Effect of Steel Plate Jacketing of Columns in Seismic Behavior of Concrete Beam-Column Connections

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Abstract
Design philosophy of having weak beam–strong column is recommended almost in all design codes. But in some cases, in prior buildings, this philosophy is ignored. In these structures, during major earthquakes, failure mechanism would begin from columns leading to sever damages. To avoid this event, column in the connection zone must be strengthened to conduct the plastic zone to the beams. There is several ways for strengthening concrete columns and one of the efficient ways is using steel plates surrounding column in the critical zone. In this paper, using steel plates for seismic upgrading of Concrete Beam-Column connections has been investigated numerically. Effect of plate thickness, length and beam-column dimensions is taken into account. Some empirical results are used to verify the finite element approach. Analyses are conducted with the use of some modeling methods including various geometrical models and material behaviors. The results from various methods are compared and the suitable model is proposed.

Keywords: Finite Element Modeling, Concrete Damage Plasticity, Steel Plate Jacketing, Joints, Cyclic Behavior

1. INTRODUCTION

By updating building codes, some existing structures may not conform to current standards even though they may have been appropriately designed and constructed consistent with previous building standards. Therefore, strengthening of some elements may be necessary in the useful lives of structures. Preferably, the strengthening must not restrict the function of the structure.

A reinforced concrete (R/C) building has usually been designed for a large earthquake load, which normally resulted in wide columns. Therefore, the damage within a beam-column joint was barely observed in the past earthquakes. However, the advancement of design calculation and the use of higher strength materials might reduce column dimensions, especially with the adoption of an ultimate strength design procedure relying on the ductility. Then, the beam-column joint may become the weak link of a chain.

A heavy damage in a beam-column joint should be avoided during an earthquake because (a) the gravity load is sustained by the joint, (b) a large ductility and energy dissipation is hard to be attained in the joint, and (c) a joint is difficult to repair after an earthquake. However, an excessive complication of reinforcement detailing should be avoided to assure good construction and workmanship. Therefore, joint shear failure should be prevented up to an expected structural deformation.

This paper discusses the strengthening procedure of joints using column steel jacketing. Some finite element models have been built and original model is verified with experimental results. Then, parametric analyses conducted to compare effects of various thickness and axial load levels on the hysteresis behavior of such connection.
2. MODELING PROCEDURE

A model is built in finite element package ABAQUS according to Kitamaya (1) and analysis procedure and material models were verified with experimental results. Finite element model of typical connection is consisting of a column using 2-half beams with details described in Table 1. Geometry of connection and test setup for experimental model is shown in Figure 1 and Figure 2 respectively.

### Table 1-model detail

<table>
<thead>
<tr>
<th>Material</th>
<th>Details</th>
<th>( f_y )</th>
<th>( P_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam (200x300 mm)</td>
<td>Top bars: 12-D10, ( a_s = 856 \text{ mm}^2 )</td>
<td>3260 kg/cm²</td>
<td>1.59 %</td>
</tr>
<tr>
<td></td>
<td>Bot bars: 6-D10, ( a_s = 429 \text{ mm}^2 )</td>
<td></td>
<td>0.79 %</td>
</tr>
<tr>
<td></td>
<td>Stirrups: 2-D6, @ 50 mm</td>
<td>3300 kg/cm²</td>
<td>0.64 %</td>
</tr>
<tr>
<td>Column (300x300 mm)</td>
<td>Total bars: 16-D13, ( a_s = 2032 \text{ mm}^2 )</td>
<td>4300 kg/cm²</td>
<td>2.26 %</td>
</tr>
<tr>
<td></td>
<td>Hoops: 4-D6, @ 50 mm</td>
<td></td>
<td>0.85 %</td>
</tr>
</tbody>
</table>

2.1. Materials used in model

There are several material models for concrete in ABAQUS (2). For cyclic analyses, one of the most appropriate models is concrete damage plasticity (CDP) model which is a continuum, plasticity-based, damage model for concrete. Damage parameters are playing an important role in this model and it is essential to predict damage parameter with a good approximation in order to achieve an accurate answer. The typical stress-strain curve for this type of material behavior is shown in Figure 3.
To consider effect of confinement of concrete caused by hoops, Mander’s relation for confined concrete (3) is used. The parameters are shown in Figure 4. These parameters can be derived as follow:

\[ f_c = \frac{f_{cc}^{ex}}{r - 1 + x^r} \]  
\[ x = \frac{\varepsilon_c}{\varepsilon_{cc}} \]  
\[ r = \frac{E_c}{E_c - E_{Sec}} \]  
\[ E_{Sec} = \frac{f_{cc}}{\varepsilon_{cc}} \]  
\[ E_c = 5000 \sqrt{f_c} \text{ (MPa)} \]

Where:
- \( f_c \): Compression stress.
- \( f_{cc}^{ex} \): Peak of confined compressive strength.
- \( E_c \): Elasticity modulus of concrete.
- \( E_{Sec} \): Secant modulus of concrete.
- \( \varepsilon_{cc} \): Strain corresponding to peak of confined compressive strength.
- \( f_c' \): Concrete compressive strength

\[ f_{cc}' = f_c' \left( 2.254 \sqrt{1 + \frac{794f_c'}{f_c}} - \frac{2f_c'}{f_c} - 1.254 \right) \]  
\[ \varepsilon_{cc} = \left[ 5 \left( \frac{f_{cc}'}{f_c} - 1 \right) + 1 \right] \varepsilon_{co} \]  
\[ f_l' = \frac{1}{2} K_e \rho_s f_{yh} \]  
\[ K_e = \frac{1 - \frac{f_l'}{2f_c}}{1 - \rho_{cc}} \]
Where:
\( f_i' \): Pressure of confinement
\( \varepsilon_{\text{co}} \): Strain corresponding to peak of uniaxial compressive strength.
\( K_c \): Transverse reinforcement factor
\( \rho_t \): Transverse reinforcement ratio
\( f_yh \): Transverse reinforcement yield strength
\( s' \): Distance between transverse reinforcements along the element
\( d_z \): Diameter of hoop
\( \rho_{cc} \): Volumetric ratio of longitudinal reinforcement

![Stress-strain curve for concrete in compression (3)](image)

In order to achieve more accurate answer, combined hardening mode which is a mixed mode of kinematic and isotropic hardening, is mentioned for plastic behavior of steel as shown in Figure 5.

![Types of hardening types: a)Isotropic hardening, b)Kinematic hardening, c)Mixed mode (combined) hardening](image)

2.2. Verification of model
This model has been analyzed under cyclic load according to amplitude imposed in experiment and the results showed a good agreement between experimental results and numerical analysis. Figure 6 shows a comparison between results. Continuous lines show experimental results while dotted lines show FEM results.
2.3. Geometric modeling concepts

18 models have been built with the same geometry of beam and column dimensions and rebar percentage according to Kitayama (1). Some loading amplitudes were applied to loading history according to Figure 7 and models have been studied with parameters of column jacket thickness and column axial load ratio variation.

There were 5 various thicknesses of column jackets in addition to 3 different ratios of column axial loads. Also the simple models without steel plate jacketing were studied to be compared with plated models. Column axial load ratio is defined as follow:

\[ n = \frac{P}{f'_c A_g} \]  

Where: \( P \) is the axial load magnitude and \( A_g \) is gross section of column.

Thickness of plates used are: 3, 6, 10, 20, 30 \( mm \) and column axial load ratios are 0.1, 0.3, 0.5. Length of plates is according to minimum length and assumed as 50 cm (4). Naming of connections is according to their plate thickness and axial load ratio. For example C-0-6-P2 refers to a connection with a steel plate of thickness 6\( mm \) and second class load ratio\( (n = 0.3) \). Schematic view of steel plate jacketing of columns in connections is shown in Figure 8. The plates can be tied to column using epoxy, anchor bolts or both of them. Neglecting slip effects in plates and reinforcement bars, contact elements used to simulate them is tie and embedded region contact type respectively.
3. Results and discussions
Cyclic responses of upgraded connections are shown in Figure 9-Figure 11. As shown in these figures and tables Table 2-Table 4, steel column jacketing caused a significant increasing in loading capacity, stiffness and amount of dissipated energy of connections. Similarly increasing of axial load ratio, leads to a slight increment in load bearing capacity of same connections due to enclosing of micro cracks in concrete subjected to tensile loads. On the other hand, in higher load ratios, initial pressure itself, caused compressive damage and the model couldn’t reach higher levels of ductility then concrete is crushed in lower drifts. Also, it has observed that by increasing axial load ratio, ultimate load capacity of the connection is growing more rapidly than the other cases. It can be concluded that, steel plate column jacketing is more effective in the case of high axial load ratios than the other cases. To derive changes in models stiffness, tangential stiffness is measured and compared in each model and as expected, axial load ratio couldn't affect it; besides, upgraded models stiffness ratio is constant in all load ratios.

<table>
<thead>
<tr>
<th>NAME</th>
<th>K</th>
<th>K/K₀</th>
<th>F_y</th>
<th>F_y/F_y₀</th>
<th>F_u</th>
<th>F_u/F_u₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-0-0</td>
<td>2.197</td>
<td>1.000</td>
<td>10.002</td>
<td>1.000</td>
<td>13.910</td>
<td>1.000</td>
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<tr>
<td>C-0-3</td>
<td>2.367</td>
<td>1.078</td>
<td>10.796</td>
<td>1.079</td>
<td>15.417</td>
<td>1.108</td>
</tr>
<tr>
<td>C-0-6</td>
<td>2.450</td>
<td>1.115</td>
<td>11.056</td>
<td>1.105</td>
<td>16.325</td>
<td>1.174</td>
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<tr>
<td>C-0-10</td>
<td>2.555</td>
<td>1.162</td>
<td>11.451</td>
<td>1.145</td>
<td>17.455</td>
<td>1.255</td>
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<tr>
<td>C-0-20</td>
<td>2.627</td>
<td>1.196</td>
<td>11.931</td>
<td>1.193</td>
<td>19.046</td>
<td>1.369</td>
</tr>
<tr>
<td>C-0-30</td>
<td>2.717</td>
<td>1.237</td>
<td>12.293</td>
<td>1.229</td>
<td>20.087</td>
<td>1.444</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NAME</th>
<th>K</th>
<th>K/K₀</th>
<th>F_y</th>
<th>F_y/F_y₀</th>
<th>F_u</th>
<th>F_u/F_u₀</th>
</tr>
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<tbody>
<tr>
<td>C-0-0</td>
<td>2.206</td>
<td>1.000</td>
<td>9.510</td>
<td>1.000</td>
<td>14.212</td>
<td>1.000</td>
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<tr>
<td>C-0-3</td>
<td>2.372</td>
<td>1.075</td>
<td>9.896</td>
<td>1.041</td>
<td>14.342</td>
<td>1.009</td>
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<tr>
<td>C-0-6</td>
<td>2.460</td>
<td>1.115</td>
<td>10.540</td>
<td>1.108</td>
<td>14.969</td>
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<tr>
<td>C-0-10</td>
<td>2.544</td>
<td>1.153</td>
<td>11.045</td>
<td>1.161</td>
<td>16.283</td>
<td>1.146</td>
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<tr>
<td>C-0-20</td>
<td>2.659</td>
<td>1.205</td>
<td>11.641</td>
<td>1.224</td>
<td>19.381</td>
<td>1.364</td>
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<tr>
<td>C-0-30</td>
<td>2.711</td>
<td>1.229</td>
<td>11.968</td>
<td>1.258</td>
<td>20.311</td>
<td>1.429</td>
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</table>
Table 4-Results of load level 0.5

<table>
<thead>
<tr>
<th>NAME</th>
<th>$K$</th>
<th>$K/K_0$</th>
<th>$F_y$</th>
<th>$F_{y}/F_{y0}$</th>
<th>$F_u$</th>
<th>$F_{u}/F_{u0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-0-0</td>
<td>2.167</td>
<td>1.000</td>
<td>4.547</td>
<td>1.000</td>
<td>4.895</td>
<td>1.000</td>
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<tr>
<td>C-0-3</td>
<td>2.348</td>
<td>1.083</td>
<td>5.110</td>
<td>1.124</td>
<td>5.110</td>
<td>1.044</td>
</tr>
<tr>
<td>C-0-6</td>
<td>2.442</td>
<td>1.127</td>
<td>7.087</td>
<td>1.559</td>
<td>7.087</td>
<td>1.448</td>
</tr>
<tr>
<td>C-0-10</td>
<td>2.540</td>
<td>1.172</td>
<td>9.552</td>
<td>2.101</td>
<td>9.552</td>
<td>1.951</td>
</tr>
<tr>
<td>C-0-20</td>
<td>2.639</td>
<td>1.218</td>
<td>10.835</td>
<td>2.383</td>
<td>14.125</td>
<td>2.886</td>
</tr>
<tr>
<td>C-0-30</td>
<td>2.709</td>
<td>1.250</td>
<td>11.453</td>
<td>2.519</td>
<td>16.853</td>
<td>3.443</td>
</tr>
</tbody>
</table>

Figure 9-Hysteresis cycles for connections with axial load ratio of 0.1

Figure 10-Hysteresis cycles for connections with axial load ratio of 0.3
4. Conclusion
In this paper, Effect steel plate jacketing of column in reinforced concrete beam-column connections has been investigated. 18 models have been built and analyzed using Finite Element package ABAQUS with different steel plate thicknesses and axial load ratios under cyclic loads. The hysteresis diagrams and result tables are obtained and the following conclusions were achieved:

- Using steel plates in columns causes increasing of column stiffness up to 25% of its initial value and is independent from axial load ratio of the column.
- Although axial load decreases load bearing capacity of connections, but upgrading them by steel plates increase load capacity and ductility of them significantly cause them act better than the column with lower axial load levels.
- Columns upgraded with steel plates in connections, yield at a higher level of lateral load up to 25% in low level axial loads and 125% in higher level axial loads.
- According to analyses results, using steel plates increase ultimate load of columns up to 44% in lower levels of axial load and 245% in the higher load ratios.

5. References