Experimental investigation of dry mechanical beam–column joints for precast concrete based frames

J.D. Nzabonimpa, Won-Kee Hong* and Seon-Chee Park

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SUMMARY

This paper proposes dry mechanical beam–column joints for fully restrained moment connections of concrete components. This novel joint can be used for reinforced concrete precast frames and steel–concrete composite precast frames. The new dry mechanical joint consists of extended steel plates with bolts designed to transfer tension and compression forces, providing fully restrained moment connections at the beam–column joint. The extended end plate with bolts introduced for column-beam joint assembly was originally used in the steel moment frame, as introduced in AISC 358. This study developed similar but unique mechanical joint details for concrete frames in order to provide fully restrained moment connections for both steel–concrete composite precast frames and reinforced concrete precast frames. Experimental and analytical investigations were performed to verify the structural behavior of fully restrained moment connections for concrete components in order to identify the parameters that influence the structural behavior of dry mechanical moment concrete connections. These connections are expected to be used in modular offsite construction for buildings and heavy industrial plants. Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS: beam–column connection; steel–concrete composite precast frames; reinforced concrete precast frames; extended end plate; moment connection; AISC 358

1. INTRODUCTION

In this study, fully restrained moment steel joints were modified to be implemented in dry mechanical joints for both steel–concrete composite precast frames and reinforced concrete precast frames. Fig. 1 illustrates an extended end plate with bolts introduced for column-beam joint assembly. Extended end plates have been used in steel construction as described in AISC 358 (AISC 2005). Fig. 2 elucidates details of mechanical moment connections for concrete beam–column joints. Bolted beam-to-column extended end-plates are widely used in steel-frame structures like pipe racks. The primary application of these extended end-plates is to provide a fully restrained moment capacity between the connected members. Conventional extended end-plates are used only for transferring moments through steel members; however, studies related to extended end-plates for steel–concrete composite precast frames and reinforced concrete precast members are largely absent from the literature. A significant number of experimental and analytical studies have been conducted in order to examine the behavior of extended end-plate connections subjected to monotonic, cyclic and seismic loads. These studies showed that these types of connections can act as either fully rigid or semi-rigid connections depending on end-plate thickness, bolt diameter, number of bolt rows and columns, bolt spacing, bolt grade, stiffeners, column and beam sizes and yield strength of the steel.

Shi et al. (2007) subjected a series of eight full-scale structural steel beam-to-column end-plate moment connection specimens to cyclic loads. They reported that end-plate connections have adequate strength, joint rotational stiffness, ductility and energy dissipation capacity for use in seismic moment

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frames. Later, Abidelah et al. (2012) carried out an experimental investigation of eight specimens consisting of beam-to-column, beam-to-beam flush and extended end-plate steel bolted connections. Four of the tested specimens were stiffened in the extended parts. The goals of their experiment were to observe the failure modes and evaluate the resistance, stiffness and rotation capacity. They concluded that stiffening of the end-plates offered a significant increase in moment resisting capacity and initial stiffness but led to a reduction in the connection ductility. Tagawa and Liu (2014) suggested a new stiffening method for bolted end-plate beam-to-column connections in which stiffeners were used as steel member assemblies for steel angles and plates. In their proposed method, the transverse stiffeners and doubler plates were eliminated because the space between the column-flanges was used for architectural purposes such as ducting. Fang et al. (2014) investigated the cyclic performance of extended end-plate connections equipped with shape memory alloy bolts. These results were compared with conventional end-plate connections, and they found that the SMA connections have both

Figure 1. Conventional steel moment joint.

Figure 2. Dry mechanical concrete joint.
excellent re-centering ability and moderate energy dissipation capability. Wang and Chen (2012) investigated the effect of end plate thickness and column section type on the static behavior and failure modes of the tested connections. They concluded that utilizing moderately thick end-plates led to extended end-plate connection joints that approach full strength. In a later study from another group (Wang et al. 2013), the seismic behavior of extended end-plate connections bolted to circular or square concrete-filled steel tubes were investigated. They reported that the rotation capacities of the test specimens satisfied the ductility design requirements of earthquake-resistance for most seismic regions. Saberi et al. (2014) investigated the behavior of bolted connections as a function of the thicknesses of the end-plate and T-stub flange using a numerical method. In their results, they pointed out that the performance of bolted T-stub connections is more sensitive to component thickness than end plate connections Muresan and Balc (2015) demonstrated experimental results where increased displacement occurred around the tension flange of the connection. This resulted in an increase in the flexibility only after redistribution of the load on the bolts during preloading. Lee and Kim (2007) proposed a new seismic design procedure for steel moment connection that is more consistent with the actual load path identified from analytical and experimental studies. They concluded that a pilot test specimen designed by following the proposed procedure exhibited sufficient cyclic connection rotation capacity without fracture. Recently, Bai et al. (2015) proposed revision for conventional design method for extended end-plate bolt connection and suggested design formulae for bending moment in bolts and in end-plates.

Several parametric studies were undertaken in order to investigate the impact of both material and geometric configuration of extended end-plates (Gantes and Lemonis, 2003; Abolmaali et al., 2005; Maggi et al., 2005; Mohamadi-shooreh and Mofid 2008; Mashaly et al., 2011; Dessouki et al., 2013). In terms of geometric configuration, some results showed that the ratio of the width of the column flange to its thickness, the ratio of the depth of the column web to its thickness and the thickness of the end-plate were critical for determining the energy dissipation within the joints. In addition, Díaz et al. (2011) conducted a parametric study of a bolted extended end-plate joint connection based on a finite element model. Therein, they explained the relationship between the design moment resistance and the initial rotational stiffness of extended end-plate joint connections. Further studies (Richard and Walter, 2010; Reza, Boroujeni and Hashemi, 2013) including a recent research on precast recycled concrete frame structure conducted by Xiao et al. (2015) were also reviewed in the literature. Although extensive studies have been carried out over past years to investigate the behavior of bolted end-plates, it is noticed that most of these studies focused on examining the structural behavior of beam end-plates for steel frames. It is clear that beam end-plates that are designed for steel–concrete precast members seem to have been overlooked. This study was proposed to substitute the conventional steel–concrete frames which require pour-forms to cast concrete. In this paper, the use of pour-forms that lengthen the overall construction period has been entirely eliminated for the sake of a rapid construction for steel–concrete precast members.

Our proposed beam-to-column dry mechanical connection for steel–concrete precast composite members and reinforced concrete precast members allowed for rapid erection as a conventional beam-to-column joint and did not require the additional expense of fireproofing because the steel section is encased by concrete. The proposed novel extended end-plate connection can be implemented in fast-track modular offsite construction for reinforced concrete buildings and steel–concrete composite buildings.

2. RESEARCH OBJECTIVES AND METHODS

2.1. The joint details for fully restrained moment connections

In this study, concrete beams are proposed to be connected to concrete columns by joining end plates of beams and column plates using bolts in order to provide fully restrained moment connections for column-beam joint assembly, as shown in Figs. 3 and 4.

The new joint system consists of steel end plates at the ends of beams and plates on the face of columns bolted together to transfer the moment between joints. The plates and bolts are designed to
Figure 3. Moment connections for precast steel–concrete composite.

(a) Composite beam and column with plate

(b) Composite joints by plates

(c) Plate connection to beam and column

(d) Joint and Fastener details

Figure 3. Moment connections for precast steel–concrete composite.
Figure 4. Moment connections for reinforced concrete precast frames.

(a) Concrete beam and column with plate

(b) Concrete joints by plates

(c) Plate connection to beam and column

(d) Joint and Fastener details
transfer force couples (tension and compression) to create fully restrained moment connections. Bolts can be designed based on either bearing type or slip critical type. Additional structural elements for the new joints include couplers, threaded re-bar and anchor re-bar. Figs. 3 and 4 depict details of a mechanical joint providing moment connections and typical beam sections for steel–concrete composite precast frames and reinforced concrete precast frames, respectively. As shown in Figs. 3 and 4, the top re-bars of beams are anchored on the rear face of beam end plates using threaded ends and nuts. Steel sections for composite beams are welded to end plates. Couplers are used to provide connections between beam plates and column plates. Anchor re-bars in a column unit are connected to beam end plates using high-strength bolts. One end of the couplers is connected to anchor re-bars in the column, and the other end is fastened with high-strength bolts. The important design parameters to transfer tensile forces from beams to anchor re-bars in columns are the stiffness of end plates and sizes and locations of bolts, allowing moment resistance at the joints. The prying action of end plates with sufficient stiffness, resisting coupled forces of tension and compression, will be precluded, contributing to moment transfer through joints. The sizes of high-strength bolts should also be determined to minimize prying actions of beam end plates in order to fully restrain joints from rotation.

2.2. Stiffness of end plates

The plates and bolts shown in Figs. 5 and 6 were designed based on non-linear inelastic finite element analysis. In Fig. 6, finite element meshing for the non-linear inelastic analysis of hybrid joints using Abaqus was developed for the design of specimens. End plates with stiffness enabling tensile forces to be transferred from beam reinforcements to reinforcing bars anchored in columns were designed. The specimens in this paper were also poorly designed with insufficient plate stiffness in order to exhibit prying actions.

2.3. Fabrication of test specimens and test set-up

Beam–column joints for testing were fabricated as demonstrated in Fig. 7. The photo exhibits the connection of couplers to the threaded end of anchor re-bars and beam end plates through high-strength bolts. Couplers were tag-welded to column plates to ensure the locations of anchor re-bar. Fig. 8 shows the test setup for loading applications with the cyclic load protocol in order to study hysteretic behavior of specimens. All of dimensions used in the experimental investigation were provided in the figure. Six test specimens equipped with instruments with extensive gauges are presented in Fig. 9. In this photo, the beam end plates in B2 have a thickness of 44 mm, while the plate thicknesses of B1, B3 and B5 are 20 mm. The plate thickness of B4 is 16 mm, and B6 is a control specimen without an end plate, instead fabricated with a conventional beam–column joint. The beam end plates with 16 and 20-mm thickness were deformed regardless of the filler type, as shown in Tab. 1 and Figs. 10–16. These end plates were unable to transfer tensile forces from beams to columns as fully restrained moment connections. However, the beam end plates with 45-mm thickness transferred tension forces from beam to column, forming a joint rigid moment connection, as shown in Specimen B2. Figs. 10–16 demonstrates the hysteretic load–displacement relationships for all column specimens.

Figure 5. Design of plates and bolts.
Figure 6. Finite element model for bolts design.

Figure 7. Fabrication of a beam–column joint for testing.
3. EXPERIMENTAL INVESTIGATIONS

In order to better understand the structural behavior of the proposed beam-to-column joint including the deformations and stresses of the beam end plates, failure mode of frame joints based on diverse stiffness of the end plates, six test specimens subjected to cyclic loadings were performed, from which the procedures of designing steel–concrete composite frames with beam end plates were established. The test data including strains of reinforcing bars/steel and beam end plates enable the accurate predictions of the deformations of the beam end plates and performances of high strength bolts. The adequately designed joint plates demonstrate fully restrained moment connection equivalent to the conventional steel–concrete composite moment frames.

All damages and deformations were initiated at a stroke of 50 mm shortly after 77 kN with premature welding fracture of re-bars fillet welded to the end plate rather than the threaded rebar end, as depicted in Specimen B1 of Fig. 10a and b. The strain in the steel section did not reach yield strain when re-bars were detached from the end plate. However, Specimen B1 did not show noticeable plate deformation with prying action because welding failure was followed by separation of concrete from the beam plate preventing the plate from being deformed even if the thin plate was used. The strength reduction of the composite Beam B1 was significant and prematurely brittle failure mode was
dominant during the degradation. The welded re-bars, thus, are not recommended for use in the dry mechanical connection proposed in this study.

Specimen B2 with a 45-mm-thick beam end plate exhibited ductile behavior up to a 100-mm stroke, followed by fracture of the steel section and necking re-bars as shown in Fig. 11a and b. The necked re-bars represented by circles were then removed from nuts which were fastened on the rear side of the beam plate. The maximum load capacity of 137 (133) kN was recorded at a stroke of 90–100 mm, and rapid load reduction was observed after the maximum load was reached, as depicted in Fig. 11a. There was no noticeable plate deformation found at the end of the test. The specimen B2 presents flexural

<table>
<thead>
<tr>
<th>Specimen (plate thickness)</th>
<th>Deformation</th>
<th>Prying action</th>
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<tbody>
<tr>
<td>B1 (20 mm)</td>
<td>Welded rebar</td>
<td>No deformation (premature failure at rebar welding)</td>
</tr>
<tr>
<td>B2 (45 mm)</td>
<td>Embedded nut</td>
<td>No deformation</td>
</tr>
<tr>
<td>B3 (20 mm)</td>
<td>Filler concrete</td>
<td>12–15 mm</td>
</tr>
<tr>
<td>B4 (16 mm)</td>
<td>Filler concrete</td>
<td>14–17 mm</td>
</tr>
<tr>
<td>B5 (20 mm)</td>
<td>Filler plate</td>
<td>13–15 mm</td>
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<tr>
<td>B6 Control specimen</td>
<td>Control specimen</td>
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Figure 9. Instrumented specimens with beam end plates.
capacity which was similar to that of the conventional concrete frame without joint plates, uncovering that the stiffness of the end plates should be adequately determined for dry mechanical joint proposed in this study. It was also observed that the steel beams and reinforcing bars were fractured as shown in Fig. 11b prior to the structural degradation of the joint plates. The ductile behavior of the test specimen was observed from the load–displacement relationships shown in Fig. 11a.

Specimen B3 which was fabricated with a 20-mm-thick end plate and a concrete filler plate between the beam and column plate demonstrated maximum load capacity of 84 kN at a stroke of 105 mm (85 kN, 75 mm), as shown in Fig. 12a. Rapid load reduction was observed after reaching the maximum load because of steel fracture and necking of re-bars as shown in Fig. 12b. The deformation of the
beam plate was about 12 mm at maximum load and increased to 15 mm at a stroke of 120 mm, as shown in Fig. 12b. Specimen B3 was one of the specimens that failed to provide enough stiffness for dry mechanical joint. Fig. 12b and Fig. 17 present the plate deformed as much as 12–15 mm.

Figure 11. (a) Load–displacement relationships for specimen B2. (b) Failure modes for specimen B2.
The load–displacement relationship exhibited ductile behavior because the inelastic energy was dissipated during the gradual deformation of the plate before the strength was lost totally when steel flange was fractured. The additional interior bolts, however, may be required to be installed to decrease unsupported length between the exterior bolts to reduce deformation of the plates.

Specimen B4 fabricated with a 16-mm-thick end plate and a concrete filler plate between the beam and column plates exhibited a maximum load capacity of 72 kN in a stroke range of 120 mm–225 mm (73 kN, 150 mm), as depicted in Fig. 13a. A constant load-bearing capacity was observed in this stroke range because the structural degradation with energy dissipation was concentrated on the beam plate,
Figure 13. (a) Load–displacement relationships for specimen B4. (b) Failure modes for specimen B4.
which was gradually deformed to 14 mm. The deformation of the beam plate increased to around 17 mm at a stroke of 150 mm. The concrete specimen did not show noticeable deterioration because all the damages were concentrated on the plate with extensive deformation as depicted in Fig. 13b.

Figure 14. (a) Load–displacement relationships for specimen B5. (b) Failure modes for specimen B5.
Specimen B4 demonstrated the least flexural strength among all test specimens because the end plate with the least stiffness with only 16 mm was used at joint. Fig. 13b shows the plate deformation as much as 14–17 mm which was responsible for the significant reduction of the flexural strength of
Nuts were displaced during the transfer of the tension from re-bars because the deformed plate pushed nuts off the re-bar tread plane. It was inferred that the unexpected distortions of nuts and tread of re-bars can be prevented by maintaining plate deformation minimum or by providing gaps between nuts and the holes prepared in plates.

Specimen B5 fabricated with a 20-mm-thick end plate and steel filler plate between the beam and column plates exhibited a maximum load capacity of 84.7 kN at a stroke of 105 mm (92 kN, 105 mm), as depicted in Fig. 14a. A constant load-bearing capacity was observed in this stroke range because the structural degradation with energy dissipation was concentrated on the beam plate. The concrete specimen did not show noticeable deterioration, as depicted in Fig. 14b for the same reason observed in Specimen B4. The deformation of 13–15 mm was observed in the beam plate at a stroke of around 150 mm as shown in Fig. 14b. The plate deformation of the Specimen B5 was predicted as 15 mm by finite element analysis using Abaqus as shown in deformed meshes in Fig. 6. This prediction was well matched with the deformation measured by the experiment as illustrated in Fig. 14b. The inelastic load displacement relationship used to design the Specimen B5 was also calculated by the non-linear inelastic FEM analysis and compared with experimental curves of the specimen with blue colors as represented by the purple line in Fig. 16. The deformation of plate in Specimen B5 was measured as 13–15 mm similar to the deformation of Specimen B3 because the plate of the same 20 mm thickness was used. The two specimens differ in that the steel filler plate was used in Specimen B5 while concrete filler plate was in used in Specimen B3. The flexural strength of B5 was found larger than that of B3 because the steel filler plate in B5 provided larger flexural stiffness even if the only 5% difference in the flexural were measured. The displacement corresponding to the maximum load in B5 was similar to the displacement in B3 as shown in Fig. 12a and Fig. 14a.

Specimen B6 was a control specimen with a conventional beam–column joint of a steel and reinforced concrete frame. Specimen B6 demonstrated a maximum load capacity of 158 kN at a stroke of 90 mm (174 kN, 90 mm), as depicted in Fig. 15a. The compressive failure modes were observed as loadings increased to the maximum load limit state, as depicted in Fig. 15b. The experimental hysteretic load–displacement relationships with the plates of 45 mm (B2) and 16 mm (B4) are compared with that of control beam (B6) in Fig. 16 for beam, showing large strength reduction of the beam with a plate of 16-mm thickness (B4). The load displacement relationships of control specimen (B6) were similar to those of Specimen B2 built with plate stiff enough to suppress deformation. It was noted that the pour-forms were used to build the joint of Specimen B6; however, dry mechanical joint with beam end plates and filler plates was only used for Specimens B1, B2, B3, B4 and B5, eliminating the use of temporary pour-forms.
The difference in structural performance observed in the test data represented by Arrow #2 in Fig. 17 was because of the size differences of the reinforcing steel plates used in Specimens B6 and B2, illustrating that the dry mechanical joint with a beam end plate with sufficient stiffness (B2) demonstrated similar structural performance to the conventional beam–column joint. The B6 sample (with re-bar of 25-mm diameter) was a control composite frame with a conventional beam–column joint, while the B2 (with re-bar of 20-mm diameter) beam was prefabricated with extended end plates and bolts. If re-bar of the same diameter had been used in these two specimens, similar strength likely would have been obtained, indicating that well-designed end plates with sufficient stiffness and strength contribute to moment transfer through the joint, similar to conventional moment connections.

Fig. 17 compares the structural behavior with hysteretic envelope of load deflection relationship of control beam (B6) of conventional moment column-beam joint with the beams of extended end plate of sufficient stiffness and insufficient stiffness. However, strength loss, indicated by Arrow #1 in the figure, was observed in the specimens with thin plates of insufficient stiffness. The Arrow #1 of Specimen B4 assembled with a beam end plate of 16 mm and filler concrete indicates strength reduction of moment resistance. Specimens B3 (20 mm, filler concrete) and B5 (20 mm, filler plate) with end plates of insufficient stiffness showed similar strength reduction.

4. RESULTS AND CONCLUSIONS

This paper was primarily devoted to the novel steel–concrete precast beam–column joints, as the experiments were performed to uncover the behavior of steel–concrete precast frame joints with beam end plates which are far more complex than that of the precast reinforced concrete frame joints. The steel–concrete precast beam–column joints plates, therefore, can be used for the precast reinforced concrete frame joints which are subjected to less stresses and deformation because of the tension forces transmitted into the beam end plates through the reinforcing bars only.

Even when the beam plates exhibited prying action, as in Specimens B3, B4 and B5 with 16-mm and 20-mm plates, constant load-bearing capacity was observed because the ductile structural degradation with large energy dissipation was concentrated at the beam plates, leading to no significant compressive failures exhibited for the specimens. Two steel plates connected by couplers, anchor re-bars in the column and high-strength bolts to transfer tension forces from beams to columns were utilized to provide fully restrained moment connections for steel–concrete precast concrete frames. Plates with enough stiffness to resist tensile forces exerted by re-bars and steel beams during bending as in Specimen B2 demonstrated identical structural behavior to the conventional joints of steel–concrete composite frames. End plate stiffness, sizes and locations of high-strength bolts must be determined in order to properly transfer moments from beams to columns, minimizing prying actions at the beam end plate. Experimental investigations presented end plates with sufficient stiffness and strength to preclude end plates prying, demonstrating similar structural behavior to conventional moment frames. The experiment also showed that the end plates with insufficient stiffness were not able to prevent strength reductions, failing to provide fully restrained moment connections.

Dry mechanical beam–column joints for steel–concrete composite precast frames were developed to replace the conventional steel–concrete composite frames requiring concrete cast. The bolted beam end-plates for steel frames used in steel industry for decades was reinstated to make fully restrained moment connections for composite steel–concrete precast frames. The deformations and stresses of the beam end plates with various failure modes of frame based on the stiffness of the end plates were observed to help one to design dry mechanical joints for composite steel–concrete frames with adequate stiffness while minimizing the reduction of flexural capacity of the composite beams. Another advantage of the mechanical joint introduced in this study is an application of the precast concrete based moment-resisting joint in order to provide similar assembly speed of the steel frame. These simplified connections can result in faster modular offsite construction of buildings and heavy industrial plants based on quick assembly and dismantle capability.
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REFERENCES


Ali Reza, Keyvani Boroujeni and Mehdi Hashemi. 2013. Linear and nonlinear analysis for seismic design of piping system.


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**Dr. Seon-Chee Park** received his master’s and PhD degrees from Kyung Hee University in Structural Engineering. His main research areas include an analysis of structural behavior and new approach to construction technologies based on composite structures.
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