FULL SCALE EXPERIMENTAL RESEARCH ON STRUCTURAL PERFORMANCE OF PC-S STRUCTURAL JOINT METHOD

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Abstract

Authors present the results of the full-scale tests on “PC-S post-tensioned joint construction method” as an earthquake resistant precast column-steel beam joint that enables easier and faster application possibilities compared to alternative methods. In the PC-S method, RC columns are connected with steel beams that implement double end-plates, concrete infill between end-plates and post tension application for the column-beam joint, instead of embedding the beams in the column. PC-S joint construction method is intending to increase the strength of the beam-end by placing a concrete filling between the double plates at the steel beam-end. Contrary to the ordinary applications, in the proposed method post-tensioning is applied to a level where further elastic elongation of the strands are possible.

In previous research regarding the PC-S method, 1/3 scale specimens were tested. This time, experiments were carried out on 2 full-scale specimens with different post-tensioning levels, to confirm the deformation performance of the steel beam and the deformation capacity of the column-beam joint. Cyclic loading tests were performed on specimens with proposed PC-S joint details and pre-stressing conditions. The experimental work also aims to find practical solutions for an actual construction with proposed method as the full-scale construction brings challenges on the welding work and installation accuracy. It was shown that structural performance was not affected by scale, meanwhile, the yielding behavior of the proposed joint can be set during design and target strength levels are exceeded.

Keywords: precast construction; post tensioning; prestressing; column joint; mixed-type structure

1. Introduction

Safe, rational and economical construction methods are required as technology develops. Under such circumstances, composite structures combining reinforced concrete members (RC) and steel members has been developed by many due to the efficiency of composite behavior. Representative composite structures include steel reinforced concrete (SRC) and concrete filled tubes (CFT). These construction methods have been developed to obtain high-performance buildings which could not be obtained by using a single material in the existing structural form. Precast construction is especially gaining attention in seismic zones when it is combined with prestressing technology. On the other hand, it has been widely recognized that composite moment frames consisting of RC columns and steel beams, or the so-called RCS system, can provide cost-effective alternative to traditional steel or RC construction in seismic regions. Previous studies showed that concrete columns can withstand large amount of axial loads and they are more cost-effective than steel columns in providing lateral stiffness and strength. On the other hand, Steel beams has high moment resistance, requires less columns and longer spans can be realized compared to RC beams. Substitution of RC beams by structural steel beams can reduce labor cost for formwork and shoring, therefore improving construction efficiency. In particular, this combination is considered effective for low or middle rise office type buildings where less columns are desired or industrial/warehouse type buildings with high design loads.

Over the past decades, many researchers conducted research on RCS and contributed to improve the method [1–5]. In 1994, ASCE Task Committee on Design Criteria for Composite Structures in Steel and Concrete, published guidelines for design of RCS connections [6]. Toyoshima et al. have done a series of tests on interior, exterior and roof-level RC-S beam-column connections [7]. Kuramoto and Nishiyama studied about RCS frames under cyclic loading with varying joint configurations in order to investigate the structural performance and the damping behavior [8]. Parra-Montesinos and Wight tested inelastic cyclic response of hybrid connections consisting of RC columns and steel beams (RCS). Experimental results from nine exterior RCS connections are presented where the primary joint details investigated are two-part U-shaped stirrups passing through holes in the web of the steel beams, steel band plates surrounding the joint region, steel fiber concrete or engineered cementitious composite material in the connection [9]. Liang et al. tested interior and exterior RC-S connections under cyclic loading, considering interaction of the concrete slab and shear studs [10]. Alizadeh et al. investigated two interior RC-S connections experimentally and numerically. Self-compacting concrete that can improve the constructability of RC-S joints was used in both specimens. Additional bearing plates that cause an increase in bearing and joint shear strength were used [11].

However, research was rarely conducted on composite moment frames consisting of precast concrete column and steel beam where the beam-column connection is not monolithic but jointed. Yuntian W. [12] has presented experimental results of precast column and steel beam composite moment frames with post-tensioned connections.

In composite structures, although improved structural performance is possible by combining members with different material properties, there is also an inevitable and difficult stress transfer problem between different members, which complicates both proper design, and construction. Regarding this fact, in a typical RCS composite structure in which Steel beams are combined with RC columns, clarification of stress transmission mechanism between the members and simplification of construction have become important subjects. In order to overcome these issues, this study proposes PC-S post-tensioned joint construction method that implements double end-plated steel beams, concrete infill between end plates and a pre-stressed joint. Full-scale cyclic loading tests were performed on 2 specimens with proposed PC-S joint details and varying post-tensioning levels. The results show that the yielding behavior of the proposed joint can be set during design and target strength levels are exceeded successfully.

2. Research Objective and Tests with Scaled Specimen

Mainly, there are two categories for RC-S connections, continuous beam type (Fig.1a) and continuous column type (Fig.1b). The idea of passing the beam through the column (Fig.1a) causes several issues such as buckling and crushing, therefore the second application where the column is continuous is often preferred.

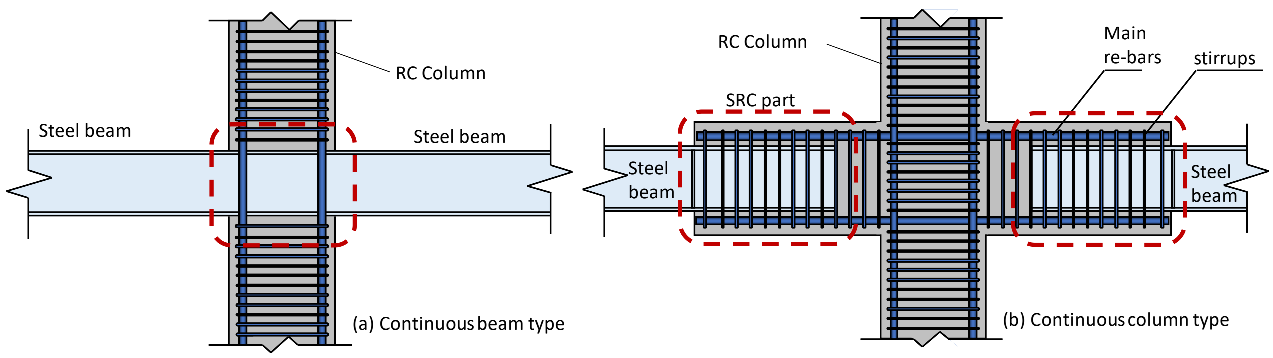


Fig. 1 – Types of RCS connections

This study focuses on continuous column type of RCS detail. Several existing research [13-17] has shown that the three are 3 main issues to be addressed in this type of column-beam connection details which are leverage effect of steel beam, local damage in concrete because of steel beam flange bearing pressure and bond slip of steel beam. The methods that can be applied in order to overcome these issues are as follows: Steel beam should not be embedded in concrete, end plate should be used to relieve local bearing stress and prestressing should be applied for interlocking connections.

In order to overcome the reported issues, it is proposed to attach steel beams to the column from both sides with post-tensioning technology. As the research progressed, it was found out that if the steel beam end plate is doubled, a stronger beam-end could be obtained. Finally, this study proposes PC-S post-tensioned joint construction method that implements double end plate (a steel beam-end detail with two separated end plates), concrete infill between the end plates and post-tensioning application for the column-beam joint, with details shown in Fig.2. Experimental study is carried out on scaled and full-scale PC-S joint specimens with proposed joint details and the deformation performance of the proposed joint is confirmed by test results.

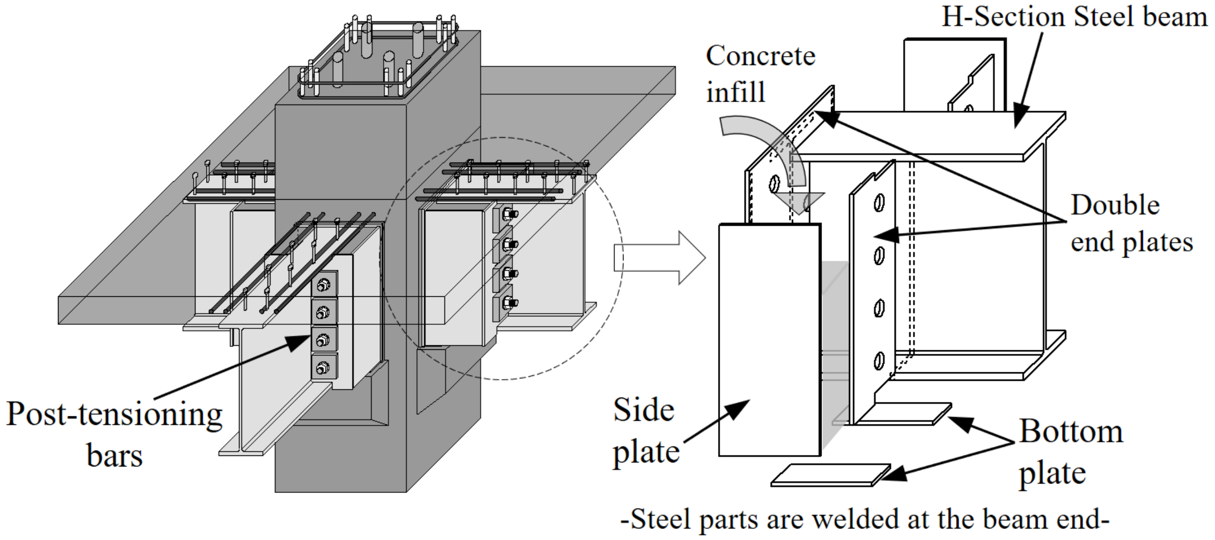


Fig. 2 – Proposed PC-S joint and beam end detail

In the proposed PC-S detail, double steel end plates are used in the beam-end where the space between two end plates were filled with concrete. Next, the beam end is connected to the RC column through post-tensioning bars. Contrary to the ordinary applications, in the proposed method when post-tensioning is applied, bars are not pulled up to the limits but to a level where further elastic elongation of the strands were allowed. As a result, at the post-tensioned zone of the beam-end, when the load exceeds the post-tensioning level, beam-end separates from column face elastically. As shown in Fig.3, in case of same total bending angle, the bending deformation of the beam member is reduced if the separation of the beam is allowed compared to the case where beam separation is not allowed. This reduction will therefore bring the reduction of beam damage. The proposed PC-S structural column-beam joint detail targets elastically behaving joint where large deformation capacity is provided by allowing beam-end separation.

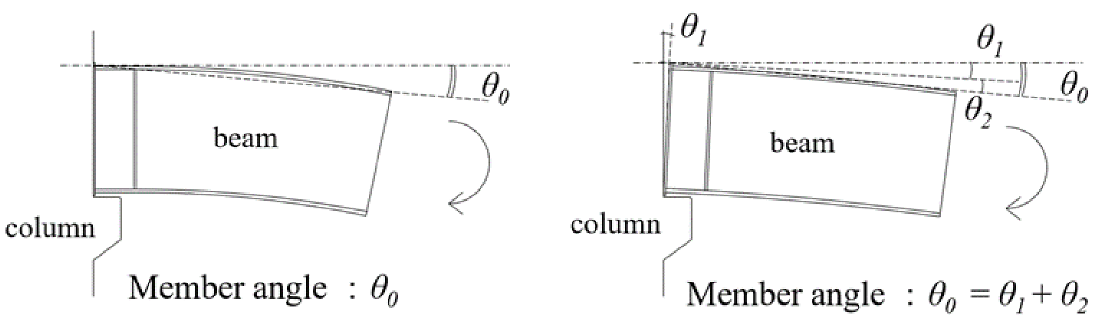


Fig. 3 – Steel beam end seperation behavior concept

In previously conducted and reported tests by Hyakutake et.al. [18] four different specimens which were approximately scaled down to 1/3 of the actual size were used. A displacement based incremental cyclic loading protocol was used according to the inter-story drift ratios (R’). Precast reinforced columns produced with corbel and ducts of the post-tensioning bars for introducing the column axial loads. Then beam-column joint post tensioning strands were stretched to a point below the yield strength and clamped. H shape steel beams were welded with steel plates by using full penetration at the end of the beam and fillet welding in the rest (Fig.4). High strength non-shrink mortar with Fc=60MPa compressive strength was filled between end plates up to the upper flange and the joint between column and beam. Post-tensioning bars were placed in the sheaths then post-tensioning was applied in different levels and the sheaths were filled with Fc=30MPa grout. Finally, 80mm cast in place topping concrete was poured to form the slab. This test aims to observe the performance of PC-S joint method under varying post-tensioning levels as shown in Table 1.

Table 1 - Details of steel members and post-tensioning forces (bonded)

Scaled Specimen No	**Steel Beam (S) H shape**	**Post-tensioning bars (bonded)**			
		Number and Diameter (mm)	**Yield Strength P_y (kN/bar)**	**Applied Tension P_0 (kN/bar)**	**P_0/P_y**
1	300x150x6.5x9mm	4-23φ	448.7	220	0.49
2	Steel plates (t: 6mm)	4-17φ	245.1	150	0.61
3	Inner: 50x300mm	4-23φ	448.7	135	0.30
4	End: 350x320mm	4-23φ	448.7	50	0.11

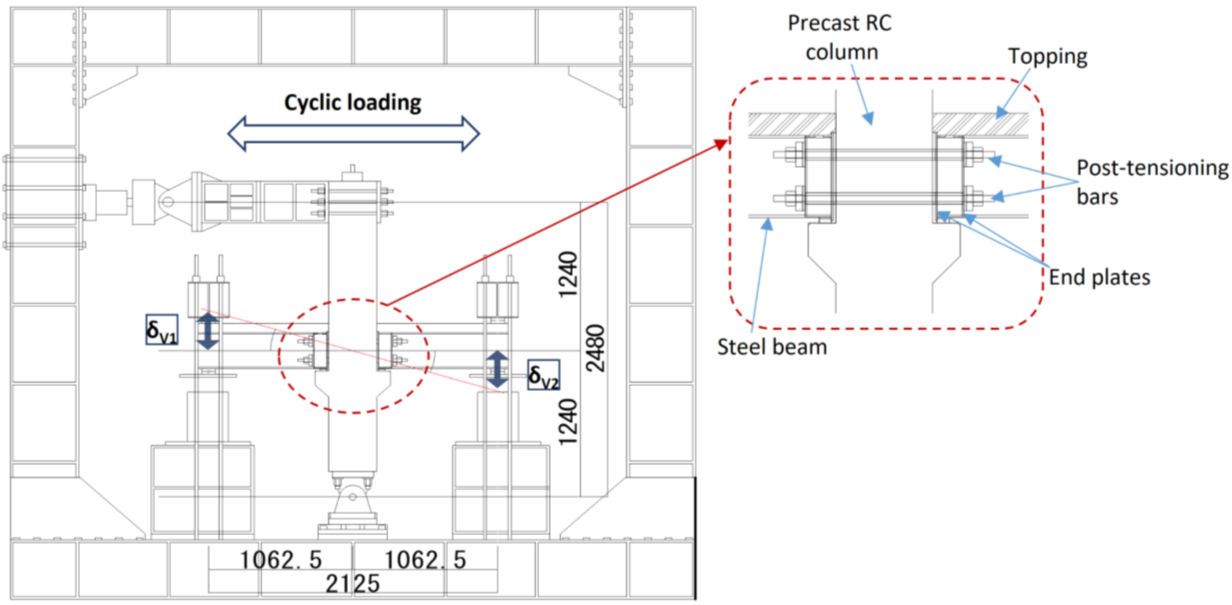


Fig. 4 – Scaled test setup

The test results showing the story shear force – interstory drift angle relationship (Q - R relation) for each specimen was presented and the failure modes was compared with the estimated failure behavior (Fig.5). In the Q-R load-deformation graph, the relation of bending stiffness and shear force level corresponding to the yielding moment of single steel beam neglecting the slab was shown by the red dashed line, where the shear force level corresponding to the full plastic moment was shown with green dash-dot line.

Scaled Specimen No.1 (Steel beam yielding mode): As shown in Fig.5a linear elastic behavior was observed up to 1/80 drift levels where the joint separation has started. Initial stiffness was well above the estimated steel beam stiffness and the yielding point of steel beam exceeded the shear force level regarding the full plastic moment. Steel beam yielded around the 1/80 joint separation point.

Scaled Specimen No.2 (Joint separation yielding mode): As shown in Fig.5b linear elastic behavior was observed up to R'=1/125 drift levels where the joint separation has started. At R'=1/50 level, the prestressing tendons yielded. It was observed that the prestressing tendons has reached yielding level before the steel beam.

Scaled Specimen No.3 (Elastic joint separation without damage): As shown in Fig.5c linear elastic behavior was observed up to R'=1/200 drift levels where the joint separation has started. Prestressing tendons, steel beams and slabs were undamaged even at 1/33 drift level. After R'=1/33level, crushing of the slab was observed.

Scaled Specimen No.4 (Prestressing declining): As shown in Fig.5d linear elastic behavior was observed up to R'=1/500 drift levels where the joint separation has started. Since the prestressing tension force is almost completely lost, the initial stiffness was relatively low at the beginning. However, the stiffness was gradually recovered and the yielding point of steel beam has exceeded the shear force level regarding the full plastic moment. Steel beam has yielded at a point exceeding the estimated yielding level and flange buckling occurred

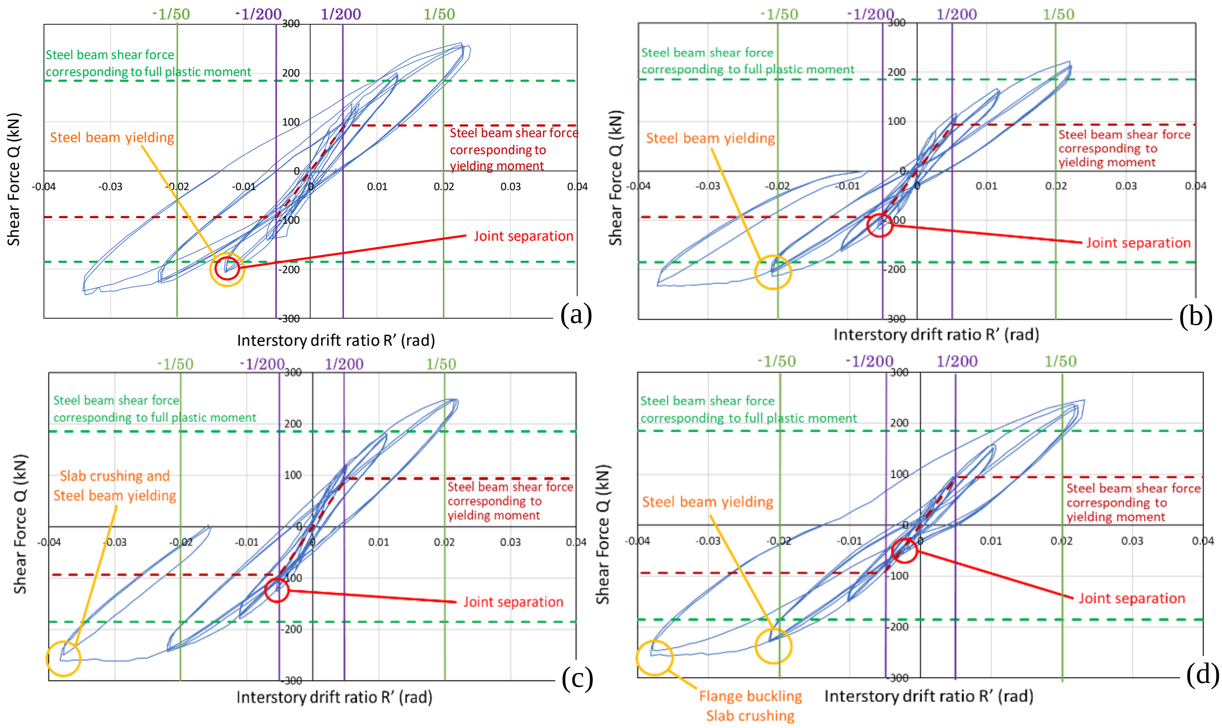


Fig. 5 – Shear force vs. interstory drift ratio
(a),(b),(c) and (d) respectively belongs to Scaled Specimen No 1, 2, 3 and 4

These tests showed that, when the prestressing force of the bars gets lower, the separation in the joint area is observed earlier stages. The failure mode is greatly affected and changed by the amount of prestressing force and the size of bars, used in the joints. In all specimens, the experimental results showed that the steel beam behavior was similar to the estimated initial stiffness and all specimens exceeded the estimated yielding point safely. Also, the steel beam shear capacity greatly exceeded the calculated value of the shear corresponding to the total plastic moment. According to Specimen 4 was confirmed that even if the prestressing force accidentally declined in the PC-S joint this issue did not have much influence on the strength and stiffness. And if the amount of prestressing tendon used for the beam connection is the same, there was no significant difference in the load-deformation relation regarding the level of introduced prestressing force. Finally within R'= 1/200 story drift the amount of prestressing bars didn't have almost any effect on the load-deformation relation, however when R'= 1/200 or more, both the stiffness and strength was increased according the amount of the bars.

3. Beam-end Structure

It should be confirmed that steel beam end should not negatively affect the member behavior. Here, the effects of non-shrink mortar infill and prestress was neglected and steel material is designed within allowable stress level under temporary loading. As shown in Fig.6, stress transfer at the end of the beam is supported by end-plates through bending resistance, and with web and side plate through shear resistance. It was designed as the end-plates will stay within allowable stress levels under temporary loading when maximum tensile force occurs at the flange. The shear effect is checked with the Eq. (1) to (4):

$$\tau = {}_{D}M_p / a \times d_s \times t_w \leqq 2{}_{s}f_{ss} \tag{1}$$

$${}_{D}M_p \leqq b_E \times t_E \times {}_{s}f_{ts} \times (a + t_E) \tag{2}$$

$${}_{D}M_p = T_f \times d_s \tag{3}$$

$$T_f = {}_{s}F \times b_f \times t_f \tag{4}$$

Parameters in the above equations are explained as follows:

τ : Shear stress between flange and prestressing tendons
${}_{D}M_p$: Bending moment generated between flange and prestressing tendons
T_f : Tensile strength of flange
${}_{s}f_{ts}$: Endplate allowable tensile stress under temporary loading
${}_{s}f_{ss}$: Endplate allowable shear stress under temporary loading
${}_{s}F$: Flange material strength
d_s : Distance between the flange and the gravity center of effective tendons
a : Clear distance of end-plates
b_f : Flange width
b_E : End-plate width
t_f : Flange thickness
t_w : Web + Side plate thickness
t_E : End plate thickness

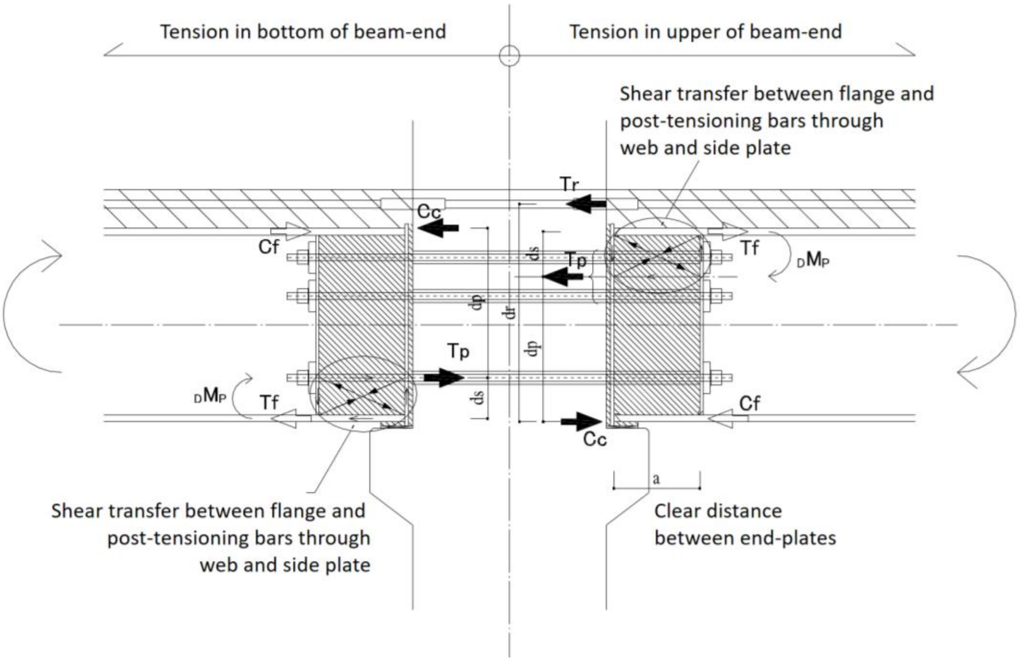


Fig. 4 – Shear transfer between post-tensioning bars and the flanges at the beam-end

4. Full-scale Experiment Outline

In contrast to the previous experiment with scaled specimens, full-scale dimensions representing actual PC-S joints were used in this study. The thickness of the flange and the web of the H beam is about three times larger compared to the scaled test specimens of previous tests, which brings the difficulty of the construction accuracy such as welding work and erection. Experiments were conducted on 2 full scale specimens to verifiy the feasibility of the construction method, as well as the structural performance of the PC-S joint with 2 different tensioning level. The material properties used in the specimen is summarized in Table 2.

Table 2 – Material strength for full scale test specimen (N/mm²)

Specimen No	Steel Beam SN490B		Plates (16mm) SN490C		Post tension bars SBPR1080/1230		Concrete			Mortar	Grout
							Beam	Column	Slab	Joint	
	Yield Strength	Ultimate Strength	Yield Strength	Ultimate Strength	Yield Strength	Ultimate Strength	Compressive Strength				
1	398	523	414	543	1163	1293	41.0	75.6	60.6	78.8	47.3
2	398	523	414	543	1163	1293	70.3	75.2	65.5	83.0	56.8

Since the experiment is conducted in full scale, the estimated corresponding beam load is approximately 1500kN. Considering the test facilities loading capacity, it was challenging to apply the reaction force through the test frame similar to the previously conducted scaled tests. Therefore, a one directional loading method was implemented where the loads exerted by both hydraulic jacks on beam far ends were transferred to the strong floor as shown in Fig.7

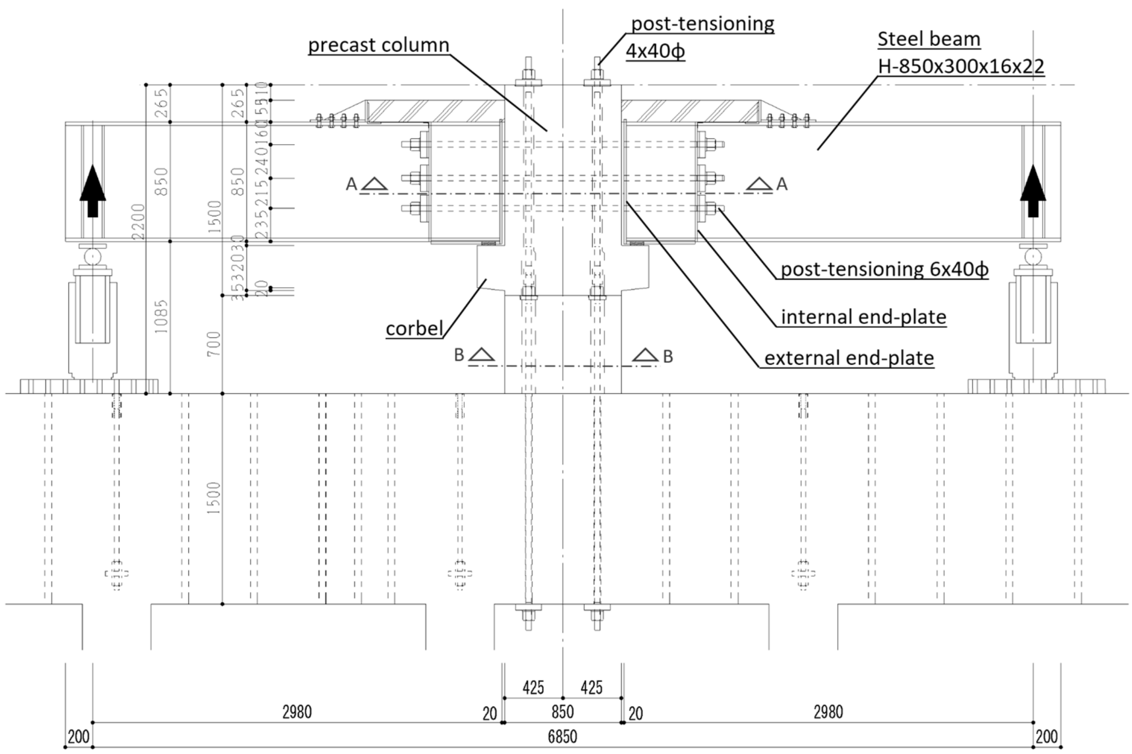
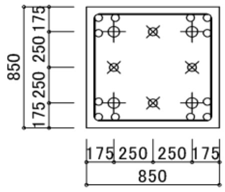
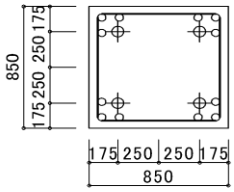
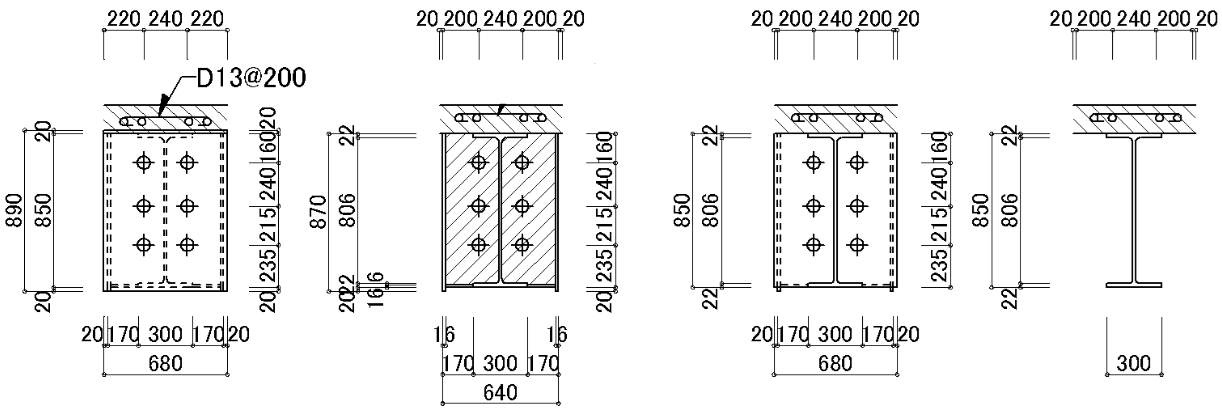


Fig. 7 – Test set-up

Assembly of the test specimen was carried out in the following procedure. Columns were prefabricated with corbels on both sides of the joint to support the beams. The column in the center of the test specimen was fixed to the reaction force floor with 4 unbonded post-tensioning bars of ϕ40 (4 × 600kN/bar= 2400kN). The test specimen is produced to have a 6.85m span due to the limitation of test area. However, the span of the beam is assumed as 14.4m in actual length, which represents a typical span length used for office type buildings. A plate was welded to the steel beam end and a second plate that is shaped to fit to the H profile was welded in the beam opening (penetration welding). Both plates are produced with pre-designed post-tensioning bar holes. After placing post-tensioning bar sheaths the volume is closed by side plates and filled with concrete. Furthermore, an RC slab of 155mm thickness is set 1m offset from the column surface. The shear force generated between the slab and the upper flange was to be resisted by the added shear jig and bolts (Fig. 7). Cross-sectional properties of the column and beam, as well as the post-tensioning bars are given in Table 3.

Table 3 – Column and steel beam details

Column (F_c=60)							
Section A-A				Section B-B			
							
PT Bars (unbounded)	Primary	4-26 Ø (C-Class)	P_0=300kN	PT Bars (unbounded)	Primary	-----	-----
	Secondary	4-40 Ø (C-Class)	P_0=500kN		Secondary	4-40 Ø (C-Class)	P_0=500kN
Re-bar	12-D32 (SD490)			Re-bar	12-D32 (SD490)		
Stirrups	D13@100			Stirrups	D13@100		

PC-S Steel Beam (Typical type of steel material SN490B)	
	
Topping Reinforcement	4-D22 (SD490)
Steel Beam	H-850 x 300 x 16 x 22
Plates	t=16mm (SN490B)
Post-tensioning bars	6-40 Ø (C- Class)
Applied Tension (kN/tendon)	**Specimen No 1** = 600 (bonded)
	Specimen No 2 = 300 (bonded)
Infill Concrete	Fc = 36MPa (or greater)

The beam end was simultaneously loaded by hydraulic jacks on both ends and test loading was repeated on one-direction. The specimens were instrumented with LVDTs and strain gauges in order to monitor the relevant drift, stress levels and the separation between beam-end and the column. A displacement controlled incremental cyclic loading protocol according to test specimen drift ratios and the corresponding inter-story drift angles of the assumed actual beam span of 14.4m is shown in Fig.8.

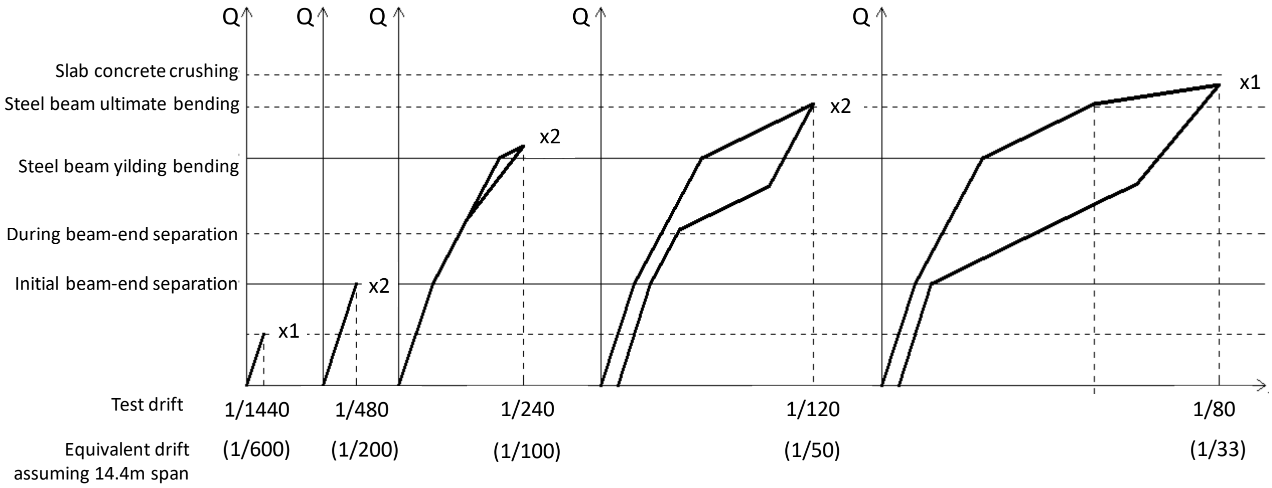


Fig. 5 – Loading protocol and estimated behavior

5. Experiment Results

The moment corresponding to the applied load and inter-story drift ratio relations for both specimens are shown in Fig 9 and Fig 10 assuming the span length as 14.4m. In these figures the elastic stiffness assuming a fixed beam joint, design load corresponding to the DBE seismic level, estimated load level for beam-end separation and steel beam yielding moment levels are also shown along with the relevant shear load values. The separation of the column and the beam-end was visually confirmed at the load level of 391kN and 234kN for test specimen No1 and No2, respectively, which agrees with the estimated values. After the confirmation of the separation, the incrementally increasing load protocol was applied according to the loading protocol. As for Specimen No2, during the last loading cycle there was an instrumentation failure, therefore, the load was released and this cycle was repeated. The repeated cycle is shown in Fig 10 with dashed line.

As seen in Fig.9 and Fig. 10, the joint stiffness is higher than the elastic stiffness level until the joint separation. Since the design load level is lower than the separation moment, the joint integrity is confirmed. Even when the load is much higher than the design load level, reaching up to 1/22 inter-story drift level, the joint re-centers without significant damage.

During the tests, the ratio of the joint rotation angle to the beam angle was compared. Results show that when Specimen No1 steel beam reaches the yielding moment at the internal end-plate position, the ratio of the joint rotation angle to the beam member angle is 33%, and at the maximum load level, it is 39%. For Specimen No2, it is 36% and 39%. This proves that the initial post-tensioning level does not affect this ratio.

The separation between the beam end and the column face was constantly observed and recorded. It was found out that even after the maximum load was applied (1203kN for No1 and 1147kN for No2) the residual separation at the bottom end was 1.2mm and 1,3mm for Specimen No1 and No2, respectively. This level of residual deformation translates to approximately 1/500 story drift angle, which is negligible (Fig 11)

On the web and both upper and bottom flange the strain-gauge readings were within elastic range up to the Steel beam yielding load level of 939kN. A slight residual strain was measured on the upper side of the web, although this was attributed to the cracks in the slab and the bolt deformation. The post-tensioning bars of 3 rows (top, middle and bottom) were also instrumented with strain gauges and the experiments has shown that even the bars in the bottom row which underwent the largest strains did not reach the yielding strain levels up to the Steel beam yielding load level. Similarly, the strain gauge readings on the end plates showed that, the strain levels didn't exceed 37% and 21% of the yielding level for Specimen No1 and No 2, respectively.

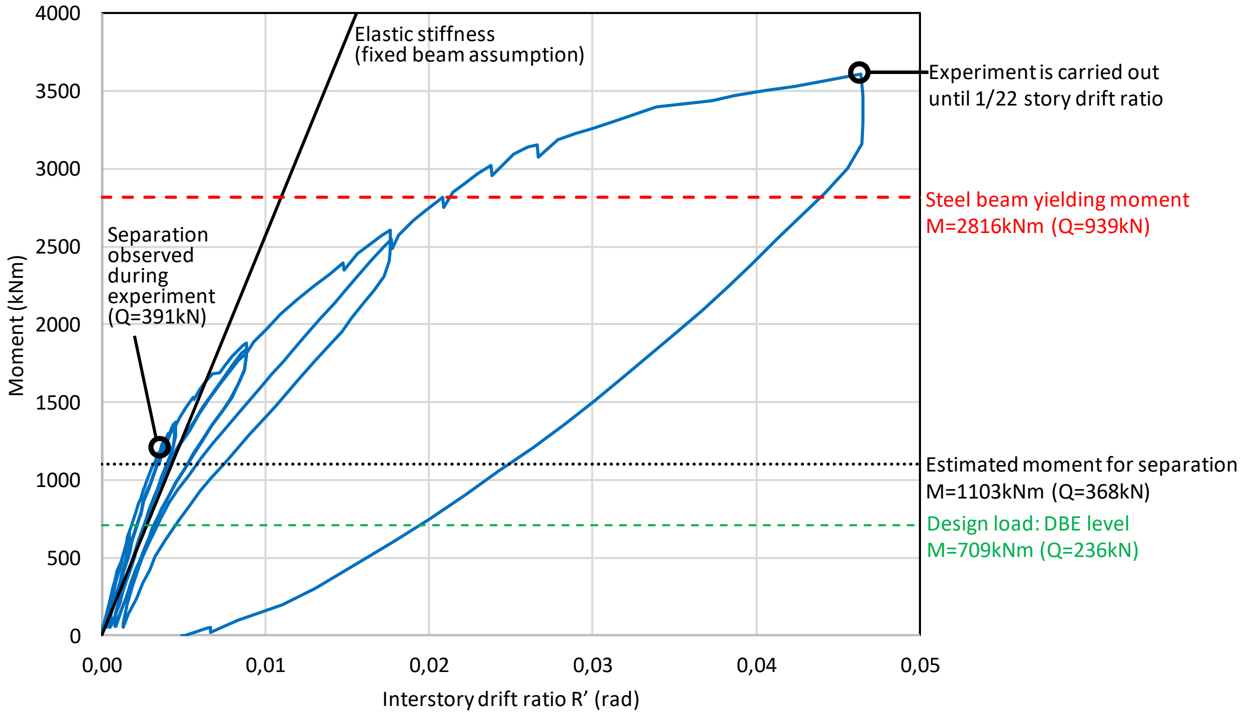


Fig.6 – Specimen No1 moment-interstory drift ratio relation (span =14.4m)

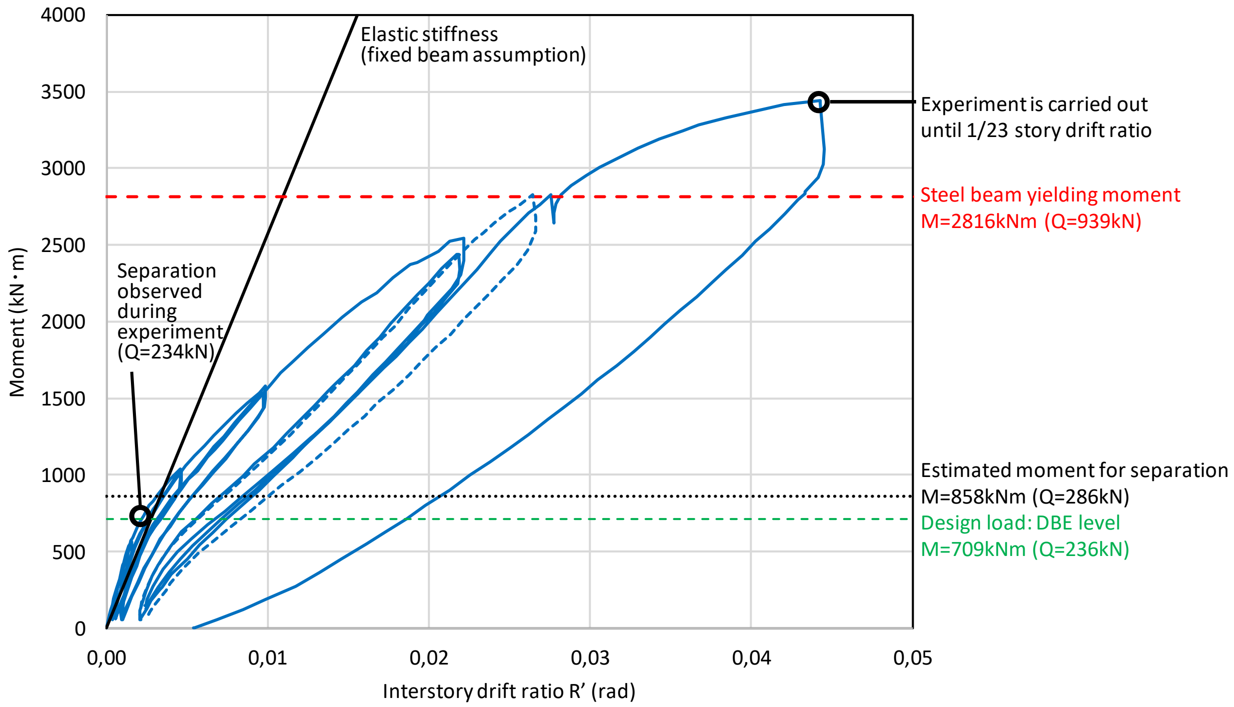


Fig.9 – Specimen No2 moment-interstory drift ratio relation (span =14.4m)

Fig.7 – Beam end instrumentation and the observed separation

7. Conclusions

The estimated value of the joint separation load level and the experimental observations agree. Also according to test result figures, the change in the stiffness is also in good correlation with the separation point. It was also shown that the separation level can be adjusted by the post-tensioning level, which enables a precise design of the joint depending on the estimated seismic level of a project. On the other hand, it was confirmed by the tests that even when the load level exceeds the steel beam yielding load by 20% no damage was observed on the PC-S beam.

In conventional structural joints with fixed configuration, the beam member behaves elastically as long as the joint is in elastic range. Thereafter, by the increase of stress level, steel beam end yields, creating a plastic hinge and reducing the stiffness of the structure. This type of mechanism dissipates energy by increasing deformation, which causes damage. On the other hand, in the case of the PC-S joint method, the joint separation occurs before the yielding of beam, keeping all components in the elastic range similar to a conventional joint. However, after the joint separation, the post-tensioning cables in the PC-S joint still behaves elastically while the stiffness is reduced as if a plastic hinge has occurred. This is also a mechanism that absorbs seismic energy by the increased deformations, but the post-tensioning provides restoring force to the system that enables re-centering.

Conventional structures absorb seismic energy by utilizing the plastic deformation of the members. Plastic deformations results with residual deformation that has a significant impact on building reuse after a major earthquake. On the other hand, the PC-S method absorbs seismic energy by nonlinear behavior while keeping all components in the elastic range. This way residual deformation is prevented and buildings can be immediately operated after a major earthquake. Furthermore, even if the seismic load specified by the relevant code is exceeded, the building can be reused with considerably little repairs.

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