Examination of erection safety of precast beam assembly using a slanted beam section based on assembly test

Dinh Han Nguyen, Eric Nkundimana and Won-Kee Hong

Department of Architectural Engineering, Kyung Hee University, Yongin, Republic of Korea

ABSTRACT
Assembling precast frames subjected to heavy construction loads may require a significant crane operation time when they were assembled by conventional steel joints having a straight beam cut. This study proposed a method that will provide a facile and rapid assembly of heavy precast frames, having the temporary bolting be established as noncritical path. Lower flanges of wide flange beam installed at end of precast beams were partially removed to prevent bottom flange of steel beam from running into flanges of L-shaped guide pockets when steel beam was inserted in L-shaped guide pockets. Permanent connections are made by bolting L-shaped guide pockets. Stable behavior was observed during an erection test of the proposed connection. This study also aimed to investigate an assembly safety of steel beam-column joints with a skewed beam section based on a nonlinear finite element analysis. Strain and stress analysis also demonstrated that stable structural behavior of joint elements was ensured during an assembly of precast frames.

1. Introduction

1.1. The state of art of the technologies

Due to a relative economy and faster construction, prefabricated structural members are gaining popularity in a construction industry (Ju, Fan, and Wu 2004; Saberi, Gerami, and Kheyroddin 2014; Trahair et al. 2007). Previous studies were performed in attempts to improve both an erection and application of precast members (Guan et al. 2016; Proverbs, Holt, and Olomolaiye 1999). Construction period and an overall construction cost significantly depend on lifting and installation processes of precast members, impacting on an overall construction project. However, structural behavior of these members during earthquakes is complex due to their connections despite of many advantages including reduced construction time. A reliable joint design for precast members should be provided to prevent an unexpected behavior at joints. Numerous ways were proposed to design connections of precast members. They were the mostly addressed concrete joints using rebars and mechanical hardware.

Three types of dry connections were introduced in an architectural precast concrete connection guide (National Precast Concrete Association 2012); wet, welded, and dowel/anchor bolt connections. Industrially produced connection parts (wet connection, bolt, or weld connection) can be used for precast connections (Elematic 2020). Sufficient minimum clearance between precast units and structure for an erection tolerance must be provided. Stresses occurred at maximum anticipated clearance must be compensated for designs. Any joints and gaps between precast members are potentially weak link, resulting in potential serviceability problems, lack of durability or structural failure (Cement concrete & aggregates 2004). Jiang et al. (2016) studied shear behavior of various types of dry joints by their experiments. They focused on shear strength of keyed dry joints of precast frame with experimental parameters including joint types, concrete types, key numbers, contacting portions in a sliding plane,
and horizontal confining stress levels. Jiang et al. (2015) also investigated full-scale dry joints with castellated keys tested under different confining stress levels. Number of keys, confining stress, depth in key geometry, and distance between two keys were identified. Jiang et al. (2019a) proposed new type of prefabricated cross joint which was constructed of a circular tubular steel column with a cantilever beam, a common beam, and a connection device consisting of a flange cover plate, L-shaped plates, and high strength bolt groups. Jiang et al. (2019b) presented seismic performance indicators including hysteresis curve, strain curve, skeleton curve, and energy dissipation of joint based on five specimens and six low-frequency cyclic loading tests. Their test results were verified by finite element analysis. Zhang et al. (2020) performed low cycle reciprocating test and finite element (FE) numerical validation on four specimens of prefabricated column-flange beam-column joint (PCFBCJ). Specimens were new earthquake-resilient PCFBCJ for connections between column-flange and beam-column.

Hong et al. (2008, 2009) and Hong (2019) investigated a use of steel sections for precast frame connections in which steel sections were encased in concrete to provide robust joints in construction of tall buildings. Hybrid steel-concrete hybrid frames were implemented in construction of the 19-story twin buildings. None of them provided implemented steel-concrete hybrid sections to facilitate erection process as the one that this study aims.

1.2. Research significance

1.2.1. Motivation of the proposed assembly method

The state-of-the-art conventional steel erection is to use conventional steel brackets with straight cuts for assembling steel frames as shown in Figure 1(a) (Hong 2019). Assembling precast frames subjected to heavy construction loads and installing all bolted stiffeners based on conventional steel joints with brackets having straight cuts may require a significant crane operation time. Steel brackets with straight cuts have been traditionally used for assembling steel frames. In the conventional steel assembly shown in Figure 1(b) (EBS YouTube 2014), splicing plates of up to the eight pieces of splicing plates (six plates for upper and lower flanges and two plates for the web) are temporarily installed to hold column and beam brackets together, ensuring that bolt holes are in proper relative positions before removing crane. Number of temporary bolts up to a 20% of total bolts at joints is used to keep bolt holes aligned, holding all splicing plates together. Figure 1(c) shows permanent plates with full bolt holes that replaced temporary web plates (EBS YouTube 2014).

This study developed slanted steel beams encased in precast concrete to help lift and assemble heavy precast concrete frames with deep depth, requiring multiple bolts and heavy stiffeners. Steel sections encased in precast concrete provided an assembly similar to that of steel frames, saving a construction time. The new erection method introduced in this study eliminate a use of temporary splicing plates and bolting, letting them be beyond critical path. Conventional erection method can be replaced by the new erection method. In previous study, Hong et al. (2017) proposed for an easy and rapid assembly of heavy hybrid precast beam-column joints. In this method, a pair of the L-shaped channels were used to receive a web of T-shaped steel beams which do not have lower flanges. However, this method cannot be used to assemble frames with wide flange beams having lower flanges since lower flanges of beam section cannot fit between L-shaped guide pockets. In this study, a novel beam-column joint consisting of a straight-skewed web (Figure 2a)) was proposed in an attempt to ease an erection of precast frames (Hong 2019). The present study was carried out to resolve mismatches that occur when wide-flange steel beams having lower flanges are inserted between a pair of the L-shaped channels (Figure 2(b)-(1) and (3)). This is accomplished by preparing skewed cuts for both lower flanges of column (Figure 2(b)-(2)) and steel beam sections (Figure 2(c)).

A use of bolts required in temporary connections (Figure 1) is reduced significantly when steel beams are placed and kept in permanent L-shaped pockets (Figure 2(b)-(1) and (3)). The suggested connection requires only a few bolts as demonstrated in a full-scale assembly test shown in Figures 2-5. Precast frames requiring multiple bolts and splicing stiffeners are effortlessly assembled by utilizing skewed connections along column and beam steel web (Figure 4a)). Lower flange of wide flange column bracket and beam are partially removed as shown in (Figure 2(b)-(2) and 3). These helped bottom flange of steel beam be inserted into L-shaped pockets (Figure 2(b)-(3)), which were pre-installed on column bracket. Splicing plates for flange and web are bolted to L-shaped pockets beyond critical path when they are erected. The proposed method can contribute to rapid and effortless erections of a precast frame.

1.2.2. Significance of the numerical analysis

The author performed a 3D nonlinear finite element study to investigate a structural behavior of the proposed skewed joint based on artificial damping factors to enhance numerical stability for irregular joints as shown in (Nzabonimpa and Hong 2018). They accurately predicted load-displacement relationships of a beam column connection having skewed cuts of joint at yield and maximum load limit states. Failure modes and stress–strain relationships of novel joints were identified at maximum load limit state when all bolts of skewed joints were installed. However, this study (Nzabonimpa and Hong 2018) did not explore a stability of skewed joint during an assembly when no bolts or only a few bolts were
installed as can be seen in a full-scale assembly test (Figures 2-5). The present study observed stable behavior during an erection test of the proposed connection. Numerical analysis of steel beam-column joints having a skewed beam section was investigated. Stress-strain analysis of joint elements demonstrated a stable structural behavior during an assembly of precast frames. Current study aimed to explore a joint behavior when installed with one bolt or no bolt. Deformations, strains of joints and dislocations, strains of bolts holes were predicted against weight of precast concrete upon a removal of cranes. Current study also delved strains of rebars, steels, concrete, and deformation of L-shaped pocket when joints were installed with and without bolts.

2. Assembly of the column-to-beam connections having skewed sections

2.1. Installation of the L-shaped guide channels

In the novel connections with skewed cuts along web of columns and beams, steel beams were inserted into
Figure 2. Pre-installation of L-shaped pocket; novel connection for assembling heavy precast frames.
(3) L-shaped guide pockets pre-installed on the column bracket.  
(b) Installation of L-shaped guide pockets.  
(c) Preparation of joint steels; steel beams with a skew cut pre-installed at the end of the precast concrete.

Figure 2. (Continued).
(a) Simulation of the assembly sequence of the steel beam sections having skew web; Connection details of the joints (skew web and L-shaped guide pocket) for the precast composite structural frames (Hong 2019, Nzabonimpa and Hong 2018)

(1) Lifting simulation (Hong 2019)

(2) Steel beam sections connected with column brackets in the L-shaped channels

(b) Lifting of beam with skew web for being guided/inserted into the pre-installed pockets

Figure 3. Installation of steel beam sections having a skew web in the L-shaped pockets.
(1) Lifted to be placed in L-type pockets

(2) Skew web inserted in L-type pockets
(a) Steel web of beam being placed in the L-shaped guide pocket

(1) Beams (H and T-types) placed in L-type pockets with no temporary erection bolt in web without cranes

**Figure 4.** Assembly of beam steels without temporary splicing plates and bolting. (1) Splicing plates connecting lower flanges; splicing stiffener plate attached to the lower flange of the column bracket.
preinstalled L-shaped pockets, holding heavy frames in L-shaped pocket angles. An installation of splicing plates and bolting are regarded as a noncritical path. Full-scale assembly test elucidates a use of only few bolt installations, as shown in Figures 3-5. Only one erection bolt (or drift pin) used to keep steel beams in L-shaped pockets column bracket, pre-installed beneath upper flange of column brackets to help insert skewed web of steel beam section into L-shaped channels. This ensures proper relative positions (refer to Figure 4(a,b)), while

(2) Beams (H and T-types) placed in L-type pockets with one temporary erection bolt in web without cranes

(3) One temporary erection bolt holding the pre-installed L-shaped angles on the column bracket, ensuring the proper relative positions of the bolt holes

(b) Skew web of steel beam completed being placed in the L-shaped guide pocket; crane released without permanent bolting to web

Figure 4. (Continued).
rapidly removing cranes to reduce crane operation time. Lower flange of beam is guided and inserted between a pair of L-shaped pocket channels shown in Figure 2(b) based on three types of web cuts (straight-skewed, skewed, and crank type, as shown in Figure 2(a)). This ensures that flanges of steel beams will not impact L-shaped guide channels. Figure 2(b)-(1) and (2) show guide pocket (consisting of a pair of the L-shaped channels), and column brackets with a skewed cut, respectively. Tolerances were provided by providing slotted holes as shown in Figure 2(b)-(1) to cope with misalignments of holes during a manufacture of L-shaped channels (Hong 2019). A use of rectangular-shaped washer plates was also proposed for these long-slotted holes as shown in Figure 2(b)-(3). As shown in Figure 2(b)-(2) and (c), column bracket and H-shaped beam with a skewed cut are prepared by partially cutting lower flange to avoid impacting bottom flange of
steel beam into L-shaped channels (shown in Figure 2(b)-(3)) when bottom flange of steel beam was inserted in L-shaped channels. An assembly more efficient than that of a conventional steel assembly was offered by establishing bolting as a noncritical work, whereas temporary bolting to hold connections was removed.

### 2.2. Structural requirement for cut web

Figure 6 cited from the previous study of the authors (Nzabonimpa and Hong 2018) shows numerical errors, which were identified at nodes #1 and #2 in the neighborhood of the sharp edges. Numerical computation for cyclic moment–displacement relationship was prematurely terminated as represented by Legend 3 (refer to Figure 7 of the previous study of the authors) (Nzabonimpa and Hong 2018) at a stroke around 60 mm. Cyclic numerical investigation of a hybrid beam with an edge too sharp may experience numerical instability. However, sharpness at the edge is not limited. Instability can be overcome by implementing virtual damping factors as shown in the previous papers of authors (Nzabonimpa and Hong 2018).

### 2.3. Beam-column assembly procedure for heavy hybrid precast beams having H-shaped steel

Full-scale assembly with a connection details and lifting simulation using skewed web (refer to Figure 3(a) and (b)-(1)) (Hong 2019) are presented in Figures 3-5. In Figure 3(b)-(2) and 4(a)-(2), bottom flange of steel beam does not impact upper flanges of L-shaped pocket channels during placing steel beam sections because lower flange of wide flange beam was partially removed. In Figures 3(b)-(2) and 4, a full-scale assembly test for beam with H-shaped steel and T-shaped steel is

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**Figure 6.** Convergence difficulties and numerical instability; locations of numerical instability (Nzabonimpa and Hong 2018).

**Figure 7.** Cyclic results without damping and with the default damping factor (Nzabonimpa and Hong 2018).
shown, in which H-shaped steel beam having a skewed web is guided and placed into pre-installed pockets. In Figure 4(a), beams are erected and inserted rapidly and effortlessly in L-shaped guide angles. Web with skewed cuts is, then, kept in L-shaped guide angles (Figure 4(b)) until permanent connections are made by bolting splicing stiffener plates (refer to Figure 5). No bolts were installed to hold relative positions of beams inside L-shaped guide angles, without cranes, as shown in Figure 4(b)(1). Only one bolt of a specified size is used to hold relative positions of joints tight until permanent connections are achieved by installing all bolts to splice stiffener plates as shown in Figure 4(b)(2) and (3). It was numerically and experimentally shown (Section 3 of this study) that bolt holes were aligned properly held in their correct positions until all splicing plates were installed. Relative positions of empty bolt holes are calculated numerically, as shown in Section 3. Web of L-shaped guide pocket was then bolted without cranes while keeping bolt holes aligned via properly sized drift pins installed in first few sets of holes or via one temporary erection bolt (refer to Figure 4(b)). Figure 4(b) shows an erection bolt installed in the second low of bolt holes, keeping holes aligned, which was followed by bolted connections of lower flanges, upper flanges, and web of L-shaped guide pocket without cranes. Beam-to-column connections are completed when bolting H-shaped steel sections and L-shaped guide pocket by permanent fasteners as shown in Figures 3(a) and 5. Drift pins and erection bolts, if any, may be replaced by new ones to complete joint connection. Finally, completed assembly with fully bolted permanent fasteners is shown in Figure 5, depicting completed beam-to-column connection of H-shaped steel sections in L-shaped guide pocket. Erection test of proposed connection achieved a reduction in amount of time required to assemble precast composite frames subjected to heavy gravity loads. This assembly method was originally developed for a use in an erection of heavy precast frames; however, it can be extended to assemble conventional steel frames.

3. Numerical evaluation of the proposed connections and discussions

3.1. Deformations and strains at the joints with/without bolts without cranes

Nzabonimpa and Hong (2018) performed a numerical analysis of column-to-beam joints having skewed web cuts to evaluate cyclic hysteretic behavior of the proposed connections with L-shaped guide angles. Cyclic energy-dissipating capacity of the proposed connection indicated that skewed connections possessed a sufficient ductility and resistance to heavy construction loads (Nzabonimpa and Hong 2018). They showed that convergence difficulties were removed when artificial damping factors were added. In the present study, a numerical investigation was performed to explore strains at skewed joints. Numerical model for skewed joint with L-shaped pocket is described in Figure 8(a)-(1), where contact model (Figure 8(a)-(2)) defining interfaces between structural elements in contact is developed to prevent penetrations between surfaces.

A half of model was performed to reduce running time of computer calculation. The concrete material of Kent-Park model was used where rebar and steel were considered as the elasto-plastic materials. Elasto-hardening model for bolts was used as indicated in Figure 8(a)-(3). Compressive strength of concrete was 27 MPa, while its tensile strength was defined as 2.7 MPa. Concrete-damaged plasticity model was used with considering non-associative Drucker-Prager formulation (Dassault Systèmes Simulia Corp. 2014) which was indicated by Equation (1) below:

\[ G(\sigma) = \sqrt{(\epsilon_0^2 \tan \psi)^2 + q^2 - \rho \tan \psi} \]  

(1)

Where \( \psi \): dilation angle (assigned as 30\(^\circ\)), \( \sigma_{01} \): uniaxial tensile stress: eccentricity (assigned as 0.1), \( \rho \): hydrostatic pressure, and \( q \): von Mises equivalent effective stress. Viscosity, ratio of the equibiaxial compressive to uniaxial compressive strength of concrete \( f_{bol}/f_{c0} \), and \( K_c \) were defined as 0.002, 1.16 and 2/3, respectively.

FEA model includes 309,812 elements with a type of C3D8R (eight-node brick element with reduced integration), which increases computational efficiency without losing an accuracy. Loading and boundary condition of FEA model with dimensions are shown in Figure 8(a)-(4).

The mock-up test focuses on safety during erection, thus, considering FEA model only during an assembly under beam loads. In this study, the authors considered critical loads occurred at skewed web when one or no bolt was used at connections.

Dislocations of empty bolt holes of 0.092 mm (Figure 8(b)-(1)), and not greater than 0.03 mm (Figure 8(c)-(1)) were calculated based on a finite element analysis at all bolt holes against gravity load (the weight of the precast beam) of 40 kN when no bolt and one bolt are used to hold joints without cranes, respectively. Small relative dislocations of empty holes were demonstrated. Dislocations with no bolt and one bolt were 0.197 mm (Figure 8(b)-(2)), and 0.065 mm (Figure 8(c)-(2)), respectively, at all bolt holes against twice weight of precast beam (80 kN) at removal of crane. In Figure 8(b)-(3) and Figure 8(c)-(3), strains of components including rebars, steel sections and concrete are plotted against deflection at middle of beam when joints are fastened with no bolt and one bolt to hold joint. Number of bolts that must be fastened to support precast concrete weights without cranes should be determined based on dislocation of bolt holes as shown in Figure 8(d). Bolt strains at Holes (4) and (5)
(1) Numerical model for the joint with L-shaped pocket

(2) Definition of the contact element

(3) Material properties of the components

*Figure 8.* Deformations and strains at the joints with/without bolts when cranes were removed.
Figure 8. (Continued).
Figure 8. (Continued).
(e) Bolt strain vs. weight of precast concrete

(f) Strain of rebars, steels and concrete vs. weight of precast concrete

(g) Deformation of the L-shaped pocket

Figure 8. (Continued).
(a) Stress of skewed web steel vs. weight of precast concrete without bolt

(b) Stress of skewed web steel vs. weight of precast concrete with one bolt

(c) Strains of skewed web steel vs. weight of precast concrete without bolt

(d) Strains of skewed web steel vs. weight of precast concrete with one bolt

Figure 9. Skewed web steel behavior.
Table 1. Strains and stress of skewed web corresponding to total uniform load of 40 kN and 80 kN ($\varepsilon_y = 0.00115, F_y = 235$ MPa).

| Point | Total uniform load of 40 kN | Total uniform load of 80 kN |
|-------|-----------------------------|----------------------------|
|       | Without bolt | With one bolt | Without bolt | With one bolt |
|       | Stress (MPa) | Strain | Stress (MPa) | Strain | Stress (MPa) | Strain |
| Point 1 | 97 | 0.00026 | 115 | 0.00031 | 194 | 0.00053 | 231 | 0.00064 |
| Point 2 | 36 | 0.00011 | 47 | 0.00011 | 72 | 0.00021 | 82 | 0.00022 |
| Point 3 | 22 | 0.00008 | 27 | 0.00007 | 45 | 0.00017 | 41 | 0.00015 |
| Point 4 | 32 | 0.00053 | 24 | 0.00007 | 63 | 0.00016 | 48 | 0.00014 |
| Point 5 | 26 | 0.00009 | 18 | 0.00006 | 32 | 0.00018 | 36 | 0.00013 |
| Point 6 | 47 | 0.00020 | 14 | 0.00007 | 84 | 0.00041 | 25 | 0.00012 |
| Point 7 | N/A | N/A | 88 | 0.00023 | N/A | N/A | 180 | 0.00049 |

are identified around 0.0005 at four times precast beam weight (200 kN) when only one bolt is fastened, as shown by Legends 8 and 9 of Figure 8(e). Strain of rebars (Location 3), steels (Location 2) and concrete (Location 1) calculated against weight of precast concrete also indicate that they are negligible when crane is removed, as shown in Figure 8(f). Steel beams were placed stably inside L-shaped pocket without crane support. It was demonstrated that L-shaped pocket shown in Figure 8(g) holds steel beam stably as verified by negligible strains and deformations of L-shaped pocket corresponding to weight of precast beam (40 kN). Strain levels of 0.0027 (Legend 3) and 0.00175 (Legend 4) at bolt hole were identified at 10 times the weight of precast beam (400 kN), whereas a deformation of 5.5 mm (Legend 3) and 3.8 mm (Legend 4) at an edge of L-shaped channel were observed when no bolt was used and one bolt was installed, respectively. The rest of bolts can be installed without crane, making an installation of temporary bolting unnecessary. Joints exhibited no structural concerns to stably hold beam-to-column connections without any bolts and without crane during an assembly of precast frames subjected to heavy loads as shown in Figure 8(b,c,f). Numerical study predicts strains of bolts, rebars, steel flanges, and precast concrete.

3.2. Structural behavior of skewed web steel

In Figure 9(a,c), bolt is not used (refer to Figure 9(a,c)) whereas bolt is fastened at Location 7 (refer to Figure 9(b,d)). Numerical sensitivity of stresses and strains when a bolt is installed at Location 7 are compared with that when a bolt is not installed at Location 7. Strain and stress at bolt holes adjacent to Bolts 1 and 2 (below Bolt 7) are larger as underlined in Table 1 with Bolt 7 than those without Bolt 7, because bolt installed at Location 7 provides resistance to the joint. They are larger at bolt holes adjacent to Bolts 3, 4, 5, and 6.

![Figure 10. Construction schedule of hybrid frames compared with that of reinforced concrete frames (KH housing solutions, GS construction, Keumho construction and Hanjin construction 2019).](image-url)
When Bolt 7 is not used, because bolts installed at Locations 3, 4, 5, 6 provide resistance to the joint. All strains and stresses are small during an erection.

3.3. Range of relative dislocation of bolt holes

There is no deformation of the plates during erection. The dislocations of bolt holes with total load of 40/80kN were 0.092/0.197 mm without bolt and 0.03/0.065 mm with one bolt, respectively (refer to Figure 8(b, c)). Bolt diameter was 20 mm, while bolt holes were created with a diameter of 22 mm. Thus, permissible dislocation of bolt holes was considered up to 1 mm. Maximum dislocations were 0.197 mm less than permissible value (1 mm), therefore assembly process went smoothly.
4. Construction time, cost and productivity

4.1. Construction schedule

A construction schedule of a hybrid precast frame introduced in this study is compared with that of reinforced concrete frames in Figure 10 where construction durations (excluding basement) of twenty seven-story precast frames having skewed cuts were estimated 4.5 floors (based on the seven days per floor) and 3.4 (based on the nine days per floor) floors per months, respectively. Use of slanted steel beam sections for erections of precast frames contributed to total construction time which was shortened by two months when compared with concrete frames (KH housing solutions, GS construction, Keumho construction and Hanjin construction 2019).

4.2. Cost and productivity

The proposed construction method was certified as the 860th New Excellent Technology by Ministry of Land, Infrastructure, and Transport of the Korean government (KH housing solutions, GS construction, Keumho...
### Table 2. Summary of life cycle cost (LCC).

| Proposed frame | Steel frame | Reduction (%) |
|----------------|-------------|---------------|
| Construction   | 10,041,070  | 10,908,909    | 7.96%         |
| Maintenance    | 3,465,184   | 3,764,661     | 7.95%         |
| Demolishment   | 14,787,981  | 14,265,211    | 3.60%         |
| Total          | 34,294,135  | 34,940,781    | 2.01%         |

Construction and Hanjin construction 2019. Design of conventional steel frames and their structural quantities of the module shown in Figure 11(a) are compared with those of hybrid frames having skewed cuts shown in Figure 11(b). Hybrid beam sections designed based on strain compatibility are presented in Figure 11(c). Concrete strength of 28 MPa was used for design whereas yield strength of rebars and steel sections were 500 MPa and 315 MPa, respectively. Depth of steel beam with 900 mm including a slab of 150 mm and fireproof (designated as SG2 in Figure 11(a)) was reduced to 750 mm for a precast beam encasing steel section. A slab depth (150 mm) is included in total beam depth as designated by the MHSG2 (Figure 11(b)). Structural quantities of steel members were also significantly reduced compared with those of conventional steel beam as shown in Figure 11(d). It should be noted that concrete and rebars are to be added into construction quantities of proposed precast beams shown in Figures 11(c) and 8(d). A weight (74 kgf/m) of a hybrid precast beam of MHSG2 was found significantly less compared with 185 kgf/m of a conventional steel beam, SG2, whereas rebars of 0.2 tonf and concrete of 7.5 tonf should be added to MHSG2. Table 2 was officially submitted by DEIRI (Dongyang economic information research institute 2018) which performed cost accounting of hybrid precast beam for the Certification 860 of New Excellent

**Figure 11.** (Continued).
Technology in Korea. In Table 2, a total of 11.31% is reduced when the proposed frame in this study is implemented. The LCC was estimated for frames shown in Figure 11(a,b).

5. Recommendations for an assembly

It will be difficult to assemble heavy precast frames using pieces of splicing plates and temporary bolts. This study introduced a simplified installation of heavy composite precast frames in which steel web was cut in a skewed manner to prevent bottom flange of steel beam from penetrating L-shaped guide pockets (which were pre-installed on column bracket) during an assembly. Skewed web of steel beam sections was held in L-shaped guide angles until permanent connections were made by bolting splicing stiffener plates, allowing the rest of the bolting to be noncritical path. In Figure 4, beam steel placed in L-shaped pocket was held stably by one erection bolt to support heavy beam loads until all permanent connections were installed. In Figure 5(a), stiffener plates were installed beneath lower flange of column bracket, achieving continuity of upper and lower flanges via double shear, as depicted in Figure 5(b). Thus, crane operation time can be minimized when steel beam sections were effortlessly inserted into guide pockets prior to installing permanent bolts. Erection test of precast frames with heavy vertical loads using proposed connection demonstrated that rapid and effortless erections similar to those obtained with steel frames were achieved via use of preinstalled L-shaped guide angles. A reduction in amount of time required to assemble heavy precast frames was resulted. An assembly safety of proposed joints during assembly of precast frames was confirmed by strains and stresses obtained by a nonlinear FEA.

6. Conclusions

An erection test demonstrated that one temporary erection bolt (or drift pin) was used to keep L-shaped pockets pre-installed on column bracket in position as shown in Figure 4(b)-(2) and (3). Proper relative positions of beam-to-column connections were ensured with reduced crane operation time, enabling rapid removal of cranes.

Time for temporary bolting that must be observed for conventional steel assembly can be reduced in the proposed assembly, in which temporary bolting can be established as noncritical paths. The proposed method will provide an assembly more facile than that of conventional steel assembly. Conventional steel assembly requires more temporary bolts to hold connections before removing cranes. This study showed a steel web with skewed cuts for a fast and easy assembly of precast frames. An erection test of the proposed connection demonstrated that a use of pre-installed L-shaped guide pockets provided rapid and effortless erections of a precast frame subjected to heavy loads.

Stable structural behavior of joint elements during an assembly of precast frames was ensured by strain analysis based on a nonlinear finite element analysis. Negligible strains and deformations of L-shaped pocket are found in Figure 8(g), rendering temporary bolting unnecessary, and keeping steel beams stably inside L-shaped guide pockets without crane support. Construction durations of 4.5 floors (based on the seven days per floor) and 3.4 (based on the nine days per floor) floors per months were estimated for constructions of a twenty-seven story hybrid frames with skewed cuts and reinforced concrete frames excluding basement, respectively. A construction schedule of 2 months can be reduced compared with that of concrete frames when hybrid frames are implemented (KH housing solutions, GS construction, Keumho construction and Hanjin construction 2019). Bolting can be established as noncritical paths (noncritical bolting) based on the following assembly sequence.

1. Pre-installing L-shaped pockets to column steel brackets.
2. (2) Preparing skewed cuts by partially removing lower flanges (placed at ends of precast concrete beams).
3. Preventing bottom flange of steel beam from running into upper flanges of L-shaped guide pocket when steel beam sections are placed in guide pockets.
4. Ensuring proper relative positions of bolt holes by holding steel beams and column bracket in preinstalled L-shaped pocket, aligning joint properly in a correct position.
5. Keeping bolts holes aligned with erection bolts when steel beam is tentatively supported by L-shaped guide angles or/and by splicing stiffener plates installed under lower flanges.
6. Connecting steel beam and column web using permanent bolts while L-shaped pockets are held in contact and tightened using permanent bolts of a specified size.
7. Continuity of lower beam flanges via double shear is provided by installing splicing plates to lower flanges of steel beams and column brackets with permanent bolts.
8. Installing the rest of splicing plates including upper flanges of column brackets and steel beams using permanent bolts to complete connections.

This assembly method can be used to erect conventional steel frames even if it was originally proposed for a use of heavy precast frame construction. However, an application of the proposed method is limited by weight of precast beams. Accordingly, a number of bolts that must be used to hold joints in L-shaped angles should be carefully selected based
on a nonlinear numerical analysis. Some design charts to help engineers rapidly determine a number of bolts and their locations were provided to facilitate the proposed method.

**Disclosure statement**

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**Notes on contributors**

Dinh Han Nguyen is currently enrolled as a Ph.D. candidate in the Department of Architectural Engineering at Kyung Hee University, Republic of Korea. His research interest includes precast composite structures.

Eric Nkundimana is currently enrolled as a Master’s student in the Department of Architectural Engineering at Kyung Hee University, Republic of Korea. His research interest includes precast composite structures.

Won-Kee Hong is a Professor of Architectural Engineering at Kyung Hee University. Dr. Hong received his Master’s and Ph.D. degrees from UCLA, and he worked for Englelirk and Hart, Inc. (USA), Nihon Sekkei (Japan) and Samsung Engineering and Construction Company (Korea) before joining Kyung Hee University (Korea). He also has a professional engineering license from both Korea and the USA. Dr. Hong has more than 30 years of professional experience in structural engineering. His research interests include a new approach to construction technologies based on value engineering with hybrid composite structures. He provided many useful solutions to issues in current structural design and construction technologies as a result of his research that combines structural engineering with construction technologies. He is the author of numerous papers and patents both in Korea and the USA. Currently, Dr. Hong is developing new connections that can be used with various types of frames including hybrid steel–concrete precast composite frames, precast frames and steel frames. These connections would contribute to the modular construction of heavy plant structures and buildings as well. He recently published a book titled as “Hybrid Composite Precast Systems: Numerical Investigation to Construction” (Elsevier).

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