Title: FEM Analysis on Structural Behavior of CFT Column to Flat Plate Slab Connection

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FEM Analysis on Structural Behavior of CFT Column to Flat Plate Slab Connection

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Abstract

Since 1990s, the construction of tall buildings has been greatly increased. For the tall buildings, the story height is an important factor to accomplish economic buildings. Many researchers including the authors have studied the structural systems reducing a story height of the buildings. A structural system consisting of concrete filled tube column and flat plate slab is one of the story reducing structural systems, in which each element has been used as an efficient component for tall buildings. However, the structural behavior of the joint has to be clearly explored. Therefore, the finite element analysis method is used to verify the stress concentration, load flow, and excessive deformation on the joints. Three types of joint details are proposed and compared, finally the better one is obtained. The design equation for the adopted joint detail is also proposed by the FEM analysis.

Keywords: concrete-filled tube column, flat plate slab, high-rise buildings, FEM analysis, regressive analysis

1. Introduction

The shear wall system, which makes effective use of facilities like elevators or stairways, is the structural system most commonly used for apartments and residential high-rise buildings in Korea. However, the shear wall system places many restrictions on residential facilities; such structures cannot satisfy the resident's desire for flexible space.

The moment-resisting frame (MRF) system, which has been widely used in office buildings, has been suggested as an alternative structural system. The MRF system which consists of column and beam, has more flexibility than the shear wall system, satisfying the resident's desire for more flexible space and easier remodeling.1

However, the current MRF system has some problems including a higher cost of construction. The story height, one of the important factors in residential high-rise buildings, also tends to be higher, further diminishing the usefulness of the MRF system.

Therefore, there is a need for a new system that offers better construction productivity, cost efficiency, and adequate story height for high-rise buildings. In this paper, a new MRF system that consists of a concrete filled tube (abbreviated as CFT) column and a flat plate slab, was proposed. For each of the CFT columns and flat plate slabs, the performance and availability has been previously tested and recognized as a superior structural system.

Fig. 1. Existing MRF System1

To combine two individual elements in the MRF system efficiently, more research should be done for the CFT column to flat plate slab connection and the structural behavior of the connection should be verified thoroughly.

Therefore, three details that are applicable to the CFT column with flat plate slab connection are proposed. When examining the economy and constructability of these three details, one final detail was obtained. Then, the design equation was proposed based on the finite element analysis.

2. CFT Column-Flat Plate Slab Connection

2-1. Example Building

Figs.2 and 3 show an example building using CFT column to flat plate slab connection. It is a four-story building and the span is 7 m in each direction.

The CFT column was designed according to the Recommendations for Design and Construction of Concrete Filled Steel Tubular Structure2. The slab was designed according to the Design of Concrete

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Structure\textsuperscript{3,4} while shear reinforcement or studrail\textsuperscript{5} was designed according to ACI 318-95\textsuperscript{6} and using an installation program. The strengths of materials are as follows:

- Yield strength of CFT column: SM490 (f\textsubscript{y} = 3.3tf/cm\textsuperscript{2})
- Compressive strength of concrete: f\textsubscript{ck} = 300kgf/cm\textsuperscript{2}
- Yield strength of reinforcing bar: SD 40 (f\textsubscript{y} = 4.0tf/cm\textsuperscript{2})

As listed in Table 1, dead and live loads were considered.

![Fig. 2. Elevation of example building](image)

![Fig. 3. Floor plan of example building](image)

<table>
<thead>
<tr>
<th>Slab</th>
<th>Load Type</th>
<th>Load (kgf/cm\textsuperscript{2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof Slab</td>
<td>DL</td>
<td>760</td>
</tr>
<tr>
<td></td>
<td>LL</td>
<td>200</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>1,404 (1.4D+1.7L)</td>
</tr>
<tr>
<td>Floor Slab</td>
<td>DL</td>
<td>550</td>
</tr>
<tr>
<td></td>
<td>LL</td>
<td>350</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>1,365 (1.4D+1.7L)</td>
</tr>
</tbody>
</table>

The size of the column is Ƒ-300×300×12 and the equivalent frame method\textsuperscript{3,4} was used for the design of the slab.

As shown in Fig.3, two reinforcing bars are arranged around the column C\textsubscript{4}. From the design result of the interior plate, the moment applied to column C\textsubscript{4} is 29.90tf/m, and the connection design is obtained using the column C\textsubscript{4}.

After calculating the tensile force of the reinforcing bar, the connection design is achieved. The tensile and compressive forces applied in slab can be calculated by dividing the moments by distance jd between tensile force and compressive force.

The total tensile force goes T=2,990/12.75=234.5tf.

This force is shared by reinforcing bars in equivalent frame. Thus the tensile force of each reinforcing rod is T=234.5/10=7.82tf. Even though the tensile force of a reinforcing bar is 7.82tf, 10tf is used in practice for safety.

2-2. Proposed Connection Details

2-2-1. Reinforcing Bar Anchored Connection

As shown in Fig.4, the rebar of the slab are anchored to an exterior diaphragm plate welded to the CFT column. The plate has a female threaded hole and the corresponding rebar has a male threading at the end. CFT column with exterior plate are fabricated in the factory. In the field, the threaded rebar is anchored to the female threaded holes of the exterior plate. The connection of the threaded rebar with conventional rebar is achieved using a coupler. Then the concrete slab is cast.

![Fig. 4. Plan and Sectional Plan of Connection](image)

![Fig. 5. Design concept of plate according to AISC-LRFD](image)

![Fig. 6. Reinforcing Bar Anchored Connection](image)

As shown in Fig. 5, the plate can be designed as a beam subject to two point concentric loads by the tensile force of reinforcing bars according to LRFD method\textsuperscript{7,8}. Full penetration welding is used between the steel tube column and exterior plate. As illustrated in Fig.6, the minimum length for full penetration welding and the corresponding minimum edge distance are 30mm, 70mm, respectively.

As most details are manufactured in the factory...
beforehand, construction time is simple and quick. In addition, shear resistance for two-way shear can be expected at the plate.

If the plates are thick, however, the amount of material increases. If the size of the bars is changed, production cost may rise.

2-2-2. Through Reinforcing Bar Connection

As shown in Fig. 7, reinforcing bars pass through the steel tube and are connected with flexural reinforcing bar with couplers.

![Fig. 7. Floor and Sectional Plan of Connection](image)

Because through reinforcing bars can be moved from side to side if they are subjected to tensile and compressive force by turns, wing plates should be installed to keep the reinforcing bars in place. These wing plates are not for load transfer like plates in the reinforcing bar anchored connection, but instead, they ensure that the reinforcing bars do not move, which in turn prevents the need for thick wing plates. Similar connection detail is used by the author between SRC column and RC beam[9]. Fillet weld that is mainly used in the field is used to connect the reinforcing bars to the wing plates.

Full penetration welding is used between the column and wing plates. The final detail with regard to the tensile force is shown in Fig. 8.

![Fig. 8. Through Reinforcing Bar Connection](image)

As most details are manufactured in the factory beforehand, construction is easier and faster. However, the two-way arrangement is difficult, and the effective length of slab can be different in each direction by doubling the reinforcing bars.

2-2-3. Channel Reinforcing Connection

This connection provides space for the reinforcing bars to settle into the manufacturing angle made on the plate. The plate angles are welded to the column tube and channels placed on the angles are connected to the plate angles by bolts. As shown in Fig. 9, reinforcing bars are put on plate angles and channels, and connected by welding. The welding size for through a reinforcing bar connection can be used again here.

![Fig. 9. Floor and Sectional Plan of Connection](image)

Shear resistance for two-way shear can be expected at plate angles and channels, but additional work is needed by welding the reinforcing bar and formwork is difficult because of the plate angle and channel.

2-3. Comparison of Connection Detail and Final Connection Detail Connection

So far, three connection details for the CFT column to flat plate slab were considered.

Each detail has advantages and disadvantages of its own, after comparing and analyzing the advantages and disadvantages of each detail, the final connection detail is proposed: using a reinforcing bar anchored connection for one direction, and a through reinforcing bar connection for the other (Fig. 10).

![Fig. 10. Final Connection Detail](image)

2-4. Design Concept for the Bars Anchored Portion

As shown in Fig. 10, for the through reinforcing bar connection, the stress flow is clear because the stress of the flexural bar is transferred to the opposite flexural bar or to a column. In addition, one-way through bars have already been used for tall buildings in the U.S. successfully though for their difficult manufacturing and the construction productivity.

For the reinforcing bar anchored connection, construction is easy but, the stress flow has not been explored fully. As shown in Fig. 5, designing the plates as a simple beam subjected to two concentrated loads by using the existing equation poses many problems for many variables (i.e. out-of-plane deformation,
stress concentration, and stress flow).

Therefore, finite element analyses were carried out under the assumption that the limit state of the column tube is reached by the out-of-plane deformation (5mm). The design equation of the connection is proposed through multiple linear regression analysis.

3. FEM Analysis for Connection

3-1. Connection Modeling

In considering geometrical symmetry, the connection analysis was performed using a one-eighth model with infinite stiffness on compression by filling concrete inside the column tube assuming the connection was subjected to a simple tension test. The verification of the program was also achieved by using existing experimental data for simple tension tests with the exterior diaphragm. Connection analysis was conducted by using the commercial finite element method program, ANSYS.

Concentrated loads were applied to nodes where the reinforcing bars are connected (Fig.11). To investigate the behaviour of the connection after yielding, material and geometrical non-linear properties were also considered.

As illustrated in Fig.12, the steel tube and plate were modeled by using a Shell43 element. The element has 4 joints, and each joint has 6 degrees of freedom. The stress-strain relationship of the steel was calculated using the bilinear kinematical hardening model with Von Mises' yield criteria and Bauschinger's effect to reflect the effect of strain hardening. As illustrated in Fig. 13, the plastic modulus is assumed at 1/100 of the initial elastic modulus. Concrete preventing the steel tube from local buckling was modeled by using Solid65 with 8 joints, with each joint having 3 degrees of freedom shown in Fig.14. Between the concrete and steel tube, Target 170 of 3-D Target Segment andConta 174 of 8-Node Surface-to-Surface Contact elements were used.

As shown in Fig.15, the steel tube could be detached from concrete when tensile force is applied. Vertical frictional force between concrete and steel tube was ignored. Finite element analysis was carried out under the assumption that the failure between the column and plate and the plate and reinforcing bar does not control the connection strength.

3-2. Determination of Variables

Since there have been no experimental results, hence the application in the construction field, the design equation of exterior diaphragm connections proposed in the codes and standards are referenced to determine connection strength.

The design equations prescribed in Korea and Japan Codes are expressed by using connection variables reflecting the stress concentration by refraction of the diaphragms. Also, for beam-column experiments, the relationship between moment and rotation is sometimes expressed using regression analysis of connection variables.

The yield strength of connection is proposed where variables that may influence the yield strength of connection are assumed to be: steel tube width ($b_c$), steel tube thickness ($t_c$), plate length ($l_p$), plate thickness ($t_p$), edge distance ($l_s$), and yield strength ratio between the steel tube and plate ($\sigma_{fy}/\sigma_{py}$) as shown in Fig.16.

\[ P_{\text{cal}} = a_0 + a_1 b_c + a_2 t_c + a_3 l_p + a_4 t_p + a_5 l_s + (\sigma_{fy}/\sigma_{py})^{a_6} \]  

As mentioned above, the calculated yield strength can be found in the Japanese Code for Concrete Filled Tube published by the Architectural Institute of...
Japan in 1997. The coefficients used can be derived from multiple linear regression analysis using yield strength computed from finite element analysis.

As shown in Fig. 17, the steel tube width is computed using a value related to the radius of the column tube, applying Ben Kato’s theory.

\[ \text{Steel Tube Width} = (4 - 1.5 \times 2) \times \text{Column Tube Radius} \]

Fig. 17. Width Regarding the Radius of the Column Corner

### 3-3. Analysis of FEM Results

When loads are applied to nodes where the reinforcing bars are connected, significant out-of-plane deformation of column flange occurs and stress concentration occurs at the corner. Modeling is labeled as follows:

<table>
<thead>
<tr>
<th>Edge Distance</th>
<th>Plate Thickness</th>
<th>Plate Length</th>
<th>Yield Strength of Plate</th>
<th>Column Thickness</th>
<th>Column Width</th>
<th>Yield Strength of Column</th>
</tr>
</thead>
<tbody>
<tr>
<td>X Type-1/3bc</td>
<td>M Type-1/6bc</td>
<td>E Type-On the Web Line</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Yield Strength of Column: 3.3tf/cm², 3.6tf/cm²  
Column Width: W-40cm, M-35cm, N-30cm  
Column Thickness: 1.2cm, 1.6cm  
Yield Strength of Plate: 4.2tf/cm², 4.5tf/cm²  
Plate Length: L-9cm, M-8cm, S-7cm  
Plate Thickness: 3cm, 2.7cm  
Edge Distance: X Type-1/3bc, M Type-1/6bc,  
E Type-On the Web Line

#### 3-3-1. The Effect on Steel Tube Width (b_c)

The effect on steel tube width \( (b_c) \) is shown in Fig. 18. The yield strength is proportional to steel tube width. But as the length of plate increases, its influence on yield strength decreases.

#### 3-3-2. The Effect on Steel Tube Thickness (t_c)

The effect on steel tube thickness \( (t_c) \) is illustrated in Fig. 20. A column flange yield line is formed (Fig. 19) by an out-of-plane deformation of the steel tube. The yield strength increases as the thickness of the steel tube increases since the fully plastic moment \( (M_p) \), a unit length on the yield line, is proportional to the squares of column thickness.

\[ M_p = \frac{1}{2} \times \frac{3}{4} \times \frac{3}{4} \times \sigma_y \times (t^2 \sigma_y) \]

Fig. 19. \( M_p \) at Unit Yield Line
3-3-3. The Effect on Plate Length ($l_p$)

Fig. 21 shows the effect on the plate length ($l_p$). As the plate gets longer, the yield strength increases by increasing the plate's shear strength. As the steel tube width narrows, the yield strength increases. For the analytical model 3.3W12-4.2L30 especially, stress concentration at the column corner can cause rapid change in the load-displacement curve.

3-3-4. The Effect on Plate Thickness ($t_p$)

Fig. 22 depicts the effect on plate thickness ($t_p$). As plate thickens, the yield strength increases due to the increasing shear strength of the plate.
3-3-5. The Effect on Edge Distance ($l_s$)

The effect on edge distance ($l_s$) is shown in Fig. 23. As the edge distance gets shorter, the yield strength increases. This is because the tensile force applied to the plate is resisted by the shear deformation of the plate and the steel tube's out-of-plane deformation for a $1/3b_c$ (X-Type) and $1/6b_c$ (M-Type). However, the tensile force is transferred to the column web directly for the E-Type which causes high yield strength for this connection type (Fig. 24).

![Fig. 23. (b) Influence on the Edge Distance](image)

![Fig. 24. Connection Type as to Edge distance](image)

3-3-6. The Effect on Yield Strength Ratio ($f_y/f_c$)

Fig. 25 shows the effect on the yield strength ratio of the column to plate ($f_y/f_c$). Generally, as the yield strength ratio gets higher, the yield strength increases. The yield strength of the column has a bigger influence on the connection yield strength than does that of the plate.

![Fig. 25. (a) Influence on the Yielding Strength Ratio](image)

![Fig. 25. (b) Influence on the Yielding Strength Ratio](image)

3-4. Preliminary for Connection Strength

The energy method was used to calculate the yield strength in the same way with as the reference thesis. To calculate yield strength, the limit displacement should be found. However, so far there is no rule for out-of-plane deformation. Thus, limit displacement is assumed to be at 5mm based on existing data of the CFT column reinforced with the exterior diaphragm and the thesis achieving finite element analysis using the same detail.

3-5. Determination of Connection Strength

After calculating the yield strength using the energy method, variables in proposed equations were formulated through multiple linear regression analysis. The multiple linear regression analysis is a useful method for predicting an equation that reflects data with more than two variables. Calculated values of the yield strength through regression analysis is as follows:

$$P_{cal} = 3.45 \times b_c^{0.065} \times t_c^{0.944} \times l_p^{0.563} \times t_p^{0.374} \times l_s^{-0.232} \times (f_y/f_c)^{0.108}$$

(2)

![Fig. 26. Comparison of $P_{actual}$ and $P_{cal}$](image)

From the above equation, it can be found that the width and thickness of the column, the length and thickness of plate, and the yield strength ratio are proportional to yield strength, while the edge distance is inversely proportional. Table 2 and Fig. 26 compare yield strength derived from the finite element analysis with that calculated using
regression analyses. The yield strength of 1/6\(b_b\) (M-type) tends to be consistent with the other models, however there are some errors for the E-Type. As shown in Fig.26, the strength ratio (\(P_{anal}/P_{cal}\)) is within 0.969 ~ 0.999 and most values are within the range of ±10%.

### Table 2. Results Comparison Between \(P_{anal}\) and \(P_{cal}\)

<table>
<thead>
<tr>
<th>Model</th>
<th>(P_{anal})</th>
<th>(P_{cal})</th>
<th>(P_{anal}/P_{cal})</th>
<th>Model</th>
<th>(P_{anal})</th>
<th>(P_{cal})</th>
<th>(P_{anal}/P_{cal})</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3W16-4.2L30</td>
<td>19.5</td>
<td>19.2</td>
<td>1.01</td>
<td>3.3N16-4.2L30</td>
<td>19.7</td>
<td>20.1</td>
<td>0.98</td>
</tr>
<tr>
<td>3.3W16-4.2L27</td>
<td>19.0</td>
<td>18.5</td>
<td>1.03</td>
<td>3.3N16-4.2L27</td>
<td>18.9</td>
<td>19.3</td>
<td>0.98</td>
</tr>
<tr>
<td>3.3W16-4.2M30</td>
<td>17.1</td>
<td>18.0</td>
<td>0.95</td>
<td>3.3N16-4.2M30</td>
<td>18.9</td>
<td>18.8</td>
<td>1.01</td>
</tr>
<tr>
<td>3.3W16-4.2M27</td>
<td>16.7</td>
<td>17.3</td>
<td>0.97</td>
<td>3.3N16-4.2M27</td>
<td>16.2</td>
<td>18.1</td>
<td>1.01</td>
</tr>
<tr>
<td>3.3W16-4.2S30</td>
<td>14.8</td>
<td>16.7</td>
<td>0.89</td>
<td>3.3N16-4.2S30</td>
<td>17.3</td>
<td>17.4</td>
<td>0.99</td>
</tr>
<tr>
<td>3.3W16-4.2S27</td>
<td>13.8</td>
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<td>1.00</td>
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<tr>
<td>3.3W16-4.2S30</td>
<td>20.0</td>
<td>19.1</td>
<td>1.05</td>
<td>3.3N12-4.2S30</td>
<td>13.9</td>
<td>15.3</td>
<td>0.91</td>
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<td>3.3W16-4.2L30</td>
<td>18.0</td>
<td>18.3</td>
<td>1.04</td>
<td>3.3N12-4.2L30</td>
<td>13.9</td>
<td>14.8</td>
<td>0.94</td>
</tr>
<tr>
<td>3.3W16-4.2L27</td>
<td>17.2</td>
<td>17.5</td>
<td>1.02</td>
<td>3.3N12-4.2L27</td>
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<td>17.7</td>
<td>1.01</td>
</tr>
<tr>
<td>3.3W16-4.2S27</td>
<td>16.7</td>
<td>17.3</td>
<td>0.97</td>
<td>3.3N16-4.2S27</td>
<td>16.2</td>
<td>18.1</td>
<td>1.01</td>
</tr>
<tr>
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<td>19.8</td>
<td>1.00</td>
<td>3.3N12-4.2S30</td>
<td>18.0</td>
<td>18.1</td>
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<tr>
<td>3.3W16-4.2L27</td>
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<tr>
<td>3.3W16-4.2S27</td>
<td>16.7</td>
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<td>17.3</td>
<td>17.7</td>
<td>1.01</td>
</tr>
</tbody>
</table>

2. Finite element analyses were carried out to verify the stress transfer of the reinforcing bar anchored portion. The results show that design strength is proportional to the width and thickness of the column tube, to the length and thickness of the plate, and to the yield strength. However, it is inversely proportional to the edge distance since the tensile force is directly transferred to the column web.

3. Using the results from the finite element analyses, design strength is proposed through the multiple linear regression analysis as follows:

\[
P_{cal} = 3.45 \times b_b - 0.065 \times f_y + 0.944 \times f_y \times 0.563 \times f_y + 0.374 \times f_y - 0.232 \times f_y
\]

To verify more detail for CFT column to flat plate slab connection, further experimentation is needed.

### References

5. http://www.decon.on.ca