(The following paper was first presented at the Seventh International Conference on Structural Faults and Repair, Edinburgh, Scotland, July 1997 and has been reproduced to tie in with the community forum being held in Christ Church Cathedral, Newcastle, as part of the Australian Earthquake Engineering Society conference in December 2009, commemorating the 20th anniversary of the 1989 Newcastle Earthquake.)

EARTHQUAKE DAMAGE REPAIR AND STRENGTHENING OF CHRIST CHURCH CATHEDRAL, NEWCASTLE NSW

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1. INTRODUCTION

In December 1989, Newcastle NSW experienced the first earthquake to affect significantly an urban area in Australia, resulting in the death of 13 people and extensive damage to masonry buildings. The most important building to be severely damaged was Christ Church Cathedral which dominates the skyline of the city.

Australia lies completely within a continental plate and has not been considered as a "seismic" zone, as are locations like California and Japan which are near plate boundaries. Academic research has concentrated on earthquakes at plate boundaries leading to a sense of complacency in locations away from these regions. Certainly, the size of earthquakes at plate boundaries ("interplate earthquakes") is potentially much greater than those elsewhere ("intraplate earthquakes"), but the different characteristics of intraplate earthquakes can make them just as damaging as their better known counterparts. It is often conveniently forgotten that the most devastating earthquake in the USA occurred well away from California (New Madrid, Missouri, 1811-12).

Intraplate earthquakes had previously occurred in Australia in sparsely populated regions and, according to the applicable Australian Standard in 1989, Newcastle was located in a "zero" seismic zone, as was most of the populated eastern seaboard. In consequence most practising structural engineers and building authorities in Australia knew little, if anything, about earthquake design requirements. That situation has changed dramatically, and the history of the damage and repairs to Christ Church Cathedral is a good illustration of the evolution of Australian practice.

The structural engineering design of a project such as the Cathedral can be undertaken in a number of ways and, as is usually the case with structural design, different engineers will come up with different valid solutions. Working on a heritage building introduces its own discipline which, in Australia, is governed by the Burra Charter, a document of Australia ICOMOS derived from the world body's Venice Charter. Establishment of heritage significance is the first step in the process of conservation under the Burra Charter.

The Heritage significance of Christ Church Cathedral is embodied in its material fabric (including its structural systems), its architecture, its setting, its contents and what it represents to people.

To best understand this significance, a methodical process of collecting and analysing all of the information, both physical and documentary, was required particularly prior to the major decision-making processes that come after extreme environmental events such as the 1989 Newcastle Earthquake.

The Christ Church experiences genuinely reinforced these principles. For six years following the Newcastle earthquake, the former Consultants, the client (The Anglican Diocese of Newcastle), the Insurance Company (NZI Insurance) and Statutory Authorities struggled with decision-making at every level.

2. THE 1989 NEWCASTLE EARTHQUAKE

At 10.27 am, Australian Eastern Summer Time, on Thursday, 28th December 1989, Newcastle was subjected to an intraplate earthquake. The earthquake had an epicentre approximately 14 km south west of Newcastle's city centre and was recorded by some distant seismographic stations as having a Richter magnitude of ML5.5 or ML5.6. The earthquake had only about a 10 second duration and there were no major aftershocks.

The Richter magnitude is the one usually quoted in any earthquake because of its relative ease of calculation from distant observations. It is a measure of the total energy released by the earthquake and has only a loose relationship with the intensity felt at the surface or, more importantly, in a building structure.

Most people would be familiar with reports on major earthquakes, particularly those that occur on tectonic plate boundaries. An earthquake of "only" ML5.6 in, say, Los Angeles or Tokyo would probably cause very little damage, so the people from earthquake prone countries (that is prone to interplate as opposed to intraplate events) wonder what all the fuss was about. One of the big differences, of course, is that in Newcastle the energy was released at a depth of about 14 km beneath the surface: typical interplate earthquakes occur at depths of the order of 100 km, so there is a lot more between them and the surface to absorb and deflect the energy.

To overcome the problems associated with the Richter scale, the scale known as the Modified Mercalli index is used in most western countries. This is a partly subjective scale which attempts to classify damage at the surface and hence give a measure of intensity. In Newcastle the Modified Mercalli index varied throughout the area, subject to local geological conditions, but it ranged up to MMVIII on an areal basis with some pockets of damage possibly being classified as MMIX: this is not much different from some of the intensities experienced in the well-known earthquake areas on a scale where total destruction is the highest at MMXII. At the Cathedral site the damage is consistent with MMVII, although most of the surrounding area was noted as MMVIII on the published studies: at the bottom of the hill on which the Cathedral stands the soils are alluvial with a greater amplification factor, which would explain the difference.

The Newcastle area has been mined for coal since 1797 and the whole area is riddled with old mine workings. No conclusive evidence has been put forward to suggest that the workings affected the intensity of the earthquake in any general way and miners working underground quite close to the epicentre are reported not to have felt the tremor.

A fuller account of the earthquake and damage caused to older buildings can be found in a previous paper by one of the authors (Jordan, Trueman & Ludlow, 1992).

3. DAMAGE TO THE CATHEDRAL

Christ Church Cathedral, which dominates the skyline of Newcastle, is the largest provincial Anglican cathedral in Australia and is of "Federation Gothic" style (Apperly, Irving & Reynolds, 1989) in brick masonry construction; building of the walls commenced in 1893 and continued until the 1970s when the tower was added. The building is of cruciform shape and 67 metres long. A tower is located at the crossing of the transepts, with small towers at the western end. The internal span of the main roof is 9 metres and a single clerestory is supported by flying buttresses.

The effect of the earthquake on the building was largely as would be expected: high-set stone crosses and other decorations were dislodged and fell to the ground or lower roofs; flying buttresses were dislodged, but none fell completely away; shear cracking occurred in the nave walls which lie roughly parallel to the direction of the seismic wave and out-of-plane movements occurred in the east wall and dislodged windows. The degree of damage varied with the state of the brickwork with very little occurring in the tower structure, completed in 1979.


Figure 1: Christ Church Cathedral, Newcastle NSW

As well as the familiar "p-" and "s-" waves associated with vibrations in solids, earthquake waves (or any vibrational wave in a solid with a boundary plane) can be shown to have two other types of wave motion associated with them: Love waves oscillate in the boundary plane, or "half space", and Rayleigh waves form alternate circulation patterns perpendicular to the boundary. Of particular interest seismically was the behaviour of the brick finials topping off the columns of the main walls of the nave. The finials could be seen to have rotated alternately along the length of the nave. This gave an interesting example of Rayleigh waves with a horizontal component. The cathedral is situated towards the top of a steep hill, with steeply dipping strata under it, and the circulating patterns of the Rayleigh waves would have produced horizontal circulating components in the building.

4. STRENGTHENING CRITERIA

4.1 History following the earthquake

In the period immediately following the earthquake an attempt was made by the responsible building authority, Newcastle City Council, to define a standard for new building works and, by implication, for repair of older buildings. Naturally, such general standards could not cope with a building such as the Cathedral, and so started years of argument among engineers and architects acting for the insurers, the church authorities and the City Council. Estimates of repair costs varied by factors of up to four because of the differing interpretations of what needed to be done.

Firstly, the emergency decisions involving immediate demolition of sections of the Cathedral without adequate recording meant reconstruction to exact detail was more difficult, requiring additional research and documentation which, in some cases, would not have been required if conservation policies had been in place to direct decision-making.

Immediately following the earthquake, the first priority was to make the damaged structure safe for the public. This was achieved through various methods of scaffolding, shoring, propping, strapping and unrecorded removal of various stone and brick elements. During this period, various proposals were considered which involved demolition of large sections of the building, including the removal of the flying buttress and parapet elements which are significant aesthetic and structural components of the Cathedral.

These aggressive approaches led to many disagreements, and ultimately confusion, between the various consultants, authorities, the Insurer and the Diocese, on the best way to approach the insurance claim and ultimate repair and reinforcing of the building. Legal argument followed and continued for a period of five years.

4.2 Australian Standard Earthquake Loading Code

The Newcastle earthquake precipitated a rapid reappraisal of the Australian design code for earthquake loading which had been under review for some time but with little sense of urgency. As a result in 1993 the new code was issued as part of the structure loading code, being designated AS 1170.4-1993, "Minimum design loads on structures, Part 4: Earthquake loads". The new Code became obligatory for structural design of the project.

However, as in so many structural design exercises, there was more than one way to interpret the Code and apply it to the structure. The different philosophies of the firms of structural engineers could not be resolved.

4.3 Appointment of Engineer Mediator

Following an agreement between the Insurer and the Diocese, a Working Party was formed to resolve the disputes. An eminent Engineer, with structural and heritage conservation credentials, Mr Harry Trueman, was appointed to assist the working party in resolving the differences, both analytical and philosophical, between the various consultants working for the Insurer and the Diocese (see Appendix).

Selection of the structural design parameters was not a clear choice, even with the help of the new Code, because the building does not fall into a readily identifiable class, nor does such a building have a design life within the boundaries considered by the Code (a "design earthquake" is based on an estimated 90% probability of the ground motions not being exceeded in a 50-year period). The difference in cost estimates due to the earthquake design parameters was A$1.6 million in a total difference of A$12.6 million.

4.4 Resolving the design differences

Of more importance in the difference in estimates was the approach to the work. On one side was a proposal to demolish large sections of the building and to reinstate it to an "as new" condition, together with drilling and reinforcing of apparently undamaged sections of masonry; damage in a design earthquake was to be minimal. At the other extreme was a proposal to only reinforce sufficiently to prevent collapse in the design earthquake, with repair rather than replacement of damaged brickwork.

After reaching agreement on structural design parameters including earthquake loading requirements, it was then proposed by Mr Trueman that the best way to approach the vast philosophical differences was to prepare a Conservation Plan for Christ Church Cathedral. The Conservation Plan in the Australian context is structured following a specific form devised under the guidance of Dr J S Kerr (Kerr, 1985), in accordance with the principles the "Burra Charter" (Australia ICOMOS, 1988). Those principles originated from the Venice Charter. Similar documents elsewhere in the world are known by names such as Historic Structure Report or "HSRs" (APT, 1997).

In the Christ Church Cathedral case, the brief from the Working Party explicitly stated "The Conservation Plan is to advise the most appropriate method of reinstatement and rectification of the Cathedral". Following expressions of interest in January 1995 and a response to the Working Party brief, EJE Architecture was selected as the Conservation Consultant to prepare a Conservation Plan to guide the decision-making processes.

5. CONSERVATION PLAN

The Conservation Plan for the Christ Church Cathedral established the Historic, Aesthetic, Social and Scientific basis upon which decisions and implementation of the reinstatement and rectification of the Cathedral could proceed (EJE Architecture, 1995).

The Conservation Plan process, through documentary research and physical analysis, provided:

1. A chronological history of the 11 different construction phases of development on the Cathedral site.
2. Identification of the important fabric of each construction phase.
3. The particular and differing construction methods, techniques and materials of each construction phase.
4. Time and environmental factors that contributed to the latent conditions of the materials and structure.
5. Information on previous repair and maintenance methods.
6. Data and descriptions of other extreme structural failures in the building due to mine subsidence.

Figure 2: The original Christ Church, 1817

The chronological history of construction on the Cathedral site began in 1817 with the erection by convict labour of a small `T' shaped Church built of brick and stone with a steeple 30.48m (100 feet) tall. From plans, artists' impressions and photographs, the exact location of any probable archaeological deposit was able to be determined. The protection and management of the remnant footing from 1817 was given equal precedence with the rest of the building. During removal of destabilised floors in the nave area, portions of the original stone footings were uncovered, recorded and retained without disturbance. The knowledge of the existence and location of the archaeological deposits greatly influenced the design and construction methods of the new reinforced

Figure 3: The spire and portion of the tower removed in 1825

concrete floors, ensuring the protection of the deposit.

From its inception in 1817, the small brick and stone church was gradually demolished with the tower being reduced in two separate stages due to instability. Firstly, in 1825 the steeple, upper tower and 3 m (10 feet) of the lower tower were removed and some time after 1868 the remaining portion of the tower was removed and a small bellcote installed. In 1883 the installation of the mass concrete footings for the new Cathedral led to the demolition of the 1817 Church in two stages, firstly the East End and then the West End. This demolition even caused consternation between the Design Architect John Horbury Hunt and the Dean of the Cathedral. This argument centred around the structural integrity of the footing and the desire of the Dean to retain the building in use for as long as possible. Horbury Hunt demanded that the tower footings must be laid at the same time as the wall footings so as to negate the possibility of differential settlement. The construction of the Cathedral continued at a slow pace with the face brick masonry walls only reaching half their intended height by 1893. Disputes over types and quality of bricks persisted between the Architect, the Contractor and the

Figure 4: The remaining tower removed and bellcote added, circa 1868

Figure 5: The footings of the new Christ Church cathedral laid in 1883

Figure 6: The lower external walls as they stood for a period of eight years from 1893

Cathedral Chapter. The brick construction consisted of solid brickwork up to 1.2 m thick in English bond, finished internally and externally as face with joints as small as 3 mm and the brick detailing providing the decoration. Externally the bricks were hard double glazed, liver coloured, internally a soft cream, intended to maximise the light quality.

In 1893, following a dispute over certified payments to the Contractor by the Architect and a bitter legal battle, John Horbury Hunt and the Contractor were dismissed. The brick walls were left unfinished and exposed to the extreme elements of a coastal climate and environmental pollution of a rapidly growing industrial town.

The building suffered damage and the mortars deteriorated due to constant wetting and drying, particularly to the interior of the brickwork from the exposed bed. This situation remained until 1901.

In 1901 a new Architect was appointed to temporarily roof the nave, the crossing, the baptistry and the porch at half the final height and prepare it for occupation. In the process, brick pilasters to the main nave columns were removed and sandstone facings to the crossing arch supports were introduced. At this time, the deteriorated brickwork was repointed with a hard cement-based mortar to all internal faces. This work was completed and the Cathedral opened for service in 1902. Within five years the Cathedral suffered severe structural damage to its western end with severe mine subsidence which occurred again two years later.

Figure 7: The temporary roof to the nave installed in 1901

Figure 8: Temporary roof to the chancel installed 1909

The next construction phase began in 1909 with the temporary roofing of the chancel and the construction of the vestries to a new design by Newcastle Architect, F.G. Castleden. With this construction the brick type changed and the joint sizing increased to approximately 10 mm. The quality of the bricklaying also decreased and little attention was given to the filling of perpend joints in the interior of the brickwork.

Figure 9: The chancel raised to its full height, 1912

1912 saw the Cathedral begin to be raised to its full height with the construction of the upper walls of the chancel. Significant in this construction was the use of hard refractory bricks as commons, which proved to be one of the many difficulties encountered in the drilling for the 1996 reinforcing. 1912 also saw the construction of the Great East Window using sandstone and stained glass imported from England.

World War 1 curtailed the construction programme on the Cathedral. However, as early as 1915 steps were taken to erect a war memorial "if we win the war" (Murray, 1991). The Warriors Chapel was completed in 1924, adding a significant aesthetic and social component to the Cathedral. The Chapel was constructed in a separate structural element on the northern side of the Cathedral and included a finely-detailed Australian sandstone and marble interior, none of which are currently quarried and as such, are unavailable for use.

Figure 10: The Warriors' Chapel constructed 1924

1926 saw the Nave raised to its full height with flying buttresses and the introduction of a cavity within the brick wall. The base of the Tower was completed and the Western

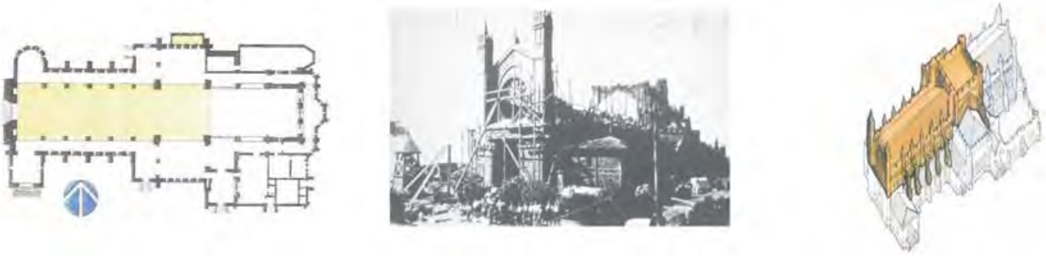

Figure 11: The nave and tower base raised 1926

Rose Window installed at this time.

The final construction phase was the raising of the transepts and the completion of the massive bell tower using cavity work, cement mortar and a relatively soft clay face brick compared to the lower portion of the building. This work was designed by Architect John Sara, of the Newcastle firm of Castleden & Sara, and completed in 1979.

Figure 12: The tower and transepts completed 1979

Following the documentary and physical research, a Statement of Significance for the Cathedral and site was established following the four criteria of Historic, Aesthetic, Social and Scientific Significance.

> *Christ Church Cathedral, Newcastle and its site is rare in Australia for its association with the early convict history of the Colony and its paralleling of the historic development of Newcastle, Australia's sixth largest city. As a focus for many historic events the Cathedral is unsurpassed in the region. Its place in Australian Anglican Church history and its association with many Bishops and political dignitaries is also of importance. The impact of the 1989 Newcastle earthquake and its effect on the physical fabric and social history of the Cathedral enhances the historic nature of the Cathedral as a centrepiece of cultural sentiment for the people of Newcastle, the region, the State and the nation.*
>
> *Aesthetically Christ Church Cathedral is an extraordinary piece of architecture in a dramatic setting. The building displays the innovative skill and ability of John Horbury Hunt and the detailed design ability of F.G. Castleden. The building's stock of stain glass, craftsmanship and artwork heightens the aesthetic value. Stylistically the building expresses the significant changes from the Victorian period of architecture with its reliance on academic correctness to the freer realisations of the Federation period and its influence by the Arts and Crafts movement in Australian architecture.*
>
> *Socially the Cathedral has been and will remain a focus for the lives of the people of Newcastle, the region and in many respects the State and nation, in terms of tourism and the perception of Newcastle as a city. At a regional and local level the Cathedral is the premier location for the expression of Anglican religious practice and is a key element of cultural activity for the community.*

> *Scientifically the site and Cathedral are of some significance, particularly in regard to European historic archaeology, the understanding of J. Horbury Hunt's work and the effect of mine subsidence and earthquake on large masonry buildings in Australia.*

6. CONSERVATION POLICIES

In order to retain the specific significance of the Cathedral, a detailed conservation policy was developed in conjunction with an implementation strategy. The policy had *as* its basis the requirements of:

- the Anglican Diocese of Newcastle
- the Insurer (NZI Insurance)
- Local, State and Federal Government Legislation
- Structural Engineering (including earthquake loading)
- Architectural considerations
- Physical condition
- Retention of significance

Nineteen separate broad Policy Statements evolved. The policy statements that specifically influenced the philosophical and technical approach to the structural repair and strengthening were:

Policy No. 2 The conservation issues to be closely and creatively linked to the overall repair strategy for the Cathedral. Specifically respect for the various stages of the Cathedral's construction be taken into account in terms of differing construction techniques and material variations.

> *Reason: So that all periods of the building's history are recognised and the various associations with Clergy, Architects and Builders are not obliterated.*

Policy No. 3 Maintain a philosophy of cultural continuity through the retention of the physical effects of historic changes to the fabric both intentional and accidental (e.g. evidence of the intentional removal of brick pilasters to the nave arcades by J H Buckeridge and evidence of the accidental cracking of masonry due to mine subsidence and earthquake).

> *Reason: So that significant historic events in the Cathedral's history can be interpreted to the broader community, particularly the dramatic events of the 1908 mine subsidence and the 1989 Newcastle earthquake.*

Policy No. 5 That the future conservation and development of the Cathedral and its surroundings be carried out in accordance with the principles of the Australia ICOMOS Charter for the conservation of places of cultural significance (the Burra Charter) as adapted by Australia ICOMOS on 14 April 1984 and revised on 23 April 1988 together with its associated guidelines as published in the illustrated Burra Charter, October 1992.

> *Reason: To ensure that management, conservation architects, engineers, builders and others involved in work on the Cathedral become sufficiently familiar with the Burra Charter for its practicality and flexibility to be fully understood.*

Policy No. 6 That a clear structure showing responsibility for the specific care of the fabric and contents of the Cathedral be set out and made available to all persons involved in work associated with the Cathedral and that this practice be continued in the ongoing management of the Cathedral and its contents.

> *Reason: To set out the need for a clear understanding of responsibility for decision, the execution of work and the relationship of all involved. This will help avoid problems of communication and demarcation which may reduce efficiency, increase costs and result in damage to the fabric.*

Policy No. 7 Modem techniques and advanced technology to achieve code requirements for structure and stability should only be used where traditional techniques cannot achieve a satisfactory level of compliance. Repair should take into account both the elemental basis as well as the overall integrity of the structure. Such methods and techniques must be proven and suitable to the extant materials of the Cathedral.

> *Reason: To retain the overall historic character of the building and its individual elements while complying with contemporary code requirements but not at the expense of historic, architectural and cultural values.*

Policy No. 8 That the protection of the potential archaeological deposit likely to be found in the area of the nave be of a high priority and that all investigation and conservation of the deposit follow the guidelines for Historical Archaeological sites produced by the NSW Department of Planning Heritage Council of NSW, March 1993.

> *Reason: So than an irreplaceable resource for interpreting Australian history and culture is not inadvertently damaged or compromised.*

Policy No. 9 Retain the existing configuration of the Cathedral and maintain the elemental fabric by repairing that fabric which no longer performs its original function or promotes further damage to the fabric.

> *Reason: To preserve the appreciation of the work of Horbury Hunt and the subsequent Cathedral architects, to ensure the retention of as much original fabric as possible.*

Policy No. 10 The form of the Cathedral while appearing complete may be changed following the adaptive program of its history. However, design resolution compatible with the existing form must be the highest priority. An understanding of the intricacy of the Cathedral's design which is summarised in this document must be mandatory for any future architects, engineers and builders.

> *Reason: To allow future development of the Cathedral in parallel with the desires and aspirations of the community and to ensure sensitive appreciation of the Cathedral by professionals and craftsmen.*

Policy No. 12 Conservation work should initially focus on identification of the stages of construction and the analysis of materials with the view that new materials used in the repair should closely match original or adjacent materials while displaying evidence of change.

> *Reason: To ensure a sound and considered technological basis, in terms of traditional and modern methods while ensuring the ability to identify the historic chronology of the building fabric*

Policy No. 13 A patina of age, evidence of use and evidence of residual damage is desirable.

> *Reason: To assist in the interpretation of the fabric and its different stages of construction. To ensure the perceived cultural continuity is maintained and that evidence of significant events is appreciated.*

Policy No. 14 Structural reinforcement installations should minimise its impact on the building's fabric with a minimalist approach to achieving the code requirement, but the long term serviceability of the building and fabric ensured.

> *Reason: To ensure minimal damage to the historic fabric and maximum benefit in terms of future maintenance and preservation of the fabric.*

Policy No. 15 Existing facade modulation, window and door fenestration both internally and externally should be maintained.

> *Reason: To preserve the significant design intent of architects Hunt, Castleden and Sara and to maintain the aesthetic image of the building for the broader community.*

7. PROCUREMENT AND MANAGEMENT OF THE PROJECT

7.1 Repair practices in Newcastle following the earthquake

As indicated previously, the 1989 Newcastle earthquake was the first destructive earthquake to occur in modern times in a major urban area of Australia. This meant that Australian engineers were not experienced in the design or reinforcement of buildings for earthquake loadings and, particularly in the major population centres of the east coast, most had no concept of the requirements, as the existing Australian Standard for earthquake loading classified those centres as being in Zone 0, where no structural consideration was necessary.

Most engineers hurriedly became familiar with the requirements as experience was imported from overseas (mainly New Zealand and California), but little help was available immediately for dealing with masonry buildings of heritage importance, particularly the Cathedral.

The co-authors of this paper were both appointed by the NSW Department of Planning, Heritage Council, to a panel comprising of three Architects and three Structural Engineers who were charged with giving guidance on the conservation of heritage properties; it was during this time that we became aware of the limitations of available strengthening systems. Typical of the systems being used were internal and external steel frameworks, which would be quite inappropriate for a building such as the Cathedral, due to visual and environmental considerations.

Some buildings were reinforced by the drilling and reinforcing of masonry, but this often caused many secondary problems, among them being:

- grout was introduced to bond and encapsulate the reinforcing but it flowed out through cracks and flooded cavities, causing considerable problems on site in cleaning it up and leading to damage to other elements of the building;
- with horizontal drill holes, there was no assurance that the grout had bonded the bar for the full length;
- low strength grouts used did not develop the bar strength close enough to the ends of reinforcing bars, leading to designs using epoxy end anchorages — the use of epoxy formulations in heritage buildings was of considerable concern to the authors and many others, but alternatives did not seem to be available.

Other practices which were common, but undesirable, included the repair of masonry by epoxy crack injection. This introduced a material into the building fabric which usually did not have compatible physical properties across the temperature range likely in the masonry and, in many cases, the fire rating of the wall was adversely affected. The performance of epoxy-type materials in buildings, such as a cathedral, with a likely future life measured in hundreds of years was also uncertain.

7.2 Finding a better way

Before work on the Cathedral had commenced, one of the authors (Jordan) became aware of the German developed and British marketed "Cintec" masonry anchoring system. Not being directly concerned with the project it was a large commercial risk for a sole-practitioner engineering consultant to introduce the appointed design consultants to the system, find a contractor with the necessary experience to train as an installer and to be instrumental in setting up an Australian branch for Cintec and import the product for the Cathedral project. This was especially so as the project turned out to be the largest installation of Cintec anchors in a single building that the company had tackled and included the longest continuously grouted anchors. Fortuitously, Cintec products were marketed by a private company based in Wales and owned by a man willing to take on such a large project with unknown people at such a distance. The risks taken on by Mr Peter James are acknowledged and played a large part in the final success of the project.

The credentials of the Cintec system are probably well known to European audiences, but a long period ensued before the system was accepted by the Engineers and Architects as being the only viable system for reinforcing the Cathedral. Trial installations were carried out, tests were undertaken and, in the end, a contract was signed with the trained Cintec installer, Australasian Concrete Services Pty Ltd, for the whole of the work on an accelerated programme.

7.3 Structural design

The prime aim of the structural design was to turn the building into a ductile structure, lack of ductility being the main cause of catastrophic collapse of buildings during earthquakes. It was accepted that different parts of the building would end up with different degrees of ductility, and so would be likely to suffer different degrees of cosmetic damage in a future earthquake. However this had to be accepted in order to maintain the aesthetic significance of the building, but with the overriding criterion that risk of personal injury to occupants of the building during a future earthquake would be reduced to a minimum.

Ductility could be introduced into the building either by the addition of ductile frames, with the obvious visually intrusive consequences or by fully reinforcing the brickwork, which had cost and practicality drawbacks. In the end, a combined system was chosen which used some frames where they are hidden from view: behind the parapets, in the roof space and inside the upper section of the tower.

With the design parameters set (see Appendix) a two-dimensional finite element analysis was carried out using a readily available computer package ("Strand 6"). Different combinations of reinforcement strength and spacing were considered and costed and, in the end, a high strength Grade 316 stainless steel deformed bar was used in sizes from 16 mm to 32 mm diameter. In order to limit the amount of drilling that had to be carried out "Hi-Proof' bar with UTS in range 790 to 920 MPa [N/mm^2], depending on size, was specified. The total length of reinforcing installed was 3770 metres.

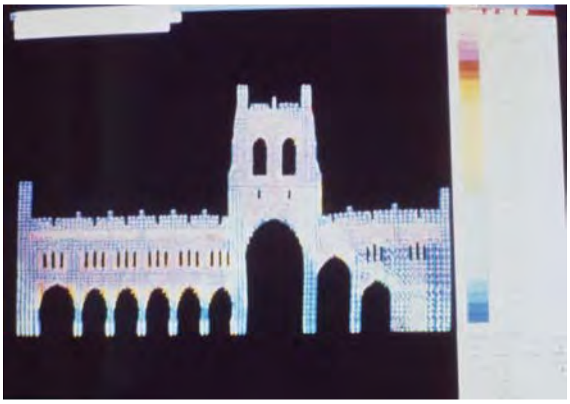

Figure 13: Typical FEA output

7.4 Anchor (Reinforcement) Design

The Cintec anchor system has three basic elements: the anchor body which carries the load, the cementitious grout formulated using micro-cement technology and the woven fabric sock which controls the grout. Details of the sock and grout can be found in company literature (Cavity Lock Systems Ltd, current).

The sock design for the Cintec system allows the sock to expand in the drilled hole, and to its maximum in voids, without the openings in the weave allowing more than the finest fraction of grout to pass through. This "grout milk" contains the inorganic adhesion agents of the grout together with the excess moisture not required for cement hydration. The final expulsion of the excess moisture does not occur until the full sock is pressurized, when the inflated sock becomes hard. This process ensures that the filling of the sock can be monitored by observing a small section, either at the injection end or by way of a small observation hole for remote chambers. For shorter anchors, the Cintec system uses return grout tubes for the monitoring of blind chamber inflation. This was not possible for most of the very long holes on the Cathedral without an increase in hole size, but small monitoring holes at joints could be drilled to the side of anchors and repaired later.

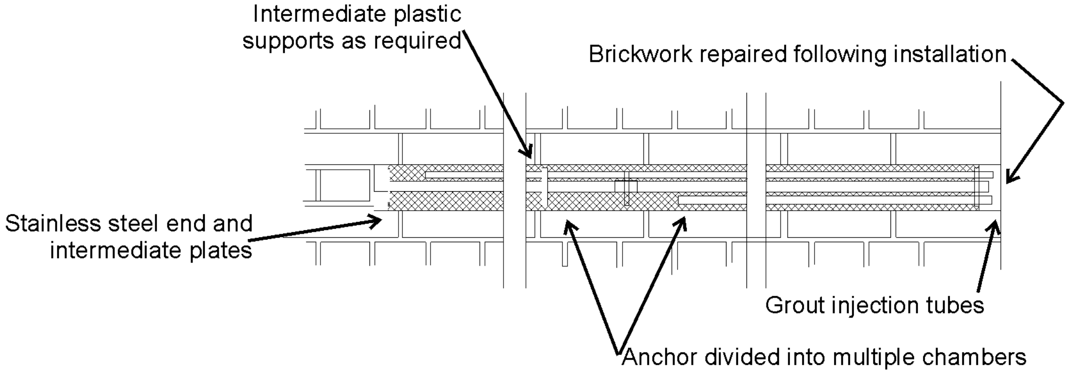

Figure 14: Typical anchor using 25 mm deformed bar in 85 mm diameter hole

Hole sizes were determined by the bond requirements at the ends of the bars, the grout cover requirements to the bar and the requirements for coupling the bars and achieving grout flow. In general, 60 mm diameter holes were adopted for the 16 mm anchor bodies up to 6 m long, 85 mm holes for longer 16 mm, 20 mm and 25 mm anchor bodies, and 120 mm diameter holes for the 32 mm anchor bodies. It would have been possible to have a greater range of hole sizes to meet the design parameters and to have saved some drilling and grout. However, the installation contractor chose to limit the range for better quality control.

7.5 Drilling and installation

Masonry drilling is usually carried out by diamond coring using water for cooling and cuttings removal. The use of water or other drilling fluids was not desirable in the Cathedral for two reasons. The more obvious was the potential damage that could be done by escaping drilling fluid: many of the more important "treasures" of the Cathedral could not be removed without damage. Also, it was calculated by the structural engineers that a saturation of the brickwork by water could so increase its mass as to risk foundation failure.

Hydraulic drills were set up by securing them rigidly to the masonry of the building. Guidance of the drills depended on the accuracy of the initial set-up in all but the 32 m long holes, where inspection panels were able to be opened along the line of the holes from where the drill rods could be redirected if necessary. Dry drilling by non-coring, polycrystalline diamond bits, using air for cooling and cuttings removal was successfully used, after trials of different bit types and drilling sequences.

Figure 15: Horizontal anchors assembled during installation

Figure 16: Vertical anchor installation by crane

Figure 17: Finished installation prior to brickwork repair

Whilst Cintec anchors are normally factory assembled, the size of most of the anchors on this project would not have allowed easy transport and an assembly facility was established on site. Vertical anchors of all lengths were preassembled at ground level and generally placed by crane. Horizontal anchors greater than about 6 m long had to be assembled on the scaffolding platform as they were being placed in the hole. Power, compressed air and clean water were available at all levels of the scaffolding and grout was mixed and injected at the site of the anchor hole.

7.6 Contractor procurement, Management and Cost control

The commencement of the physical works occurred immediately after the appointment of the consultant team. A cost plan that reflected the fast track nature of the project procurement was prepared with preliminary design investigation based on the indicative scope of works identified by EJE Architecture and HTL Reinhold, with provisions for undefined earthquake restoration works that would be identified as detailed investigations were made available.

The works were separated into "Trade Packages" at the initial documentation stage, the purpose being twofold:

- to enable documentation efforts of the project to be concentrated on the major structural repairs and to provide for their early on-site commencement;

- to provide control over the tendering and selection of suitable contractors having appropriate specialist expertise, experience and capacity in all required trade works.

Specialist contracts were tendered and let as Lump Sum Contracts with Schedules of Rates used for the control of project variations. Specifically within the drilling contract:

Figure 18: Drill hole survey

- locations for drilling were provided by survey directly under the control of the site engineer;
- maintenance of accuracy of alignment of the drill holes was documented as the contractors responsibility to be verified by progressive "as executed" survey documentation;
- down-the-hole video was used to verify the integrity of every drill hole;
- the documents provided for drilling to be undertaken in masonry having a compressive strength of up to 70 MPa generally and included the onus of proof on the Contractor to provide for test data confirming any higher compressive strength;
- an issue which proved to be an item of considerable dispute and cost variation, was the internal state of some brickwork — internal mortar jointing proved in some areas to be of extremely poor quality both in terms of its low strength and the non-existence of internal joint perpends, resulting in internal brickwork collapse at the drill, drill blockages and difficulties in clearing of the drilling spoil — these problems were eventually overcome by down-the-hole grout injection to stabilise the masonry.

The significant role implemented by the quantity surveyors was the cost management of the project budget during the construction phase using trade schedules for the major trades of brickwork, reinforcement and brickwork restoration, preparing estimates for various trade packages and monitoring of the cost plus categories of the work.

Monthly Forecast Final Cost Reports and preparation of progress payment recommendation reports for all subcontractors ensured that the client was provided with constant monitoring of the project budget and audit procedures for contract payments.

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APPENDIX

SETTING THE EARTHQUAKE DESIGN PARAMETERS

(The following extract from Mr Trueman's progress report is important in establishing the philosophy of the building repair and is reproduced with thanks. The report was written at the time when Mr Trueman was acting in the capacity of Mediator, and had not yet been appointed to carry out the design.)

The Philosophy Behind the Earthquake Code

The Earthquake Code (AS 1170.4-1993) is unusual amongst the Codes used by structural engineers. Most Codes are concerned with safety and serviceability. The Earthquake Code is solely concerned with safety. Design to the Code does not necessarily prevent structural and non-structural damage in the event of an earthquake.

The Code is also unusual in that overseas experience was generally not relevant to Australian conditions. Most other loads and materials are similar or the same as those in other countries, and the data available is enormously increased. With little guidance on earthquakes, considerable innovation was necessary during the development of the Code. Several revisions were necessary as the resulting economic and practical effects became apparent. The final result is something of a compromise, and must be interpreted using the designer's experience and skill.

Like all Codes it is applicable to "normal" buildings. Special structures are specifically excluded, and it is only possible to use the Code recommendations as a direction or guide on non-standard structures.

Lastly it is intended for new structures. There is an informative Appendix for alterations, but little mention of repair. A new Code is under preparation for existing buildings.

Christ Church Cathedral is not a normal building in size, shape, importance or use.

The Code can only be applied as a guide, and results considered for practicability and economy. Designers will look behind the raw figures and statements for intent, rather than applying them in a rigid manner.

Regardless of the actual numbers, common engineering sense suggests that these conditions be considered whether mathematically required or not — provided the economic impact is not too onerous.

The major requirement of the Code at this level of risk for new structures is "Ductility". The ductility of a structure or element is a measure of its ability to undergo repeated and reversing inelastic deflections beyond its point of yield (elastic failure), while maintaining a substantial part of its initial load carrying capacity. In effect the ductility of a structure or element is a measure of the energy absorption capability of the system.

Ductility is highly desirable. The Earthquake Code is unashamedly intended for the protection of life by minimising the likelihood of collapse of structures. This does not necessarily prevent damage to the building structure or its attachments, or its contents. With ductility a building may be damaged by cracking but will remain standing even in an earthquake somewhat in excess of the design earthquake. As well as protecting the occupants, a building will remain that could possibly be repaired, in lieu of a possible pile of rubble.

A normal masonry building such as the Cathedral is extremely non-ductile i.e. brittle. While it is highly desirable to include at least some measure ductility in repairs, this is both difficult and costly. Yet at least in some parts of the building it is essential.

All parties to the discussion accepted the desirability of incorporating ductility with the reservation expressed by [the structural engineer representing the insurer] as to the cost involved and the responsibility of meeting this cost.

However it was decided to test the increase in costing by a rough redesign.

To convert an existing masonry building to a ductile structure is not simple. Two main alternatives exist — either providing ductile frames to support the masonry, or providing steel reinforcing to the masonry.

The first alternative — additional frames — is unacceptable in a building such as the Cathedral, both for the effect on appearance and perhaps the heritage significance of the building.

Installing reinforcing is the logical answer and was the original method proposed by both consultants, although based on different loading parameters and a slightly different philosophy.

Design parameters

For a rough redesign it was necessary to establish uniform design parameters to allow a direct comparison of the resulting effect on the original proposals.

It is not proposed to detail here the parameters used because, as previously discussed, they remain only guidelines to engineering judgement.

It is sufficient to say that the parameters discussed, and eventually used, were considered relative to one another and their individual level of risk. For instance where one factor was considered conservative it was reasonable to be less conservative on another.

Additionally the effect on economics of increased loads was considered. There are strong reasons for being conservative for a building of the importance of the Cathedral, with an anticipated long life span under normal loads. The question of the responsibility for the payment of the increased cost must be considered. It is accepted in the conservation of very significant heritage buildings which have deteriorated from age, that the cost of rehabilitation should be at the expense of the community rather than the owner. It is felt that this should apply to this Cathedral were it to be upgraded to a higher standard befitting its anticipated life span. Normal buildings are designed for a 50 year life span and hence the Earthquake Code is based on a seismic event that has a 90% probability of not being exceeded in 50 years. If the same probability were extended to a longer life, there is a resulting cost to someone.

If this cost is to fall on the general community, the effect of accepting such a principle must be compared to the effect on other similarly important buildings and structures. On this basis, the suggested Cathedral design loads were limited to those applicable to a building that has an important post-disaster function.

At the same time consideration was given to other factors that influence the design process. These included the factors for loads and materials in various Codes to cover the intangible variations that occur. Examples are uncertainty of material quality, of workmanship and even the accuracy of the measurement, or prediction, of loadings. There were reservations about the final resulting parameters by [both the engineering consultants]. Selection of criteria being an art, there will always be different opinions.

In searching for guidance from overseas on selection of parameters for earthquake repair of important buildings such as the Cathedral, some New Zealand examples were considered relevant. The established standard for strengthening of old buildings in New Zealand accepts a relatively higher risk due to the costs involved. The value of earthquake load suggested to be used is equal to one half to two-thirds of those prescribed. However for important long life buildings such as the High Court Building in Auckland it was felt that an attempt should be made to comply if possible with the "spirit and intent" (i.e. philosophy) of their Earthquake Code. This has therefore been the aim with Christ Church Cathedral.

Repairs to heritage buildings are often difficult to achieve without affecting the quality of the building. As the standard of workmanship and the quality of materials are known, it is usual to reduce considerably or remove the risk factors associated with these elements. A similar philosophy was applied in this case.

It was agreed to undertake the rough design using the chosen parameters. From the results it would be possible to see two things - the effective variation of cost incurred by the change from the preferred criteria of each consultant, and any variation in construction methods proposed.

Despite adopting uniform design parameters the application of parameters was left to the discretion of the designer. As previously discussed mathematical analysis is only a guide and the resulting stresses must be examined and interpreted using experience and understanding of structural mechanics For instance, there may be areas where reinforcing is theoretically not required, but should be installed due to the likelihood of stress concentrations, or because of the risk associated with failure.

The resulting rough designs were found to be quite compatible, and not extraordinarily different to the original layouts.

There were, however, differences in approach that may be affecting estimates.

ADOPTED EARTHQUAKE CODE PARAMETERS

Acceleration Coefficient	A = 0.11
Importance Factor	I = 1.25
or	a = 0.11 x 1.25
(The latter has the same result but a different philosophy)	
Site Factor	S = 1.5
Load Factor (for limit state design)	F = 1.0
"Materials" Factor or	
Strength Reduction Factor	C, or O =1.0