EXPERIMENTAL TEST PROGRAM AND MODELLING TO ADDRESS THE PERFORMANCE OF RC WALLS DURING THE CANTERBURY EARTHQUAKES

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SUMMARY

The current seismic design practice for reinforced concrete (RC) walls has been drawn into question following the unsatisfactory performance of several RC wall buildings during the Canterbury earthquakes. An overview of current research being undertaken at the University of Auckland into the seismic behaviour of RC walls is presented. The main objectives of this research project are to understand the observed unsatisfactory performance of several walls in Christchurch, quantify the seismic loads on RC walls, and developed improved design procedures for RC walls that will assist in revisions to NZS 3101. A database summarising the performance of RC wall buildings in the Christchurch CBD was collated to identify damage modes and case-study buildings. A detailed investigation is underway to verify the seismic performance of lightly reinforced concrete walls and an experimental setup has been developed to subject RC wall specimen to loading that is representative of a multi-storey building. Numerical modelling is being used to understand the observed performance of these Christchurch case-study RC wall buildings. Of particular interest is the influence that interactions between walls and other structural elements have on the seismic response of buildings and the loads generated on RC walls.

INTRODUCTION

The 2010/2011 Canterbury earthquake series tested the built infrastructure to beyond the design level seismic loading and caused significant damage to both traditional and modern reinforced concrete buildings. In particular, severe damage was observed to reinforced concrete (RC) walls in several modern multi-storey buildings. As reported by Kam et al. (2011), approximately 30% of modern RC wall buildings in the Christchurch CBD were tagged as unsafe immediately following the 22 Feb 2011 earthquake, and two buildings with RC walls collapsed. Undesirable failure modes that were observed included a lack of distributed flexural cracks, fracture of vertical reinforcement, global and local wall buckling, bar buckling, shear failure, and evidence of poor detailing. The Canterbury Earthquakes Royal Commission (CERC) highlighted the need for further research to improve the seismic design of RC walls and there have been interim design recommendations developed by the Structural Engineering Society of New Zealand (SESOC) (CERC 2012; SESOC 2011).

A research program has been initiated at the University of Auckland to understand the observed performance of RC walls during the Canterbury earthquakes and verify improved design methods and detailing practice. To define the scope and priorities of the research program, a database of damaged RC wall buildings in the Christchurch CBD was developed from existing reconnaissance and CERC reports. Additionally, preliminary RC wall typologies have been developed to understand typical wall details used in different building
types throughout New Zealand. The research program has been split into four main topics, including:

1. Lightly reinforced concrete walls
2. Loads on RC walls
3. Precast concrete wall connections
4. Ductile RC walls with high design loads

Research into the four topics listed above will be completed through a combination of experimental testing and numerical modelling. A summary of the RC wall database is presented followed by current progress towards assessing and testing of lightly reinforced RC walls and modelling of case-study RC wall buildings.

DATABASE OF DAMAGED RC WALLS

A database of RC wall buildings damaged during the Canterbury earthquakes was collated from various sources. The building data was categorised based on the era, number of storeys, structural system, and extent of damage. The current research program is focused on modern multi-storey commercial and residential buildings constructed from the 1980s onwards. A total of 8 modern buildings greater than 4 storeys were classified as severely damaged RC walls, all of which were demolished following the 22 Feb 2011 earthquake. A further 27 modern buildings were classified as having either minor or moderate RC wall damage, over half of which were subsequently demolished. An additional 14 RC wall buildings were classified as pre-1970's era and a number of buildings have yet to be classified due to insufficient data being available.

Examples of damage observed to RC walls are shown in Figure 1. Well detailed RC walls were observed to have formed a large number of distributed flexural cracks in the plastic hinge region. However, several lightly reinforced RC walls were observed to have formed only a small number of flexural cracks, resulting in fracture of vertical reinforcement, as shown in Figure 1a and Figure 1b (Bull 2012; Kam et al. 2011). Other severe failures included inclined shear-axial failure of a central RC wall in a residential apartment building (Figure 1c), severe damage and local web buckling at the base of a non-rectangular RC wall (Figure 1d), and wall compression failure in the Hotel Grand Chancellor. There were also several examples of poor detailing including inadequate splices in both vertical and horizontal reinforcement, inadequate confinement reinforcement, bar buckling, unconfined drossback ducts, and ungrouted sleeve connections.

Figure 1 Examples of observed damage to RC walls

(a) Few flexural cracks (Credit: Ken Elwood)  (b) Fractured reinforcing (Credit: Des Bull)  (c) Inclined shear-axial failure  (d) Damaged plastic hinge region
LIGHTLY REINFORCED CONCRETE WALLS

Assessments of buildings following the Canterbury earthquakes highlighted several examples of RC walls in multi-storey buildings that had formed a single crack in the plastic hinge region as opposed to the expected larger number of distributed cracks (Bull 2012; Kam et al. 2011). After breaking out the surrounding concrete it was found that the vertical reinforcing steel was often fractured due to the inelastic demand at the single crack location. This type of failure is characteristic of RC members with low vertical reinforcement contents and was also observed in buildings following the 1985 Chilean Earthquake (Wood 1989; Wood et al. 1991). If too little vertical reinforcement is used in walls, there is insufficient tension generated to replace the tensile resistance provided by the surrounding concrete after a crack forms, resulting in a reduced number of cracks in the critical moment region, large crack widths, and possible fracture of the reinforcing steel. The Canterbury Earthquake Royal Commission recommended that research be conducted to refine design requirements for crack control in RC walls (CERC 2012).

Minimum Vertical Reinforcement Limits

Prior to the introduction of NZS 3101:2006 minimum vertical reinforcement in RC walls was governed by shrinkage and temperature effects. The minimum vertical reinforcement limit in RC walls increased significantly in NZS 3101:2006 when a similar equation to that previously used for RC beams was adopted. Some of the RC walls in Christchurch that were observed to have only a few flexural cracks and fractured vertical reinforcement had vertical reinforcement contents below the current limit. Additionally, higher than expected concrete strengths may have contributed to the lack of flexural cracks in some lightly reinforced RC walls.

Moment-curvature analysis was used to provide an initial assessment of the current vertical reinforcement limits for RC walls (Henry 2013). From this analysis it was found that even when the concrete strengths are known, the current minimum vertical reinforcement limits in NZS 3101:2006 may be insufficient to ensure well distributed cracking in ductile plastic hinge regions. A significant axial load is often required to ensure that the flexural strength is greater than the probable cracking strength of the wall and even then the effective plastic hinge length was equal to approximately half of what is typically assumed.

Experimental Testing

A series of experimental tests of lightly reinforced RC walls have been planned. The main objective of these tests is to evaluate the current minimum reinforcement limits in the New Zealand Concrete Structures Standard NZS 3101:2006, and to determine whether changes are required to ensure that a ductile seismic response is achieved for multi-storey RC walls.

The maximum height of test specimen that can be accommodated in the current University of Auckland structural test hall is only 4 m. In order to test RC wall specimen that represent buildings 4-18 storeys high, a test setup was designed to simulate the expected seismic loading on the lower two storeys of a 40-50% scaled wall. Based on an assumed lateral-load distribution, the moment, shear, and axial loads at the second storey height can be calculated, as shown in Figure 2. A multi-storey RC wall is typically designed to form a plastic hinge at the wall base and so the lower two storeys is considered the critical region to be tested.

A sketch of the proposed RC wall test setup is shown in Figure 3. The foundation beam is post-tensioned to the laboratory strong floor and the longitudinal reinforcement at the top of the wall is attached to a steel load beam. A total of three actuators are required to simulate the boundary conditions at the top of the wall specimen. A horizontal actuator is primarily
used to apply shear force or lateral displacement to the wall, and two vertically mounted actuators at each end of the wall are adjusted to achieve the required moment and axial load at the top of the wall. A steel load frame has been designed to support the vertically mounted actuators as well as provide lateral restraint to the loading beam. For high axial load cases the capacity of the vertical actuators may be exceeded and so additional axial load will be provided by external post-tensioned bars.

Figure 2 Seismic loading on multi-storey RC walls

Figure 3 Test setup

The first series of experimental tests will evaluate the current minimum reinforcement limits for RC walls in the New Zealand Concrete Structures Standard NZS 3101:2006. The wall test specimen was designed to approximately represent a 40% scale version of a 13-storey RC wall that performed poorly during the Canterbury earthquakes. As shown in Figure 4, the
The wall test specimen has a length of 1.4 m, a thickness of 150 mm, and a height of 2.8 m. The height represents the lower two storeys of the prototype walls and is equal to twice the wall length to ensure that the expected region of inelastic behaviour is included in the specimen.

A total of 6 walls will be tested, as described in Table 1. All 6 walls specimen will be constructed identically, with a concrete compressive strength of 40 MPa and minimum vertical reinforcement in accordance with NZS 3101:2006. The two variables altered during the test series are the moment/shear ratio (M/V) and the axial load. Three M/V ratios of 2, 4, and 6 will be applied to the test walls, representing walls in building having a range of heights. The applied axial load will also be varied from 0-10% of the wall axial capacity.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Aspect ratio (M/VL&lt;sub&gt;w&lt;/sub&gt;)</th>
<th>Axial load ratio</th>
<th>Materials</th>
<th>Longitudinal reinforcement ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>5%</td>
<td>40 MPa</td>
<td>0.53</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>5%</td>
<td>40 MPa</td>
<td>0.53</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>5%</td>
<td>40 MPa</td>
<td>0.53</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>0</td>
<td>40 MPa</td>
<td>0.53</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>2.5%</td>
<td>40 MPa</td>
<td>0.53</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>10%</td>
<td>40 MPa</td>
<td>0.53</td>
</tr>
</tbody>
</table>
The loading and control will be based on a reverse cyclic lateral-displacement protocol in accordance with recent ACI guidelines (ACI 374.1-05 2005; ACI Innovation Task Group 5 2009) and a predetermined M/V ratio. As shown in Figure 2, the M/V ratio is based on an assumed inverse triangular lateral force distribution. A control algorithm has been established to determine the required force in each of the vertical actuators to achieve the required moment at the top of the wall based on the measured lateral resistance, in addition to maintaining a constant axial load applied throughout the duration of the test. Following the completion of these tests, further tests may be conducted using a hybrid test method. Hybrid testing would enable the upper storeys of the RC wall to be modelled to update the moment, shear, and axial load combinations applied to the top of the wall based on the estimated seismic response of the RC wall.

**Finite Element Modelling**

The experimental testing of lightly reinforced RC walls will be supplemented with numerical modelling. Detailed finite element models have been developed using VecTor2 software that is specifically designed for modelling RC components (Wong and Vecchio 2002). An example of the predicted crack pattern in an RC wall with minimum vertical reinforcement is shown in Figure 5a. As expected, the lateral deformation is concentrated at a large crack that opens up at the wall base, eventually resulting in fracture of the vertical reinforcement. The finite element models will be validated using the experimental test data and will then be used to investigate additional variables that were not investigated in the physical tests. These models will allow for a wider investigation of the seismic performance of lightly reinforced RC walls and facilitate verification of the observed performance of several buildings in Christchurch.

![Figure 5 Predicted crack patterns for RC walls modelled using VecTor2](image)

(a) Minimum vertical reinforcement  
(b) 9-storey coupled wall

MODELLING CASE-STUDY BUILDINGS

Numerical modelling is currently being conducted for several Christchurch RC wall buildings. These models will be used to understand the observed performance during the earthquakes, identifying the causes of severe damage to some RC walls and the lack of damage to others. A combination of both detailed finite element modelling using VecTor2, such as that shown in Figure 5, and time-history analysis of entire buildings using ground motion records from the
earthquakes will be conducted. In addition to understanding the observed performance during the earthquakes, the modelling will be used to compare the estimated loads on the RC walls with the typically calculated design loads. Previous research has indicated that the interaction between RC walls and other structural elements may significantly alter the lateral load behaviour of a building (Henry et al. 2012; Waugh and Sritharan 2010). These interactions may result in an overstrength causing a reduction in the expected lateral displacements but also increasing shear and axial demands on walls. The increased shear and axial loads generated on RC walls is not typically accounted for during design and may have contributed to the unexpected failures of some RC walls in Christchurch. The CERC concluded that structural interactions contributed to the failure of the RC wall in the Grand Chancellor Hotel and also that the floor diaphragms may have altered the expected behaviour of diagonally reinforced coupling beams in several buildings (CERC 2012).

A summary of three buildings currently being investigated is given in Table 2. Each of the three buildings represents a different typology, level of performance, and failure mode. However, a common theme is that interactions between structural elements, notably the walls, floor diaphragms, and gravity load elements, may have contributed to the observed performance and damage. Following the development of models of these three case-study buildings a parametric investigation will be conducted to assess the influence of different variables.

<table>
<thead>
<tr>
<th>Building</th>
<th>Number of storeys</th>
<th>Structural system</th>
<th>Observed damage</th>
<th>Point of interest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gallery Apartments</td>
<td>13</td>
<td>Precast concrete walls</td>
<td>Severe</td>
<td>Minimum reinforcement and interaction between walls</td>
</tr>
<tr>
<td>Terrace on the Park</td>
<td>9</td>
<td>RC walls + gravity columns</td>
<td>Severe</td>
<td>Interaction between walls and gravity columns</td>
</tr>
<tr>
<td>IRD building</td>
<td>8</td>
<td>RC core wall + perimeter frame</td>
<td>Minor/moderate</td>
<td>Interaction between elements and overstrength</td>
</tr>
</tbody>
</table>

CONCLUSIONS

Severe damage was observed to several RC wall buildings during the Canterbury earthquakes. A research program has been initiated to understand the observed performance of RC walls during the earthquakes and verify improved design methods and detailing practice. A series of experimental tests of lightly reinforced concrete walls have been planned. An experimental test setup was designed to simulate the seismic loads on the lower portion of a multi-storey RC wall. Additionally, numerical modelling is underway to investigate three case-study buildings in the Christchurch CBD. The models will be used to investigate the influence of interactions between RC walls and other structural elements.

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