UNDER	**THE COMMISSIONS OF INQUIRY ACT 1908**
IN THE MATTER OF	**ROYAL COMMISSION OF INQUIRY INTO BUILDING FAILURE CAUSED BY CANTERBURY EARTHQUAKES** **KOMIHANA A TE KARAUNA HEI TIROTIRO I NGA WHARE I HORO I NGA RUWHENUA O WAITAHA**
AND IN THE MATTER OF	**THE CTV BUILDING COLLAPSE**

JOINT REPORT OF NON-LINEAR TIME HISTORY ANALYSIS PANEL

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INTRODUCTION

1. This is the joint report pursuant to clause 9 of the Order of the Royal Commission dated 18 May 2012, in relation to Non Linear Time History Analysis (NLTHA).

2. The purposes of the experts conferring were:

   2.1. To endeavour to reach agreement on the input data to be used to conduct a NLTHA of the response of the CTV Building which provides the most reliable model of the response of the Building to the earthquakes at 4.35am on 4 September 2010 and 12.51pm on 22 February 2011

   2.2. Where agreement cannot be reached on the inputs, to identify:

      (a) The inputs which cannot be agreed.
      (b) The reasons for the disagreement.

   2.3. To produce NLTHA results which provide the most reliable model of the response of the Building to the earthquakes at 4.35 am on 4 September 2010 and 12.51pm on 22 February 2011, and which can then be analysed and interpreted.

TOPICS

3. This report will address the following topics:

   3.1. Areas of agreement.
   3.2. Areas of disagreement, including the reasons for the disagreement.
   3.3. The results of the further NLTHA.
   3.4. Additional issues the panel was asked to address.

AREAS OF AGREEMENT

Concrete Strength

4. After some discussion it was accepted that the concrete strength be taken as 1.5 times the design strength and not the design strength plus 2.5kPa as used in the

original Compusoft analyses. Mr Smith accepted this on the understanding he could still compare the results with those from the original analyses to check the potential effects of variable concrete strength.

5. Profs. Mander and Shepherd and Dr Bradley consider that an examination of the sensitivity of the results of the analysis to the assumed concrete compressive strength is necessary.

6. Note there is to be a future 'hot tub' discussion between concrete experts at the Royal Commission to discuss the various concrete test results and it is hoped this may provide further guidance on the likely concrete strengths.

Column Plastic Hinge Modelling

7. The panel was unanimous in the requirement that the columns should use an axial-force / bending-moment / bending-moment (P-M-M) yield interaction instead of the bending-moment / bending-moment (M-M) yield interaction surface used in the original analyses. The vertical ground accelerations were large and the variations in the axial force in the columns could be very important and should therefore be included in the column hinge model.

Masonry Infill Panels

8. The previous analyses incorporated two cases for masonry infill walls - the first case with the masonry panels isolated so as not to interact with the concrete frame at any level of drift, and the second case with the masonry panels in direct contact with each other and with the concrete frame (with lateral stiffness and strength of the masonry based on flexural yielding at each floor level). It was agreed that these DBH analyses gave an adequate insight into the potential masonry interaction effects. Due to time constraints for future analyses only one of these cases could be considered, the one taken would correspond to the masonry infill panels being completely isolated from the structure. This could be considered to reflect the design intent.

Floor Diaphragm Modelling

9. In general the modelling used to represent the overall behaviour of the structure was satisfactory, but if there were localized floor deformations then the stiffnesses used need to be decreased and the finite element mesh may need to be further

refined. These effects were regarded as being of much less significance than the modelling of the column plastic hinges and the modelling of the beam-column joints. The diaphragm model was adjusted to better represent the behaviour near the North tower and along the beam lines. Potential fracture of the mesh has not been modelled and will need to be considered when evaluating the results.

Ground motions used in analyses

10. The use of the Resthaven (REHS) ground motions as part of the analysis suite for the February earthquake was accepted. These have been incorporated in the revised analyses.

11. There was also agreement that some analyses should take the September earthquake and then follow this with the February earthquake to see how using the damaged structure for the February earthquake would differ from starting the analyses for the February earthquake with the original, undamaged, structural model.

12. This sequential analysis should include the Christchurch College (CCCC) ground motion. It was suggested by Prof. Shepherd that it could, time permitting, be done for all four ground motions.

13. These results for two ground motions, including the CCCC ground motion, are reported in the revised analysis report.

Duration of Shaking

14. There was agreement in that the duration of shaking included in the September and February earthquakes needed to be further investigated. The start and finish times for the revised NLTHA were adjusted.

Damping Model

15. There was agreement that the damping model is accepted but that the level of reduction in the specified damping for the February earthquake needs to be adjusted to give a more realistic damping level for the vertical modes of free-vibration. This is reported in the results of the revised NLTHA.

Beam Pull-out and Exterior Joints

16. There is agreement that this needs to be modelled. This is incorporated in the beam-column joint model discussed below. Compusoft stated that this could be done, however were unsure of the behaviour of the hinge and requested guidance as to the back-bone curve that would suitably present the response. No guidance was provided despite numerous requests, so bar pull out was not incorporated in the revised NLTHA.

17. Compusoft also has concerns over attempts to simplify this mechanism through a backbone curve as the pull out strength will be greatly influenced by the axial compression in the joint. In addition, we are not sure how pull out will manifest itself, e.g. should bar pullout take with it a wedge of concrete then the ability of the joint to support axial load could be compromised. If so, then there is little to be gained by modelling this failure mechanism, as pullout would mean local collapse, which can be achieved through monitoring of the demands rather than through explicit modelling.

Beam-Colum Joints

18. The panel was unanimous in its request that the beam-column joint model must be modelled in a non-linear manner. There was considerable discussion on the manner in which the beam-column joints could be modelled and the way the degradation of strength could be represented. Compusoft had concerns that the methodologies promoted would not accurately capture the joint behaviour.

AREAS OF DISAGREEMENT

Drag Bar Strength

19. There was agreement from the panel that consideration be given to the revised drag-bar tensile strengths provided by BECA. The BECA strengths are considerably less than those used in the Hyland/Smith report. However, as noted by BECA there is considerable uncertainty in the estimation of these tensile strengths and the range of strengths given by BECA could not be considered to be either an upper or a lower bound.

20. Mr Smith advised that one reason why the BECA values are lower is because they had used lower characteristic material strengths and not the expected (or nominal)

material strengths which are necessary for this NLTHA. Mr Smith advised that the strengths computed for the original DBH report were considered to be upper bound expected strengths and yet disconnection of the drag bars was still predicted in those analyses. There was no subsequent discussion. The original strengths were used in the revised analyses.

21. In order to assess the impact of this assumed drag bar modelling, Profs. Mander and Shepherd and Dr Bradley argue that analyses should be performed using both sets of the reported values.

Column Plastic Hinge Modelling

22. The panel unanimously agreed that the column hinge definition should provide for PMM interaction. In an attempt to consider this the column hinges have been modelled considering lumped plasticity fibre based hinges at the column ends. In these hinges the interaction surface and hysteretic form is governed by the material properties and geometry. Both shear and torsion are considered to be linear and uncoupled from the PMM behaviour. This solution is consistent with the desires expressed by members of the panel to include PMM interaction. However, many of the panel members would prefer a line model as they consider that this would better represent the behaviour of the hinge, but is not available in the SAP2000 software.

Floor Diaphragm Modelling

23. Profs. Mander and Shepherd and Dr Bradley consider that there is contention as to the equivalent flexural stiffness of the floor. Prof. Mander proposed to use an effective stiffness of $0.1EI_g$, whereas Prof. Priestley has contended that the effective stiffness is significantly greater. Given the inferred importance of vertical ground motion effects in the 22 February 2011 earthquake, the sensitivity of the results to the effective stiffness used should be examined.

Duration of shaking

24. Drs Bradley and McVerry suggested that the whole length of the ground motions should be used for the analyses and that this should include the first arrival of the P-wave. The computational times would be considerably extended.

25. Demonstration of the effects on the significant responses of a simple structure showed that omitting of up to 20 seconds of the original September ground motions had minimal effect on the response and that once the major part of the ground motion had passed then little more would be learned by persisting with the latter parts of the ground motions. Compusoft Engineering Ltd. list in their report the start times and durations of ground shaking used for the revised analyses.

26. Profs. Mander and Shepherd and Dr Bradley argue that the omission of the start of the February ground motion will have an effect on the displacements and velocities, and hence the damping and inertia forces acting in the structure. They also consider that the September records should have been run for a longer duration to see if further damage occurred in the diaphragm to North wall connection.

Ground Motions Used in the Analyses

27. Profs. Mander and Shepherd and Dr Bradley now argue that the September analyses should include the Christchurch Hospital (CHHC) and Resthaven (REHS) ground motion noting that as damage was indicated in the September earthquake the analyses to get a measure of sensitivity of the results to the ground motions.

Beam-Column Joints

28. There were still some differences of opinion between Prof. Mander and Messrs Bradley et.al. (Compusoft) on the beam-column joint models but by the time that the analyses had to be carried out, these differences were very slight and it was agreed to disagree. The model was analysed as it stood at that time.

29. The models used, as well as most of those models suggested, can only really represent the behaviour of the joint itself and not the effects of the joint behaviour on potential shear failure of the connection between the adjoining beams and the joints themselves. Such models are not available in SAP2000, and would require a large amount of time to develop and then calibrate against experimental results. Such time was not available at this stage in the process. It should be noted that there is no recognised modelling technique for modelling two way interacting beam column joints. In addition, there is little research on the structural type and configuration used in the CTV building, so that there will always be considerable uncertainty as to the adequacy of any modelling of the joints.

30. Profs Mander and Shepherd and Dr Bradley point out that the Takeda modelling of the joint is 'peak oriented' in that there is no cumulative degradation, with only degradation due to post-peak softening. If cumulative degradation is considered then more damage will concentrate in the joint, and less in the columns. Hand calculations illustrate that the beam-column joint has a lower moment capacity than the column moment capacity and hence that (potentially) the columns cannot reach yield. The analysis of the Compusoft report needs to be reconciled with this. Compusoft have commented that the joint model is a pivot model.

RESULTS OF FURTHER NLTHA

31. Compusoft Engineering Limited submitted the results of the revised NLTHA on the 13th July 2012. This report covers the responses to the building subjected to the ground motion inputs for all four recording sites in the CBD for the February earthquake, for two of the sites for the September earthquake and for analyses using the September and February earthquakes such that the damaged state of the building following the September earthquake was used as the starting state for the February earthquake.

32. The results of the analysis were not included in the terms of this panel and will be presented by representatives of Compusoft Engineering Limited.

33. Profs Mander and Shepherd and Dr Bradley argue that the Compusoft report requires discussion on the failure mechanism that is predominant. In particular one of the key outputs of the NLTHA is the collapse sequence. It is likely that the collapse sequence will be different for different modelling assumptions.

FURTHER ISSUES

34. The Panel was also asked to consider some further issues. These are set out below.

Modelling of Earthquake

35. In an email dated 15 June 2012, Buddle Findlay suggested that the NLTHA expert analysis should include modelling of the "significant earthquake events between 4:35am on 4 September 2010 and 22 February 2011 so that the cumulative fatigue effect can be considered".

36. The only comment was from Prof. Carr and Dr. Davidson. Magnitude 5 records are two magnitudes smaller than the September earthquake, i.e. released energies about 1000 times smaller than the energy released in the September earthquake. Most were at similar distances from the CBD as the September events, the exception being the Boxing Day 2010 earthquake.

37. A study by Prof. Carr using the Boxing Day earthquake on another building in the CBD showed that the building response to that earthquake when compared with the September and February earthquakes indicated that the response to the Boxing Day earthquake was in the noise level of the earlier response. This may be a little different for the CTV building as its natural period of free-vibration is shorter but the earthquake magnitude is still of an order of magnitude that is relatively small. Dr. Davidson responded with the statement that yes, it could be done but how many weeks were available to do and extract the results from the analyses.

38. A suggestion was to carry out the September analyses, then using the response spectra from the September to just prior to the February earthquakes, get an estimate of the significance of the later shakes on the likely response of the structure. This has not been able to be carried out to date.

Masonry

39. On 15 June 2012, Counsel for the Royal Commission asked the panel to consider comments from Dr Clark Hyland, and a suggestion by Dr Hyland that there is a need for, "additional SAP analysis using the base Compusoft input files. These would then be modified appropriately to consider the masonry wall in contact with surrounding beams and columns at the start of the February Aftershock and calibrate the input motions to allow assessment of drifts and demands on the South Wall, and masonry infill prior to Drag Bar failure using the Capacities set out in the BCR". Compusoft does not support scaling of input motions to calibrate analysis results.

40. The modelling of contact between the masonry infill and the columns could be modelled using gap elements to represent the contact, no-contact, states between the masonry and the columns. The panel had agreed earlier that the two limit states used in the earlier analyses was sufficient. The earlier Compusoft model had discussed such contact. However, to do what was suggested would require a considerable amount of both computing time as well man-hours to set up the

modelling, its calibration and then extract the solutions. This was not possible in the very limited time that was available.

Signed: .....

ATHOL CARR

Date: 16th July 2012

Signed: .....

ASHLEY HENRY SMITH

Date: 25/7/2012

Signed: .....

DEREK BRADLEY

Date: 17/07/12

Signed: .....

JOHN MANDER

Date: 16/7/12

Signed: .....

ROBIN SHEPHERD

Date: 17/07/2012

Signed: .....

BRENDON BRADLEY

Date: 16/7/2012

Signed: .....

GRAEME MCVERRY

Date: 25 July 2012

Ross Jnr Y

25 JULY 2012