Abstract
SRC column–RC beam joint is frequently used for the construction of underground structure in the Top-Down construction method. Various types of joint details have been proposed and implemented for the anchorage of the reinforcing bars. The types can be classified by anchoring methods as follows: (1) passing through type; (2) wing plate type; and (3) H-beam bracket type. Although these types are widely used in Korea, the structural performance is not clearly understood.
For each type of joint, the structural characteristics such as strength, stiffness, energy dissipation capacity, stiffness degradation, and ductility under monotonic and cyclic loads were tested. The test results showed that the passing through type has the best structural performance.
By advancing the passing through type, the wide beam type specimens were experimentally investigated for the field application. The wide beam type uses a number of reinforcing bars that are placed at the edge of the slab not to intersect a steel column without changing its sectional shape. It is concluded that the wide beam type is adequate in the SRC column-RC beam joint not only for its structural capacities, but also for its economic merits.

1. Introduction

General
The Top-Down method is frequently used at a downtown construction site, because it requires less construction space than other methods. Also, this method reduces construction time, noise and vibration, and prevents unequal settlement of the surrounding ground. Since its invention by Mr. Arup in 1936, characteristics, construction procedure and several details of this method have been studied to promote the construction efficiency. As one of these efforts, when deciding structural type, the composite structure is mostly preferred.1)
In Japan, since the early recognition of the necessity of the composite structure, several beam-column joint types have been developed. Focused joint types are SRC column-SRC beam, RC column-steel beam, and SRC column-steel beam. When using SRC column-RC beam joint type, the passing through type is preferred, because of the safety from the earthquake. The reinforcing bar is anchored by making a hole at the steel column and passing through the column. SRC column-RC beam joint is usually adopted for the underground structures in Korea. However, its beam cannot maintain the continuity because of the construction characteristics. The various joint types, such as the passing through type, the wing plate type, the bracket type, and the coupler type have been proposed and implemented to settle this problem. In spite of frequent usage of these types, there were not comprehensive experimental bases of their structural behaviors.

Research Scope
In this study, the passing through type, the wing plate type, and the H-beam bracket type were considered. Although the coupler type is known for its best reliability of anchorage of the reinforcing bar, it was not considered, because it can be implemented immediately if its welding condition is proved to be good enough. First of all, the monotonic and cyclic loading experiments were conducted for each joint type to investigate the structural behaviors. Then, additional monotonic tests were performed to efficiently develop the type that showed the best performance. Special attentions were paid to investigate the efficiency of placing the tensile reinforcing bars within the effective beam width. For the field application, the wide beam type was explored by experiment.

2. Comparative Experiment

Monotonic and cyclic loading tests were performed to investigate the structural capacities of three types as follows; (1) passing through type, (2) wing plate type, and (3) H-beam bracket type. Specimens were designed as the interior joint of the underground structure whose clear length of span was 790cm.

The same materials were used for all specimens. The measured properties of the materials are as follows: (1) uni-axial compressive strength of the concrete (28day) was 254 kgf/cm², (2) average uni-axial tensile strengths of the re-bars were 4,147 kgf/cm² (D10) and 3,999 kgf/cm² (D22), and (3) average uni-axial tensile strengths of H-beam and plate were 3,813.5 kgf/cm² and 3,024.67 kgf/cm², respectively.

2.1 Monotonic Loading Test

General
Three different types were designed and tested under the monotonic load. The seismic design was not considered. The flexural failure criteria were expected to all of the specimens. Fig. 1 shows the dimensions and the details of each specimen. As shown in Fig.2, a static actuator was bound by the reaction frame to apply load to the top
The ends of the beam were supported by hinge and the ends were free to rotate only. Several transducers were placed to measure the displacement of the column and the rotation of the beam against the column.

Test Results
The results showed that the passing through type and the wing plate type have the satisfactory structural performances. As Table 1 presents, their ultimate strengths exceeded the design strengths by about 20% and their ductility factors also satisfy the required value of ordinary reinforced concrete structure, which is 4.0. However, the bracket type specimen did not surpass either the yield design strength or the ultimate strength. Fig. 3 shows the load-displacement relations and Fig. 4 presents the observed cracks of the specimens.

2.2 Cyclic Loading Test

General
Reverse cyclic loading tests were conducted to investigate the behavior of the interior beam-column joint for each type. The details of the passing through type and the H-beam bracket type are shown in Fig. 5(a) and 5(b). The only differences from the specimen of the monotonic loading test are the length of the column and the reinforcing...
[Fig. 2] Loading Method

[Table 1] Monotonic Loading Test Results

<table>
<thead>
<tr>
<th>Specimen Type</th>
<th>Yield Strength</th>
<th>Ultimate Strength</th>
<th>Displacement Ductility Factor</th>
<th>Curvature Ductility Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Design (ton)</td>
<td>Test (ton)</td>
<td>Ratio (T/D)</td>
<td></td>
</tr>
<tr>
<td>Passing Through</td>
<td>24.76</td>
<td>23.80</td>
<td>0.96</td>
<td></td>
</tr>
<tr>
<td>Wing Plate</td>
<td>24.76</td>
<td>24.51</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>H-Bracket</td>
<td>25.78</td>
<td>21.34</td>
<td>0.83</td>
<td></td>
</tr>
</tbody>
</table>

|                 | Design (ton)   | Test (ton)        | Ratio (T/D)                 |                           |
|                 |                |                   |                             |                           |
|                 | 25.38          | 31.06             | 1.22                        | 7.87                      |
|                | 25.38          | 30.15             | 1.19                        | 5.34                      |
|                | 27.11          | 24.11             | 0.89                        | 1.86                      |

[Fig. 3] Load-Displacement Relations

[Fig. 4] Observed Cracks of Specimens

bars of the beam due to seismic resistance.3, 4, 5, 6)

Fig. 6 shows test setup. The column was tied to the reaction frame and was allowed to rotate only. Constant axial load (150tonf), which was about 25% of the design axial strength of the column, was applied to the top end of the column during the test. In all tests, a sinusoidal displacement control wave form consisting of completely reversed cycles at the amplitude of 1δ, 2δ, 4δ, 6δ, 8δ, where δ is the displacement when the
Tensile reinforcing bar started yielding. Fig. 7 shows the detail of the location of the transducers to measure the displacements of the loading points and the rotation of the beam against the column. Prefabricated angle set was used to fix all the transducers. This angle set was attached to the specimen at the supporting point, but using ball bearings, was not affected by the movement of the specimen.

![Dimensions and Reinforcement Details](Fig. 5)

![Test setup](Fig. 6)

![Measuring points](Fig. 7)

**Test results**

The measured hysteresis loops of equivalent interstory shear force ($V$) versus equivalent interstory drift ($\delta$), which can be obtained using equation (1), are shown in Fig. 8(a), 8(b), and 8(c).

$$V = \frac{P_1l_1 + P_2l_2}{l_c}, \quad \delta = \frac{\delta_{b1} + \delta_{b2}}{l_1 + l_2} \times l_c \quad (1)$$

Where, $P_1$ and $P_2$: loads applied to both beams
$l_1, l_2$: distance from the center of the column to the loading point

$l_c$: distance from upper supporting point to lower point of the column

$\delta_{B1}, \delta_{B2}$: displacements at the loading point of each beam

The external work curve of each specimen versus cumulative displacement is shown in Fig. 8(d). Table 2 shows the equivalent inter-story shear force and energy dissipation capacity. The passing through type and the wing plate type surpassed the design strength by 14% and 27%, respectively. However, H-beam bracket type did not reach its design strength due to the premature shear failure of concrete, which resulted from the bond failure between steel and concrete. Therefore, the test was interrupted as soon as the shear failure occurred.

![Cyclic Loading Test Results](image)

The passing through type specimen showed a stable behavior until $4\delta$. However, the deformations due to bond slippage at the panel zone became very significant, and pinching and severe degradation of stiffness were observed in the hysteresis loops at the second cycle of the $4\delta$. The wing plate type specimen also showed a stable behavior. Pinching and degradation of stiffness did not occur until $4\delta$. Because the welded area between the wing plate and the flange of the H-beam was torn out, the test was stopped at the first cycle of $6\delta$. In the case of the H-beam bracket type, inverse shear crack was observed during the first cycle of the loading. Several inverse shear cracks occurred as the test continued. Finally, it caused the specimen to fail.
### Table 2: Cyclic Loading Test Results

<table>
<thead>
<tr>
<th>Specimen Type</th>
<th>Yield Equivalent Inter-Story Shear Force</th>
<th>Ultimate Equivalent Inter-Story Shear Force</th>
<th>Dissipated Energy (tonf-mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Analysis (tonf)</td>
<td>Experiment (tonf)</td>
<td>Analysis (tonf)</td>
</tr>
<tr>
<td>Passing Through</td>
<td>13.02</td>
<td>12.68</td>
<td>13.45</td>
</tr>
<tr>
<td>Wing Plate</td>
<td>-13.02</td>
<td>-13.07</td>
<td>-13.45</td>
</tr>
<tr>
<td>H-Beam Bracket</td>
<td>17.39</td>
<td>16.10</td>
<td>17.39</td>
</tr>
</tbody>
</table>

3. Monotonic Loading Test for Wide-beam Sectional Specimens

**General**

The passing through type specimen and the wing plate type specimen satisfied the required structural performance. However, there were some problems to be solved for the field application. In case of passing through type, the thickness of the steel was the significant factor. As the thickness of column steel increased, it was difficult to make holes in thick flange and it made the passing through type less efficient for field application. In case of wing plate type, the tensile reinforcing bars of the slab were arranged in double layers and welded on and below the wing plate. It was difficult to weld the bar below the wing plate while easy to do on the plate.

Therefore, additional tests for wide beam type were performed to implement these types efficiently for the field application. Special attentions were paid to investigate the efficiency of placing the tensile reinforcing bars. Five different specimens were constructed, as shown in Fig. 9, based on Chapter 10.6.6 of ACI 318-99. The SRC1 specimen used the reinforcing bars that were placed in two layers and welded on the wing plate for their anchorage. The design of SRC2 specimen was similar to that of the wide-beam. Only two reinforcing bars were placed in the beam and bypassed the steel column. The others were placed in the slab within the effective width of beam. Since the compressive area of the beam, which was affected by the negative moment, satisfied the required design moments, the modification of the sectional shape was not necessary. The detail of SRC3 specimen was similar to that of the SRC2, except the anchorage of the two reinforcing bars in the beam, which were welded on the wing plate. RC1 and RC2 specimens, shown in Figs. 9(c) and 9(d), were also tested to compare with SRC series specimens.

During the test, the same value of the load was applied until it reached the ultimate strength. Strain gauges were attached to the reinforcing bars to evaluate the strain distributions. They were attached at the critical section that was 30cm away from the center of the column.
Test results
As shown in Fig. 11, behaviors of all the specimens were similar until they reached the yielding strength. Fig. 12 shows the strain distribution of reinforcing bars of RC1, RC2, SRC1 and SRC2 at each loading step. Since there were only two reinforcing bars in the beam section of the SRC2, the strain increment at each loading step was larger than those of the RC series. This phenomenon could be corrected by modifying the placement of reinforcing bars.

![Fig. 9] Dimensions and details of the specimens

![Fig.10] Testing setup

![Fig.11] Load-displacement relations
[Table 4] Monotonic Loading Test Results

<table>
<thead>
<tr>
<th>Specimen Type</th>
<th>Yield Strength</th>
<th>Experimental</th>
<th>Ratio (E/A)</th>
<th>Experimental Ultimate Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRC1</td>
<td>26.18</td>
<td>26.58</td>
<td>1.02</td>
<td>27.858</td>
</tr>
<tr>
<td>SRC2</td>
<td>27.77</td>
<td>24.09</td>
<td>0.87</td>
<td>30.476</td>
</tr>
<tr>
<td>SRC3</td>
<td>27.77</td>
<td>25.42</td>
<td>0.92</td>
<td>28.897</td>
</tr>
<tr>
<td>RC1</td>
<td>26.35</td>
<td>27.00</td>
<td>1.02</td>
<td>29.785</td>
</tr>
<tr>
<td>RC2</td>
<td>27.93</td>
<td>28.58</td>
<td>1.02</td>
<td>28.615</td>
</tr>
</tbody>
</table>

[Fig. 12] Strain distributions

[Fig. 13] Observed cracks of the beam
Testing results are presented in table 4. The yield strengths of SRC2 and SRC3 were lower than the analytical value, because the experimental yield strength was evaluated when at least one of the reinforcing bars reached its yielding strain. Fig. 13 shows the cracks of the beam when the test was finished. All the cracks showed typical flexural failure mode regardless of the specimen type. The cracks of the slab of all the specimens also showed similar failure trend.

4. Conclusions

In this study, monotonic and cyclic loading test were conducted to investigate the structural behavior of the several SRC column-RC beam joint types which are frequently used in the Top-Down construction method such as the passing through type, the wing plate type, and H-beam bracket type. Advanced joints for the field application, where the most of reinforcing bars were placed in the slab within the effective width of the beam, were also tested under the monotonic load. The following conclusions were made:

(1) The passing through type and the wing plate type showed the satisfactory structural performance to be implemented as SRC column-RC beam joint type. Both types surpassed their analytical strengths and the required ductility.

(2) When using the wide beam type, it is recommended that all the reinforcing bars bypass H-beam of the column through the slab except for the minimum number of reinforcing bars, which can be anchored to the wing plate by welding.

(3) When the tensile reinforcing bars of the beam are placed within the slab, the bars work as both beam and the slab, and this method is expected to reduce the construction cost.

References