Mechanical Splice of Grid CFRP Reinforcement and Steel Plate

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Shield Tunneling Method

• Generally, the substructures in urban areas of Japan have a tendency to become deep and constructed in the soft ground with a high water pressure.

• The closed type shield tunneling is an appropriate method to secure this situation.

• The lateral wall of a vertical shaft used for breaking in or breaking out of a shield tunneling machine is constructed with a continuous underground reinforced concrete wall, steel sheet-piles and so on.
Shield-Cuttable Tunnel Wall System

- The low shear strength of CFRP reinforcement perpendicular to the carbon fibers was effectively used as the reinforcement in the concrete wall of a vertical shaft.

- This system enables a shield tunneling machine to break in or break out by directly cutting the launch or arrival part of the wall with its cutter bits without performing prior ground improvement works and manual demolition.
Examples of Application

- Continuous underground reinforced concrete wall
- Caisson
Column-Type Diaphragm Wall

- When this system is applied to a column-type diaphragm wall of a vertical shaft, H-shaped steel piles used as the reinforcement in the wall should be replaced by the bit-cuttable mixed-in-place concrete piles reinforced with CFRP reinforcement.
Abstract of This Study

• In order to connect the grid CFRP reinforcement and the flange of H-shaped steel, a specially designed mechanical splice has been developed.

• The splice was made of some pieces of steel plate and resin mortar, and it contained three cross points of the grid CFRP reinforcement.

• The tension test of the mechanical splice was carried out to investigate its mechanical behavior.
Grid CFRP Reinforcement

- Specification
  Fiber: PAN type high-strength carbon fiber
  Resin: Vinylester resin
  Volume content of fibers: 43 %

- Tensile properties

<table>
<thead>
<tr>
<th>Bar No.</th>
<th>Nominal cross-sectional area (mm²)</th>
<th>Tensile capacity (kN)</th>
<th>Ultimate strain (%)</th>
<th>Tensile strength (N/mm²)</th>
<th>Young's modulus (kN/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C16</td>
<td>100</td>
<td>170</td>
<td>1.59</td>
<td>1,700</td>
<td>104</td>
</tr>
<tr>
<td>C19</td>
<td>148</td>
<td>223</td>
<td>1.58</td>
<td>1,510</td>
<td>93.6</td>
</tr>
<tr>
<td>C25</td>
<td>260</td>
<td>355</td>
<td>1.48</td>
<td>1,360</td>
<td>86.9</td>
</tr>
<tr>
<td>C29</td>
<td>320</td>
<td>426</td>
<td>1.39</td>
<td>1,330</td>
<td>94.5</td>
</tr>
<tr>
<td>C32</td>
<td>395</td>
<td>522</td>
<td>1.38</td>
<td>1,320</td>
<td>94.2</td>
</tr>
</tbody>
</table>
Test of Strength of Cross Point

- The grid CFRP reinforcement has a high strength at cross point, therefore the transverse bar provides a good bond and an anchorage to concrete.

- A specially designed mechanical splice also made use of the high strength of cross point.

- The strength of cross point of five types of the grid CFRP reinforcement of large diameters were investigated.
Specimen

- The specimens were made by referring to “Test Method for Bond Strength of Continuous Fiber Reinforcing Materials by Pull-out Testing” proposed by the committee of the Japan Society of Civil Engineers.

- The grid CFRP reinforcement which had only one cross point was arranged in the center of a cubic form, and then concrete was placed.
Specimen

- The longitudinal bar of the grid CFRP reinforcement was wound with a thin polyethylene film and a vinyl tape to remove bond between the longitudinal bar and concrete.

- A spiral steel reinforcement hoop was arranged to prevent a splitting failure of concrete.
Test Method

- A tensile force was applied to the longitudinal bar of the specimen by pulling the steel pipe with the jack.
- The load, the displacement of the free end and the strain of the longitudinal bar were measured.
Failure Mode of Cross point

- There were three types of failure modes:
  - mode A: two facial shear failure of the transverse bar
  - mode B: rupture of the longitudinal bar at cross point
  - mode C: mainly rupture of the longitudinal bar at cross point, but partly slipping out
Test Result

- The strength of cross point was defined as the maximum load divided by the nominal cross-sectional area.

<table>
<thead>
<tr>
<th>Bar No.</th>
<th>Maximum load (kN)</th>
<th>Strength of cross point (N/mm²)</th>
<th>Ratio of strength of cross point and tensile strength</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>C16</td>
<td>61.5</td>
<td>615</td>
<td>0.36</td>
<td>A, A, A</td>
</tr>
<tr>
<td>C19</td>
<td>102</td>
<td>690</td>
<td>0.46</td>
<td>B, A, A</td>
</tr>
<tr>
<td>C25</td>
<td>183</td>
<td>703</td>
<td>0.51</td>
<td>B, B, B</td>
</tr>
<tr>
<td>C29</td>
<td>203</td>
<td>634</td>
<td>0.48</td>
<td>B, C, C</td>
</tr>
<tr>
<td>C32</td>
<td>220</td>
<td>556</td>
<td>0.42</td>
<td>B, A, B</td>
</tr>
</tbody>
</table>
Strength of Cross Point

- Relationship between strength of cross point and nominal cross-sectional area
Strength of Cross Point

- As for the specimens larger than C19, the strength of cross point became lower as an increase of the nominal cross-sectional area, and a scale effect was observed.

- However, the strength of C16 was lower than that of C19.

- The grid CFRP reinforcement was composed of carbon fibers and vinylester resin, and carbon fibers were laminated alternatively at cross point.

- In case of C16, the strength of cross point decreased owing to a small number of carbon fiber laminates at cross point.
Test of Mechanical Splice

- Material
  Grid CFRP reinforcement: C16, C19, C25 and C29
  Steel plate: SS400
  (nominal tensile strength: 400-510 kN/mm²)

- Since the strength of cross point of the grid CFRP reinforcement was from 36 to 51% of the tensile strength, three cross points would be necessary to transmit the tensile capacity of the grid CFRP reinforcement to the steel plate.
Specimen

- The mechanical splice was mainly made of three steel plates.
- Eight small pieces of steel plate with a circular hole were welded on the surface of the lower steel plate to make a U-shaped groove.
Specimen

- The grid CFRP reinforcement which had three cross points was arranged in the groove of the lower steel plate.

- Resin mortar was placed to fill up a gap between the grid CFRP reinforcement and the steel plates.
Specimen

- The upper steel plate was tightened to the lower steel plate with bolts and nuts.

- After a steel pipe had been installed at the end of the longitudinal bar, it was filled with a highly expansive paste.
Test Method

- The steel pipe and the opposite end of the middle steel plate were gripped by the devices of a testing machine, and then a tensile force was applied to the specimen.

- The load and the strain of the longitudinal bar were measured until a rupture of the specimen.
Failure Mode

- There were two types of failure modes;
  mode R: rupture of the longitudinal bar
  mode S: slipping out the longitudinal bar from the steel pipe
The performance of the splice was defined as the ratio of the ultimate load $P_u$ and the tensile capacity $F_u$.

<table>
<thead>
<tr>
<th>Bar No.</th>
<th>Ultimate load (kN)</th>
<th>Ratio of ultimate load and tensile capacity</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>C16</td>
<td>154</td>
<td>0.91</td>
<td>R, R, R</td>
</tr>
<tr>
<td>C19</td>
<td>214</td>
<td>0.96</td>
<td>R, R, R</td>
</tr>
<tr>
<td>C25</td>
<td>365</td>
<td>1.03</td>
<td>R, R, R</td>
</tr>
<tr>
<td>C29</td>
<td>436</td>
<td>1.02</td>
<td>S, S, R</td>
</tr>
</tbody>
</table>
Performance of Splice

- Relationship between performance of splice and nominal cross-sectional area
Performance of Splice

- The performance of the splice of one specimen for C16 was a little bit low, however those of the other specimens except two specimens for C29, which were failed owing to a slipping out of the longitudinal bar from the steel pipe, were higher than 90%.

- It was confirmed that the mechanical splice could transmit the tensile capacity of the grid CFRP reinforcement to the steel plate.
Application for Subway

- Mechanical splice
- Mechanical splice
Application for Subway

- Column-type diaphragm wall
- Shield tunneling machine
Conclusions

- In order to connect the grid CFRP reinforcement and the flange of H-shaped steel, a specially designed mechanical splice made of some pieces of steel plate and resin mortar has been developed.

- The mechanical splice contained three cross points of the grid CFRP reinforcement, because the strength of cross point was from 36 to 51% of the tensile strength.

- The mechanical splice could transmit the tensile capacity of the grid CFRP reinforcement to the steel plate.