The 14th World Conference on Earthquake Engineering
October 12-17, 2008, Beijing, China

EXPERIMENTAL INVESTIGATION ON THE INTERACTION OF REINFORCED CONCRETE FRAMES WITH PRECAST-PRESTRESSED CONCRETE FLOOR SYSTEMS

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ABSTRACT :

A three dimensional, approximately half scale experimental test has been carried out to investigate the effect of precast-prestressed floor units on the seismic performance of reinforced concrete moment resisting frames. This paper gives an overview of the experiment and summarizes the results obtained from the test. The paper focuses on the level of strength enhancement and elongation within the plastic hinges. The results show that the presence of prestressed floor units partially restrains elongation of plastic hinges such that elongation in the exterior and interior plastic hinges differs significantly. This increases the strength of the beams more than that specified in the major structural design codes. This is a cause of great concern as this underestimation of beam strength may result in brittle column failure modes in a major earthquake.

KEYWORDS: Reinforced concrete moment resisting frames, precast-prestressed concrete floor, beam elongation, flange effect, strength enhancement

1. INTRODUCTION

Under the capacity design philosophy, plastic hinges in reinforced concrete (RC) moment resisting frames are allocated in beams so that a ductile beam sway mechanism will develop in preference to other less ductile modes such as a column sway mechanism in a major earthquake. This approach requires the columns to resist the maximum actions from the over-strength of the beam plastic hinges. Therefore the determination of the maximum likely flexural strength (over-strength) of plastic hinges in beams is a critical issue for the design of moment resisting frames.

For beams where there is no composite action with floor slab, the flexural strength and the over-strength of the plastic hinges can be calculated using standard flexural theory. For beams coupled with cast-in-situ floor slab, the negative flexural strength of the beam increases significantly due to elongation of the plastic hinges and its interaction with the floor slab (Jirsa 1991). To accommodate this, an effective width of the floor slabs is assigned to calculate the negative flexural strength and over-strength of the beams. This is commonly referred to as ‘flange effect’. Empirical equations accounting for the strength enhancement were developed based on those experimental results. These equations were later adopted by the New Zealand Concrete Structures Standard (NZS3101:1995) and ACI concrete code (ACI318-95).

More recently, large scale experimental studies of moment resisting frames coupled with precast-prestressed flooring systems in New Zealand have shown that the presence of the prestressed floor units increases the strength of the beams more than those specified in the codes where cast-in-situ slabs are used (Fenwick et al. 2006). The level of strength enhancement varies with different structural arrangements used in the tests. This strength enhancement in some cases was due to prestressed floor units, spanned pass a column, providing additional localized restraining force to elongation of the plastic hinges. In other cases, the prestressed floor units, supported on transverse beams, confined the major cracks to the weak sections at the supports and forced the floors to bend like two deep beams providing additional global restraining force as illustrated in Figure 1 (Fenwick et al. 2005).

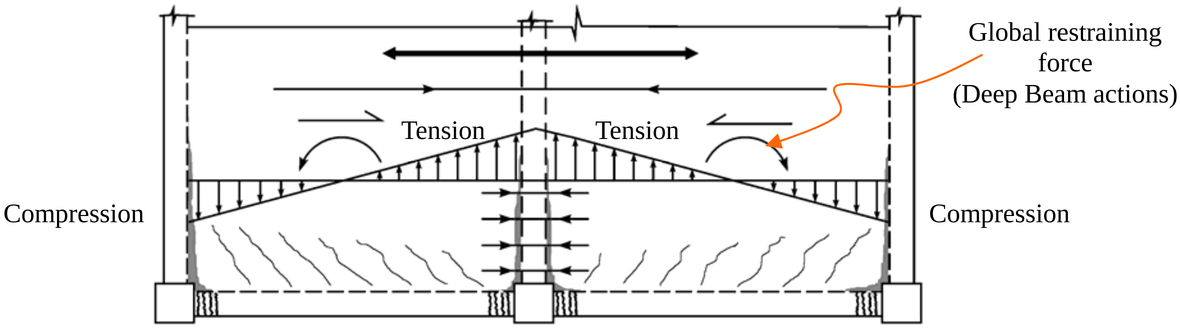


Figure 1 Deep beam actions and crack pattern in floor slabs

While the tests conducted in NZ gave some insight into the level of strength enhancement expected to occur in frames with prestressed floor units, they can not by themselves be used to develop satisfactory design rules due to wide range of structural arrangements and prestressed flooring systems used in practice. Repetitive experimental studies on this topic would be complex, time and resource consuming, therefore numerical simulation provides a more feasible alternative.

To analytically simulate the strength enhancement of beams with cast-in-situ slabs or prestressed flooring units, the model must be able to predict elongation response of plastic hinges as well as its interaction with the flooring units. However, there is currently no analytical model that can accurately predict the elongation response. Therefore, a research is underway at the University of Canterbury to develop an analytical model that can reliably predict the seismic performance of RC frames. The initial steps in the development of the plastic hinge model and its experimental verification for cantilever beams and moment frames are summarized elsewhere (Peng et al. 2007; Peng et al. 2008).

An approximately half scaled, 3D sub-assembly test of a two-bay reinforced concrete frame containing precast-prestressed floor units was carried out as part of this research to further investigate the mechanisms associated with floor-frame interaction as well as to provide complete experimental data for 3D validation of the analytical model. This paper summarizes the results obtained from the experiment with the main focus on elongation, flexural strength and over-strength of beam plastic hinges.

2. EXPERIMENTAL PROGRAMME

2.1. Description of the Sub-assemblage

The test unit and the key details of the members are illustrated in Figure 2. It consists of a two bay moment resisting frame with transverse beams connected into each column. The flooring system consists of 100mm deep precast prestressed Stahlton™ ribs spaced at 500mm centers with 45mm cast-in-situ concrete topping. Grade 300 deformed 10mm bars at 210mm centers in both directions are placed in the topping. These bars are lapped with the same size starter bars along the transverse and perimeter beams. The rib units are supported on low friction bearing strips and 40mm ledges on the transverse beams. The floor is connected to a 175mm thick heavily reinforced end slab to represent the stiff continuation of floor diaphragm in the rest of the building. The column was designed to remain elastic during the test to ensure the maximum strength of the beam plastic hinges could be developed.

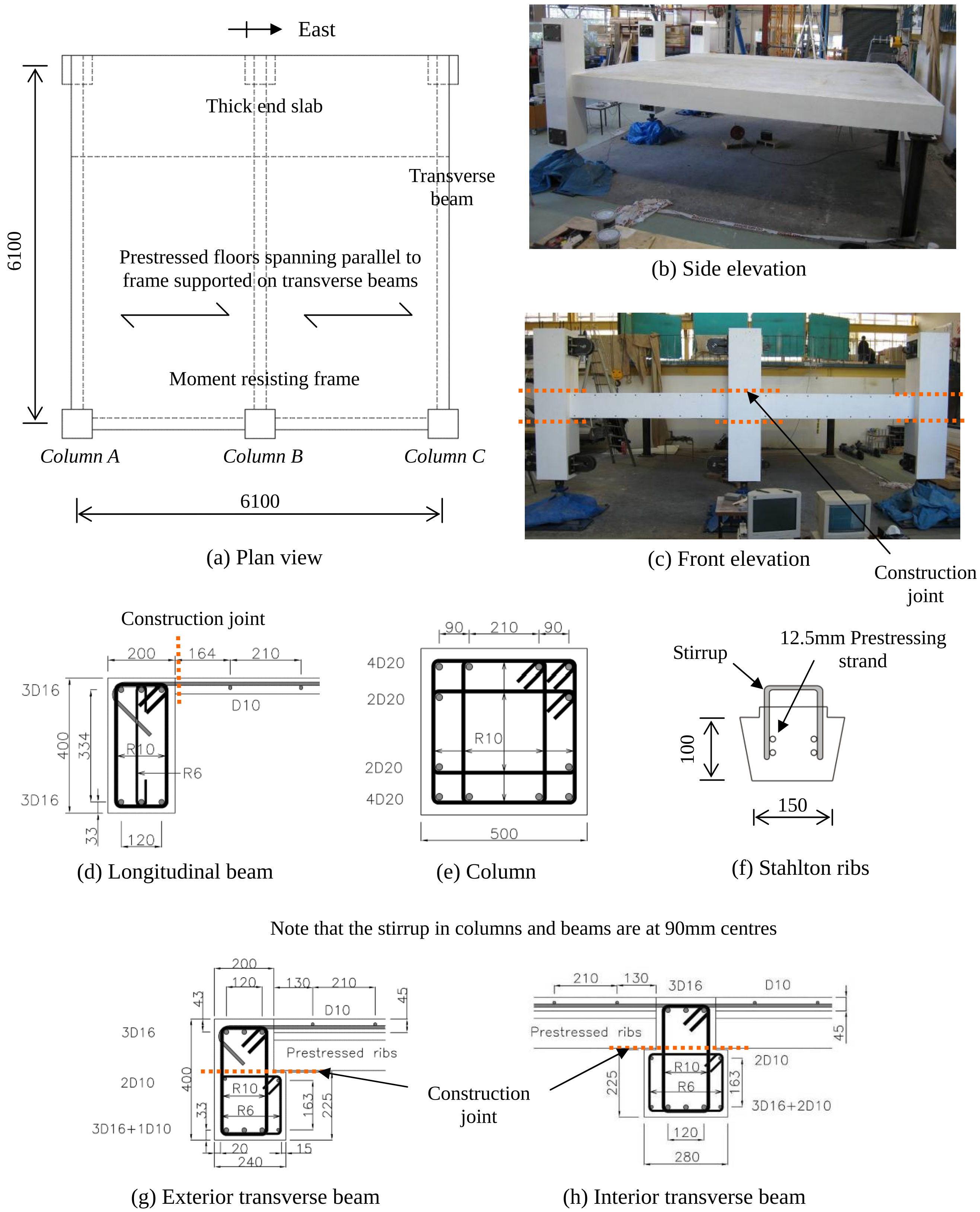


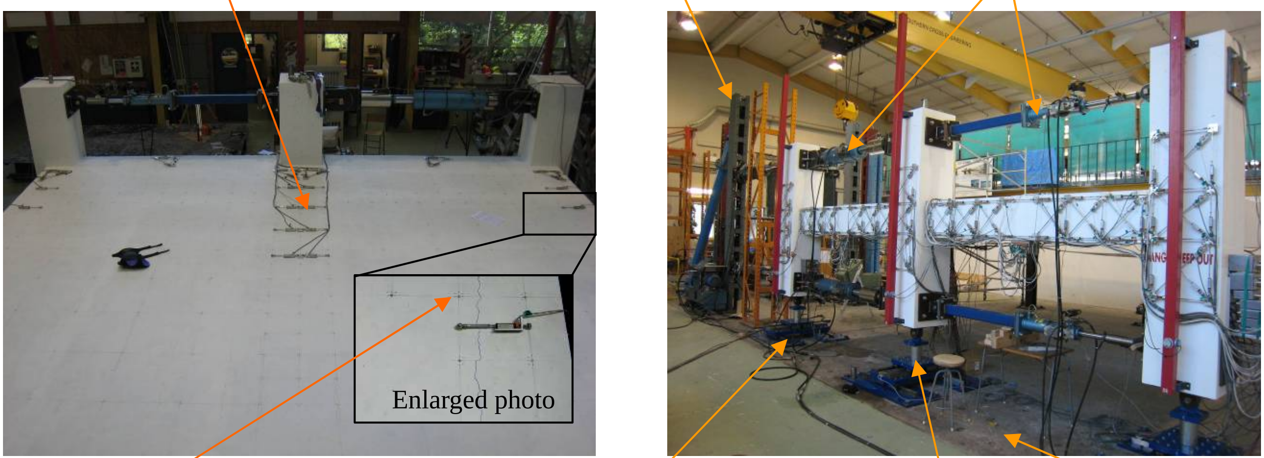
Figure 2 Details of key structural members

The test unit was built in four stages. Initially, three bottom columns with longitudinal reinforcement protruding; three half height transverse beams; and full depth longitudinal beam including beam-column joints that contained ducts to allow the column reinforcement to pass through were precast. Next, the columns and the longitudinal beam units were assembled and the beam-column joints were grouted. The top of columns and the lap splice between the transverse beam and the columns were then cast-in place. Finally, the prestressed ribs were placed between the transverse beams and the floor topping, end slab and the rest of the transverse beams were poured.

The concrete cylinders were cured alongside the test unit. The averaged concrete compressive strength measured at the start of the test for the three different casts was 31.2, 42.4 and 33MPa respectively. The averaged yield stress of the D10, D16 and D20 reinforcing bars was 373, 365, 319MPa respectively.

2.2. Test Setup and Instrumentation

The sub-assemblage is extensively instrumented in order to gather as much information as possible on the force-displacement responses of the test unit, deformation of the beams, columns, beam-column joints and floor slab. The forces were measured using load cells and the deformations were measured using linear potentiometers, rotary potentiometers, inclinometers, sonic displacement transducers and DEMEC gauges. The instrumentation and the test set up are illustrated in Figure 3. The columns were supported on two way linear bearings, allowing movement in the horizontal plane. The exterior transverse beams were supported on steel column with one way linear bearing for floor movement parallel to frame and the central transverse beam was supported on ball bearings allowing movement horizontally.



(a) Instrumentation on the floor (b) Test setup and instrumentation of the frame

Figure 3 Test set up and instrumentation

2.3. Loading Sequence

The loading was displacement controlled; quasi-static cyclic loading was applied to the top and bottom of each column through six hydraulic rams. The loading history started with two elastic cycles at 0.25%, 0.35% and 0.5% drift. These elastic cycles were applied to check the loading rig, the data loggers and the overall elastic behavior of the frame. Following these elastic cycles, the peak displacement was increased gradually in increments of 0.5% drift until the maximum lateral force in the frame has dropped by more than 35%. In general, two large cycles and a small cycle, equal to 30% of the large cycle amplitude, were applied.

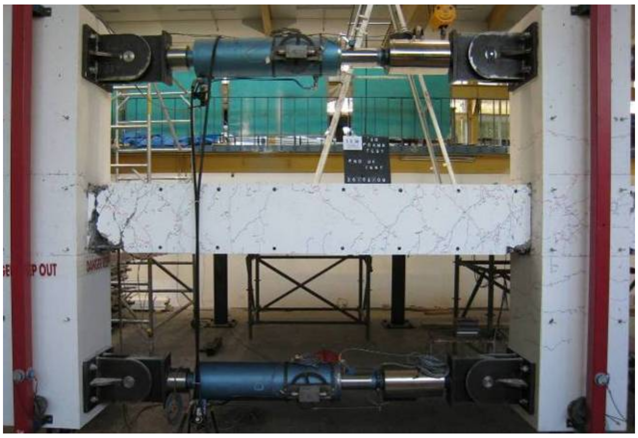
The displacements at the top and bottom of columns were corrected iteratively within each loading increment to ensure that beam elongation is not restrained or exaggerated; the columns remained parallel to each other; and equal and opposite shear forces were applied to each column during the test.

3. EXPERIMENTAL RESULTS

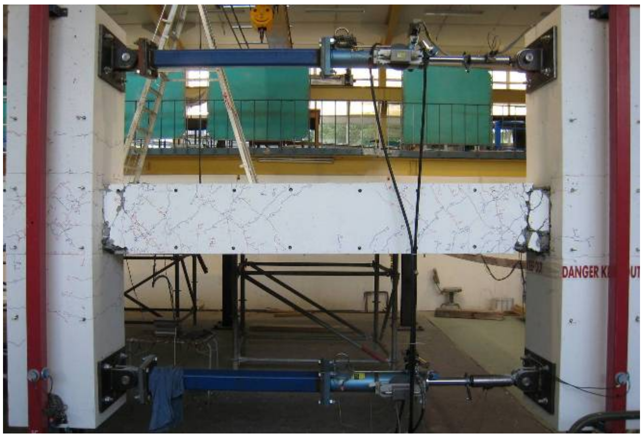
3.1. General Observations

First sign of cracking in beams and floor slab occurred at 0.25% drift. Minor cracking in the columns and prestressed floor connections appeared at 0.35% drift. Diagonal cracks developed in the beams and floor slabs at 0.5% drift. First sign of yielding occurred at 0.75% drift. At 1.0% drift, torsional cracks developed in the transverse beams and the differential movement between slabs and beams became apparent. Spalling in the exterior plastic hinges occurred at 2.0% drift. The reinforcement in the exterior plastic hinges buckled at 3.0% drift and fractured at 3.5% drift. At 4.5% drift, the total force had dropped by 35% and the test was terminated.

Photographs showing the damage in the structure at the end of the test are illustrated in Figure 4. It can be seen from Figure 4 (a) to (f) that the region around the exterior plastic hinges suffered much more damage than region around the interior plastic hinges. This is due to deep beam action providing additional restraining force to the elongation of interior plastic hinges.

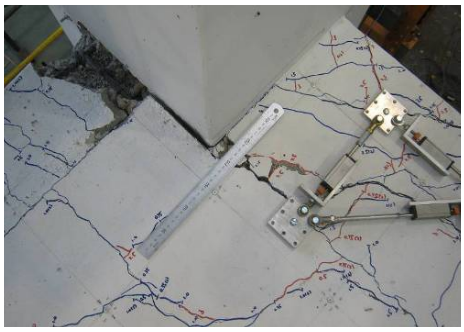


(a) Damage between *Column A* and *Column B*

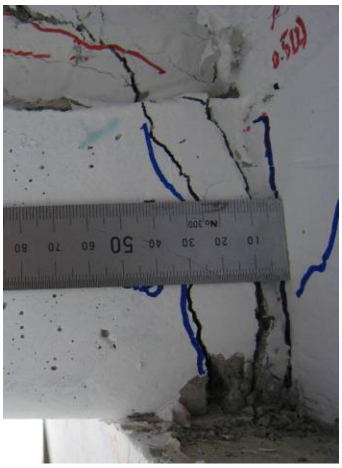


(b) Damage between *Column B* and *Column C*

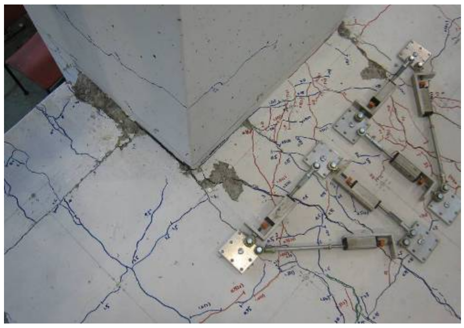
(e) Damage around the exterior column



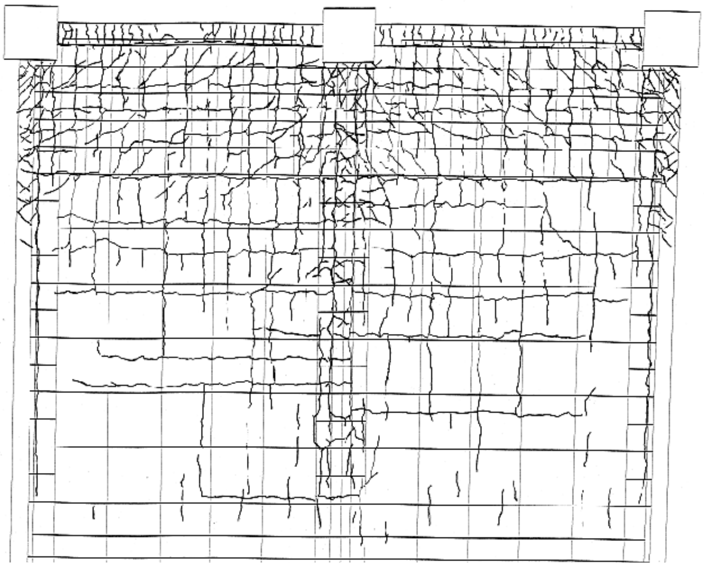
(c) Prestressed floor connection next to exterior plastic hinge



(d) Prestressed floor connection next to interior plastic hinge



(f) Damage around the interior column



(g) Crack pattern on the top of the floor

(h) Torsional cracks in the transverse beam

Figure 4 Permanent damage observed at the end of test

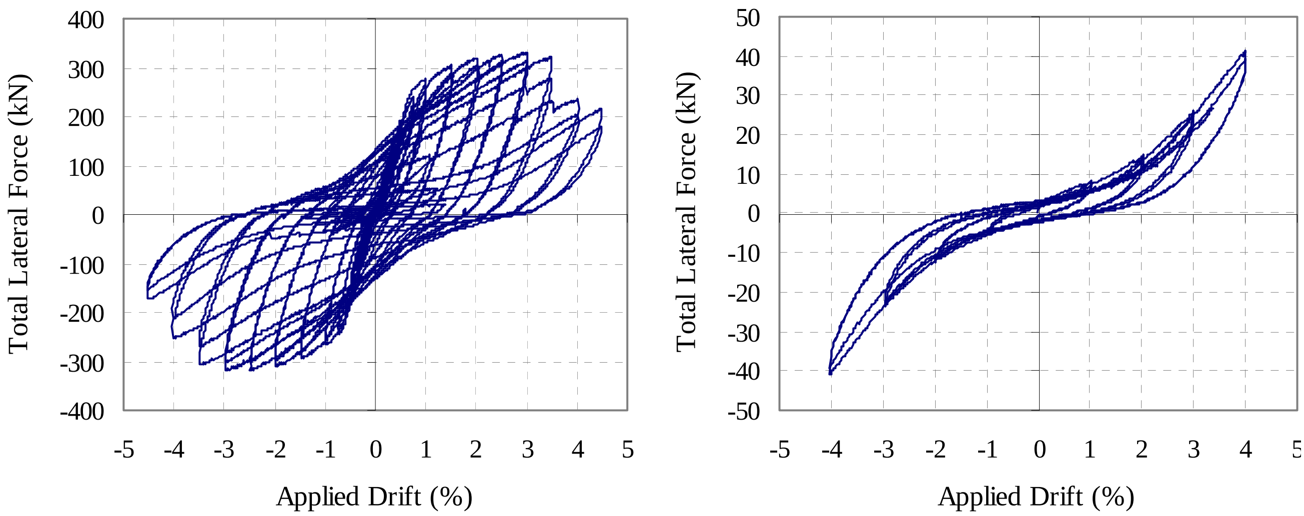
The columns and beam-column joints only sustained minor damage as they were designed to remain elastic. The overall crack pattern on the floor slab is illustrated in Figure 4 (g). It can be seen that there are many cracks forming parallel, perpendicular and diagonal to the frame. It should be noted that all the diagonal cracks were inclined towards the interior column implying that the floor is restraining elongation of the plastic hinges. Moderate torsional cracks formed in the transverse beams can be observed in Figure 4 (h). This indicates that the transverse beams may have provided some resistance to the strength of the moment frame.

3.2. Force-displacement and Elongation Response

The total column shear force and column drift response of the frame is plotted in Figure 5a. Figure 5b shows the lateral force contribution from torsional resistance of the transverse beams. The values were obtained in a follow up test where the longitudinal beams between the columns were removed and the displacement history was re-applied to the columns. A breakdown of the theoretical and experimental shear force in each column for the positive drift cycle (i.e., top of the column moving eastward) is summarized in Table 1. In this case, the shear force in *Column A* and *Column C* correspond to the positive and negative strength of the plastic hinges respectively where as the shear force in Column B correspond to the combination of positive and negative strength of the plastic hinges in the two sides of the column.

The gravity load imposed on the longitudinal beam is assumed to be the self weight plus 150mm wide topping slab. This gives a shear force of 2.65kN at the column face. The provision for calculating the flexural strength of T-beam with flange on one side only in ACI318-05 resulted in an effective flange width of 210mm. This provision was based on beam-column experimental results at 2.0% drift (Jirsa 1991). To design the flexural strength of columns, an over-strength value of 1.2 is specified. The corresponding column shear force is given in rows 2 and 3 in Table 1. According to NZS3101:2006, the effective flange width for calculating the theoretical strength is 360mm. A larger effective flange width is specified for calculating over-strength. The corresponding column shear force is summarized in rows 4 and 5 in Table 1.

It can be seen from the comparisons that the theoretical and over-strength of the beams specified in both the ACI and NZ codes are un-conservative. The ACI code under predicts the beam over-strength by 29% at 2.0% drift and 34% at 3.0% drift. Whereas the NZ code under predicts the over-strength by 17%. Breaking it down to each individual column, it can be seen that the ACI code under estimates both the positive (*Column A*), and negative (*Column C*) strength of the beam plastic hinges. The recent changes in NZS3101:2006 allow for the strength enhancement in negative plastic hinges and it can be seen that the negative strength calculated using NZS3101:2006 matches well with the experiment. However, it under estimates the positive and combined strength of the plastic hinges. The increase in the negative strength can be attributed to the participation of the floor slab. However, more research is required to establish the reason of positive strength enhancement. The level of strength enhancement is of great concern to the engineer as column sway mechanisms may occur in the event of a major earthquake.



(a) With longitudinal beams (b) Without longitudinal beams

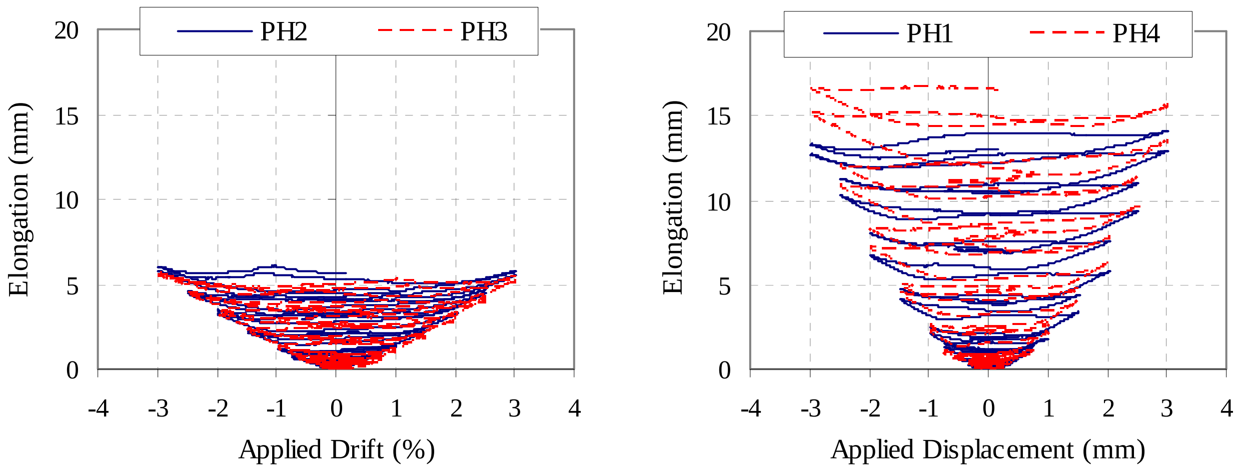
Figure 5 Overall force-displacement relationship of the frame

Table 1 Summary of the experimental and calculated strength

	Averaged individual shear force (kN)			Total averaged shear force (kN)
	Column A	*Column B*	*Column C*	
ACI theoretical strength	49.7	103.9	54.2	207.8
ACI over-strength	59.7	124.6	64.9	249.2
New Zealand theoretical strength	51.0	109.2	58.2	218.4
New Zealand over-strength	58.0	145.9	82.4	286.3
1st cycle at +0.75 % drift (yield strength)	62.4	119.1	59.7	241.2
1st cycle at +2.0 % drift	74.7	163.3	82.9	320.9
1st cycle at +3.0 % drift (maximum strength)	76.4	171.6	85.6	333.6
Contribution from transverse beams at +3.0 % drift	5.0	15.0	5.0	25.0

The contribution of the transverse beams to the strength of the frame at 3.0% drift is given in the last row in Table 1. Note that as the transverse beams have already cracked, the actual contribution of the transverse beams to the strength of the frame would be greater than that specified in the table.

Elongation in the exterior and interior plastic hinges before buckling of reinforcing bars is plotted in Figure 6. It can be seen that the measured elongations in the exterior plastic hinges are much more predominant than those in the interior plastic hinges. This can be attributed to deep beam action of floor slabs as mentioned earlier and illustrated in Figure 1 where additional global restraining force is applied to the plastic hinges adjacent to the interior column.



(b) Elongation in the interior plastic hinges (c) Elongation in the exterior plastic hinges

Figure 6 Elongation histories of the interior and exterior beam plastic hinges

5. CONCLUSIONS

The experimental results in this paper have highlighted the importance of floor participation in the overall strength of the lateral moment resisting system. It has shown that both the ACI and NZ concrete codes under-predict the flexural strength of the beams where precast-prestressed flooring is used. The level of strength enhancement from floor participation is of concern as it may lead to an undesirable column sway mechanisms in an earthquake. Further research is required to examine the mechanisms associated with the interaction between prestressed flooring and moment frames. An analytical model is currently being developed to predict this behavior.

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