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HYBRID FRC-ENCASED STEEL TRUSS BEAMS FOR PRECAST SEISMIC-RESISTANT FRAMED CONSTRUCTION

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SUMMARY

This paper evaluates a new type of precast frame structure that consists of steel-concrete hybrid beams and reinforced concrete (RC) columns for use in zones of moderate to high seismisity. The hybrid beam consists of a steel truss encased in steel fiber reinforced concrete (FRC). The FRC-encased truss provides excellent strength, stiffness and energy dissipation capacity while the randomly oriented steel fibers enhance material ductility and beam shear strength. Energy dissipation is achieved through yielding of the truss at a designated hinge region slightly away from the beam-column interface. Moment connection between precast beams and columns is achieved through external steel rods, eliminating the possibility of slippage of rebars often experienced in conventional RC joints. Adequate shear transfer is ensured through a bolted connection between the precast column and the steel truss. In order to evaluate the seismic performance of the proposed precast system, four beam-column connection subassemblies were tested under large displacement reversals. Experimental results showed that the proposed connection scheme is effective in transferring moment and shear during load reversals. In addition, beam inelastic rotations of up to 4% were measured in the hybrid beams, leading to excellent system displacement and energy dissipation capacity.

INTRODUCTION

Hybrid structural systems consisting of structural steel and reinforced concrete (RC) members have become popular during the last few decades. One attractive combination of steel and RC members is achieved in steel sections encased in RC, typically referred to as SRC members. SRC members have been shown to possess excellent strength, stiffness and energy dissipation capacity (Elnashai [1], Ricles [2], Azizinamini [3], Gong [4]). However, significant labor is generally required in order to assemble the reinforcing cages around the embedded steel section. During the late 1990s, researchers at the University of Michigan (Khunthia [5]) proposed an alternate type of SRC member that consists of steel trusses embedded in fiber reinforced concrete (FRC). The embedded steel truss exhibits excellent behavior under load reversals because the FRC provides support to the truss chords and web members, preventing them from buckling. In addition, the FRC contributes to shear resistance, and offers fire protection to the embedded steel members. Through tests of FRC-encased steel truss beams and frames under reversed

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cyclic loading, Khunthia [5] showed that these hybrid members exhibit excellent seismic response, and thus are suitable for use in seismic-resistant construction. Further, while the steel truss allows for omission of longitudinal steel rebars, fibers minimize the necessity of having stirrups for confinement.

Because of the excellent seismic performance exhibited by FRC-encased steel truss beams, their use in new precast construction has recently been investigated at the University of Michigan. In particular, the use of FRC-encased steel truss hybrid beams as prefabricated members in combination with RC columns could be attractive for seismic-resistant precast construction. However, moment connections between the beams and columns represent a major concern in precast seismic-resistant frame construction. Several precast connection configurations have been recently proposed and tested in beam-column subassemblies (Priestley [6]) as well as in a five story precast concrete test building (Priestley [7]), as a part of the PRESSS (PREcast Seismic Structural Systems) research program. Even though the connections performed well, they were complicated and sophisticated. Beams and columns were held together through a combination of unbonded pre- or post-tensioned tendons and partially bonded reinforcing bars passing through the column and beam. Clearly, the construction of these joints is labor intensive and costly. Thus, there is still room for the development of simpler precast moment connections that would lead to more practical precast frame construction systems.

PROPOSED CONNECTION

A simple precast connection scheme for hybrid FRC-encased steel truss beam-RC column moment resisting frames is proposed. Moment transfer is achieved through external steel rods connected to the internal truss chords by transverse steel tubes (Figure 1). For an interior joint, the rods are anchored at the hybrid beam framing into the column from the opposite side of the connection, whereas for an exterior joint, a short beam stub is used for rod anchorage. Top and bottom rods are only subjected to tensile forces because compression forces are transferred through bearing of the beam compression concrete region against the column face. Shear transfer is achieved through a bolted connection between the steel truss and the precast RC column. All the connection components are designed to remain elastic during a seismic event to avoid ‘pinching’ in the load-displacement hysteretic response of the frame resulting from connection slippage. Energy dissipation is then primarily achieved through inelastic rotations in the hybrid beam outside the connection region.

In order to evaluate the seismic performance of the proposed precast connection, a series of beam-column connection subassemblies were tested under large displacement reversals. Results from these tests are evaluated in terms of load versus displacement behavior, flexural and shear capacities, cracking pattern, deformation in connection components, and energy dissipation capacity.

EXPERIMENTAL PROGRAM

The experimental program consisted of the testing of four beam-column connection subassemblies (Specimen 1 - 4) under displacement reversals. Specimen 1 represented a beam-column subassembly while Specimens 2 - 4 simulated the connection between a hybrid beam and a precast RC column through the use of a re-useable steel column. All the specimens represented exterior connections (only one beam framing into the column). Figure 2a shows the test setup used for the beam-column subassembly, whereas Figure 2b shows the test setup used for the specimens with re-useable steel column. In Specimen 1, the beam and column were pinned at their ends to simulate inflection points at member midspans. Lateral displacements were applied at the top of the column through a hydraulic actuator that was in turn connected to a strong reaction wall. In Specimens 2 - 4, beams were oriented vertically and connected to a rigid steel support made of rectangular tubular members, as shown in Figure 2b. In these three specimens, lateral displacements were applied at the top end of the beam.

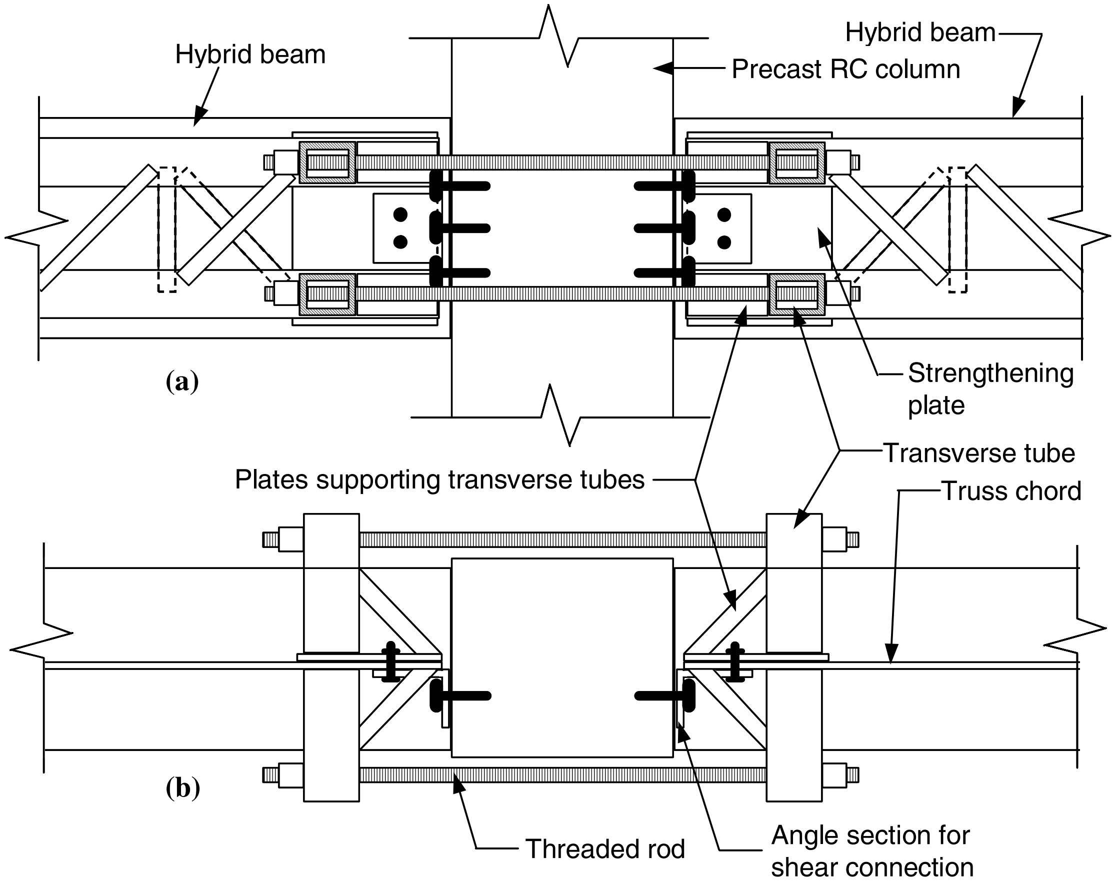
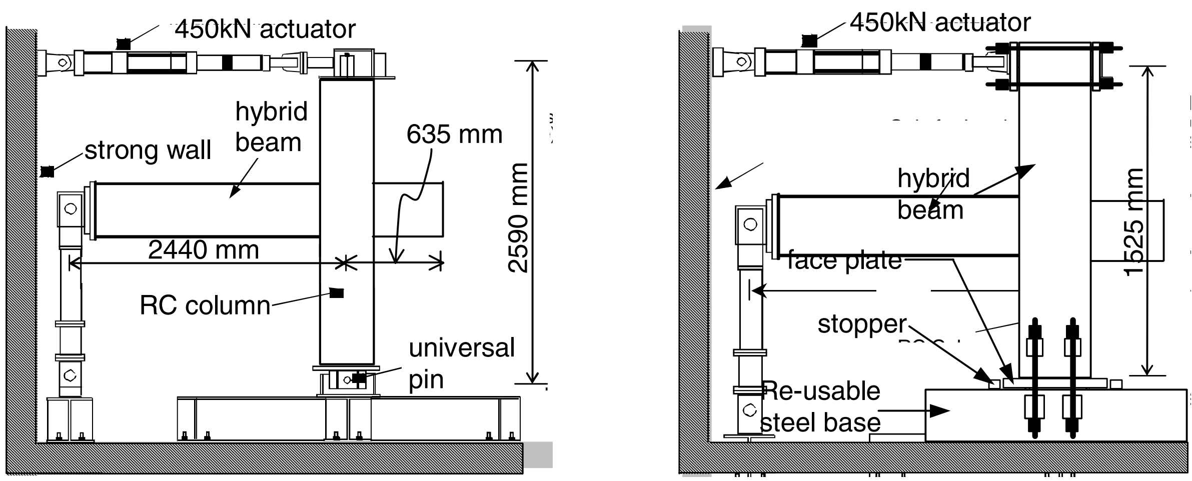


Figure 1: General configuration of proposed connection



(a) (b)

Figure 2: Experimental setup for (a) beam-column subassembly test, and (b) beam-column connection tests

A similar truss configuration was used in all four specimens. The intended plastic hinge location was moved away from the column face and outside the connection region by strengthening the front end of the truss through an additional steel plate (Figure 1). The plastic hinge region was strengthened by an X web member configuration to ensure adequate shear strength at large beam rotations (Figure 1). Truss chord to rod force transfer mechanism was provided through tubular members transversely connected to the truss chords, as shown in Figure 1. Fiber reinforced concrete (FRC) containing 30 mm long and 0.5 mm diameter hooked steel fibers in a 1% volume fraction was used.

Specimen 1 featured a 510 mm square beam connected to an RC column. The RC column was constructed separately from the beam to simulate a connection between precast members. An axial load of approximately 180 kN was applied to the RC column during the test. In this specimen, the truss chords consisted of flat plates and the tubes used to anchor the external reinforcement were supported by flat bars, thus having a truss mechanism to transfer the tension force from the truss chord to the external reinforcement (Figure 1). The rods were adequately tightened to avoid any slip during load reversals. Also, stirrups were placed at 75 mm spacing in the plastic hinge region for confinement of concrete.

Specimen 2 consisted of a 380 mm deep and 335 mm wide hybrid beam connected to a rigid steel base. In addition, a few changes in truss configuration and connection details were made compared to those used in Specimen 1. In this specimen, the truss chords were made of double angles with reduced sections (dog-bone) in the plastic hinge region (Figure 3). The second major change was the elimination of the plates used to transfer tensile forces from the truss chord to the external rods through truss action. However, the transverse tubes were flexurally under-designed to carry the maximum tensile force in the chords. This was done to investigate a possible formation of a load resistance mechanism through a concrete strut and steel ties in the tubes. Plates were attached to the transverse tubes to help the formation of transverse concrete struts in the beam (Figure 3). #16M rebars were attached to the face of the tubes through couplers to strengthen the tube-FRC interface and to inhibit opening of a major crack at that location. In addition, the use of steel rebars would lead to a more uniform cracking distribution in the plastic hinge region.

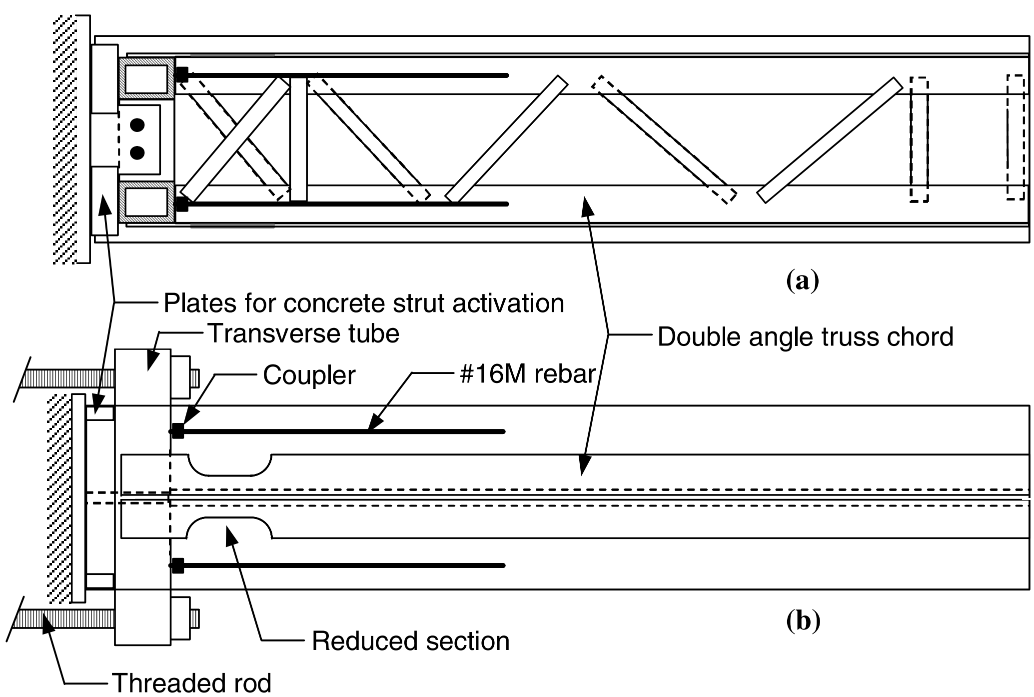


Figure 3: General configuration of hybrid beam in Specimen 2 (a) side view and, (b) plan view

In Specimens 3 and 4, the same truss and connection details as in Specimen 1 were used (Figure 1). However, different arrangements of rebars were investigated (Figure 4). In Specimen 3, four #13M bars were used at the top and bottom of the beam to strengthen the tube-FRC interface (Figure 4a). Specimen 4 had two #13M bars extending up to the center of the plastic hinge, in addition to two #10M bars that extended across the hinge region (Figure 4b).

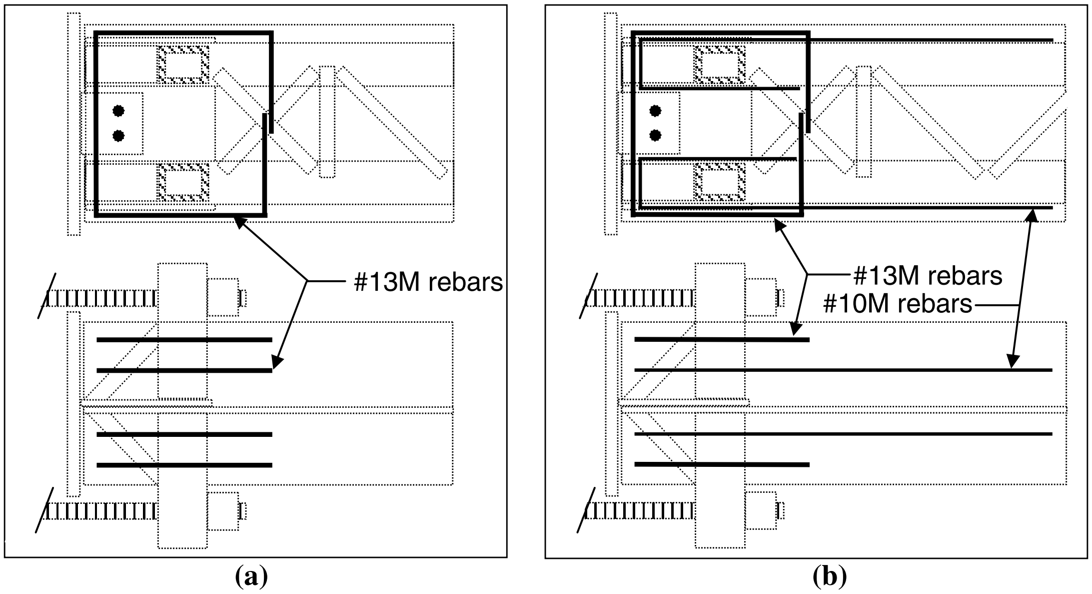


Figure 4: Rebar arrangements in (a) Specimen 3: side view and plan view, and (b) Specimen 4: side view and plan view

DISPLACEMENT HISTORY AND INSTRUMENTATION

A displacement history similar to that proposed in the ACI ITG/T1.1-99 document [8] (Figure 5) was used for testing the beam-column subassemblies. After the cycles to 3.5% drift were completed, some additional cycles at larger drift levels were typically applied to the specimens. Applied lateral loads and displacements were monitored through a load cell and LVDT attached to the hydraulic actuator. Beam rotations were measured through linear potentiometers and clinometers. Strains in steel bars and plates at selected locations were monitored through strain gages.

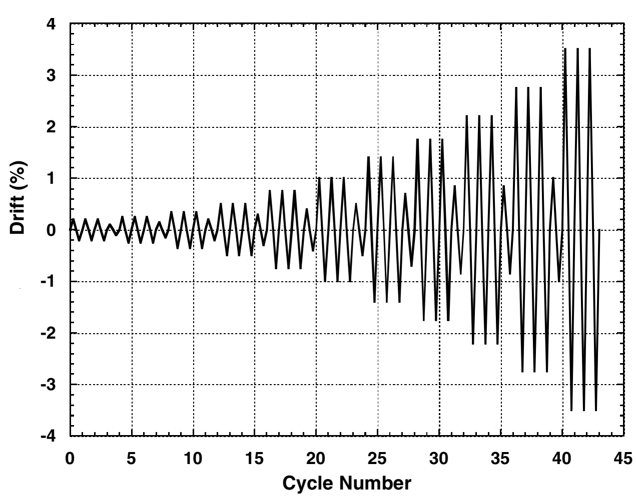


Figure 5: Lateral displacement history

MATERIAL PROPERTIES

Ready-mix concrete supplied by a local concrete company was used in all four specimens. For the fiber reinforced concrete used in the beams, 30 mm long and 0.5 mm diameter hooked steel fibers were used in a 1.0% volume fraction. The concrete strength on the test day ranged between 25-35 MPa for the beams, and was about 27 MPa for the column. A36 steel (nominal f_y = 250 MPa) was used for the steel plates and angles. A500 Grade B steel (nominal f_y = 345 MPa) was used for the transverse tubes in all specimens. For external reinforcement, Grade B7 (nominal f_y = 725 MPa) threaded rods were used in Specimen 1, whereas high strength threaded rods with yield strength of 880 MPa were used in Specimens 2 through 4. Grade 60 steel (nominal f_y = 415 MPa) was used for the reinforcing bars.

EXPERIMENTAL RESULTS

Overall Response

Figures 6a through 6d show the load versus displacement hysteretic response for Specimens 1 through 4, respectively. Ultimate beam strengths, calculated analytically by considering expected overstrength and strain hardening of steel plates and rebars, are superimposed on the experimental results. However, tensile strength of the FRC was neglected in calculating ultimate strengths. Because the strength of Specimen 2 was not governed by beam flexural strength, as described later, predicted strength is not shown in Figure 6b.

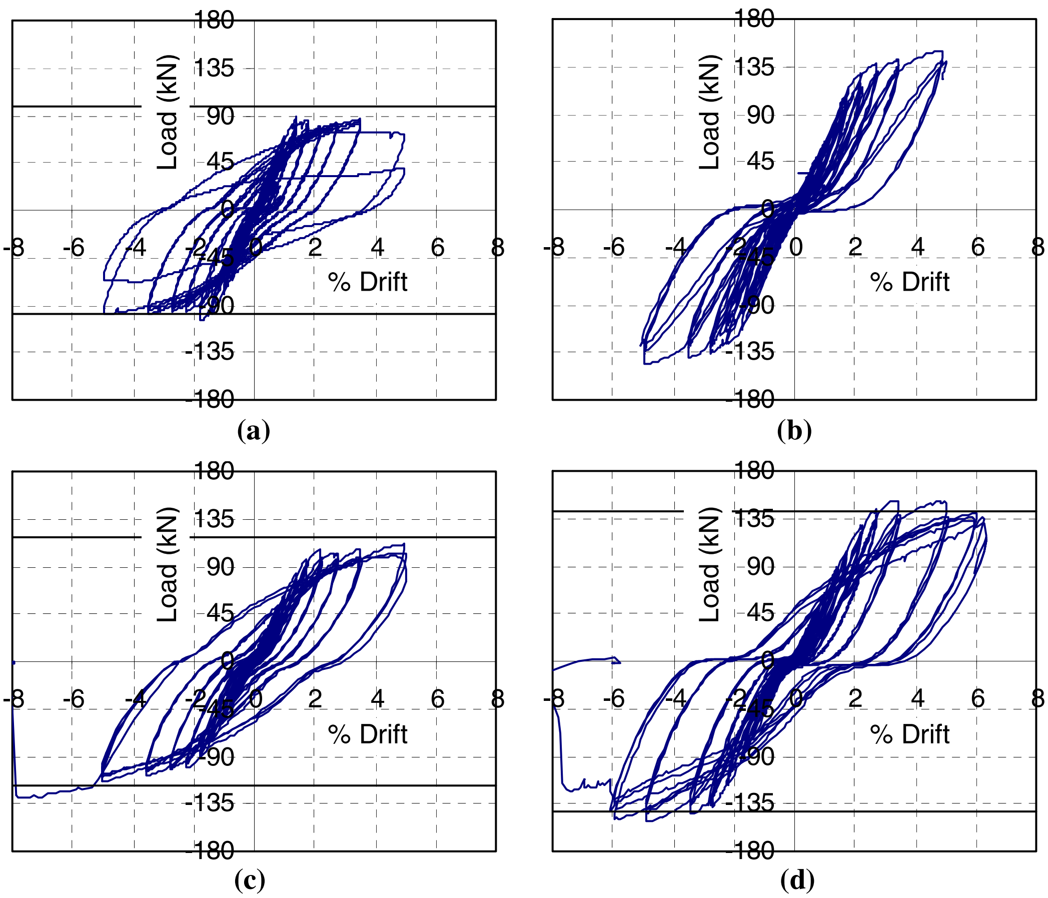


Figure 6: Load-displacement response of (a) Specimen 1, (b) Specimen 2, (c) Specimen 3, and (d) Specimen 4

Specimen 1 exhibited excellent hysteretic response, as shown in Figure 6a. In this specimen, a tight connection between the steel rods and the transverse steel tubes (shown in Figure 1), could be easily achieved, eliminating the possibility of external reinforcement slip in the connection region. The opening of a small gap at the beam-column interface due to elastic elongation of the external rods was noticed throughout the test. However, upon unloading of the specimen, this gap was fully closed. The behavior of Specimen 1 was characterized by yielding of the embedded steel truss, which first occurred at about 1.4% drift during the cycle to 1.75% drift. Flexural cracking in this specimen concentrated primarily in the region near the transverse steel tubes. As the test progressed, one major crack opened in the region adjacent to the transverse tubes (Figure 7a), leading to significant rotations over a short beam length. This imposed severe deformation demands in the embedded steel truss and led to local buckling of the truss chords (Figure 7b) with a subsequent loss of lateral strength in the specimen during the cycle performed to 5.0% drift. The lateral strength of Specimen 1 was predicted with reasonably accuracy by neglecting the tensile strength of FRC. The FRC was not found to contribute appreciably to beam moment strength, primarily due to the presence of a weaker section adjacent to the steel transverse tube. Strain readings indicate that the external rods, as well as the steel plates and tubes used for force transfer between the steel truss and the external reinforcement, remained elastic throughout the test, as intended.

(a) **(b)**

Figure 7: Damage in Specimen 1 at 5.0% drift (a) single major crack at transverse tube face, (b) buckling of truss chord

Specimen 2, with a re-useable steel column, exhibited poor hysteretic response (Figure 6b). The transverse tubes, without any plates to form a steel truss action, did not perform adequately and the overall response of the beam was governed by bending of the tubes rather than the embedded truss. The transverse tubes exhibited large inelastic rotations with the consequent slip in the connection region, while the beam exhibited only minor damage. These results indicated that a concrete strut-steel tie mechanism could not be formed inside the connection region and thus, the beam failed to reach its expected flexural strength. This test clearly showed the need for plates to provide a truss mechanism for load transfer between the steel truss chords and the external reinforcement.

Specimen 3, with similar truss and connection configurations as in Specimen 1, exhibited good behavior with full hysteretic loops (Figure 6c). At low drifts, a significant fraction of the total beam rotation was concentrated at the hybrid beam-steel base interface. Because transfer of compression forces was achieved through bearing of the steel beam end plate on the steel base, it is believed that some connection slip occurred throughout the test due to a lack of adequate contact between the steel plates at the beginning of the test. However, those bearing conditions will not exist in real connections, and thus no such slip, with the associated increase in connection flexibility, would occur as observed in Specimen 1.

Yielding of the truss chords took place during the 2.5% drift cycles, which corresponded to about 1.3% plastic hinge rotation. The use of #13M rebars across the steel transverse tube-FRC interface inhibited the formation of a major crack at that location. However, a single major crack opened at the center of the plastic hinge region where the rebars ended (Figure 8). Most of the beam inelastic rotations concentrated at this location and eventually, one of the truss chords fractured at about 7.8% drift. The strength reached by Specimen 3 was approximately equal to that predicted neglecting the tensile strength of FRC. Except for the plastic hinge region, all parts of the truss and the connection region remained elastic.

Figure 8: Cracking pattern in Specimen 3 – single major crack at middle region of plastic hinge

Specimen 4 differed from Specimen 3 only in the arrangement of the steel rebars (Figure 4b). In this specimen, #10M rebars were placed across the hinge region to enhance the plastic hinge cracking pattern. This beam exhibited some ‘pinching’ in the load-displacement response (Figure 6d) with a significantly lower stiffness compared to Specimen 3 due to substantial slip in the connection region. Strain gage readings suggest that the connection slip was due to a lack of adequate bearing at the beam end-steel base interface, as explained earlier. Because this end plate would not be there in a real application, the load-displacement curve was corrected by subtracting the measured steel base-beam interface slip and the modified curve is shown in Figure 9. The truss chords yielded at about 1.5% corrected drift. Rebars passing across the hinge region were effective in developing a number of cracks during the smaller drift cycles. However, at larger drifts, a single crack at the center of the hinge region opened widely and eventually most of the plastic beam rotation concentrated at this location. Rebar and truss chord fracture occurred at this location at corrected drifts of 4.0% and 4.8%, respectively.

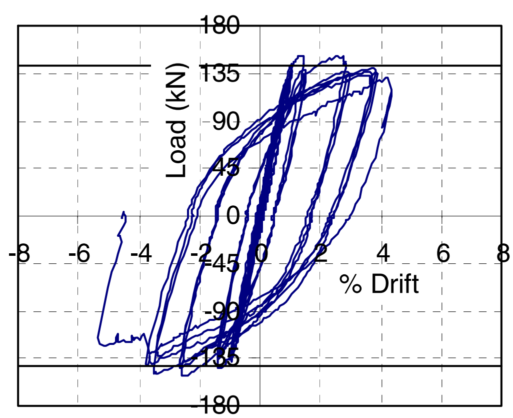


Figure 9: Corrected load-displacement response of Specimen 4

Beam Flexural Capacity

Comparing the test results of Specimens 1, 3 and 4, which exhibited beam flexural hinging, with the beam strengths predicted analytically (Figures 6a, c and d), it is evident that the FRC was not effective in increasing the ultimate flexural capacity of the hybrid beams. Beam ultimate strengths calculated by neglecting the tensile strength of the FRC agreed well with the test results. Superimposing the load-displacement loops of Specimen 4 with the analytically obtained yield strengths including and excluding FRC tensile strength (Figure 10), it is seen that a better prediction of beam yield moment strength was obtained when the FRC tensile strength was considered in the analysis. A similar observation was made for Specimen 3. In Specimen 1, however, FRC did not contribute to beam yield strength because of the lack of tensile stresses at the tube-concrete interface. Thus, FRC could be assumed to contribute to flexural strength at low drift levels. However, rapid decay in tensile strength of FRC thereafter makes it ineffective at large drift levels when ultimate strength is reached.

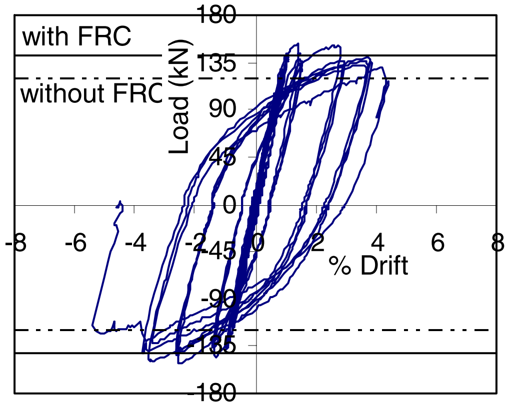


Figure 10: Predicted yield strengths with and without FRC

Shear Capacity

Figure 11 shows the relative shear contributions of the steel truss (web members) and FRC versus drift for Specimens 3 and 4. Both specimens exhibited similar trends with the fiber concrete carrying approximately 70% of the applied shear during small drift cycles. A decreasing concrete contribution for larger drifts was also observed, with a residual strength contribution of approximately 17% at the end of the test. Thus, a reasonable lower bound for the shear strength of the hybrid beam can be obtained from the shear strength capacity of the truss web members.

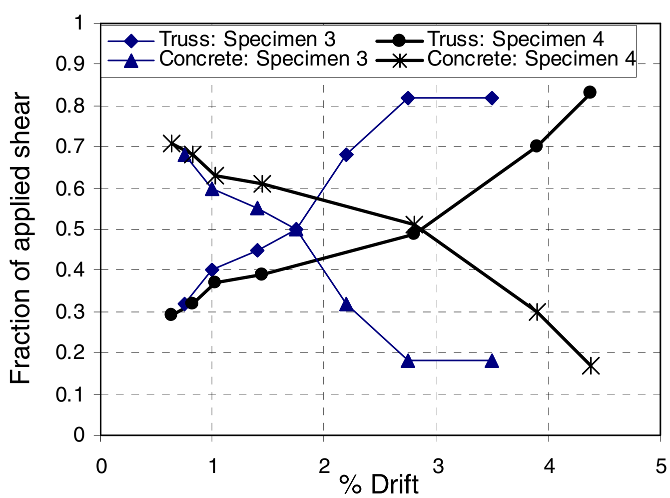


Figure 11: Relative shear contribution from truss and fiber concrete

Energy Dissipation Capacity

In order to quantify the energy dissipation capacity of the test specimens, an energy ratio, defined as the ratio between the energy dissipated by the specimen during each loading cycle and the energy that would be dissipated by an equivalent elasto-plastic system, was calculated for all four specimens. Figure 12 shows the energy ratio for the test specimens and for drifts ranging between 1.0% and about 3.5%. As can be observed, Specimen 1 exhibited excellent energy ratios throughout the test, with values ranging from 17% at low drift levels, up to nearly 50% at 3.5% drift. Specimen 2 exhibited a poor energy dissipation capacity. Unlike Specimen 1, this specimen exhibited decreasing energy dissipation with increasing drift cycles. This was due to an increase in the amount of permanent bending deformation in the transverse steel tubes, as explained earlier. Both Specimens 3 and 4 (corrected) had satisfactory energy dissipation capacities. Energy ratios as high as 38% and 54% were computed at approximately 3.5% drift for Specimens 3 and 4 (corrected drift), respectively.

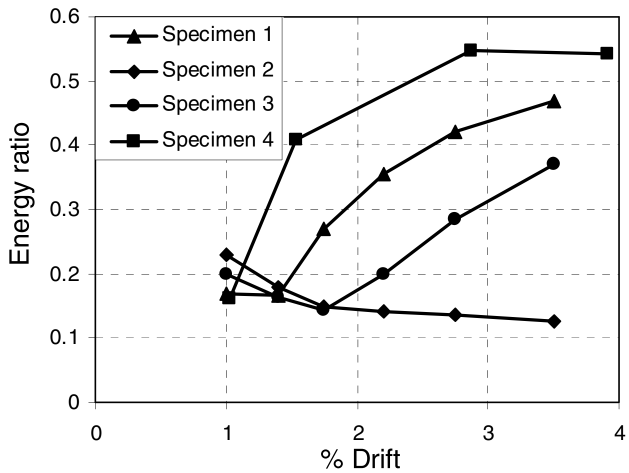


Figure 12: Energy ratios obtained for test specimens

SUMMARY AND CONCLUSIONS

Results from tests of four hybrid beam-RC column connection specimens under displacement reversals are presented in order to evaluate the performance of a new precast moment resisting frame system consisting of hybrid Fiber Reinforced Concrete (FRC)-encased steel truss beams and RC columns. The proposed connection scheme relies on external steel rods for moment transfer while a simple bolted connection between the embedded truss and the RC column ensures adequate shear transfer. All components of this external connection scheme are to remain elastic during a seismic event, forcing most of the inelastic activity to occur in the beam regions away from the column face.

Experimental results indicate that the proposed connection scheme is sound for use in precast seismic resistant frame structures. Except for Specimen 2, all connection components behaved elastically as intended. From the test of Specimen 2, it was found that a combination of steel plates and transverse tubes is necessary to form a truss mechanism for satisfactory force transfer between the truss chords and the external rods. In the other three tests, inelastic beam rotations as large as 4% were obtained without significant strength degradation. Energy dissipation ratio, calculated as the ratio between the energy dissipated by the system in a given cycle and the energy dissipated by an equivalent elasto-plastic system, ranged between 38% and 54% for the 3.5% drift cycles.

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