Nonlinear parametric analysis of reinforced concrete coupled walls

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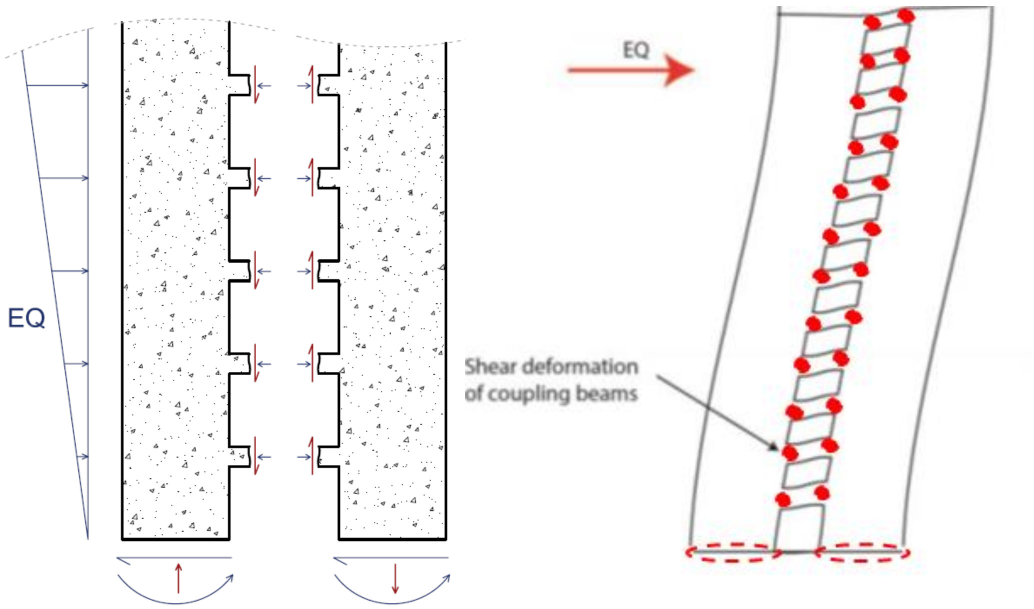
ABSTRACT: Reinforced concrete coupled wall systems can be designed to perform as an effective seismic load resisting system with high levels of energy dissipation. However, during the 2010/2011 Canterbury earthquakes, several coupled walls were found to have not conformed to the inelastic mechanism intended by current concrete design standards. The current NZS 3101 design philosophy for coupled walls follows the capacity design approached, and strength assessment of structural elements is an essential requirement of this method. Following recommendations made by the Canterbury Earthquakes Royal Commission, the draft amendment 3 to NZS 3101:2006 included provisions to account for the axial restraint of the floor when estimating the over-strength of coupling beams. A finite element model was developed to capture the non-linear cyclic response of coupled walls systems and verified against existing experimental results. The model was used to conduct a parametric study to benchmark the effect of the floor systems on the seismic response of coupled walls typical of that built in New Zealand. The key parameters investigated included the wall, coupling beam, and floor dimensions, as well as reinforcement ratios in the wall piers and coupling beams, and foundation beam designs. The results obtained from this parametric study illustrated the increase in the shear capacity and reduction in the axial elongation of coupling beams due to interaction between the floor system and coupled walls, leading to considerable change in the coupling ratio and inelastic response of the wall system.

1 INTRODUCTION

Coupled Wall (CW) systems occur in structural wall with openings that are often governed by architectural requirements. In general, a CW consists of at least two wall piers and a group of Coupling Beams (CB) that connect two wall piers. There is a wide range of available options for CBs, however, the most common CB type is the diagonally reinforced concrete beam. The length to depth ratio of CBs is referred as the CBs aspect ratio. Current building standards recommend the use of diagonal reinforcement for CBs with the aspect ratio less than 4. However, for CBs with the aspect ratio less than 2, diagonal reinforcement is a compulsory reinforcement layout.

The force transfer mechanism in the CW systems is shown in Figure 1-a. The axial force in wall piers is equal to the accumulation of shear forces in CBs. In the design process, the CW is substituted with an equivalent frame system and inelastic behaviour is accounted for by using stiffness modifiers (Paulay & Priestley 1992). Deign forces are determined based on the stiffness of cracked wall piers and CBs. However, at the ultimate state, actions on wall piers depend on the strength of components. The ideal mechanism of CW systems considered in the design process is to ensure that the CBs yield in addition to plastic hinges that form at the base of the two wall piers, as illustrated in Figure 1-b.



a) Force transfer mechanism *b) Ideal inelastic mechanism assumed in design*

Figure 1. Coupled wall systems

During 2010/2011 Canterbury earthquakes, several CWs did not perform according to the intended mechanism considered in the design. It was reported that the CBs did not always yield and were still undamaged when damage was observed to the wall. The Canterbury Earthquake Royal Commission (CERC 2012) made several recommendations and highlighted the possible impact of the floor system on the CW systems. CERC postulated that the floor induced an axial restraint on CBs increases their strength, leading to an increase in lateral capacity and reduction in CB yielding.

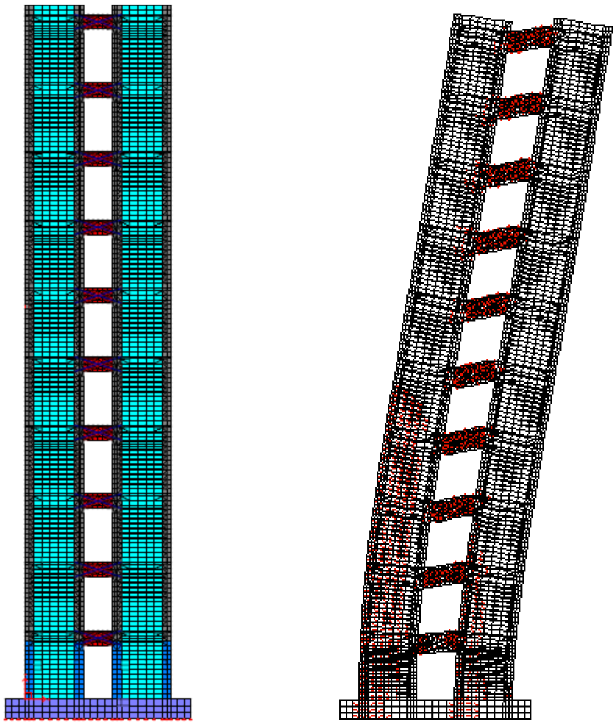
In this paper, a parametric study on coupled wall systems is presented and the response of coupled walls has been investigated through a nonlinear parametric analysis considering the axial restraint induced by the floor. The global response (monotonic pushover) was the primary output to make a comparison between the systems.

2 DETAILED WALL MODELLING AND VALIDATION

In order to model the lateral-load behaviour of CWs and investigate the impact of floor systems on the response of CW systems, a non-linear finite element model was developed in VecTor2. VecTor2 provides nonlinear finite element approaches for reinforced concrete components and reinforcements, developed by University of Toronto, and previously has been used by Mohr (2007), Malcolm (2015) for modelling CW systems.

2.1 Detailed model of coupled wall

The coupled wall systems were modelled in VecTor2 by using shell and truss elements and the finite element package provides a wide range of nonlinear constitutive material models for concrete and reinforcement. Wall piers were modelled by using shell elements and smeared reinforcement layers. Diagonal reinforcement in the CBs was modelled using uniaxial truss element. Figure 2 illustrates the typical CWs model in VecTor2.

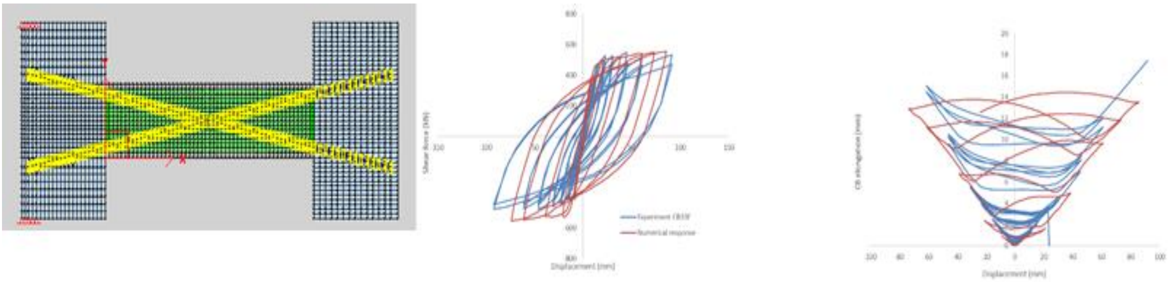


a) VecTor2 typical model *b) VecTor2 visualised output*

Figure 2. Detailed wall model in VecTor2

2.2 **Model Validation**

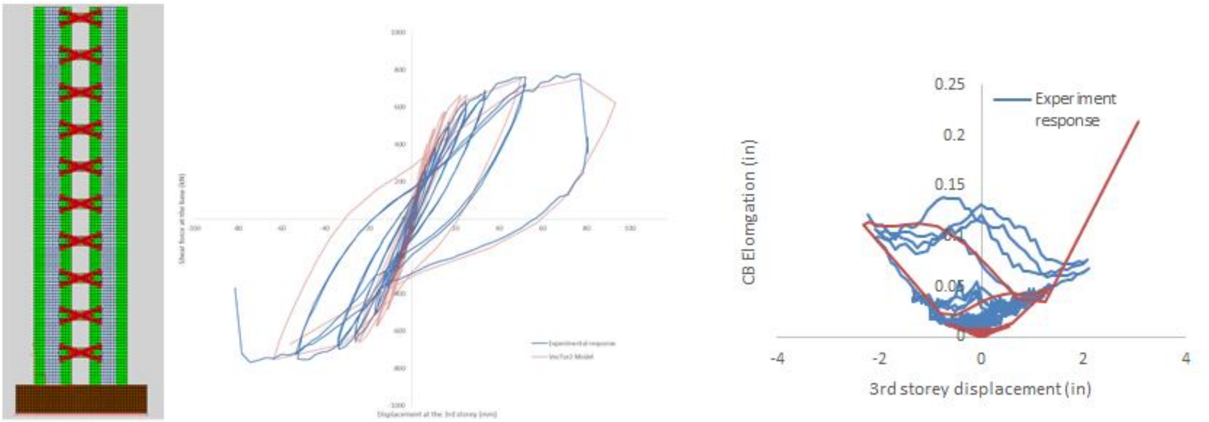
The VecTor2 model was first calibrated by using experimental data of a flexural CB tested by Naish et al (2009). Subsequently, the calibrated model's assumptions and constitutive models were used in the modelling of diagonally reinforced CBs. Two CBs with two different aspect ratios and a CB with the incorporated slab were modelled and validated against the Naish et al. (2009) experimental data. The detailing of these CBs was similar to the current CB's details used in New Zealand. An example comparison between the numerical and experimentally measured responses of the Naish et al. CB is illustrated in Figure 3. The numerically calculated shear-displacement curve and axial elongation of the isolated diagonally reinforced CB demonstrated that VecTor2 provided accurate estimation of the CB response.



a) VecTor2 model *b) CB's global response* *c) CB's elongation*

Figure 3. VecTor2 calculated response of CB compared to the Naish et al. (2009) test response

After validating the numerical model of CBs, the coupled wall system tested by Lehman et al. (2013) was modelled to validate the global response of CWs. In the typical coupled wall model, in addition to global response of the system, local responses of CBs (axial elongations) and their yield points were compared to experimental data and it was concluded that the numerical model can predict global and local responses of CWs with sufficient accuracy. Figure 4 shows that VecTor2 was able to accurately predict the peak strength and the stiffness of CWs and the local response of CBs was successfully measured in the numerical model compared with experimental results.



a) VecTor2 model *b) CW's global response* *c) CB's elongation*

Figure 4. VecTor2 calculated response of CW compared to the Lehman et al. (2013) test response

3 PARAMETRIC STUDY

A set of 10-storey coupled wall systems were modelled in VecTor2. The base coupled wall was designed in accordance with recent NZS 3101:2006 and was reported previously by Malcolm (2015). In the VecTor2 modelling, lateral load distribution was chosen based on NZS 1170.5 and 0.1 *f'c* axial stress on the wall piers at the first storey. The wall piers ranged from 2000 to 5000 mm with the fix storey's height of 3500 mm and wall's thickness of 375 mm. The typical cross section is shown in Figure 5. The key parameters investigated included the wall, coupling beam, and floor dimensions, as well as reinforcement ratios in the wall piers and coupling beams, and foundation beam designs. In this paper, the influence of following parameters on the response of CWs have been highlighted.

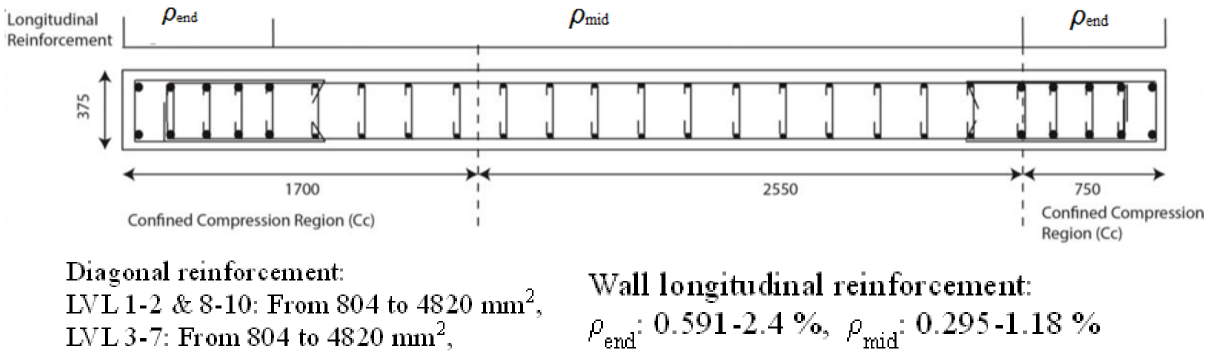


Figure 5. Typical cross section of wall piers (Malcom 2015)

3.1 Highlighted parameters

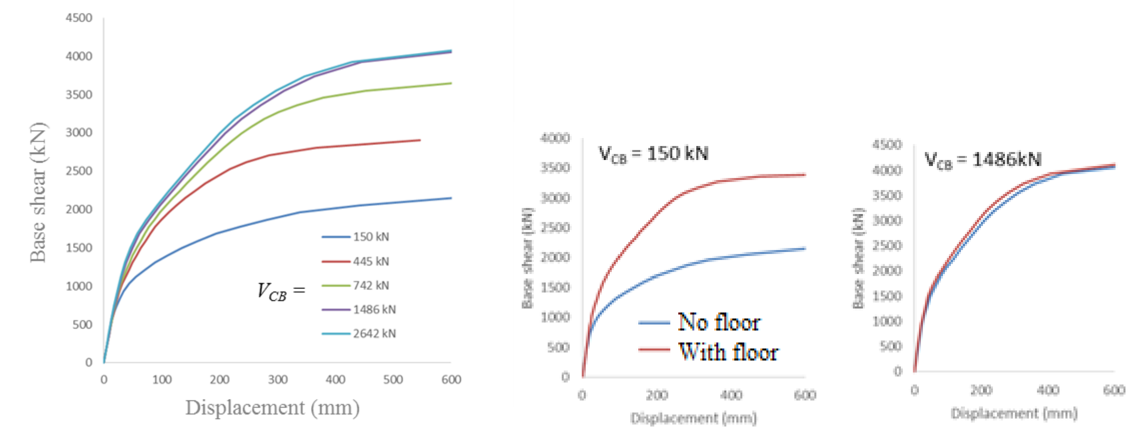
The length to height ratio of CBs (CB's aspect ratio) varied from 0.7 to 4.0 and the shear strength of CBs ranged from 145 to 4500 kN. The floor axial restraint was modelled by using a tensile tie model recommended by Malcolm (2015). The benchmarked was chosen based on Malcolm (2015) typological study on the common floor systems in New Zealand. The benchmarked tie strength of the floor system was 1467 kN with the effective width of 2000 mm for a precast floor system with panels parallel to the CB.

3.2 Global response

Wall piers in a coupled system perform separately when the CBs are weak and in the contrary, CWs with strong CBs perform as a singular cantilever wall (Shui et al 1984). The strength of the coupled system is a function of the axial load imposed on wall piers. The aforementioned force transfer mechanism shows that the axial load imposed on wall piers is equal to the accumulation of CBs' shear

force. Thus, the maximum accumulative shear strength of CBs cannot be higher than the tensile strength of a wall pier. The global responses of the CWs modelled have been divided into three sections based on modification to the CB shear strength, CB aspect ratio, and floor axial restraint.

The influence of CB's shear strength on the global response of CWs, and how the floor effect on CWs is limited is illustrated in Figure 6. As the shear strength of CBs increased, the peak strength of the CWs also increased but plateaued at a maximum strength. The limited increase in CWs strength beyond a CB strength of 1486 kN can be explained by the limited tensile capacity of wall piers. It is apparent that if the accumulative shear strength of CBs exceeds the tensile strength of wall piers, the increase in the shear strength of CBs due to the floor system is ineffective and the CBs cannot yield prior to the wall piers. Examples of the impact of the floor is shown in Figure 6-b and Figure 6-c for two different CB strengths.



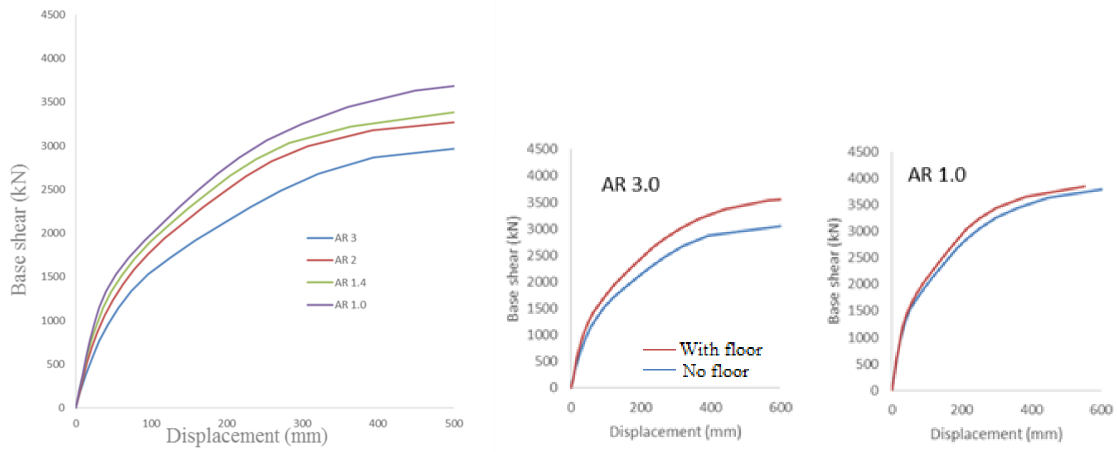
a) Effect of CB's strength on CW's responses

b) Floor impact on CW's response with the weak CB

c) Floor impact on CW's response with strong CB

Figure 6. Effect of CB's shear strength on the global response of CWs

The effect of the CB's aspect ratios when the CB's shear strength remains constant is illustrated in Figure 7a, with examples of the floor impact on two different CW system shown in Figure 7-b and Figure 7-c. The aspect ratio of CBs affected the initial stiffness and peak strength of the CW system. As the CB's aspect ratio decreased, the peak strength and initial stiffness of the CW increased. The increase in the peak strength of CW was again limited due to the tensile limit of wall piers.



a) Effect of CB's aspect ratio on CW's responses

b) Floor impact on CW's response with the high aspect ratio of CB

c) Floor impact on CW's response with the low aspect ratio of CB

Figure 7. Effect of CB's aspect ratio on the global response of CWs

The global responses of CWs as the function of axial restraint force induced by the floor system is

illustrated in Figure 8. The impact of the axial restraint level on the global response of the benchmarked CW demonstrated that the low levels of axial restraints could increase the peak strength significantly, however, this increase is a dependent of CB and wall pier strength.

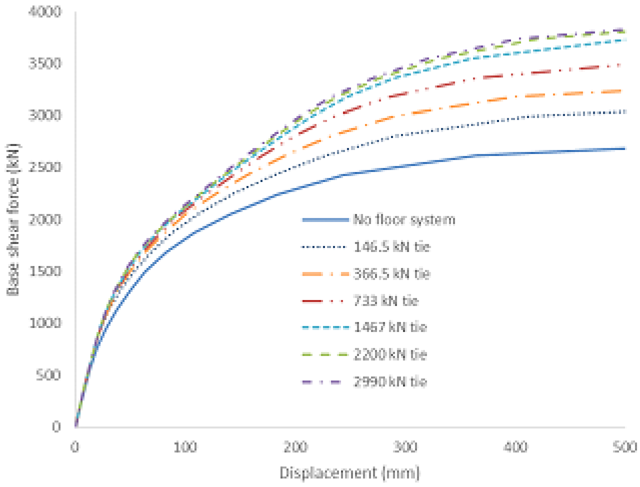


Figure 8. Effect of CB's axial restraint on the global response of CWs

4 CONCLUSION

According to modelling presented, the impact of the axial restraint induced by the floor system on global response of coupled wall system is rational and depends on wall pier and coupling beam strength. The floor system can considerably increase the lateral load capacity of coupled wall systems and consequently the wall shear demands and foundation demands. Variation in diagonal reinforcement and the axial restraint force does not affect the stiffness of coupled wall systems and the stiffness is mainly influenced by geometrical details, i.e. coupling beams aspect ratio and dimensions of the wall piers. Furthermore, it has been observed that depending on wall pier and coupling beam strength, low levels of the axial restraint of coupling beams (10% of benchmarked axial restraint in this study) could increase the demand on the foundation significantly. Thus, it can be concluded that modelling the floor axial restraint is a crucial factor to perform an accurate seismic analysis of buildings with coupled wall systems.

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