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Punching shear strength and post-punching behavior of CFT column to RC flat plate connections

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Abstract

This paper summarizes full-scale test results on CFT (concrete filled tube) column to RC (reinforced concrete) flat plate connections subjected to gravity loading. CFT construction is gaining wide acceptance due to its various structural and constructional advantages. However, efficient details for CFT column to RC flat plate connections have not been proposed yet. Based on the strategies that maximize economical field construction, several connecting schemes were proposed and tested in this study. Test results showed that the proposed connections can exhibit punching shear strength and connection stiffness exceeding those of RC flat plate counterparts. A semi-analytical procedure is presented to model the behavior of CFT column to RC flat plate connections. The parameters needed to model the behavior from elastic to post-punching range are calibrated based on the test data of this study. The application of the proposed model to progressive collapse analysis is also illustrated.

Keywords: Composite construction; CFT column; Connection; Flat plates; Progressive collapse; Punching shear

1. Introduction

The use of CFT column in tall buildings is rapidly increasing due to its advantages on structural performance and construction process over conventional RC (reinforced concrete) construction. In Korea, using RC flat plate system in the basement and residential floors of tall buildings is often mandatory to reduce story height and to enable rapid construction. The use of flat plate floors for the basement parking areas also minimizes the amount of excavation so that total construction time and cost can effectively be reduced.

It is expected that a combination of CFT column and RC flat plate (or replacing RC column with CFT column) can further enable rapid construction of such floors. However, it appears that the issues related to connecting CFT column to RC flat plate have not been fully addressed yet. The primary objective of this study was to propose efficient and robust connection details for CFT column to RC flat plate based on full-scale gravity load test. The second objective was to propose a semi-analytical model of punching behavior of the proposed connections and to show the application of the proposed model to a simplified nonlinear static progressive collapse analysis.

2. Testing program

This study is a part of on-going research. Gravity load tests conducted for typical interior joints are presented in the following with focusing on punching behavior. Currently cyclic lateral load test is under preparation and will be conducted as the next phase study. The connection details proposed in this study were developed based on the following considerations:

(i) Structural integrity and the ease of construction were the primary concerns. Normally, longitudinal bars of a slab within the width of the column need to be welded to the surface of the steel tube at the field to develop full strength. However, such field welding was avoided in this study due to the difficulty in quality control and to reduce construction time. Instead, alternatives which ensure the development of full strength and easy construction were explored.

(ii) The CFT column–RC flat plate connection does not have any structural element that can reliably transfer shear forces between two nonhomogeneous materials (i.e. column faces and slabs) while, in conventional RC flat plate connections,

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Notation

The following symbols are used in this paper:

A_{sc}	sectional area of post-punching bars;
A_{sm}	minimum required area of post-punching bars;
A_{st}	sectional area of tension bars;
a	length of an edge of the slab;
b_0	length of the critical section for punching;
D	flexural rigidity of the slab;
d	effective depth of the slab;
E_c	modulus of elasticity of concrete;
F_y	measured yield strength of rebars;
f_{ck}	compressive strength of concrete;
f_y	yield strength of post-punching bar;
h	thickness of the slab;
L	span length;
l_1, l_2	slab span lengths in each direction;
K_1	initial secant stiffness until punching failure;
K_2	negative stiffness right after punching failure;
K_3	positive stiffness for a region after K_2 and before formation of local catenary mechanism;
K_c	vertical stiffness of interior slab in the idealized two-spring serial system;
K_E	vertical stiffness of exterior slab in the idealized two-spring serial system;
K_e	elastic stiffness of a simply supported square slab at its center;
P_s	axial load at the first story column;
P_u	punching shear strength;
$P_{u,\text{post}}$	post-punching residual strength;
$w_{\max}$	vertical deflection at the center of a simply supported square slab;
w_u	design load per unit area;
α_c	kink angle of post-punching bar;
α_t	kink angle of tension bar;
δ_{bal}	maximum downward deflection at energy balance point;
ϕ	strength reduction factor;
v	Poisson's ratio of concrete.

structural continuity is ensured by monolithic casting of concrete. It was speculated that a certain type of shear key is required to increase both structural continuity and redundancy in the connection regions. The punching shear strength of connections using this shear key was aimed to be higher than that of conventional RC flat plate connections.

(iii) To obtain reliable results, full-scale specimens were prepared and tested.

3. Connection details of test specimens

Based on aforementioned rationale, connection details as following were proposed (see Figs. 1 and 2). For bending moment transfer from slabs to columns, three types of anchoring method for longitudinal bars were considered: (i) a full penetration type (FP type), in which longitudinal bars completely pass the CFT column through the holes on both sides of the steel box (Fig. 1(a)), (ii) a half penetration type (HP type), where separate longitudinal bars pass through the holes on each side of steel box, but stop at the inner face on the other side of steel box such that the lap splice between the bars from each side is formed (Fig. 1(b) and (c)), and (iii) a hook anchorage type (HK type), where longitudinal bars are hook-anchored into the hole of the tension tab which is shop-welded to the outside of the column (Fig. 1(d)). For FP type, passing longitudinal bars through the holes on both faces by pushing from one side may not be easy when the size of the column is large. Guide conduits can be used temporarily to lead the rebars to the right position. HP type was intended to make this job easier. It is expected that the strength of the lap splice within the column can be improved, in addition to bonding with concrete, by extra contributions provided by the out-of-plane bending stiffness of steel plates composing the steel box. When rebars are anchored at the outside of the column using standard hooks and the steel box is built with relatively thin plates, the plates can deform in the out-of-plane direction due to the bar-pulling force. In this case, stud anchors were attached to the inner face of the column so that a complete load path can be provided (see Fig. 1(d)). For punching shear transfer from slabs to columns, two types of shear key were considered: (i) a tee section (ST type) and (ii) a wide flange section (SH type).

4. Design of test specimens

Each specimen in Figs. 1 and 2 represents a slab–column joint of a parking structure with a span length of 6 m long in each direction, 200-mm-deep flat plates, and 400-mm-square columns. The slab was designed using the ACI direct design method [2] to resist design loads consisting of dead and live load (5.88 kN/m^2) for indoor parking area according to AIK 2000 code [4]. Design compressive strength of concrete for the specimens was assumed as 27 MPa. The column strip of the flat plate was reinforced using D16 bars (SD40, $F_y = 400$ MPa) with a reinforcement ratio of 0.64%.

The wide flange shear key was sized by following the ACI design provisions for shear heads (ACI 318-05 [2], Corley–Hawkins [6], and Wang and Salmon [10]). A wide flange section of H-100 × 100 × 6 × 8 (SS400 steel, $F_y = 235$ MPa) with 320 mm long was required to ensure punching shear strength comparable to that of RC flat plate counterpart (see Fig. 1(c)). On the other hand, the web thickness of the tee shear key was sized considering the shear yield limit state of the tee-web against factored gravity shear (AISC [5]). The length of the tee shear key was simply taken to be equal to the slab depth (or 200 mm long) such that punching failure plane is within the shear key. A built-up tee section using 9-mm-thick steel plates (SS400 steel, $F_y = 235$ MPa) was attached to the column because appropriate rolled section was not available. All welding was made using the electrode of tensile strength $F_{EXX} = 490$ MPa. All specimens, except for the specimens with wide flange shear key, had a stud welded on each outer surface of the steel box at the level of tensile