Connection of Reinforced Concrete Flat Slab and Concrete Filled Steel Tube Column: Proposed Structures, Experiment, Simulation and an Analytical Prediction Model for Shear Strength

Dao Ngoc the Luc, Truong Quang Hai, Truong Hoai Chinh, Dao Ngoc The Vinh

Abstract: Concrete filled steel tube column (CFST) combined with reinforced concrete (RC) flat slab provides potential structural solution to replace the traditional structures in high-rise buildings. The CFST column – RC slab connection is the key factor for this structure type to work effectively. This paper proposes an improved structure for connection of concrete filled steel tube column and reinforced concrete flat slabs using steel plate shear-head. The experiments of two large-sized specimens are performed to assess the capacity and reliability of the proposed connection. Numerical simulation using Abaqus is also performed to validate the test results. Based on experimental and numerical simulation results, an analytical prediction model to estimate the punching shear capacity of the flat slab is presented.

Keywords: Concrete filled steel tube, Reinforced concrete, Column, Flat slab, Connection.

I. INTRODUCTION

In the high-rise buildings, the use of beam in slab increases story height that affects the layout of the structure and efficient use of the building, especially for large span buildings. The reinforced concrete flat slab structure has many advantages such as reduction in story height, easy and fast construction, flexibility for arranging space and technical equipment systems.

Currently, the concrete fill steel tube column with great technical advantages such as high strength, high stiffness, energy dispersion and rapid construction is considered as a suitable replacement for the traditional reinforced concrete column in high-rise building construction.

Thus, the combination of CFST column and RC flat slab creates an effective structural system for tall buildings. CFST column – RC slab connection is the most important to ensure proper behaviour of this structure type. Some authors have investigated this connection such as Satoh H. and Shimazaki K. (2004) [1], Eder M. A. et al (2010) [2], Kim J. W. et al (2014) [3], Bompa D. V. and Elghazouli A. Y. (2016) [4].


The connections between the CFST column and RC flat slab proposed by current researches still have limitations in terms of construction and reliability. This paper proposes improved connection structures for concrete filled steel tube column with reinforced concrete flat slabs using steel plates as shear head. Experiments of two large-sized specimens are then performed to assess the behaviour and reliability of the proposed connection. Numerical simulation with Abaqus is also carried out to provide the better view on the connection behaviour. Based on experimental and numerical simulation results, the critical section perimeter is determined and used to establish an analytical model for predicting punching shear capacity of the flat slab at the connection.

II. PROPOSED CONNECTION OF CONCRETE FILLED STEEL TUBE COLUMN TO REINFORCED CONCRETE FLAT SLAB

As the connection between the CFST column and RC flat slab is interrupted at the steel tube surface, it is therefore important to design connection structure to ensure the integrity at the connection as well as proper behaviour of the structural system. Proposed connection structure consists of:

+ Steel plate shear head: As the quality of joint of steel plates welded to column surface is difficult to control during manufacturing and this joint is easy to break down, the steel plates are inserted inside the column through the hole on column surface and are welded to the outer surface of the column. This improvement increases the safety of the connection and punching shear for flat slab. In addition, the portion of steel plate inside column core plays a role to prevent the slip of concrete core. It should be use the least two steel plates for each column surface.

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+ Stirrups around steel plate: Due to the relatively small thickness of the steel plate, concentrated stresses occur in the surrounding concrete. Thus, stirrups around steel plate are used to distribute the load. This increases the contact area and transmits the load from the concrete to the steel plate and increases the punching shear capacity.  

+ Reinforced bars anchored to column: At the connection, the top layer reinforcement must be anchored to the column. The previous anchor forms of current researches are relatively complex. This study proposes a simple anchor form for easy fabrication: the steel bars are bent at one end and inserted into the column through the holes.

Fig. 1. Proposed CFST column - RC flat slab connection

(1) CFST column; (2) Top layer reinforcement anchored to column; (3) Steel plate; (4) Shear reinforcement; (5) Holes; (6) Bottom layer reinforcement anchored to column or Post punching bar

III. EXPERIMENTAL PROGRAM

To validate the strength of the proposed connection, the experiment program is performed on large-sized specimens. Specimen size is based on load capacity analysis of 6m × 6m flat slab system with slab thickness \( h_s = 180\text{mm} \).

Fig. 2. Design details of specimen S1, S2

The design details of two specimens are the same, except: Specimen 1 (S1) does not have post-punching bars, Specimen 2 (S2) has post-punching bars in the compression zone. The specimen size is given in the following Table I and material properties in Table II.

Experimental devices are used to investigate the behaviours of anchored reinforced rebars, steel plates as well as the behaviour of the slab. Strain gauge 1, Strain gauge 2 measure the deformation of the longitudinal reinforcements anchored to column. Strain gauges 3 measures steel plate deformation at the position steel plate welded to column. A load cell is located at the top of the hydraulic jack, and two linear displacement sensors (LVDTs) are located at the base of the column to measure the slab displacement as shown in Fig. 4.

IV. EXPERIMENTAL RESULTS

Loads are increased with each load level \( P_l = 20kN \) until damage occurs. Both specimens show the first crack at \( P = 140kN \). These cracks are very small perpendicular to the surface of the column and spread from the column corner to the slab edge. These cracks called radial cracks are caused by bending moments.

Increasing load with \( P_l \) level, the cracks continue to grow on the slab surface and develop evenly around the column surface with many cracks extending and spreading out to the...
supporting beam. The concrete floor at the adjacent side of the column has no separation from the column. In the load range from \( P = 300 \text{kN} \) to \( P = 420 \text{kN} \), the cracks develop more and the tangent cracks connect to one another with larger crack widths.

### Table-I: Specimen details

<table>
<thead>
<tr>
<th></th>
<th>Slab thickness (mm)</th>
<th>Column dimension (mm)</th>
<th>Steel plate size (mm)</th>
<th>Top layer Reinforcement</th>
<th>Bottom layer Reinforcement</th>
<th>Stirrup</th>
<th>Post-punching bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen S1</td>
<td>180</td>
<td>300\times300\times9</td>
<td>400\times100\times15</td>
<td>( \phi 12 \times 100 )</td>
<td>( \phi 10 \times 200 )</td>
<td>( \phi 10 \times 50 )</td>
<td>--</td>
</tr>
<tr>
<td>Specimen S2</td>
<td>180</td>
<td>300\times300\times9</td>
<td>400\times100\times15</td>
<td>( \phi 12 \times 100 )</td>
<td>( \phi 10 \times 200 )</td>
<td>( \phi 10 \times 50 )</td>
<td>2( \phi 22 )</td>
</tr>
</tbody>
</table>

### Table-II: Material properties

<table>
<thead>
<tr>
<th></th>
<th>( f_c ) (Mpa)</th>
<th>( f_y, \text{stirrup} ) (MPa)</th>
<th>( f_y, \text{reinforcement} ) (Mpa)</th>
<th>( f_y, \text{steel plate} ) (Mpa)</th>
<th>( f_y, \text{steel tube} ) (Mpa)</th>
<th>( f_y, \text{post-punching bar} ) (Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen S1</td>
<td>17</td>
<td>350</td>
<td>350</td>
<td>220</td>
<td>220</td>
<td>350</td>
</tr>
<tr>
<td>Specimen S2</td>
<td>17</td>
<td>350</td>
<td>350</td>
<td>220</td>
<td>220</td>
<td>350</td>
</tr>
</tbody>
</table>

**Fig. 3.** Reinforcement layout of the testing specimens

**Fig. 4.** The experiment set up

At \( P = 484.6 \text{kN} \) for the S1 and \( P = 499.6 \text{kN} \) for the S2, the concrete surface breaks off and the flat slab is divided into two parts, at the same time the slab is pushed up like a mushroom, the displacement of the column increases very fast, while the load decreases rapidly, proving that the connection to the flat slab is no longer loaded. The flat slab is completely damaged as shown in Fig. 5.

Thus, the behaviours of the two specimens during testing are the same. The bottom of the slab in the compression area has no failure. The post-punching reinforcements are used in the specimen S2 for the purpose of examining the possibility of increasing punching shear capacity and the results show no difference between the two cases with and without the post-punching bar.

The data obtained from the strain gauges attached to anchored reinforcements show that there is not significant difference in the reinforcement deformation in the columns of S1 and S2. The stress in the reinforcement increases with the load, indicating that the reinforced anchor solution is guaranteed.
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V. SIMULATION OF CFST COLUMN WITH RC FLAT SLAB CONNECTION USING ABAQUS SOFTWARE

In this section, the Abaqus program [9] is used to simulate the connection. Abaqus software has a very rich library of elements, so choosing the right component for each element is essential. The C3D8R is selected to simulate steel tube, concrete cores, steel plates and loading plates. The T3D2 bar element is used to simulate longitudinal reinforcement and shear reinforcement. In Abaqus, each component is built into its local coordinate system (Part), independent of the model.

Table-III: Concrete plastic damage parameters

<table>
<thead>
<tr>
<th>$K_c$</th>
<th>$\varepsilon$</th>
<th>$\sigma_{th}/\sigma_{cr}$</th>
<th>$\psi$</th>
<th>$\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6667</td>
<td>0.1</td>
<td>1.16</td>
<td>13</td>
<td>0</td>
</tr>
</tbody>
</table>

Table-IV: Interactive types used in simulation

<table>
<thead>
<tr>
<th>Elements</th>
<th>Interactive types</th>
<th>Interactive element</th>
</tr>
</thead>
<tbody>
<tr>
<td>RC flat slab</td>
<td>C3D8R</td>
<td>Surface to surface</td>
</tr>
<tr>
<td>Steel tube column</td>
<td>C3D8R</td>
<td>Concrete core</td>
</tr>
<tr>
<td>Steel plate</td>
<td>C3D8R</td>
<td>Tie</td>
</tr>
<tr>
<td>Longitudinal bar</td>
<td>T3D2</td>
<td>Embedded element</td>
</tr>
<tr>
<td>Stirrup bar</td>
<td>T3D2</td>
<td>RC flat slab</td>
</tr>
</tbody>
</table>
An elastic-plastic model is used to describe the steel behavior. Elastic modulus of steel is $E_s=2.1\times10^5\text{Mpa}$, Poisson ratio by 0.3. Longitudinal bar and reinforcement stirrup have yield stress $f_y=350\text{Mpa}$. Steel pipe and shear plate steel have yield stress $f_{ys}=220\text{Mpa}$.

Behaviour of concrete is described by the relationship between stress and strain on the tension and compression region. These curves are based on the theory of Alfarah B. et al (2017) [10]. In the elastic behavior, the concrete is characterized by elastic modulus and Poisson ratio, compressive strength concrete. After elastic zone, Concrete Damaged Plasticity Model (CDP) [10][11] is used to simulate the working state of the material in both the tension and the compression zone. In the Abaqus software, plastic damage state is described by parameters given in the Table III.

After meshing, load and boundary conditions are assigned to the model. In this model, the boundary conditions include joints around the perimeter of the slab. The load is applied according to the method of increasing the displacement at column.

Fig. 8 shows the load - displacement curves from experimental results and Abaqus simulation. The results show that the simulation results are quite consistent with the results of experiments.

![Fig. 8. The load-displacement curves of test and ABAQUUS simulation](image)

![Fig. 9. Distribution of stresses in slab reinforced bars and steel plate](image)

![Fig. 10. Comparison of top surface behavior between simulation and experiment at different load levels](image)
VI. PROPOSED ANALYTICAL PREDICTION MODEL FOR SHEAR STRENGTH

Punching shear failures in conventional RC flat slabs are instantaneous and characterized by dislocation of a conical surface from the flat slab. Before failure, the forces are transferred from the column to the slab through a tri-dimensional strut that develops at variable inclination angles from the root of the column to the tension reinforcement, as a function of the slab thickness, flexural characteristics and material strengths [4]. However, in the case of shear-head using two steel plates as in Fig. 4, as no support for the strut to develop, the compression struts thus tend to directly transfer the compression force to the column through the folding compression struts. For the flat slab with shear-head, the presence of stirrup with distance about φ10a50 is considered as the fulcrum for development strut. This shear crack extends from the tip of the shear head to tensile reinforcement. Whereas, the flat slab without shear-head, the crack propagation is similar to that of the reinforced concrete flat with location d/2 from the column face.

Fig. 11. Shape of failure surface of flat slab

Fig. 12. Cross-sections A-A and B-B from simulation results

Fig. 13. Proposed critical perimeter for punching strength prediction using steel plate

The punching shear capacity of the flat slab is a function of the slab thickness, the longitudinal bar ratio and the characteristic of the material. Experimental cracks only cut through concrete. The MC 2010 [12] standard calculates the punching shear capacity based on the material characteristics of the working mechanism on the inclined cracks that is suitable for predicting the punching shear capacity of the flat
slab. However, the perimeter of the critical section is not clearly defined so it is difficult to design. Therefore, the punching shear capacity of the flat slab at the CFST column-RC flat slab connection using steel plates without transferred reinforcement and non-prestressed reinforced utilize the formula of MC 2010 with the proposed perimeter of the critical section as in equation (1):

\[ V_c = k_v \sqrt{a}b_0d_0 \]  
(2)

\[ k_v = 1/(1.5 + 0.9\psi d_k) \]  
(3)

\[ k_{dy} = 32/(6 + d_y) > 0.75 \]  
(4)

\[ \psi = 1.5 - \frac{f_{sl}}{f_{d}} \]  
(5)

\[ b_0 = 4(b_0 + 3d_y) \]  
(6)

Where: \( d_y \) - maximum aggregate size; \( d_y \) - effective shear depth; \( d \) - effective bending depth; \( r_i \) - denotes the position where the radial bending moment is zero; \( f_{sl} \) - longitudinal steel strength, \( E_i \) - longitudinal elastic modulus

Table-V: Punching shear strength prediction for connection using steel plates

<table>
<thead>
<tr>
<th>( b_0 ) (mm)</th>
<th>( f_{sl} ) (MPa)</th>
<th>( d_y ) (mm)</th>
<th>( f_c ) (MPa)</th>
<th>( \psi ) (rad)</th>
<th>( K_{dy} )</th>
<th>( k_v )</th>
<th>( d_0 ) (mm)</th>
<th>( b_0 ) (mm)</th>
<th>( V_c ) (kN)</th>
<th>( V_{S1} ) /( V_c )</th>
<th>( V_{S2} ) /( V_c )</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>350</td>
<td>30</td>
<td>17</td>
<td>0.0233</td>
<td>0.6957</td>
<td>0.2709</td>
<td>150</td>
<td>300</td>
<td>502.6</td>
<td>0.96</td>
<td>0.99</td>
</tr>
</tbody>
</table>

Table V shows the comparison between punching shears using proposed model for Specimen 1 (\( V_{S1} \)) and Specimen 2 (\( V_{S2} \)) with test results. The results show the rationality of the proposed critical perimeter and possibility of using formula (1) along with the MC2010 to predict the punching shear strength the reinforced concrete flat slab connected to CFST column using shear steel plates.

VII. CONCLUSIONS

This paper proposes an improved structure for concrete filled steel tube column with reinforced concrete flat slab connection. Connection details are relatively simple and easy to apply. Two large-sized test results confirm the strength and reliability of the connection. Experimental results with post-punching reinforced in the compression area of the flat slab do not increase the punching shear capacity but must be added to ensure the safety and integrity of the flat slab. The paper also uses Abaqus software to simulate the connection between the CFST column and the reinforced concrete flat slab. The behaviours of the specimens according to simulation and experiments are quite similar. Therefore, using the Abaqus simulation to analyze and evaluate the behavior of the connection between the CFST column and the reinforced concrete floor is sufficiently reliable. From the experimental and numerical analysis results, a critical perimeter as well as an analytical prediction model for punching shear strength of the RC flat slab accordance with MC2010 is proposed. The analytical model can be used to reliably predict the punching shear strength for reinforced concrete flat slab at connection with CFST column by shear steel plates.

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