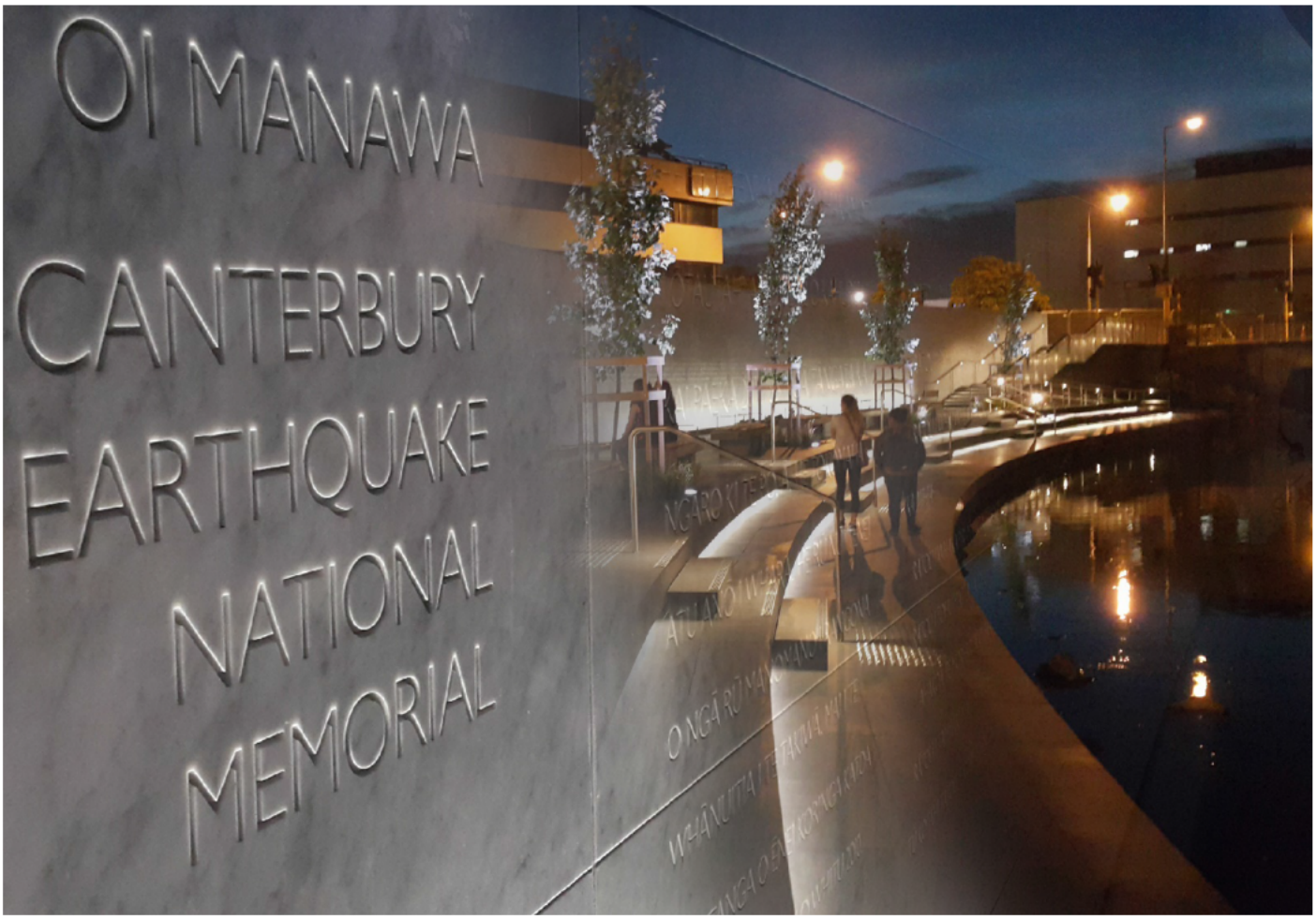
NEW ZEALAND POLICE
Ngā Pirihimana o Aotearoa

2017

CTV Investigation



Engineering Peer Review

North America

[redacted]

[redacted]

25 October 2016

Peter Read
Detective Superintendent, Southern
New Zealand Police
68 St Asaph St DX WX10057
Christchurch 8011
New Zealand

Project No: [redacted]

Subject: **CTV BUILDING COLLAPSE**
PEER REVIEW OF ENGINEERING OPINION REPORT BY BECA LTD.
CONFIDENTIAL – FOR POLICE PURPOSES ONLY

Dear Detective Superintendent Read:

The New Zealand Police are currently investigating the potential criminal culpability of individuals in connection with the 115 deaths that occurred as a result of the collapse of the CTV Building in the 22 February 2011 Christchurch earthquake. The police have engaged Beca, a large engineering firm with offices throughout New Zealand, to provide expert opinion on structural engineering matters to assist them in making this determination. Their conclusions, along with summaries of studies undertaken to inform their findings, are contained in the document "CTV Building Collapse – Engineering Opinion Report", dated July 15, 2016.

The New Zealand Police have commissioned [redacted] a consulting structural engineering firm located in [redacted] to perform an independent peer review of Beca's findings, including the following services:

- Review background information provided by Beca;
- Review findings of Beca's opinion;
- Review the Beca opinion in relation to the duty, omission, causation and identified departures highlighted in the legal briefing to Beca;
- Pose written questions to Beca where clarification is deemed necessary;
- Prepare a report documenting the findings of the review; and
- Answer questions from the police, regarding the findings of [redacted] review.

This letter report documents the findings of [redacted] peer review. This report is intended for Police use only and is considered "confidential" in accordance with Conditions of Engagement.

[redacted]

REVIEW OF BACKGROUND INFORMATION

Prior to this engagement, the Peer Reviewer (PR) did not participate in any of the investigations or hearings regarding the collapse of the CTV Building and had not reviewed any of the associated reports or testimony. Beca provided the PR with background information for review that included:

- Drawings and structural calculations prepared for the building's original construction;
- Drawings and calculations prepared for modifications to the building to address identified structural deficiencies in the original design;
- Structural assessments that were made subsequent to the original construction, but prior to the February 2011 earthquake; and
- Excerpts from hearings and investigation reports that happened following building's collapse in the February 2011 earthquake.

Beca also furnished copies of building standards and references that were in common use in the local practice at the time that the CTV building was designed.

The files that were furnished by Beca and reviewed by the PR are listed in Attachment 1.

Review of the relatively voluminous information was necessarily brief and intended to serve only as background to review of the Beca report and structural calculations and other reports prepared in conjunction with Beca's investigation. The material was generally familiar to the PR, who is a structural engineer with 40 years of broad experience in the design of buildings in seismically active regions and who has been actively involved in the development of provisions for the seismic design of buildings in the US over the course of his career.

REVIEW OF FINDINGS OF BECA OPINION

Building Design

Beca has performed a thorough review of the original structural design of the CTV Building for conformance with building code and standard documents that were in effect and/ or widely used in practice at the time, as well for conformance with common standards of practice in the Christchurch area. The review included interviews with other practitioners designing similar structures and review of structural drawings for other similar buildings in the area to supplement Beca's internal experience regarding whether adopted standards were commonly being used.

Beca has identified several deviations from codes or standards of practice in effect at the time, and has opined that certain of these deviations substantially contributed to the collapse of the CTV Building. Listed below (as indicated in italics) are the Beca findings that we consider to be key and our review of these findings.

- *The original 1986 structural analysis and design of the building was undertaken using appropriate codes and analysis techniques but contained a number of errors in relation to the application of the codes. There was also a significant mathematical error.*

  We agree with this finding. Beca's review included making an independent analysis of the structure using the same codes and analysis techniques employed in the original design, and

then comparing the results with the original structural calculations. We have reviewed the original calculations and the results of Beca's analysis, and concur with their finding that the original calculations contained several errors.

Although errors commonly occur in the design of structures, and the standard of practice is certainly not perfection, it is our opinion that the number, nature and magnitude of errors that was made in the design of the CTV Building exceeds the normal standard of care and evidences that the design was accomplished without benefit of adequate experience and/ or review.

As identified by Beca, and discussed later herein, errors in the design computations resulted in substantially larger lateral building displacement than would have occurred in a Code-compliant building and the increased lateral displacement demand on building columns substantially contributed to the collapse. We concur with these findings.

- *The transverse beam-column joint steel specified on the drawings in the primary gravity frames did not comply with the code requirements.*

  We agree with finding that the transverse steel specified at beam-to-column joints was substantially noncompliant with the concrete building standard in effect at the time.

  Beca has shown by nonlinear analysis and physical testing that inadequate joint reinforcement resulted in substantially increased demands on the critical zone of the columns, where failure is alleged to have initiated. This finding was discussed in detail during the course of the peer review and we are convinced that Beca's assessment is valid.

  As identified by Beca, and discussed later herein, errors in the design computations resulted in substantially larger lateral building displacement than would have occurred in a Code-compliant building and the increased lateral displacement demand on building columns is expected to have substantially contributed to the collapse. We concur with this finding.

- *Away from the joints, the transverse column steel was light (i.e. small diameter and large spacing), but compliant with the minimum requirements of the code in the critical areas. Although the transverse column steel in the CTV building complied with the minimum requirements of the concrete code, it was very light compared with general practices of the day. We have found no other similar sized buildings of the era in Christchurch with as little transverse steel as was specified in the CTV building columns and beam-column joints.*

  The transverse reinforcement that was used in interior building columns is much less than we have seen used in practice in seismically active areas. We are not surprised by Beca's finding that the specified steel is much less than was typically used in other Christchurch buildings at the time, even though this small amount may have conformed to code requirements.

  Provision of transverse reinforcing steel in columns seeks to protect against sudden and catastrophic failure when forces and/ or deformations exceed expected levels due to the large uncertainties that are present in design for earthquakes. This serves to provide resilience against collapse when load and/ or deformation demands exceed levels accounted for in design. The testing of full size column specimens emulating those in the CTV Building has demonstrated that columns should have been expected to perform well, until they are laterally displaced beyond a "tipping point" where failure occurs suddenly and is catastrophic in nature.

  At the level where failure is alleged to have originated, the transverse column steel was found to be compliant with requirements of the building standard in effect at the time. Although code-compliant, the provision of such light transverse reinforcement in the columns results in their being ill-suited to accommodate demands that exceeded their "tipping point". In the opinion of

the peer reviewer, the lack of resilience of the columns is also an operating cause of why the building collapsed so catastrophically.

- *The structural design was carried out by Mr David Harding, an employee of Dr Alan Reay. According to Dr Reay's evidence at the CERC, neither he, nor any other engineer in his practice, or outside it, provided any oversight or checking. Mr Harding was a senior engineer and employee of Dr Reay, but inexperienced in multi-storey design. The stated lack of oversight by Dr Reay, or any form of review or checking by another experienced person, was contrary to accepted practice of the time. Our experience and the conclusion we reached following discussions with other practitioners of the day was that a principal of a design company, partner of a partnership, or sole practitioner with staff, would oversee a design such as this (often completing the concept design themselves), or organise another senior employee or external consulting engineer to review it. In our opinion, relevantly experienced oversight or review at concept stage would have questioned the low lateral seismic displacements and/or the decision not to detail the primary gravity frames with ductility. To appoint a newly employed senior engineer without experience in similarly sized structures and rely on him to ask questions if needed, was not in accordance with generally accepted and expected practice.*

  We agree with this finding. Analysis and design of building structures is commonly performed by relatively inexperienced staff. As such, it is common practice to have oversight that is commensurate with the nature of the work and experience of persons performing the work Methods of supervision and quality control vary to suit the size, structure and culture of the firm.

  Although Mr. Harding had several years of general engineering experience, we understand that Dr Reay knew that he was completely inexperienced in designing structures similar to the CTV Building. In our opinion and experience, oversight of staff that is known to be inexperienced is a fundamental professional responsibility of a project principal or sole practitioner and the failure to do so is well outside the standard of practice.

Collapse Initiation and Progression

Beca has undertaken substantial efforts to establish the cause of collapse initiation at the CTV building, including:

- Review of prior reports and calculations prepared by others that investigated the probable cause of the collapse;
- Performing nonlinear time history analysis of the structure, using a time history ground motion located in relatively close proximity to the site;
- Performing collapse progression analysis to determine failure locations that would have resulted in observed total "pancake" collapse;
- Requesting and reviewing the results of physical testing of full size replica specimens of building columns and beam-to-column joints; and
- Requesting exposure of remaining foundation elements at south shear wall and examining for earthquake induced distress.

Based on these efforts, Beca has concluded that:

> *The collapse was initiated by loss of stiffness in one or more beam-column joints resulting in column axial failure, probably in the ground floor of an internal frame, probably on Grid 2. The capacity and stiffness of the beam-column joint regions associated with these columns was significantly reduced by the lack of transverse and shear reinforcement and this was a significant contributor to the collapse.*
>
> *The characteristics of axial failure in these relatively slender columns were such that their ability to support gravity loads would have been completely lost once it occurred. This would be either by progressive crushing/failure of the column concrete and/or sliding of the column to one side once at least one end became effectively detached from the structure.*
>
> *Once collapse of these columns was initiated there was no ability for the gravity loads to be redistributed to adjacent columns with the result the remaining columns were progressively overloaded, leading to the pancaking collapse of one floor on top of another.*

Based on our review of Beca's efforts, as well as review of background materials including other possible collapse initiation scenarios, we agree with Beca's opinion that collapse initiated in an interior column at its base and progressed through the structure.

Although an analysis conducted using a single earthquake record located off site cannot be taken as precise, such analyses can be taken as indicative of general building response. In the case of the CTV Building, the analysis indicates that lateral building displacement sufficient to fail the columns would have occurred if the ground motion matched or exceeded that recorded nearby and used for the analysis. Further, to inform the question of the contribution of design errors, analyses of a code-compliant design indicate that demands produced by the same level of shaking would not have resulted in collapse.

Although physical testing on one set of specimens cannot be taken as a precise predictor of behavior, such testing can inform the nature of failure and be indicative of the general level of displacement at which it might occur. The physical testing performed for the CTV building indicated that failure would be sudden and catastrophic, with little indication of imminent failure. The results of testing on samples with varying joint reinforcement are consistent with Beca's analyses that indicated that softening of beam-to-column joints at the first elevated level would increase demand on the columns and therefore contribute to the likelihood of failure.

Based on the results of analysis and testing, Beca has concluded that the following design errors contributed to the collapse and that collapse would not have occurred in the 22 February 2012 Earthquake in the absence of these conditions.

- Although walls did not fail in the earthquake, they lacked the strength and stiffness to control drift to acceptable levels and protect building columns. As a consequence of errors in design, demand was substantially increased.

- The softening of beam-to-column joints that resulted from failure to provide code-prescribed reinforcement, substantially increased demand on columns at the base, contributing to their failure.

We agree with Beca's finding regarding the location of collapse initiation, based on the results of analysis, testing and collapse propagation analysis that are fully consistent with this assessment. We also agree that design errors substantially contributed to the collapse. We agree that it is highly probable that failure

would not have occurred absent the design errors, based on Beca's analyses and test results that indicate such and the substantial affect that the errors are estimated to have had on building response.

However, because the experience and response of individual buildings to individual earthquakes cannot be precisely established by analysis and testing, we cannot concur that the collapse would not have occurred in the absence the identified errors. We base this conclusion on the relatively large dispersion that we see in assessing earthquake response and the lack of resilience in the building columns to accommodate excess demand. The lack of resilience afforded by poorly reinforced columns in combination with other aspects of the gravity force resisting system selection and detailing is in our opinion likely to be a substantial operating cause of why the CTV Building collapsed so completely when strongly shaken.

Discounted Options for Collapse Initiation

The Beca report review and discounts various other causes that have been suggested as contributing to the collapse.

- We concur that ground settlement or subsidence and foundation failure are ruled out by general review of the damage and subsequent investigations that were undertaken as part of the study.

- We concur with Beca's observations regarding observations of the North Core and associated floors in the vicinity, coupled with their analysis of the probable effect of failure of floor attachments. We see no evidence to suggest that this contributed to the collapse.

- We concur with Beca's assessment that construction defects in the connection of beam-to-column joints (i.e. lack of roughening of ends of precast beams and lack of provision of very light ties in the joint zone) had no impact. There is no evidence that a shear-friction failure at the beam-to-column interface could have contributed to the collapse and specified ties were much too light to have a meaningful affect.

The Beca report reviews the question of whether the larger-than-code ground motions that were recorded was the principal cause of the collapse and identifies that, based on their analysis, there would not have been initiation of failure if the structure had been properly designed to code requirements. However, in our opinion, it is possible that collapse could have occurred in the absence of the design errors due to higher than expended ground motions in combination with the lack of resilience that this structure possessed. It is anticipated by the profession and its standards that some few number of code-compliant buildings, especially those that do not contain resilient detailing, will experience collapse in extreme earthquake events.

Conclusions on Beca Findings

Based on our review, we conclude that Beca has correctly identified errors in the original analysis and detailing of the building that contributed substantially to the initiation and subsequent progression of collapse through the CTV Building and that there is a high likelihood that such collapse would not have occurred in the absence of those errors. In our opinion, the number, nature and magnitude of errors exceeds the normal standard of care for building design.

Tempering this opinion, we find that provisions of the code in effect at the time required inadequate transverse reinforcement in columns to provide the degree of resilience that is desirable in high seismic regions. We understand that revisions to NZ building standards have been made in subsequent years to address this potential problem.

REVIEW OF BECA'S FINDINGS IN RELATION TO DUTY

Dr. Reay

The Beca report concludes that:

1. *Dr Reay, as the person who undertook to design the building, omitted to discharge his duty to allocate appropriately experienced personnel to the design, checking and review process of the building structure.*
2. *This omission was a substantial and operating cause of the collapse, and*
3. *The omission was a major departure from the expected standard.*

We fully agree with this conclusion.

David Harding

The Beca report concludes that:

1. *Mr Harding, as building designer, omitted to discharge his duty in relation to the design of the CTV building as the design did not comply with generally accepted practices and standards of the day.*
2. *The omission was a substantial and operating cause of the deaths, and*
3. *The omission was a major departure from the expected standard.*

We agree that the errors and omissions exceeded the customary standard of care and evidence that Mr. Harding was inexperienced in the work that he undertook (Item 3). We agree that Mr. Harding's errors were a substantial and operating cause (Item 2).

However, in the course of supervising many engineers over the years, the PR has found that an inexperienced engineer is rarely aware of what he or she doesn't adequately know. Engineering, similar to other industries, uses staff with limited experience to accomplish work that may exceed their capabilities, absent counsel and/ or review. In evaluating the performance of staff, including licensed engineers, it is our experience that one would review whether one performed to the best of their ability to a normal standard of care.

Geoff Banks

The Beca report concludes that:

1. *Mr Banks omitted to discharge his duty in relation to the design of the strengthening works, but*
2. *The omission was not a substantial and operating cause of the deaths.*

We agree that Mr Banks would not have been expected to have initiated a full structural review of the building at that time of retrofit, or to have identified the beam-column joint issue, and that the evidence does not establish failure at the retrofit as cause of collapse.

Graeme Tapper/Bryan Bluck - Assistant Building Engineer Christchurch City Council (CCC)/Chief Building Engineer CCC

The Beca report concludes that:

1. *While the CCC may or may not have discharged their responsibilities under the relevant legislation of the time (we have not checked as it is a legal matter and beyond our brief), they did not depart from their usual practice of not doing a thorough structural check.*

   The CCC may or may not have omitted to discharge their duty by not doing a thorough structural check and consequently issuing a building permit for a defective design.

2. *The undetected defective structural design of the CTV building was a substantial and operating cause of the deaths, but*

3. *Issuing a building permit without a thorough structural check prior to issuing a building permit was not a major departure from the expected standard of the day in Christchurch.*

We agree. In the PR's experience, which is grounded in US practice, plan check would not be relied upon to capture structural defects or errors in projects of larger size, except in those cases where the building department outsources the plan review to an independent structural engineering office or agency that is engaged in the design or review of large buildings. This is in recognition that the vast majority of projects submitted to local agencies for plan review are small commercial and residential buildings and such reviewing agencies have limited experience with the design of larger structures to enable a proper review.

Bill Jones/Gerald Shirtcliff – employees of Williams Construction managing construction of the building:

The Beca report concludes that:

1. *Messrs Jones and Shirtcliff as managing the construction work omitted to discharge their duties in relation to the construction of the CTV building by not constructing it in accordance with the plans and specifications, but*

2. *The omission was not a substantial and operating cause of the deaths.*

We agree that the errors in construction were not an operating cause.

QUESTIONS TO BECA

Based on review of a draft Final Report in May 2016, written questions were posed to Beca, reference May 18 and June 26 emails, to request clarification and additional information regarding specific items. These items included:

1. Significance of the very low amount of binding reinforcement in the columns that would have been allowed at the lower levels of the building by building standards in effect at the time.
2. Clarification that softening of beam-to-column joints would result in increased demands on building columns at base, which is not apparent based on traditional analysis methods.
3. Review of nonlinear time history analysis and very large drifts computed in the first level, which exceed what would generally be expected.

Beca has addressed the questions that were posed to our satisfaction in various email correspondence and in two video conferences. Various revisions to the draft report were also made to address these comments. We have no outstanding comments at this time.

CONCLUSION

Based on our review of Beca's report, including review of Appendices documenting analysis and testing efforts in more detail, it is our professional opinion that Beca has performed a comprehensive assessment of the cause of the CTV Building collapse and identified errors in the design and detailing of the structure that substantially contributed to the collapse.

Based on our own professional experience, which is grounded in US practice, we concur with Beca's findings regarding duty and cause, except that we have reservations with regard to the duty as related to Mr. Harding.

CLOSING

We would be pleased to meet by teleconference or video conference to discuss any questions that you may have regarding the findings of our review.

Respectfully Submitted,

[redacted]

[redacted]
Structural Engineer
Principal Emeritus and Senior Consultant

[redacted]

Attachment: Attachment 1: Background Information Provided

[redacted]

[redacted]

ATTACHMENT 1: BACKGROUND INFORMATION PROVIDED

1A: Reports and Calculation

- 1986 Gravity Calculations
- 1986 Seismic Calculations
- 1990 Pre-Purchase Report
- Building and Housing - Christchurch Earthquake Final Report
- Compusoft - Code Compliance ETABS Analysis Report_BUI.MAD249.0577[1]
- Hyland-Smith - Report_Part 1
- Hyland-Smith - Report_Part 3
- Hyland-Smith - CReport_Appendix L - structural drawings
- Hyland-Smith - Materials Tests Report
- Hyland-Smith - Report_Part 2
- Latham - Secondary Frame Design Review Report_WIT.LATHAM.0003[1]
- Latham - Seismic Analysis Report_WIT.LATHAM.0002[1]
- Latham Presentation - CTV Building Seismic Analysis and Review of Secondary Frames_BUI.MAD249.058...
- Royal Commission Vol 6_Section 1_2-Page1-118[1]
- Royal Commission Vol 6_Section 3_4-Page119-162[1]
- Royal Commission Vol 6_Section 5_pt1-Page163-177[1]
- Royal Commission_Vol 6_Section 5_pt2-Page-178-195[1]
- Royal Commission_Vol 6_Section 6_to_end-Page-196-324[1]
- Tonkin and Taylor - Geotechnical Advice

1B: Codes and Standards

- Kolston and Buchanan - Diaphragms in Seismic Resistant Buildings
- NZS 3101-1982 Commentary
- NZS 3101-1982
- NZS 4203-1984
- Paulay and Williams - Analysis and Design of Reinforced Concrete Ductile Shear Wall Structures