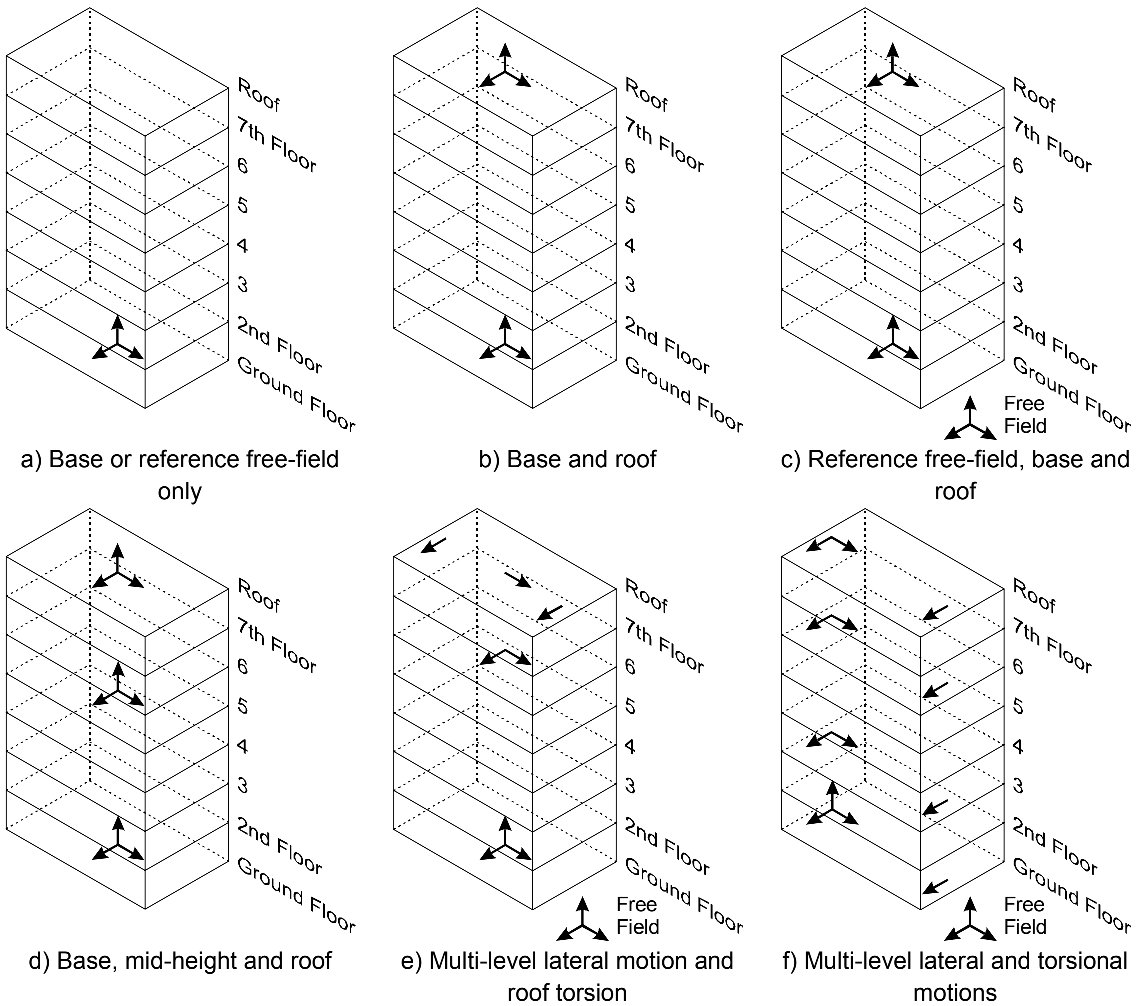

Figure 1 Instrument configurations suggested from the CSMIP (Huang & Shakal 2001)

Unfortunately, the instruments and all of the Figure 1 configurations rely on the following:

i) Integration of accelerations to obtain structural deformations;
ii) Differences between accelerations in two locations to obtain rotations in a horizontal plane;
iii) Rotations at the base of the building being negligible;
iv) Floor diaphragms remaining torsionally rigid; and
v) Interstorey deformations being distributed uniformly throughout the height of the building.

None of these are particularly good assumptions for establishing the relative positions of the instruments in symmetric buildings with square or rectangular plans – let alone irregular buildings – that are required to give a reliable indication of the building damage. The first three represent problems associated with indirect measurement techniques and the other two by taking two few recordings.

The best solution appears to be to develop an interstorey displacement sensor and install these within every storey in the building. It would appear that the best locations for these sensors would be within lift shafts, particularly because they extend the full height of the building and simplify the wiring. However, this, usually central location, reduces their sensitivity to building rotation (in the horizontal plane) and the stiff walls surrounding the shaft may influence the measurements. A vertical chain of sensors at each end of the building may provide the optimal arrangement, although these may need to be installed within a false column to protect them from the occupants.

4.3 *Data Use and Ownership*

Data use and ownership are a significant problem for US researchers, particularly when private instrumentation is included in the network. Many US building owners are unwilling to release recorded data to anyone other than their own design engineers because it could reduce the value of a damaged building. This even extends to the situation where buildings are not able be identified. Verifying building analysis models is difficult in this situation. Data access is not currently an issue with the publicly funded GeoNet, which places the data in the public domain, but could be an issue when a GeoNet instrumented building changes ownership or when privately owned instruments are included in the network, using some of the GeoNet infrastructure.

5 CONCLUSIONS

The GeoNet building instrumentation project offers a significant potential advance in understanding how buildings respond to earthquakes, in order to improve their construction and design. Both the instruments and the buildings need to be carefully chosen to provide the most effective use of the resources, balancing the need for detailed measurements of individual buildings with providing a representative sample of the multiplicity of New Zealand building types. The instruments have complex technical requirements and the data they produce has equally complex distribution and analysis paths. The US ANSS experience provides a good background for planning GeoNet but needs to be significantly tailored for local conditions.

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REFERENCES:

Consortium of Organisations for Strong Motion Observation Systems (COSMOS). 2001. *Workshop on Strong-Motion Instrumentation of Buildings. Emeryville, California 14-15 November 2001.* COSMOS: California. 95 pp.

Cousins, W.J. 1993. Highlights of 30 years of strong-motion recording in New Zealand. *Bulletin of the New Zealand National Society for Earthquake Engineering*. 26 (4): 375-389.

Huang, M.-J. & Shakal, A.F. 2001. CSMIP building instrumentation measurement objectives and models. Presented at *Workshop on Strong-Motion Instrumentation of Buildings. Emeryville, California 14-15 November 2001.* COSMOS: California.

USGS 1999. Requirement for an Advanced National Seismic System. *United States Geological Survey Circular 1188*, ISBN 0-607-92932-4. 55 pp.