

COMPOSITE SLAB EFFECTS ON BEAM – COLUMN SUBASSEMBLY SEISMIC PERFORMANCE

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Abstract. *The experimental behaviour of the beam-column joint subassemblies with (i) no slab, (ii) a slab fully isolated from the column, and (iii) isolation on the outside of the column face with a slab shear key between the column flanges to activate Eurocode Mechanism 2, were investigated. It is shown that with full isolation of the slab from the column, the peak strength was similar to that with no slab, but the strength degradation during cyclic loading was significantly less. Also, for the assembly with the slab shear key, the lateral strength was 23% higher than that of the other specimens with no slab touching the column faces, but the strength was not maintained through large displacements because rebar placed to prevent shear key failure caused delamination/spalling of the concrete slab both inside and outside the shear key.*

1 INTRODUCTION

Composite slabs are widely used in steel moment resisting frames in seismic zones, however their effects are seldom considered in seismic design while sizing the beams. In New Zealand, slab effects are not considered while determining the beam end moment resistance, but they are considered when determining the overstrength from the beam/slab to determine column and panel zone demands. If the slab is fully isolated from the column then the slab effect on the panel zone and connection can be ignored. However, there is an increased likelihood of column buckling due to decreased restraint. In case of the traditional construction i.e. slab touching to the column, on the sagging moment side, the slab bears against the column flanges and transfers forces through bearing. However, on the hogging side, the force transfer largely depends upon the activation of the strut and tie mechanism. The amount of force transfer between the concrete slab and the column is a function of the (i) concrete strength, (ii) slab confinement,

(iii) number and location of beam shear studs, and (iv) provision of additional reinforcement for the strut tie mechanism and to prevent shear key failure.

Slab forces can increase the demand on the connection, panel zone and column, possibly resulting in an undesirable inelastic deformation mechanism. In no-gapping configurations, participation of the slab to beam overstrength is considered only in the New Zealand code (NZS3404:1997) [1] for column design. This overstrength factor is also affected by material characteristics. For economical design, it would be advantageous if the slab contribution to the beam strength could be considered both in the traditional bolted end plate connection as well as in newer low damage sliding hinge connections. Also for the overstrength design, realistic estimation of demand from the beam and slab are required for the column and panel zone. One idea for an economical connection which considers the slab in sizing the beam involves the slab force only being transferred to the column via a shear key between the column flanges, referred to as Mechanism 2 in the Eurocode, which is reinforced to prevent a shear failure.

Based on the above discussion it may be seen that there is a need to better understand slab interaction effects in steel moment-frames for better design. This paper seeks to address this need by seeking answers to following questions:

- i) How does a slab isolated from the column affect the subassembly performance?
- ii) By isolating the outside flanges of a column, and relying on a shear key between the column flanges, can a reliable increased strength be developed for beam and overstrength design?

2 SLAB ISSUES

2.1 General

The failure sequence of beam-column-slab joint test specimens depends on the strength hierarchy. Past research studies of some specimens reveal the following failure sequence; initially there is yielding of beam bottom flange. This is sometimes followed by column web panel yielding. Finally there is slab degradation due to crushing/spalling of the concrete near the column flange [2,3,4]. The slab performance can be improved by providing additional reinforcement near the connection or by providing a full depth slab around the column [5]. For effective force transfer, a strut-and-tie mechanism is necessary to resist the force applied by the column on the slab [6]. Primarily, two-force transfer mechanisms known as a “Mechanism 1” and “Mechanism 2” [7] have been described as shown in Figure 1.

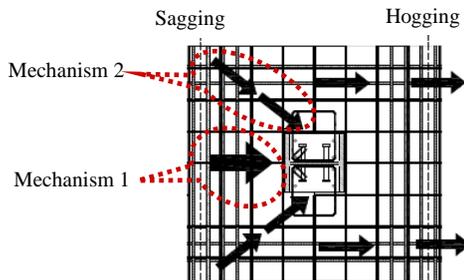


Figure 1: Slab Internal Force Interaction between Hogging and Sagging side [Braconi et al. 2010]

2.2 Slab Confinement

In New Zealand, the current construction practice is to locate the first shear stud/connector at a distance of 1.5 times depth of a beam from column face as specified in NZ3404:1997 code. This is to avoid the stress concentration in beam yielding zones, however in doing so, the slab immediately above the beam is typically confined from three sides (confinement offered from slab bottom and from either side) and there is no confinement at the level of the top of the slab. In order to avoid the spalling failure at the top of the slab, the concrete strain (ϵ_c) should be less than equal to 0.002 (approximately).

Maintaining this strain in practical situations may be difficult. Several approaches like (i) providing active confinement on the top of the slab, (ii) slab isolation, or (iii) development of reliable force transfer mechanisms, may be useful to control the early strength degradation of the slab.

This paper presents a test results performed on the isolated slab assembly and the specimen with a shear key activating mechanism 2.

3 TEST SETUP

A full scale internal joint of a steel structure was constructed at the University of Canterbury. The column and beam ends are pin supported at the mid-span representing the points of contraflexure in a moment resistant frame subjected to the lateral loads. A displacement controlled loading ram is at the column top. Roller supports are provided at the beam end to control out-of-plane movement. The test specimen is subjected to the lateral load without gravity load as shown in Figure 2.

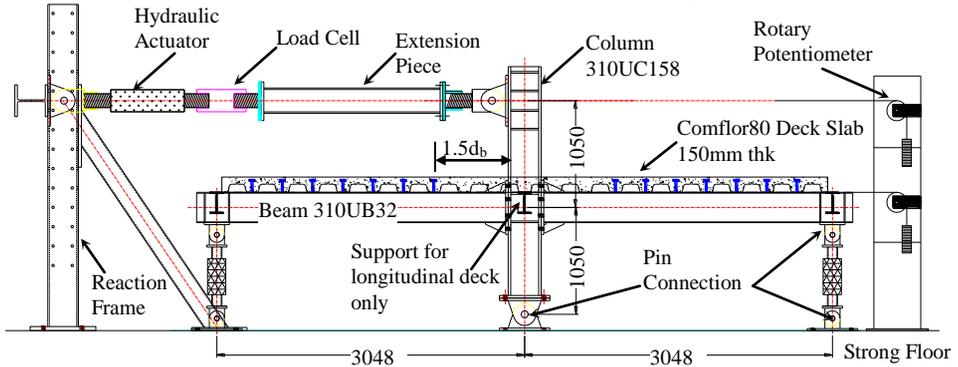


Figure 2. Test Setup

4 CONFIGURATION OF THE TEST SPECIMENS

The test specimen is comprised of a 3.0m wide and 6.0m long, Comflor80 [8] deck slab (150mm thick) supported on two Grade 300plus 310UB32 primary beams. The column is a Grade 300 310UC158. Two shear studs (125mm x 19mm dia) per trough at 300mm spacing were provided. To control the shrinkage cracks, SE82 [9] mesh is placed across the whole slab. As recommended by ComFlor, additional reinforcing was provided in the form of 2-D12 rebars of 1.5m length around the column at 200mm spacing. Concrete had a 28 day target strength of 30MPa.

4.1 Fully Isolated Slab (Transverse Deck)

In this test configuration, the slab was separated from the column by using a gapping material 'Actifoam' [10] as shown in Figure 3. In order to fully isolate the concrete, a gapping material is provided in such way that it will not only isolate a concrete from the column flanges but also the gusset plate, haunches, and the bolts. Three gapping material were identified as (i) Polystyrene, (ii) Actifoam and (iii) Spiralite. The selection of the gapping material was done by using subjective qualitative analysis (SQA)[11] based on the following criteria:-

- Fire proof
- Stiff enough to act as a formwork to wet concrete
- Compressibility under seismic loading
- Waterproof
- Ease of application

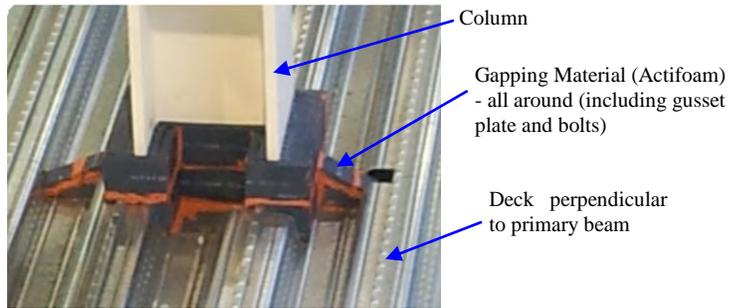


Figure 3. Details of Isolated Assembly.

4.2 Shear Key-Hair Pin (Longitudinal Deck)

The primary objective of this test is to study the effect of the slab by activating the force transfer Mechanism 2 (shear key in the form of hairpin reinforcement) and switching off the Mechanism 1 (providing gaps at outer face of column) as shown in Figure 4. An additional force transfer mechanism, mechanism 3, caused by force applied through the transverse (secondary) beam was prevented. This was done by providing no shear studs on the secondary beam. The shear key was designed based on the shear friction concept as per New Zealand code (NZS3404:1997) and adequate development length was provided. On the shear key rebar, strain gauges were located 200mm away from the column flange tips. To prevent direct contact between the slab and the outer face of column flanges, a layer of actifoam sheets have been placed adjacent to column flange.



Figure 4: Shear Key Construction Details around Column

5 LOADING PROTOCOL

Testing was carried out using displacement control with ACI (2001) testing protocol as per Figure 5.

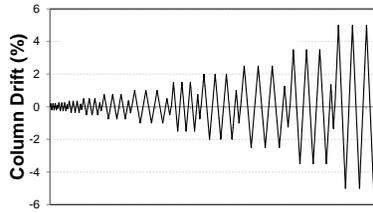


Figure 5. Test Regime [ACI, 2001]

6 INSTRUMENTATION

The test specimen was equipped with instrumentation to capture deformation/rotation/strains at various locations. Since the specimen was tested under the displacement controlled cyclic loads, a rotary potentiometer with range of $\pm 250\text{mm}$ displacement was installed at the column top matching with centre line of the loading ram. To measure applied load, a load cell with 1000kN capacity was attached to the hydraulic actuator. The pinned ends of the primary beam were equipped with 150kN capacity load cells to measure the reaction at the beam-ends. Linear potentiometers were installed at the column panel zone, to capture the deformation. A series of linear potentiometer was also installed at the top and bottom flange of the main beam to measure beam growth. Inclinometers were installed to capture the rotation of column and beams. Spring potentiometers were installed at the column base as well as at the beam column joint to monitor slippage between different components. A linear potentiometer, in a grid format, was installed to measure the slab deformation. Strain gauges were also placed on the reinforcing bars and at the top and bottom flanges of the main beam. A detailed layout of the instrumentation is presented in Figure 6.

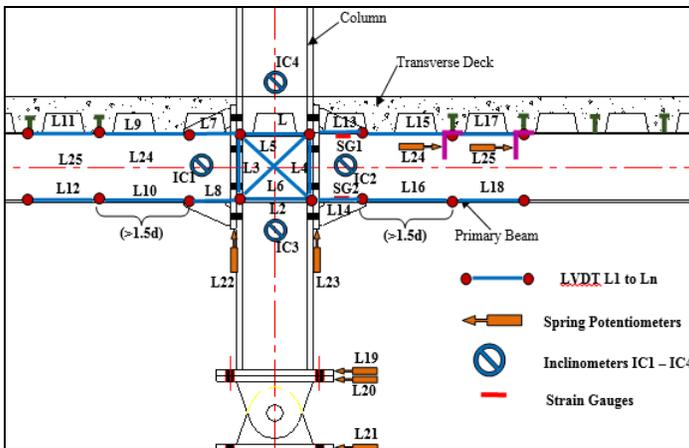


Figure 6. Instrumentation Details

7 EXPERIMENTAL RESULTS AND DISCUSSION

7.1 General

Failure modes of the different specimens are summarised in Table 1.

Table 1. Specimen Description and Failure Mode

Test Specimen	Deck Tray Direction (to main beams)	Slab details	Behaviour
Isolated	Transverse	Slab separated from column (all around)	Beam buckling @ 3.5% drift
Shear Key	Longitudinal	Slab separated from column outer flanges	Spalling of Concrete in between the column flanges @ 1.5% drift
Bare frame	NA	NA	Beam buckling @ 3.5% drift

7.2 Cyclic Behaviour

Beams were designed to dissipate the energy through plastic hinges and the beam end connection, panel zone and column to remain elastic during the test. Figure 7 presents the load verses global deformation for each specimen.

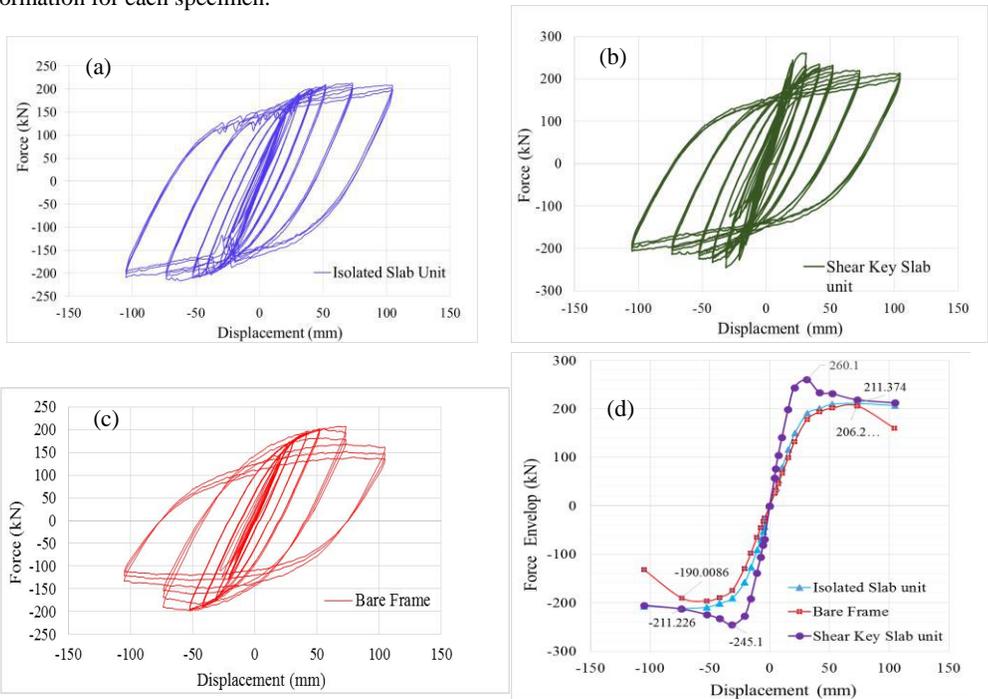


Figure 7. Cyclic Behaviour: (a) Column top force verses column displacement- Isolated Slab unit; (b) Column top force verses column displacement- Shear Key Slab unit; (c) Column top force verses column displacement- Bare Frame; (d) Force envelope verses column displacement

The isolated slab unit (211 kN) behaved similarly to the bare frame (206.2kN) up to 3.5% drift. However, in case of shear key unit, it was active up to 1.5% drift (260kN) and started strength

degradation in later drift cycles. In both the slab units, the steel section was in elastic state up to 1.0% drift followed by bottom flange yielding at 1.5% drift and finally yielding of top flanges at 2.5% drift. No spalling was observed at the isolated side, whereas some spalling was noted at the inner flanges in the case of the shear key unit in later cycles. The strength offered by shear key slab unit is 23.0% higher than the isolated slab unit.

7.2 Shear Key Behaviour (Shear Key slab unit with longitudinal deck)

The failure sequence of the shear key was as follows: (i) initiation of a diagonal tension crack at the column tips at 1.0% drift, (ii) at 1.5% drift, shear key rebar caused horizontal delamination of the concrete followed by development of shear crack along the column tips, (iii) complete concrete lift off of the upper delaminated concrete in between the column flanges exposing shear key rebars at larger drift levels.

The delamination of the slab occurred along the main beam approximately at the level of shear studs, which further extended through the shear key rebars as shown in Figure 8.

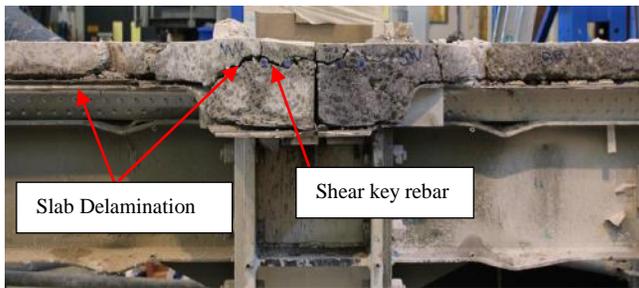


Figure 8. Slab Delamination along the main beam

The reason for the delamination is shown in Figure 9 for the EC8 mechanism 2. Here there are bearing stress on the shear key rebars both inside and outside the shear-key region. The rebars acted as knives pushing into concrete that was not confined on the top. The shear crack occurred when the concrete could no longer carry the shear stress. This crack was necessary to activate the rebars to carry the shear force in dowel action.

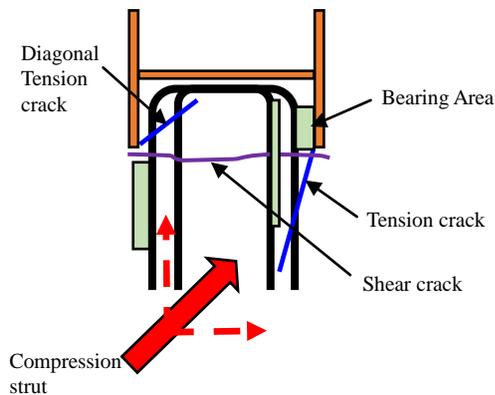


Figure 9. Force transfer mechanism

8 CONCLUSIONS

Experiments of three composite beam–column sub-assemblages were conducted. The first had no slab. The second fully isolated unit had a slab but no slab contact with the column, end-plate, haunches, and nuts and bolts. The third used a shear key to transfer force to the column between column flanges. It was shown that:

- i) The sub-assembly with full isolation showed no sign of spalling around the column. Beam yielding occurred primarily at the beam bottom flange due to the presence of the slab. The peak strength was similar to that of the sub-assembly with no slab, but less strength degradation occurred.
- ii) For the assembly with the slab shear key, the lateral strength was 23% higher than that of the other specimens with no slab touching the column faces. However, the strength was not maintained through large displacements because after an initial crack occurred beside the shear key, the rebar placed to prevent shear key failure acted in dowel action pushing against the concrete and causing slab delamination/spalling of the concrete slab both inside and outside the shear key. The behaviour seen in this economical composite assembly did not provide the reliable strength desired, and further studies are continuing.

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