FINITE ELEMENT ANALYSIS OF EXISTING RC BEAM-COLUMN JOINTS STRENGTHENED BY PRESS-JOINT WITH ADDITIONAL RC MEMBERS

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Only a few specialized research studies and examples of seismic strengthening methods for beam-column joints in existing reinforced concrete (RC) buildings exist. In a previous study, we proposed a seismic strengthening method that press-joints additional RC members around existing steel-reinforced concrete (SRC) beam-column joints. This study used finite element analysis to investigate the reinforcement effect of the proposed seismic strengthening method on existing RC beam-column joints. Initially, finite element analysis was conducted to imitate the assembled test in which the RC beam-column joint was fractured. The model analysis results agreed well with the test results. For this existing RC beam-column joint model, three types of models with reinforcement methods as parameters were analyzed. The first type model press-joints additional RC members only in the in-plane direction. The second type model press-joints additional RC members in the in-plane and orthogonal directions. The third type model press-joints additional RC members in the in-plane direction, and the additional RC members and existing part are joined by post-installed anchors in the orthogonal direction. According to results, cracks at the existing RC beam-column joints were confirmed to be reduced in the strengthened models. The model that press-joints additional RC members in the in-plane and orthogonal directions most significantly reduced the minimum principal stress in existing RC beam-column joints the most.

Keywords: Earthquake engineering, Seismic retrofit, PC rod, Minimum principal stress.

1 INTRODUCTION

Several methods have been proposed to improve the bending and shear strength of columns and beam members, and there are many examples of their application to real buildings. However, only a few specialized research studies and examples of seismic strengthening methods for beam-column joints in existing RC buildings exist. In a previous study (Maida et al. 2022), we proposed a seismic strengthening method that press-joints additional RC members around existing steel-reinforced concrete (SRC) beam-column joints. This study investigates the reinforcement effect of the proposed seismic strengthening method on existing RC beam-column joints by finite element analysis.
2 SUMMARY OF THE FINITE ELEMENT ANALYSIS

2.1 Analysis Object

Table 1 shows the specifications of the analysis model. The specimen used for analysis is the “TH specimen” described in the previous study (Maida et al. 2023). For further information on the test, readers are directed to the previous study (Maida et al. 2023).

The TH specimen is a half-scale RC beam-column joint assembled with column and beam members designed to maintain the column-to-beam strength ratio of 1.0. The column-to-beam strength ratio calculated using the material test results was 1.1. In the test, beam-column joint failure was confirmed. A model that reproduces this test specimen (TH specimen) with only the existing RC beam-column joint assembly is called the E model. Three types of reinforced models are created, and a total of four models are examined. Figure 1 shows the outline of the reinforcement method. In the R-P-N model, additional RC members are added along both sides of the existing RC beam-column joints, and press-joints reinforce the additional members and existing RC beam-column joints only in the in-plane direction with PC rods. In the R-P-P model, additional RC members are press-jointed by PC rods in both in-plane and orthogonal directions. In the R-P-A model, the additional RC members are press-jointed with PC steel rods in the in-plane direction, and the additional RC members are joined to the existing part with post-installed anchors in the orthogonal direction.

Table 1. Specifications of the analysis model.

<table>
<thead>
<tr>
<th>Models</th>
<th>E</th>
<th>R-P-N</th>
<th>R-P-P</th>
<th>R-P-A</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Existing part</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Beam</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Span length (mm)</td>
<td>3000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BxD (mm)</td>
<td>265x390</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compressive strength of concrete, $f_c$ (N/mm$^2$)</td>
<td>23.9</td>
<td>4-D19 (SD345)</td>
<td>2-D10@100 (SD295A) $P_w=0.54%$</td>
<td></td>
</tr>
<tr>
<td>Longitudinal rebar</td>
<td>4-D19 (SD345)</td>
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<td></td>
<td></td>
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<tr>
<td>Stirrups</td>
<td>2-D10@100 (SD295A) $P_w=0.54%$</td>
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<tr>
<td><strong>Column</strong></td>
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<tr>
<td>Height of story (mm)</td>
<td>1700</td>
<td></td>
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<tr>
<td>BxD (mm)</td>
<td>400x400</td>
<td></td>
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</tr>
<tr>
<td>Compressive strength of concrete, $f_c$ (N/mm$^2$)</td>
<td>23.9</td>
<td>12-D19 (SD345)</td>
<td>2-D10@50 (SD295A) $P_w=0.60%$</td>
<td></td>
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<tr>
<td>Longitudinal rebar</td>
<td>12-D19 (SD345)</td>
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<tr>
<td>Hoop</td>
<td>2-D10@50 (SD295A) $P_w=0.60%$</td>
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<tr>
<td><strong>Beam-column joint</strong></td>
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<tr>
<td>Hoop</td>
<td>2-D10@80 (SD295A) $P_w=0.36%$</td>
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<tr>
<td><strong>External part</strong></td>
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<tr>
<td><strong>Additional member</strong></td>
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<tr>
<td>BxDxh (mm)</td>
<td>67.5x100x390</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Compressive strength of concrete, $f_c$ (N/mm$^2$)</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Longitudinal rebar</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hoop</td>
<td></td>
<td></td>
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</tr>
<tr>
<td><strong>Joining method between existing part and external part</strong></td>
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<tr>
<td>In-plane direction</td>
<td>Press-joint</td>
<td></td>
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<tr>
<td>Transverse direction</td>
<td></td>
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<td></td>
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<tr>
<td>Post-installed anchor</td>
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</table>
The tension force introduced by the PC rods was designed such that the average stress in the area of the additional members around the RC beam-column joint joints was approximately 7.9 N/mm². This is because the average stress was set to the long-term allowable compressive stress \((f_c/3)\) of the concrete strength for the existing part of the specimen. Predetermined tension was applied to the PC rods using 4-\(\phi11\) in the in-plane direction and 3-\(\phi13\) in the orthogonal direction.

### 2.2 Modeling

Figure 2 shows the FEA model. FINAL software (ITOCHU Techno-Solutions Corporation 2011) was used for the FEA. Only half of the specimen was modeled as a three-dimensional FEA geometry due to the symmetric condition of the specimen’s shape and loading. The concrete and steel plates were modeled using solid elements. The rebar and PC rods were modeled using truss elements. The post-installed anchors were modeled using beam elements. Joint-type elements were inserted between the longitudinal rebar and concrete and between the post-installed anchors and concrete to incorporate bond–slip behavior. A joint element was set for the contact surface of the existing part and the additional part.

### 2.3 Material Properties

#### 2.3.1 Concrete

In the tensile phase, the concrete model was treated using a linear model before cracking. After cracking, the specimens were subjected to tension softening based on Izumo’s model (Izumo et al. 1987). In the compressive phase, the modified Ahmad model (Naganuma 1995) was applied to the concrete model. The concrete compressive strength \((f_c)\) and split tensile strength \((f_t)\) are \(f_c = 23.9\) N/mm² and \(f_t = 2.0\) N/mm².

#### 2.3.2 Steel material

Based on the experimental test results from the aforementioned study, the steel materials (longitudinal rebar, shear reinforcement, steel plate, anchor, etc.) were assumed to obey the theory of elastoplasticity. For the strength of the longitudinal rebar and shear reinforcement, the readers are directed to a previously published study (Maida et al. 2023). The strength of the steel plate, anchor, and PC rod was set to the standard value.
2.3.3 Bond characteristics between concrete and steel material

The Elmorsi model (Elmorsi et al. 2000) was applied to the bond between the rebar and concrete and between the post-installed anchors and concrete. The maximum bond stress was obtained from the proposed formula (Architectural Institute of Japan 1999), and the slip at the maximum bond stress was assumed to be 0.1 mm.

2.3.4 Joint element of the contact surface of the existing part and the additional part

The joint element of the contact surface of the existing part and the additional part are described. Regarding the interface normal direction, the stress was set to be transmitted only in the compression direction. When the tensile stress reaches the specified strength, the joint is loosened, and subsequently, when stress occurs in the tensile direction, the stiffness is set to zero. As for the shear direction, the effect of friction was considered when subjected to compressive stress.

2.4 Boundary Conditions and Loading

Figure 2 shows the outline of the boundary conditions and loading. The boundary conditions were that the cut surface was supported by rollers in the Y direction, the central row of the column capital was restrained in the X direction, and the central row of the column base was restrained in the X and Z directions. For loading, initial tension was first introduced to the PC rods in the reinforcement model. After that, in all models, a shear force was applied to the center row of the beam ends by displacement control in the same way as in the test.

![Finite element analysis model](image)

Figure 2. Finite element analysis model.

3 DISCUSSION OF THE ANALYSIS RESULTS

3.1 Relationship Between Displacement and Force

Figure 3 shows the relationship between story shear force $Q$ and story drift ratio $R$. The figure also shows the calculated value of the story shear force at beam flexural ultimate strength $Q_{bmu\_cal} (=192kN)$.

Comparing the analysis and test of the E model, the initial stiffness on the positive side is larger in the analysis. Although the reproducibility of the hysteresis loop was low on the negative side, it was mostly reproducible on the positive side. This is because a load was applied to the beam on one side due to malfunction of the actuator before the test.
Figure 3. Relationship between story shear force $Q$ and story drift ratio $R$.

Figure 4. Cracks on the concrete around the beam-column joint at $R=+1/100$rad.

Figure 5. Minimum principal stress distribution in concrete around the beam-column joint at $R=+1/100$rad.
Comparing the analysis of the E model and the R-P-N model, the E model did not reach $Q_{bmu,\text{cal}}$, while the R-P-N model reached $Q_{bmu,\text{cal}}$, confirming a slight reinforcing effect.

R-P-P and R-P-A models have larger story shear forces at the same story drift ratio than the E and R-P-N models. This is because the yield hinge position of the beam was on the column face in the E and R-P-N models, while it was on the edge of the additional member in the R-P-P and R-P-A models.

3.2 Damage to the Concrete

Figure 4 shows the cracks on the concrete around the beam-column joint at $R=+1/100$rad.

While many diagonal cracks occurred at the beam-column joint in the E model, the occurrence of diagonal cracks was reduced in the reinforced model.

3.3 Minimum Principal Stress of the Concrete

Figure 5 shows the minimum principal stress distribution in the concrete around the beam-column joint at $R=+1/100$rad. The position of the cross-section is shown on the upper side of the figure.

In section B, the compression strut is confirmed in the E model, but the stress is distributed in the R-P-N model. The R-P-P and R-P-A models can reduce the stress in the beam-column joint compared to the E and R-P-N models in any cross-section. The width of the compression strut is wider in the R-P-P model than in the R-P-A model. The width of the compression strut can be effectively secured by additionally introducing tension in the orthogonal direction.

4 CONCLUSIONS

In this study, a finite element analysis was performed on the existing RC beam-column joints to which the additional RC members were press-jointed, and the reinforcement effect was confirmed. According to analysis results, cracks at the existing RC beam-column joints were confirmed to be reduced in the strengthened models. The model that press-joints additional RC members in the in-plane and orthogonal directions significantly reduced the minimum principal stress in existing RC beam-column joints. A quantitative evaluation of the reinforcing effect is a subject for future study.

References


