# SLAB EFFECTS ON BEAM-COLUMN SUBASSEMBLIES - BEAM STRENGTH AND ELONGATION ISSUES

Gregory MacRae
Department of Civil and Natural Resources Engineering, University of Canterbury
Christchurch 8140, New Zealand
gregory.macrae@canterbury.ac.nz

Michael Hobbs
Department of Civil and Natural Resources Engineering, University of Canterbury
Christchurch 8140, New Zealand
michael.hobbs@pg.canterbury.ac.nz

Des Bull
Department of Civil and Natural Resources Engineering, University of Canterbury
Christchurch 8140, New Zealand
des.bull@pg.canterbury.ac.nz

Tushar Chaudhari
Department of Civil and Natural Resources Engineering, University of Canterbury
Christchurch 8140, New Zealand
tushar.chaudhari@pg.canterbury.ac.nz

Roberto Leon
Virginia Tech
Blacksberg, Virginia, USA
rleon@vt.edu

Charles Clifton
Department of Civil and Environmental Engineering, University of Auckland
Auckland, New Zealand
c.clifton@auckland.ac.nz

Geoff Chase
Department of Mechanical Engineering, University of Canterbury
Christchurch 8140, New Zealand
Geoff.chase@canterbury.ac.nz

## ABSTRACT

This paper describes the effect of composite slabs in increasing beam strength and its implications for design. It also discusses the “beam-growth” phenomena, which can detrimentally influence the performance of a frame with reinforced concrete or precast concrete beams, and its impact on steel beams with RC slabs. From the subassembly testing conducted the slab increased the beam strength by around 40%. However the slab could not maintain strength at large drifts without degradation with transverse or longitudinal decking placed around the columns. This indicates that while transverse or longitudinal slabs should not be considered in design to size the beam, they should be considered in the beam overstrength calculations for the design of other members. Also, both rational considerations and experimental results

indicate that beam growth effects tend to be small for composite steel beams because the steel beams are able to yield in both tension and compression.

## SLAB ISSUES

A. Slab Effects on Subassembly Strength and Degradation

Steel beams in buildings in seismic regions generally support a floor slab. While the effects of this slab are generally ignored in specifications around the world, New Zealand design specifications require the slab effect to be considered in capacity design to determine column sizes.

It was hypothesized that:

a) For isolated/separated slabs, slab effects should not be considered in beam strength design to resist the lateral forces or in overstrength design, but axial force effects on the beam from the slab may be significant.
b) For slabs which are full depth for a significant distance (say equal to the beam depth) from the column face, a strut-and-tie approach is used to reinforce that area, and which has sufficient confinement, then the slab effect could be considered both in beam strength design to resist the lateral forces and in overstrength design.
c) For slabs which are placed in contact with the column face, but without special attention to design and detailing, that the current NZ design approach should be continued to be used where the slab effect is not considered for beam strength design to resist the lateral forces, but it is considered in overstrength design.

Cases (a) and (c) above are self-explanatory. The means of providing the reliable strength through large deformations in (b) is consistent with NZS 3404 Clause 13.4.11.3.3(b) for composite beams expected to sustain large seismic demands which *states the slab should be reinforced and confined so that the steel beam can reach a maximum tensile strain of 24 times the yield strain before developing the nominal compression capacity of the concrete and compression reinforcement. Here the maximum compressive concrete strain reached is not permitted to be any more than 0.004*. References regarding possible means of achieving this are given in the commentary to this clause, but it is not known if this option has ever been used in practice. There also similar to recommendations by AISC (2009) for partially restrained composite members for a full depth reinforced slab, but there is no specific confining requirement. Some means of providing the strut-and-tie and confinement effects are discussed below.

i) A strut and tie mechanism

A slab strut-and-tie mechanism is necessary in order to resist the force applied by the column to the slab. Such a mechanism is shown by Umarani et al. [2008] for a reinforced concrete column as shown in Figure 1. Here, the concrete provides the compressive diagonal struts as the column tries to push the slab on either side of the column apart, and the longitudinal and transverse steel (provided by well anchored rebar or continuous decking) provide tension. The reason for the pushing of the slab apart is described in the beam-elongation section below.

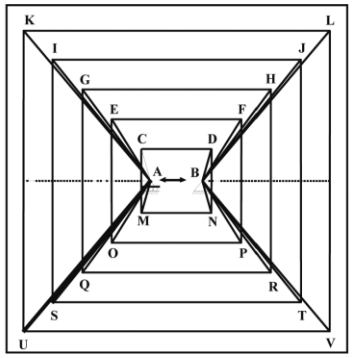



Figure 1. Strut and Tie Mechanism for Slab-Column Interaction [Umarani et al. 2008]

ii) Prevention of slab shear/spalling failure

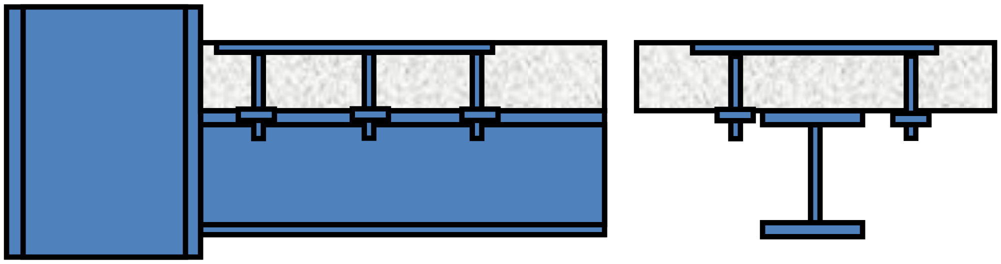
When the column pushes against the slab, the slab will only carry the load if it the concrete does not lose strength through an axial stress, shear stress or spalling failure.

A typical slab is confined on three sides – below and on the two sides. There is generally no confinement on the top, so the stress and strain associated with the initiation of spalling can be conservatively considered to be the unconfined concrete crushing strength $f'_c$ and $\varepsilon_c$ = 0.002 respectively. As a result of this, two possible ways to determine the likelihood of spalling are given below.

The likelihood of spalling can be assessed simply from ***strength considerations***. The force on the slab may be as great as that caused by axial yielding of the beams, which is $\Sigma A_s f_y$, where $A_s$ is the area of the steel beam cross-section and $F_y$ is the steel yield stress It may be slightly less than this as a result of axial forces being carried in the beams, and as a result of sharing of force between the outside of the column and that carried on the inner flange. If the beam axial yield force is greater than $A_c f'_c$, then there is a possibility of yielding. Here $A_c$ is the area of the concrete slab bearing on the outside of one of the column flanges and $f'_c$is the compressive cylinder strength of the concrete at the time of testing.

Alternatively, the likelihood of spalling can be understood from ***strain compatibility considerations*** as follows. Unconfined concrete stress-strain curves indicate the unconfined stress of the concrete reaching the crushing strength $f'_c$ which occurs at a concrete strain of about 0.002. The displacement imposed at the top of the concrete, $\Delta_c$, may be estimated as the inelastic rotation of the plastic hinge multiplied by the distance from the neutral axis to the top of the concrete slab. The position of the neutral axis may be found from standard methods allowing for composite action. The strain in the stab may conservatively be estimated as the displacement divided by the length over which this strain occurs. In standard NZ design, the slab is disconnected from the beam over a distance of 1.5 times the depth of the steel beam (1.5*d*) from the column face. At the end of this length, 1.5*d*, the slab is connected by shear studs which can deform. If they are conservatively assumed to be rigid, then the strain, $\varepsilon$, is $\Delta_c/(1.5d)$. If this is less than 0.002, then there is little likelihood of spalling failure.

The deformation capacity of the subassembly and slab may be increased by increasing the strain capacity within the concrete slab, through confinement of the top of the slab. One way it could be accomplished is by placing a plate over the top of the slab and tying it down as shown in Figure 2. Note that the tie-downs do not go through the beam member, as this is subjected to severe inelastic deformations and any hole or discontinuity in this plastic hinge region could lead to failure.

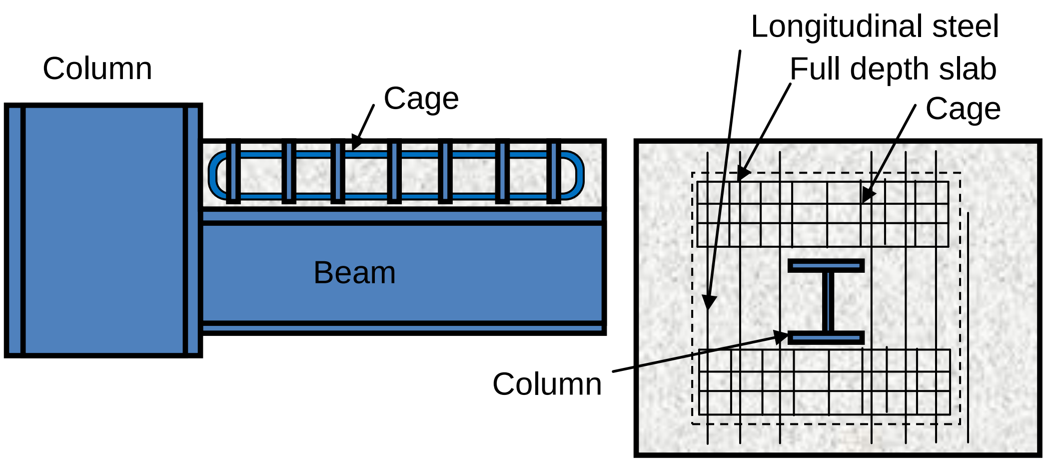


(a) Side View (b) End View

Figure 2. Slab Confinement with a Plate

Another way of providing confinement involves placing a steel cage in the slab placed in front of the column in a region of full-depth slab around the column as shown in Figure 3. This has the advantage of not only confinement of the concrete, but it also works as part of the truss mechanism with longitudinal steel. (The longitudinal and transverse steel is not shown in Figure 3a and transverse steel is not shown in Figure 3b). This concept was also advanced in Section 13.3.5 of the HERA Design Guides Volume 2 (referenced from NZS 3404 Part 2 C13.4.11).

Both of these configurations are being considered as part of the research program of Tushar Chaudhari at the University of Canterbury.

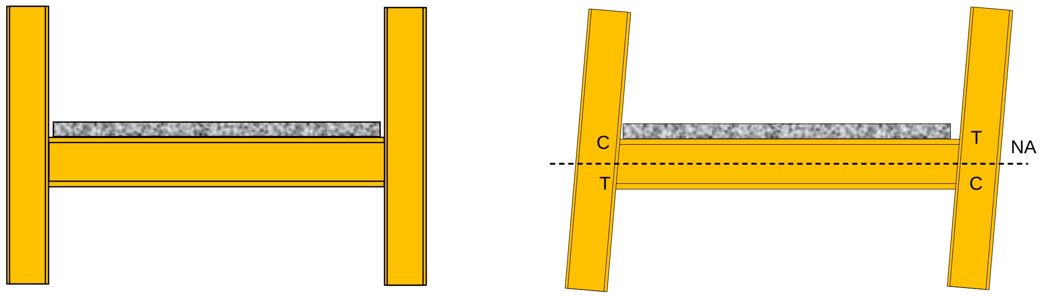



(a) Side View (b) Plan View

Figure 3. Slab Confinement with a Reinforcing Cage (Chaudhari)

B. Slab Effects on Beam Growth

Beam growth occurs in reinforced and prestressed concrete structures and full description of this phenomena is given by MacRae and Clifton (2013). It causes damage the slab and it can push columns apart causing additional demands on the steel frame. This is because the concrete structures carry load well in compression, but tend to crack/gap in tension. The situation for steel structures is quite different when the slab is separated from the column face to prevent contact during the lateral deformations as shown in Figures 4a and 4b. Here the top of the beam lengthens due to both elastic and plastic deformation. Similarly, the bottom of the slab shortens by the same amount so the theoretical beam growth, measured at the beam centerline, is approximately zero. During displacement in the reverse direction, the lengthening and shortening at the top and bottom of the column are recovered and the top and bottom shorten and lengthen respectively. Another way of stating it is that the neutral axis of the steel beams is at the steel beam centroid so there is unlikely to be any significant beam growth (or shortening) during all stages of testing until effects such as buckling become significant.



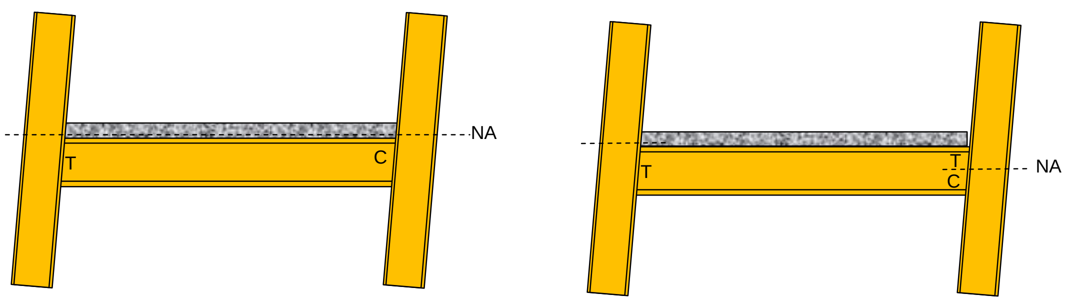

(a) As-built (b) With lateral deformation

Figure 4. Steel Beam with Slab Separated from Column

If the slab touches the columns, and is strong in tension and compression, the neutral axis may be in the slab and the beam will yield axially in tension and compression as shown in Figure 5a. Since it is the elongating on the left hand side, and shortening on the right hand side, the net effect is that the columns remain the same distance apart and there is zero beam elongation.

If the slab is not strong, then the neutral axes at the different ends of the beam are at different heights as shown in Figure 5b. Here, the neutral axis due to flexure is on the right hand side is through the centre of the beam, while that on the left-hand side of the beam may be in the slab. This would imply more tension yielding at the centre of the beam than compression yielding and some net elongation. This elongation would be expected to be much less than that of a concrete beam where cracks/gaps open at both ends of the beam.

It should be noted that in the discussion above, the neutral axis position due to flexure is considered to be significant. It will also vary somewhat due to the horizontal axial force being transferred from the inertia forces of the beam and slab, through the connections at the end of the beam to the column and this may make some difference to the elongations discussed above.




(a) Strong Slab Around Column (b) Weak Slab Around Column

Figure 5. Deformation of Steel Beam with Different Strength Slabs

## BEHAVIOUR OF TEST UNITS

A series of full scale beam-column-joint-slab subassembly tests were recently conducted at the University of Canterbury to quantify the effects of slabs under cyclic loading [Hobbs et al. 2013, Hobbs 2013]. Specimens tested have haunched moment end plate connections as shown in Figure 6. The height of the column between loading and reaction pins was 2.0m. The beams were two 3m 310UB32 sections connected to a 2m tall 310UC158 column using bolted moment-endplate connections. Panel zone doubler plates were used. All steel was specified to be Grade 300. The ends of the half beams were pinned to represent the point of inflection of the full length beam whilst the column was pinned at its base and a ram mount located 2m from the base pin centreline.

ComFlor 80 profiled sheet steel decking was used with a total slab depth of 150mm and slab dimensions of 6m by 3m. The decking was connected to the main beams with two 125mm×19mm diameter shear studs every 300mm. Where secondary beams were used one shear stud was provided every 300mm. No studs were placed over the length of beam 1.5 times the beam depth from the column face. Reinforcing steel provided included SE82 seismic mesh across the whole slab and 1.5m lengths of D10 bar centred across beams at approximately 100mm centres in the direction of the deck tray. Further reinforcing was provided around the column opening in the slab as per ComFlor recommendations (Corus 2005). The target strength for the concrete was 30MPa.

The units with different deck configurations are described in Table 1. The isolated unit was separated from the column by 25mm polystyrene glued to both sides of the column flanges, but it was still in contact with the web and the end of the haunch implying that the column was not fully isolated. While isolated connections are simple to consider, axial forces from the slab through the beam onto the columns should also be considered in design. The transverse units had the deck placed transverse to the column. The outside of the column flanges beared against the full depth of concrete both sides with the distance to the beginning of the trough being about 30mm. In the full depth test unit, a square area of full depth slab was placed 300mm from the column making an area of approximately 910mm x 910mm which is in effect a “column capitol”. In this unit, extra reinforcing in the full depth portion of the slab was 2 D10's across each column face as recommended by Comflor.

The test protocol was that in Figure 6 [ACI, 2001].

Table 1. Unit Descriptions and Failure Mode

| Unit | Deck Tray Direction (to main beams) | Concrete Detailing | Behaviour |
|---|---|---|---|
| Isolated | Transverse | Separated from column | Beam buckling at 3.5% drift |
| Transverse | Transverse | Poured up to column | Beam buckling at 2.5% drift. Slab spalling at 3.5% drift |
| Longitudinal | Longitudinal | Poured up to column | Beam buckling at 2.5% drift. Slab spalling at 2.5% drift |
| Full Depth | Transverse | Poured to column, large full depth block | Beam buckling at 2.5% drift. Then slab spalling between flanges |

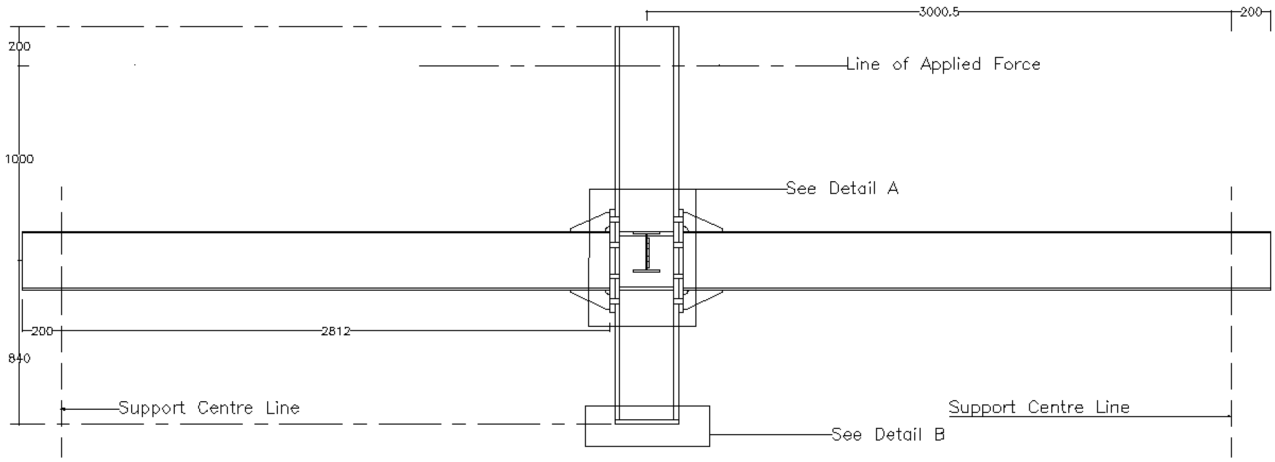



Figure 6: Beam and column setup for all tests.

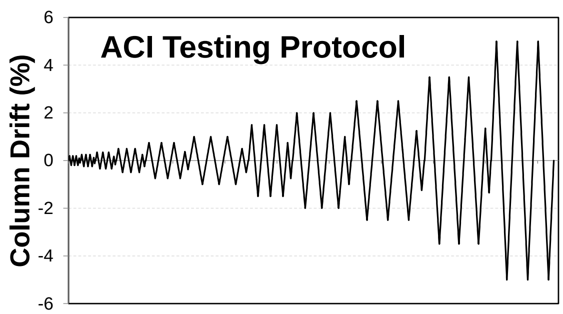



Figure 7. Test Regime (ACI, 2001)

In the tests, the column, panel zone and beam end connections remained essentially elastic. The unedited hysteretic behavior of the units is shown in Figure 8. It may be seen that the isolated column had the lowest lateral resistance. Lateral force resistances were increased by up to 40% due to the presence of the slab in contact with the column. The increase in strength was greater for decking running in longitudinal direction than in the transverse direction as a result of a more substantial full depth slab bearing on the column. However, at 100mm displacement (5% drift) all units had strength similar to that to that of the isolates unit as a result of strength degradation. This degradation in the unisolated connections generally occurred at drifts from 2.5% to 3.5% as a result of shear failure of the concrete between the flanges of the units shortly followed by spalling of the concrete. In the transverse unit, the deck failure mode involved compression perpendicular to the ribs. For longitudinal floor, there was a longitudinal concrete shear failure at both edges of the trough of the profiled floor that was centred in the column. This extended over the full 3m of the beam length. In the isolated slab case, there was minimal damage to the slab because it was separated from the column. When full depth concrete was placed around the column, there was no significant cracking near the column but there was compressional concrete strain there. This resulted in lower strength at repeated cycles to the same displacement. In all cases with concrete around the column, there was a shear failure of the concrete between the column flanges at drift ratios greater than 3.5%.

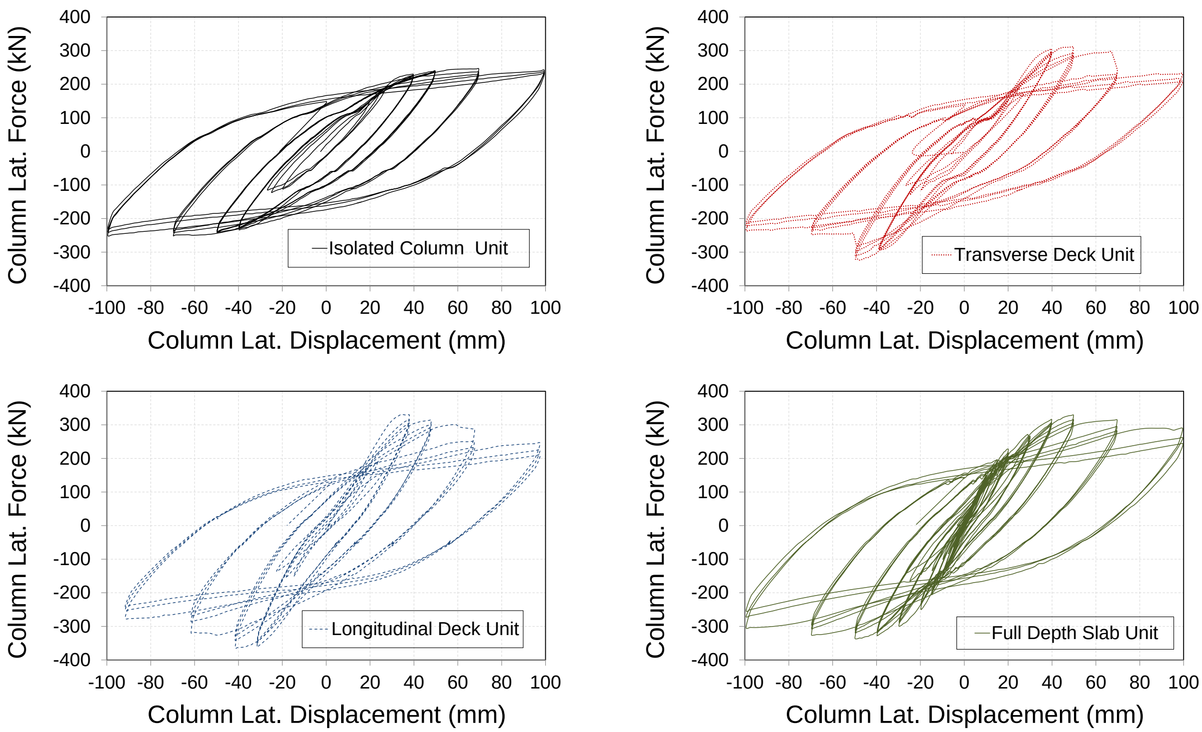



Figure 8. Subassembly Hysteresis Curves

From the discussion above, it may be seen that degradation occurred in both slabs with traditional longitudinal or transverse deck placement. While the degradation was less for the full depth slab unit, there was still significant strength degradation. For the envelope curve, the degradation was less than to 80% of the peak strength obtained even at the large drifts of 5% (i.e. column displacement of 100mm). This would make this configuration satisfactory according to many standard evaluation criteria. Also, with greater depth beams and similar depth slabs, the slab effect would likely be smaller so that it is likely to behave satisfactorily in these cases too. The need to specifically provide confinement of the slab around the column face is therefore not clear from these tests.

The elongation experienced by the different beams is shown in Figure 9. The load points shown here are the same as those in Figure 7, and these are plotted at the same scale so it is possible to estimate the beam elongation at each level of displacement. The red line shown here is between the values of beam elongation only at the points of zero column displacement. If the neutral axis were expected to be at the top of the column flange, then the beam elongation at 4% drift, assuming 1% elastic frame drift, would be (4% -1%) x 320mm/2 = 3.2mm. At greater drifts slightly greater displacements would be expected based on kinematics alone.

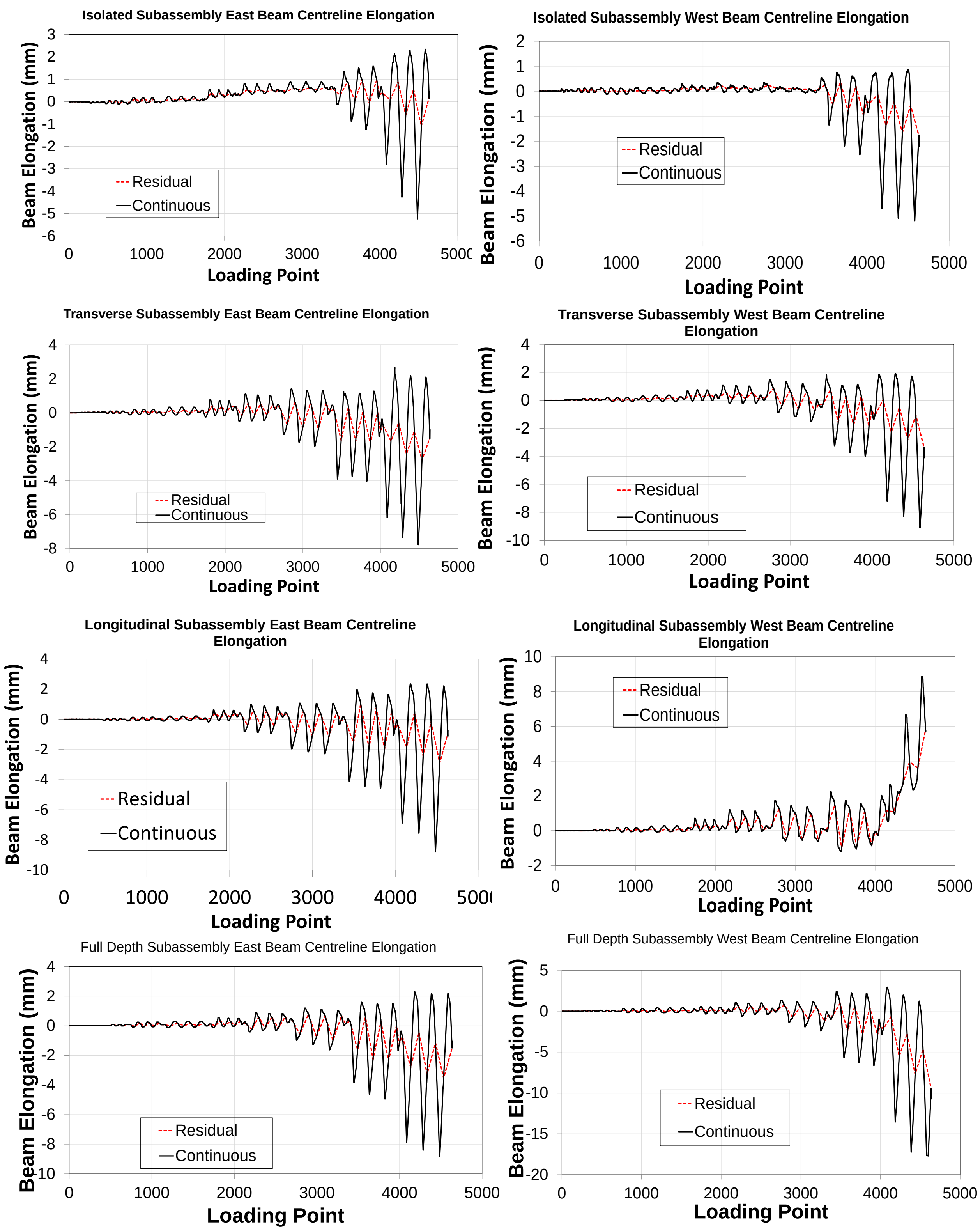



Figure 9. Beam Elongation During the Tests

The elongation shown here tends to be negative, and it is likely a result of buckling of the beam and some spalling of the concrete at the slab/column interface. In most units it is a similar magnitude to that from the kinematic considerations. Until the very last set of cycles, the absolute value of elongation at zero displacement, termed the residual displacement here, is generally less than 2mm. This is small and it is likely to be smaller in a building with more realistic boundary conditions (such as other columns) which would resist the possibility of positive or negative beam elongation. It is not likely to adversely affect the structural response.

## CONCLUSIONS

A series of tests were conducted to evaluate the effect of beam strength and beam elongation effects considering the presence of a slab. It was found that:

1) Traditionally placed composite slabs could not maintain beam strength to large drifts. In the case studied, the used of a full depth slab immediately around the column was effective.
2) Beam elongation measurements showed that the beam tended to shorten in length. In this study, the residual shortening, measured as the shortening at zero column drift, was less than 2mm during cycles up to about 3.5% drifts.


## ACKNOWLEDGEMENTS

This work has been financed by the Ministry for Science and Innovation through the Natural Hazards Platform under the Composite Solutions project. Materials and manufacturing have been donated by Fletcher Steel, John Jones Steel and Tata Steel (ComFlor).


## REFERENCES


American Concrete Institution, 2001. T1.1-01: Acceptance Criteria for Moment Frames Based on Structural Testing, Farmington Hills, Mich, USA.

Corus New Zealand, 2005. ComFlor 80 Composite Floor Decking, Auckland, NZ.

Heavy Engineering Research Association, 2003. R4-100 Structural Steelwork Connections Guide, Part 1: Design Procedures, Manakau City, NZ.

Hobbs M., “Slab Effects on Beam-Column Joints”, Master of Engineering Thesis, Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch, to be submitted, 2013.

Hobbs M., MacRae G. A., Bull D., Gunasekaran U., Clifton G. C., and Leon R., “Slab Column Interaction - Significant or Not?”, Steel Innovations Conference, Steel Construction New Zealand, Wigram, Christchurch, 21-22 February 2013, Paper 14.

MacRae G. A and Clifton G. C, “Low Damage Steel Construction”, Steel Innovations Conference, Steel Construction New Zealand, Wigram, Christchurch, 21-22 February 2013, Paper 1.

New Zealand Standard (NZS 3404:1997), Design of Composite Members and Structures, Standards New Zealand, Wellington.

Umarani C. and MacRae G. A. “A New Concept For Consideration Of Slab Effects On Building Seismic Performance”, Journal of Structural Engineering, Structural Engineering Research Centre, Chennai, India, No. 34-3, Vol. 34, No.1, April-May 2007, pp. 25–32.