Cyclic Loading Tests on Semi-rigid Partial-strength Connections with Column Skin Plate Deformation

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ABSTRACT

This paper presents an experimental investigation of semi-rigid partial strength beam-to-column connections. An H-shape beam is connected to a column with bolted connection. Four different types of connection details are studied: Extend end plate, Flush end plate, Top and seat angle with Double web angle, Double web angle connections. The sub-assemblages of beam-to-column connections with different detailed configurations and various degrees of column-skin stiffened conditions were subjected to quasi-static cyclic loading. The moment-rotation relationships observed are compared with an existing poly-line characterization proposed in the past for semi-rigid connection behavior. Comparison between them shows a similar behavior when failure occurs at the semi-rigid connection. These test data enrich the databank, and consequently provide information to improve semi-rigid design procedure.

Keywords: *Semi-rigid connections; Partial-strength connections; Moment rotation curve*

1. Introduction

With the rapid advance of the performance-based structure engineering, the semi-rigid philosophy has proved an efficient and convenient alternative for design not only under static loading but also seismic loading [1]. Semi-rigid partial-strength connection shows complicated behaviors because more components, such as bolts, angles and plates, are introduced into the congest connection zone. Thus, this kind of connection tends to exhibit a complicated manner with a variety of failure mode. Many aspects then affect the behavior assessment of such a connection. The complicated nature of semi-rigid connection enables it to be a vexing problem that the analysis and design process is based on some connection test database. The tests aim in evaluation of the connection behavior subjected to quasi-static cyclic loading and compare it with a past proposal for characterization of moment rotation curves. The tests enrich the databank and consequently provide information in the development of semi-rigid design recommendation.

Connection here means the association of the beam end, connecting plates (including cleats) with high-strength bolts, and column surfaces. Three general failure modes can be classified: (1) Failure at column skin, (2) Failure in the pair 'connecting plates and bolts' and angles, and (3) Failure at the beam end. A proper design or desirable behavior is to avoid failure in the column and beam in order to obtain a pure mechanical interface, easy to replace it after damaged.

A total of nine series tests are conducted on rolled H-400x200x8x13 beams connected with a semi-rigid connection to a column, where member flexibility as a column is prevented in the test

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setup and the observation is concentrated only in local deformation of skin surface. The tests were a follow-up to numerous tests that were previously conducted, which considered most popular semi-rigid connections types [2]. In order to check experimentally those conclusions, examined connections are: Flush End-plate (F), Extended End-plate (E), Top & Seat Angles with Double Web Angles (TW) and Double Web Angles (DW).

Two types of column surface conditions were prepared, stiffened and non-stiffened surface. Three type of surface stiffening methods were arranged: (1) welding a stiffening plate to the column surface, (2) attaching a single backing plate with high strength bolts, and (3) using double backing plates.

Beam and column section sizes are chosen from possible sections in a low-rise and middle-rise steel building, which might make it useful for real applications.

2. Test Setup and Instrumentation

A common test setup for all the test series was devised as shown in Figure 1. All the tests consist of a constant length of 1,930 millimetres H400x200x8x13 beam, and it is vertically connected with different types of semi-rigid connections to a horizontally placed column piece. Distance between supports of the column piece is short enough to consider only local flexibility, and the member flexibility of column is negligible. Two different columns are used: One is a cold-formed rectangular hollow-section column piece, 350x350 with 12mm of skin thickness. The other is a hot-rolled H-400x400x13x21 column piece, where angle cleats are attached to the column web of 13mm thickness.

Figure 2 shows the four types of connection details and their dimensions. Beam depth is large enough to allow four arrays of bolts in the web.

Loading response is measured at the load cell in the actuator.

Total rotation is measured using the X3 displacement meter. X4 and X5 displacement-meter are placed at beam flange, joint rotations for all the series are measured using the X4-X5 pair of relative displacement divided by the distance between them. Monitoring of the connection uplift through the cross section along bolts heads are obtained at eight points with X6 through X13 displace meters. In case of only 8 bolts connections, all the measuring points were kept arranged. In the angle type connections, an unequal-side angle, L-150x100x15 (Japan Industrial Standard SS400 grade) was used. In all the cases, torque-shear type high-strength bolts (JSSC Standard S10T M20) are commonly used. For end plate connections, 16mm of plate thickness was commonly used. Mechanical properties for materials are listed in Table 1.2.

Column surface was stiffened with different methods. Figure 3a, and 3e, show the beam connected directly to the column surface, and they represent the non-stiffened case or weak surface. A stiffening plate with 22 mm thickness and 200x600 mm in dimensions, was attached to the column surface using three variations: (1) Plate was welded to the surface with 0.5 cm of fillet size welding as is depicted in Figure 3c. Resulting base was regarded rigid enough with the combined thickness of skin column plate and stiffening plate. (2) A second surface was arranged using a backing plate inside the box (Figure 3b) without welding. (3) Two plates were placed in both sides as shown in Figure 3d.

Codes for these four connections with different types of column surface are shown in Table 1.1.

Three specimens, Extended, Flush, and Top & seat angle with double web angle connections were tested connected to the rectangular hollow section column piece directly or with a plate welded (P). Double web angle connections were connected to the web of H-shaped column piece, and stiffened by using double plates (PD). One specimen of the extended end plate type was tested with the single backing plate (PB, Figure 3b). All the specimens were subjected to the same quasi-static loading history: 1/500, 1/ 250, 1/125 two cycles for each rotation; a final cycle of 1/67.5, and then loaded up to the failure or 1/10 of total rotation.

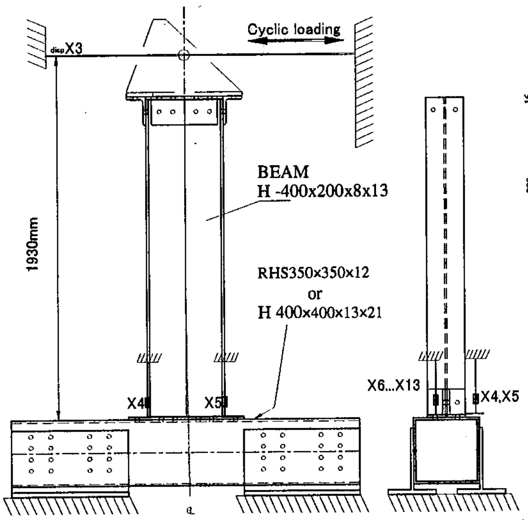


Figure 1.Test setup and connection

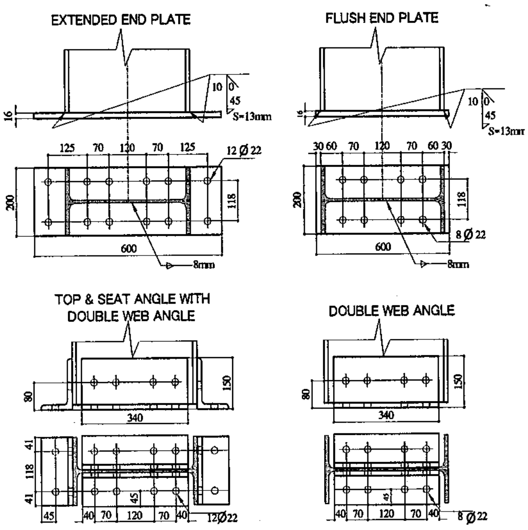
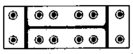
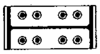
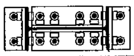
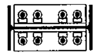


Figure 2.Connection dimensions

	Extended (E) 	Flush (F) 	Top & seat with double web angle (TW) 	Double web angle (DW) 
Weak surface	E12SC	F8SC	TW12SC	DW8SC
Stiffened Surface	E12SC-P E12SC-PB	F8SC-P	TW12SC-P	DW8SC-PD
Column	RHS BCP 350x350x12			H Shape 400x400x13x21

Legend: SC Static cyclic, 8 or 12 indicates number of bolts.

P (welded plate), PB (backing plate), PD (Double plate)

Table 1.1. Layout of experimental program

	Fy	Fu
Angle L-150x100x15 (Grade SS400)	280	440
End plate PL-16 (Grade SN400B)	250	420
H400x200x8x13 (Flange) (Grade SS400) (Web)	290 340	450 470
RHS 350x350x12 (Grade SS400)	315	440
H400x400x13x21(Flange) (Grade SS400) (Web)	340 320	460 440
	Ty	Tu
S10T M20* (In kN)	150	210

* Mill sheet values.

Table 1.2 Material properties (in MPa)

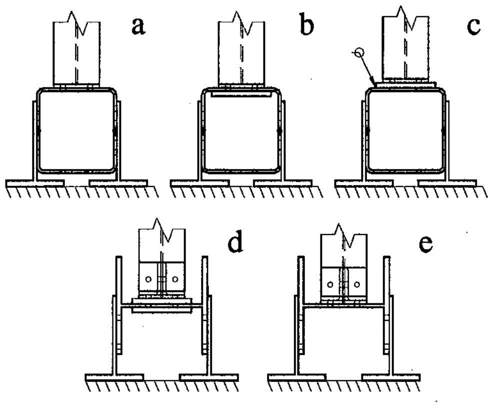


Figure 3. Stiffened methods adopted for column

3. Test Results

Extended end plate connections

Extended end plate connection behavior showed greater strength and rigidity properties than other details depending on the degree of surface stiffened. Failure mode was different for each case. Figure 4 shows the hysteresis loop for the specimens, E12SC and E12SC-P, and Figure 5 the corresponding for the specimen, E12SC-PB. Photo 1 shows the view of failure mode for all of three specimens. In all the cases photos were taken at 1/10 of the total rotation. Cross-sectional uplift or downward deformation along the bolts connection is sketched at 1/250 and 1/40 of joint rotation. The straight lines in all those figures represent the joint rotation measured by X4 and X5 displacement-meters. From those sketches, it is observed, and also applied for all non-stiffened connection tests, that the joint rotation source is mainly at the column skin. Even for the extended plate stiffened specimen, source of rotation is the welded plate and column skin.

When connection was placed over the weak surface of the column, (E12SC specimen), the column skin suffered large displacement.

Traction-side skin uplift was 6.4 mm measured at X4 channel and compression downward displacement was 3.4 mm (at X5 channel), leading joint rotation equal to 1/25. Hysteresis loop showed certain degradation at the final cycle, and slight pinching effect was observed. Ultimate joint moment (Muj), performance value adopted at 1/25 of joint rotation, was 109 kN·m.

E12SC-PB with the backing plate showed an increase of strength (Muj=159 kN·m). Backing plate helped to stiff the connection traction side, but less effective for the compression side. Uplift and downward displacement was 3mm and 7.2 mm respectively, leading to large rotation similar to E12SC.

Specimen E12SC-P, with the plate welded, made the column skin stiffer and stronger, leading to a mixed source of resistance, the column skin and end plate partial yielding, increasing the strength to Muj=259 kN-m, (again monitored at 1/25 of joint rotation).

Compared with E12SC specimen, E12SC-P strength was increased more than 2.5 times. Around 1/30 of joint rotation, part of the welding of stiffening plate was cracked, as is observed in the photograph.

In general, the slipping of the end plate connections itself between the end plate and the column was not observed.

Flush end plate connections

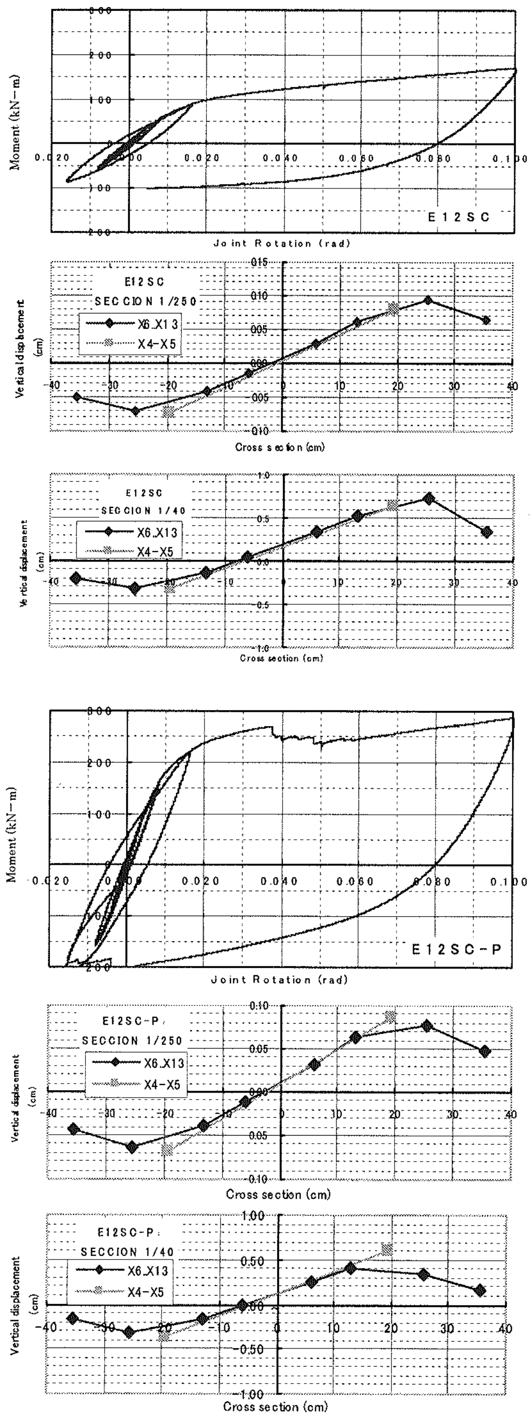
In this type of connection, for F8SC specimen, the weak surface of column dominates in deformation, and yielding is originated at the column skin. Displacement observed along the cross-section shows that the high strength bolts were keeping the end plate together with the column skin attached and rotating them together. Traction-side was separated in the vicinity of beam flange from the column skin.

Because of the configuration of flush type end plate, the distance between traction and compression side is shorter than beam depth, (opposite to extended type) which leads to reduce initial stiffness and connection strength.

Yielding is concentrated, between the beam flange and the vicinity bolts; for the final cycle, strength degradation and pinching is much pronounced. It was not observed separation between the end plate and the column surface at the inner bolts. Rotation center was moved near the compression-side beam flange as observed in the cross-sectional displacement graphs at 1/250 and 1/40 for joint rotation. Similar phenomenon can be observed commonly in all tested connections.

Top & seat angle with double web connections

TW12SC specimen, angles are distributed similarly to end plate connections over the column skin, and same pattern of skin failure like extended end plate was observed, initial stiffness and moment joint strength have almost identical values. When this connection is placed over the welded plate (TW12SC-P specimen), a mixed type of failure is observed, three sources of yielding are shown in Photo 2, at the top angle, shear failure of bolts (at beam flange side), at beam web (holes were found enlarged). In the hysteresis loop, moment strength dropped at about 0.08 radians, it was mainly due to the flange bolt failure. The effect of welded stiffening plate can be confirmed from the cross-sectional displacement graphs at 1/250 and 1/40 of joint rotation, where the contribution of column surface rotation was reduced to 40% of total rotation, and the remaining rotation was induced by the yielding of other connecting elements. Failure in the vicinity of beam-web hole was observed clearly at the double web angle elements.



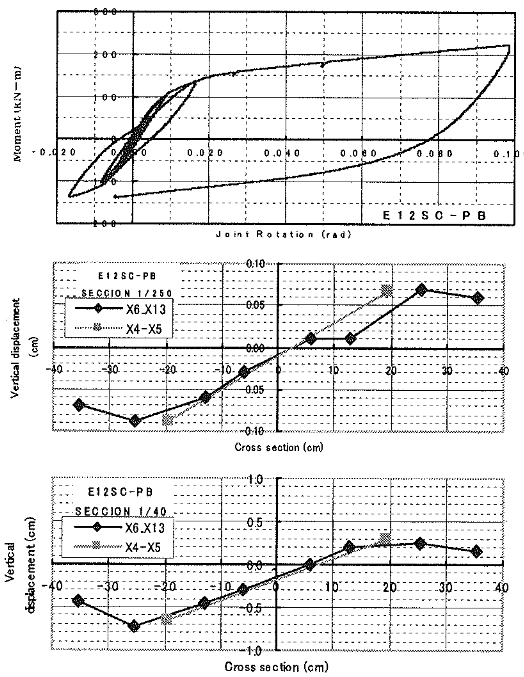
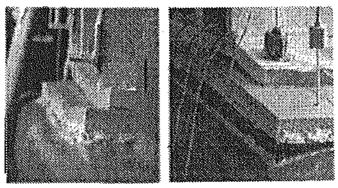
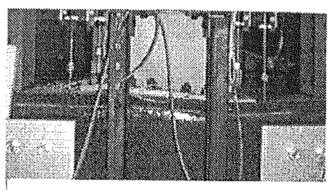


Figure 5. Extended end plate Hysteresis loops, and cross section connection displacement for E12SC-PB specimen.

(a) Specimen E12SC

(b) Specimen E12SC-P





(c) Specimen E12SC-PB

Figure 4. Extended end plate Hysteresis loops, and cross section connection displacement of E12SC, E12SC-P specimens.

Photo 1. Failure mode of Extended end type connections. at 1/10 of joint rotation

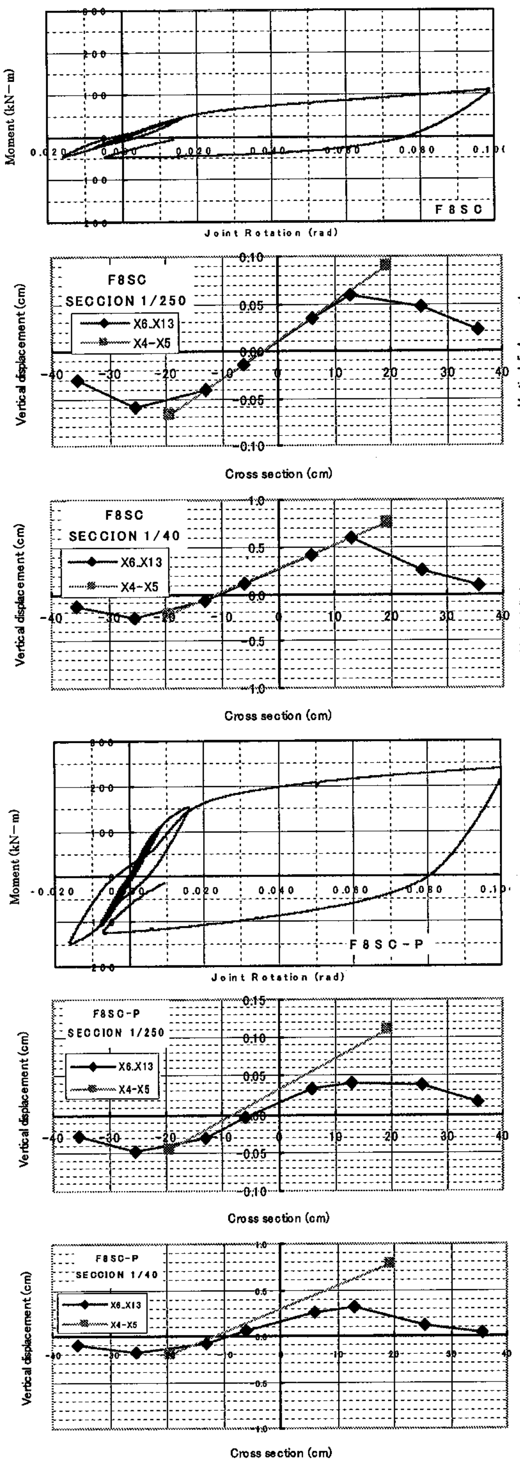


Figure 6. Hysteresis loop and cross-sectional displacements at 1/250, 1/40 of Flush End-plate connections

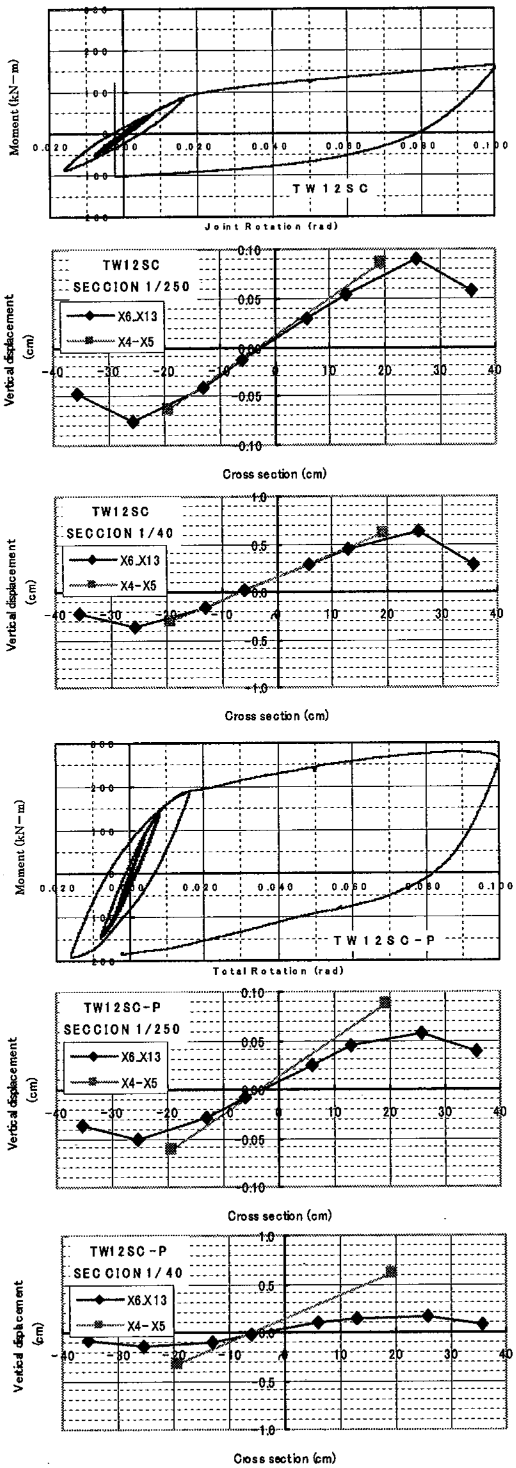


Figure 7. Hysteresis loops of Top & seat angle with double web angle.

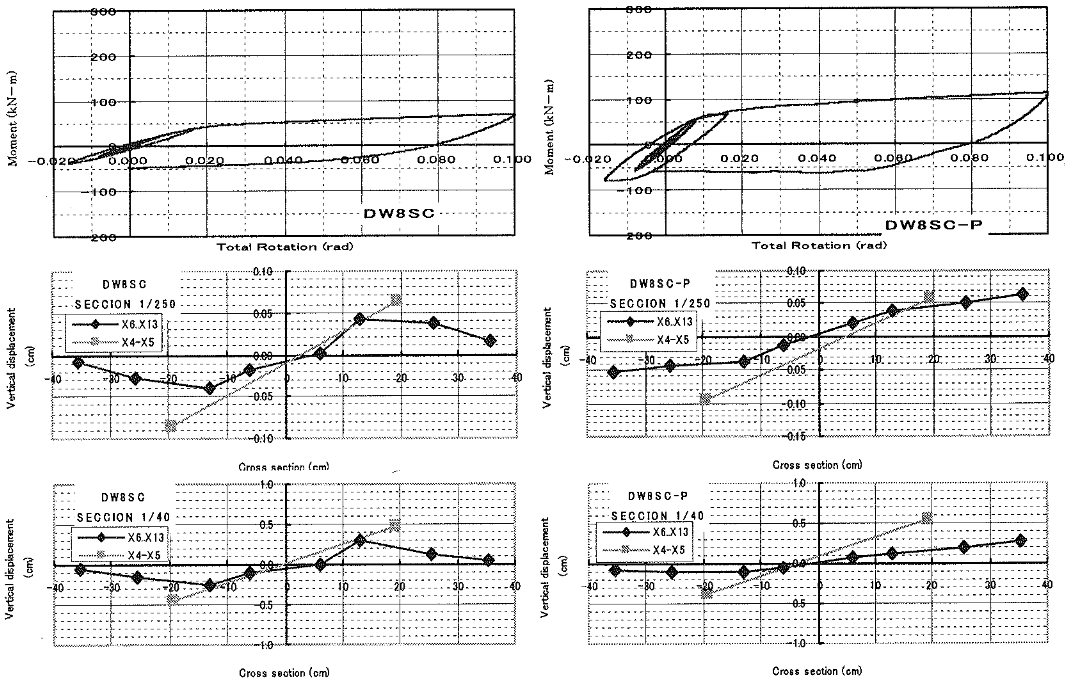
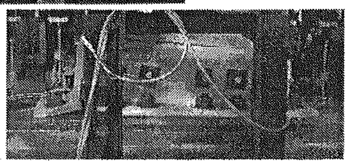
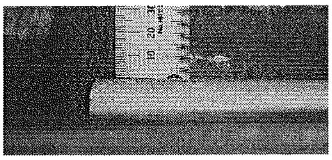


Figure 8. Hysteresis loops of double web angle connections and cross-sectional displacement at 1/250, 1/40 of joint rotation

F8SC-P

TW12SC-P





DW8SC-P

Photos 2. Photos of failure mode in connections with the stiffened surface for F, TW and DW cases at 1/10 of joint rotation

Double web angle connections

The specimen DW8SC was connected directly to the weak column surface (the web of H-shaped column), and also column-side web-plate failure was observed in the test. Similar values about stiffness and strength to those of flush type end plate specimen, F8SC, were measured. This is explained by similar structure and configuration of these two types of connections.

In case of DW8SC-PD specimen, the stiffening method by use of double backing plates was adopted. In such a case, each of double backing plates works for either of compression or traction side in contrast to the E12SC-PB specimen. For this case, failure mode was observed at the beam web end: Joint rotation was mainly due to enlargement of boltholes in the web.

Photo 2 shows relative displacement as much as about 1 cm between the angle and the web.

4. Mechanical Properties of Connections

Detailed properties of the specimens are read from the test curves and summarized Table 1.3. When the column surface is not stiffened, lower values of stiffness and moment resistance are read than those of the corresponding stiffened case.

In general observation of these kinds of connections, the lower secant stiffness values coincide with the lower strength level. That is, secant stiffness tends to vary in almost 'proportion' to the strength level within similar structure and configuration. This proportionality or high correlation between strength and stiffness may justify a simple poly-line formulation for design, which is described in the following section.

Table 1.3. Strength and stiffness properties of all connections. Units kN, m

Specimen	Ki kN-m	Surface contribution (%)	Muj kN-m	m_{1000}	m_{500}	m_{250}	m_{125}
E112SC	11.64	100	108.78	0.11	0.19	0.34	0.57
E12SC-PB	26.58	97	158.09	0.17	0.30	0.49	0.70
E12SC-P	49.77	84	259.18	0.19	0.32	0.52	0.74
F8SC	4.95	100	62.38	0.08	0.14	0.26	0.47
F8SC-P	30.66	67	181.43	0.17	0.27	0.46	0.69
TW12SC	8.37	93	105.22	0.08	0.16	0.30	0.53
TW12SC-P	36.98	39	208.59	0.18	0.32	0.54	0.78
DW8SC	4.78	34	47.20	0.10	0.16	0.30	0.52
DW8SC-P	11.86	36	82.86	0.14	0.26	0.45	0.74

Ki : Initial stiffness as secant stiffness measured at 1/1000
m_{1000} : M/Muj at 1/1000, m_{500} : M/Muj at 1/500
m_{250} : M/Muj at 1/250, m_{125} : M/Muj at 1/125 in joint rotation
+ Surface contribution: Ratio of column surface rotation to the joint rotation at 1/40 in %

5. Poly-line for Description of Semi-rigid Connections

A piecewise linear curve to characterize the moment vs. joint rotation curve of semi-rigid connections was proposed by the authors [2], which was derived from 147 past experimental curves including broad ranges of test parameters, such as beam depth, column dimensions, connection layout, strength, use and non-use of stiffeners.

The maximum joint moment capacity M_{ju} is defined at 1/25 (40/1000). Connections that do not reach this prescribed rotation for some reason, for instance, due to early bolt failure, were excluded. Values of M/M_{ju} of each curve were read at 1/1000, 1/500, 1/250, and 1/125. Averaged values of M/M_{ju} at those specified rotations are summarized in Table 1.4. Also values of standard deviation are listed. If these values are rounded around one decimal place, a unique poly-line for a ductile category of semi-rigid connections can be sketched with 0.2, 0.33, 0.5, 0.7 and 1 in the vertical axis. Thus this poly-line was derived just empirically from the past experimental data.

Table 1.4. Summary of average levels M/M_{ju} at joint rotations**

Join rotation	Extended end plate	Flush end plate	Top & seat with double web angle	Double web angle
1/1000	0.20 (0.12)	0.21 (0.06)	0.23 (0.07)	0.15 (0.08)
1/500	0.33 (0.13)	0.35 (0.08)	0.35 (0.08)	0.26 (0.12)
1/250	0.52 (0.13)	0.52 (0.08)	0.51 (0.07)	0.39 (0.12)
1/125	0.73 (0.11)	0.70 (0.08)	0.67 (0.05)	0.57 (0.11)
1/25	1.00	1.00	1.00	1.00

** (Parenthesis shows standard deviation)

It should be noted, however, that most of column surfaces in the previous databank were flange plates of H-shaped columns, and did not include skin plates of rectangular hollow sections. Then for each connection in the present tests, normalized moment vs. rotation curve is plotted in Figure 9 and compared with the past poly-line proposed by the authors. It is found that the past poly-line can be applied so far as the column skin failure is prevented by stiffening plate. A softer curve than the past poly-line, however, may be adequate in case of dominant failure and deformation at column skin or column surface.

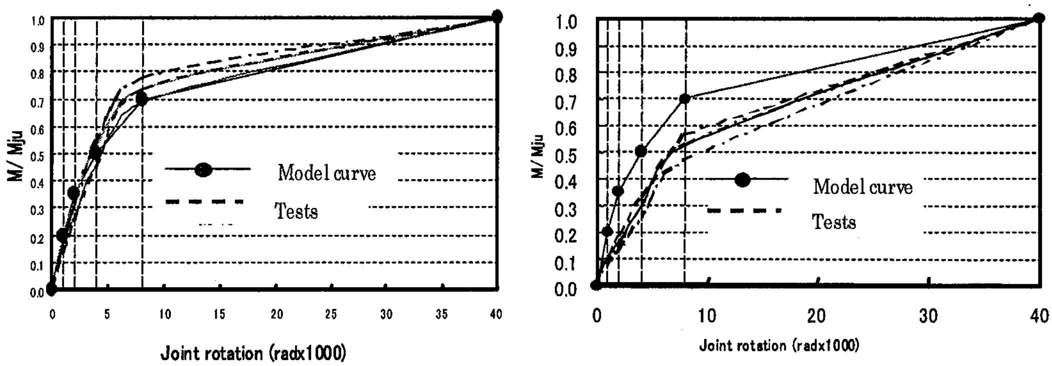


Figure 9. Characterization with semi-rigid connections. Left graph, curves of stiffened surface connections. Right graph non-stiffened surface connections

6. Conclusions

(1) Different type of sub-assemblage has been tested, obtaining various types of possible failure modes of semi-rigid partial-strength connections.

(2) All the connections possess a joint rotation capacity more than 1/25. Compared with F and DW connections, E and TW connections retain superiority in stiffness and strength under same surface condition.

(3) Column skin stiffened condition is an important parameter to the assessment of connection behavior. For weak column surfaces not stiffened, the surface deformation dominates the joint rotation, leaded to an extremely flexible connections and smaller strength than stiffened column surfaces.

(4) A standard poly-line for moment vs. joint rotation curve proposed for a ductile category of connections (no early bolt failure), that is, *Ductile Set of* (θ: M/M_{ju})=(1/1000: 0.2), (1/500: 0.33), (1/250: 0.5), (1/125: 0.7), and (1/25: 1.0), matches with the test curves in case of stiffened column surface, where failure is observed at connecting elements, that is, end plates, angles, and/or high-strength bolts.

(5) In case that the column-skin failure and deformation are dominant, test curves are softer than the above-mentioned standard poly-line. To match with a few test results herein, it may be tentatively modified into a flexible category of connections as: *Flexible Set of* (θ: M/M_{ju}) =(1/1000: 0.1), (1/500: 0.15), (1/250: 0.3), (1/125: 0.5), and (1/25: 1.0).

References

[1] Ohi K. et.al. Pseudo-dynamic tests on serviceable and robust steel frames with the combination of hysteretic damper and semi-rigid connections. Paper 2300. 12 WCEE 2000.
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