Nonlinear Finite Element Analysis on the Transmission of Column Loads through Slab-Column Connections

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ABSTRACT

This paper presents the structural characteristics of slab-column connections by using nonlinear finite element analysis. FEA considering material non-linearity was performed to investigate average column strain, failure mode, principal stress distribution, and steel yielding conditions for various slab-column members. In addition, to investigate alternative methods for improving the strength of interior column-slab joints, some specimens were provided with different reinforcing types of high-strength concrete puddling, high-strength column longitudinal steels, dowel bars, and high-strength concrete core. To make certain of the reliability of the analytical program, analysis results for concrete material model developed and two specimens with and without puddling were compared with experimental results. It was found that providing the alternative reinforcing methods in the slab-column joint results in a significant improvement in performance. This includes an increase in the axial compressive strength, greater loading stiffness, and ductility.

1. Introduction

For reasons of economy, concrete columns are often made with higher-strength concrete than are the flat slabs or plates they support. In the preferred method of construction, the slab concrete is cast continuously through the column-slab joint. As a result, the part of the column forming the joint between the slab and the column is made with a lower grade of concrete than the rest of the column. But if such a construction method is used when the ratio of column concrete strength to slab concrete strength is very high, it cannot make full use of the column's high strength due to weaknesses in the slab-column joint. In that case, it is necessary to provide alternative design or construction strategies for the transmission of column loads through slab-column connections. Therefore, in this study, some different reinforcing types were suggested as the alternative methods for the slab-column joints. The structural members reinforced by the alternative methods were analyzed to investigate an applicability of the reinforcing types by using nonlinear finite element analysis.

2. Details of Analysis Specimens

Before the structural analysis for the specimens, structural experimental tests had been performed to investigate behaviors of two slab-column specimens. The one specimen, NS was constructed with ultra-high-strength concrete (UHSC) stub columns that extended above and below the normal strength concrete slab. The other specimen, PS contained the UHSC puddling over the entire depth of the slab in the immediate vicinity of the column. In this structural analysis, to compare the results of analysis and experiment, specimens had the same dimensions and basic reinforcement details as specimens which had been used in the experiment. In addition to the experimental specimens, some other specimens were analyzed to investigate alternative methods for improving the strength of interior slab-column joints. These specimens had different reinforcing types such as UHSC puddling, high-strength column longitudinal steels, dowel bars, and UHSC core. Fig. 1 shows the details of the specimens and main parameters for analysis.

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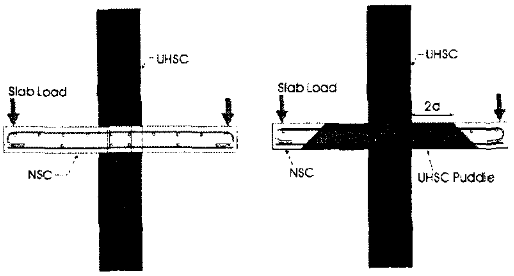
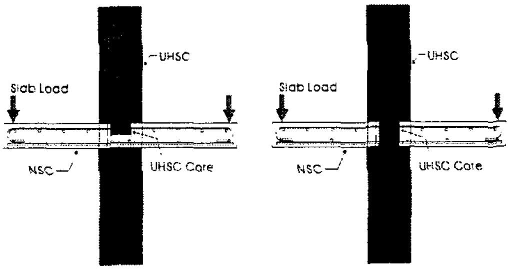
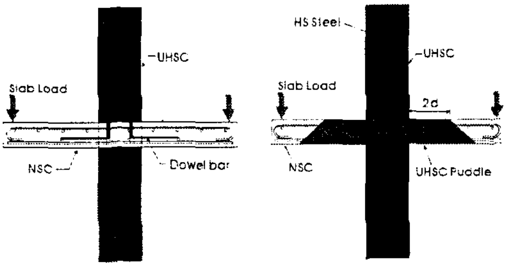


(a) *NS* : No puddling (b) *PS* : Puddling



(c) *NS-HC* : UHSC half-depth core (d) *NS-FC* : UHSC full-depth core



(e) *NS-DW*: Dowel bar (f) *PS-HS* :High-strength steel

Fig. 1 Sections and main parameters for analysis

Table 1 Concrete properties

Type	f_c' (MPa)	ε_c' (%)	E_c (MPa)	ν
NSC	46.89	0.1749	35639	0.1667
UHSC	88.33	0.2421	43320	0.2

Table 2 Steel properties

Designation	f_y (MPa)	ε_y (%)	E_s (MPa)	ν
SD-40	450	0.27	1.67×105	0.3
SD-60	600	0.20	3.0×105	0.3

Table 3 Comparison of experiment and analysis results

Specimen	Peak Load (kN)		Ultimate Strain ($\mu\varepsilon$)	
	Experiment	Analysis	Experiment	Analysis
NS	5138	6600	2870	2620
PS	5920	7100	2873	2720
NS/PS	0.87	0.93	0.99	0.96

3. Analysis conditions and procedure

Three-dimensional nonlinear static analysis was carried out by using finite element analysis program, DIANA. The element type is an eight-node isoparametric solid brick. For concrete, Drucker-Prager plasticity is used to model the failure surface in plane stress. Von Mises plasticity and hardening models are used for embedded reinforcements. It was the boundary condition that lateral displacements were restrained on the top and bottom surface of the column. Vertical displacements were also restrained on the bottom surface of the column.

For slab-column specimens, the full service load was initially applied to the slab, and then the column load was increased to failure while holding the full slab load constant.

4. Verification of Analysis model

4.1 Material model

Table 1 and 2 show properties of concrete and steel, respectively. Uniaxial experimental data of normal strength concrete (NSC) and ultra-high-strength concrete (UHSC) were translated to the equivalent cohesion, $\bar{c}$ and internal state variable, κ. For a unit volume element of concrete, material nonlinear analysis was performed to verify the availability of developed material model by using the $\bar{c}$ - κ relation. As shown in Fig. 2, the results of the analysis were very similar to the experiment.

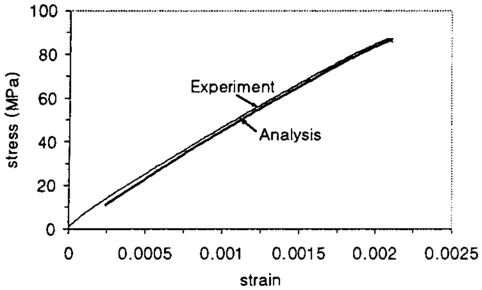
4.2 Analysis model for specimen

To verify the availability of the analysis model for specimens, the analysis results for Specimen NS and PS were compared with experimental results, as shown in Table 3. Analysis results of peak load were somewhat larger than the experiments. However ultimate strain was predicted almost accurately. In addition, the ratios of Specimen NS to PS for the analysis results were similar to the experimental results. Therefore, this analysis model can be used to evaluate the relative capacity of specimens.

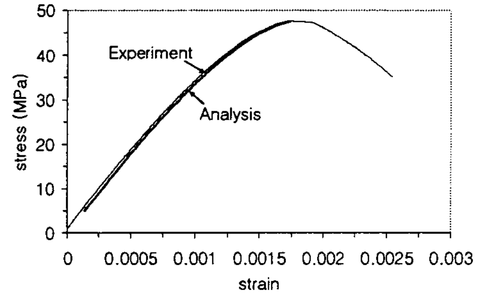
5. Analysis results

5.1 Failure mode

Fig. 3 shows the failure modes of analysis and experiment. Failures of all specimens were explosive at the top column stub in the analysis and experiment. Even though column loads transmitted from the top column to the bottom column has caused some displacement at the mid part of the bottom column, most of the displacements causing the failure occurred at the top column. After embedded reinforcement in the top column yielded, spalling of concrete cover was induced by buckling of reinforcement.

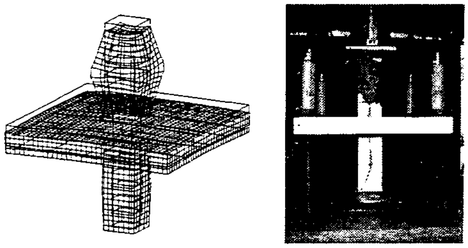


(a) Ultra-high-strength concrete



(b) Normal strength concrete

Fig. 2 Verification of material model



(a) Analysis (b) Experiment

Fig. 3 Failure mode

5.2 Distribution of principal stresses

Though all specimens had different quantities of principal stress at each loading stage, they had similar aspects of principal stress distribution. As shown in Fig. 4, a specimen to one side of an intersection plane at column center was cut away so as to reveal the interior principal stresses. Shade and light areas represent compression and tension, respectively. As column loading was increased, tensile stresses in the joint were also increased. At peak loading stage, tensile stress occurred in the column overall except in the interior of the mid-part of the top and bottom column.

5.3 Yielding condition of reinforcement

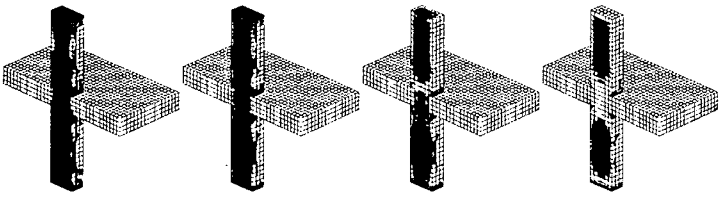
Fig. 5 shows the yielding condition of reinforcement at peak loading stage for all specimens. A bold-shade line represents the yielding of reinforcement. Column longitudinal steel of specimen NS yielded in the top column, bottom column, and joint in order. For all specimens, the yielding order is the same as specimen NS. However specimen PS, PS-HS having puddled concrete and specimen NS-DW did not yield in the joint. It is noted that specimen NS-DW had no UHSC puddling.

5.4 Load-strain responses

Fig. 6 shows the influence of several key parameters on the axial load versus strain responses of the slab-column specimens.

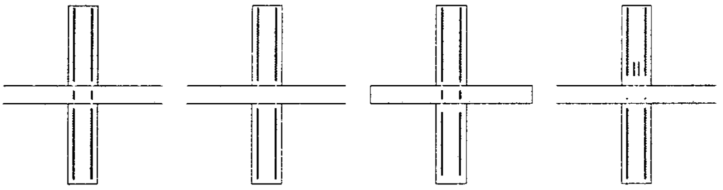
5.4.1 Effect of UHSC puddling

Fig. 6(a) illustrates the influence of puddled UHSC on the axial load versus average strain responses at the joint for the slab-column specimens. It is evident that the puddled UHSC increased both the strength and the loading stiffness of the slab-column specimens.



(a) Initial load (b) Yielding load (c) After yielding (d) Peak load

Fig. 4 Distribution of principal stresses

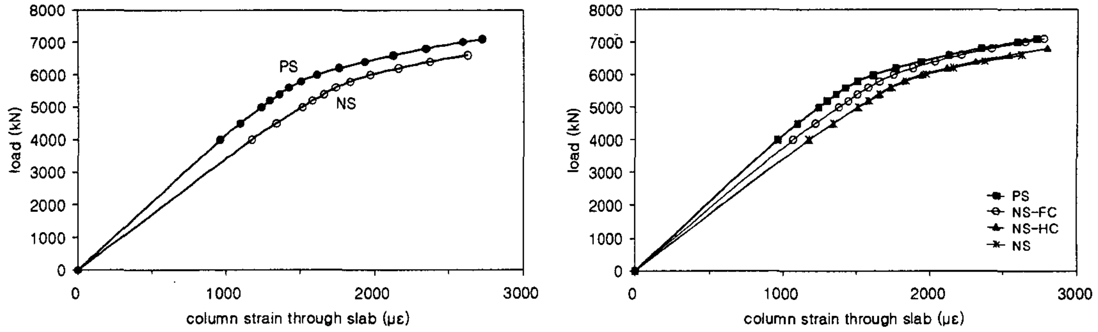


(a) NS (b) PS, PS-HS (c) NS-HC, NS-FC (d) NS-DW

Fig. 5 Yielding condition of reinforcement at peak load

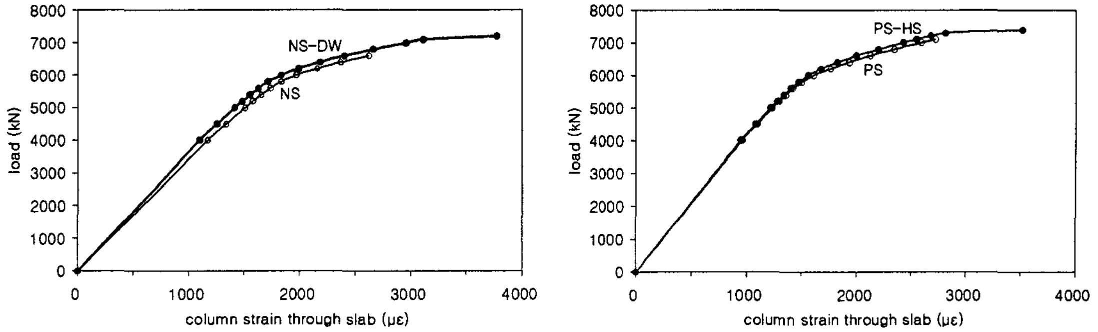
5.4.2 Effect of UHSC core

Specimen NS-FC had a UHSC core which extended the full thickness of the slab. Although the area of the core accounted for 16% of the cross-sectional area of the column, specimen NS-FC reached an ultimate load that was similar to specimen PS, as shown in Fig 6(b). This suggests that the longitudinal stress distribution in the joint is nonuniform, with the UHSC core carrying a disproportionate fraction of the total applied load. However specimen NS-HC, which had a UHSC core only in the top portion of the joint, had no improvement in the load-strain response.



(a) UHSC puddling

(b) UHSC full- and half-depth core



(c) Dowel bar

(d) High-strength steel

Fig. 6 Comparison of load-strain responses for several parameters

5.4.3 Effect of reinforcement

Specimen NS-DW was reinforced with dowel bars. SD-60 was used instead of SD-40 for the column longitudinal reinforcements of Specimen PS-HS. The strength was slightly increased for both specimens NS-DW and PS-HS. However, it was noted that the ductility of both specimens was considerably increased.

6. Conclusions

1) Three-dimensional nonlinear static analysis performed in this study can be used to investigate the relative behavior of slab-column specimens.
2) For improving the behavior of interior slab-column joint, UHSC puddling, UHSC core, dowel bar, and high-strength steel can be used as an alternative method. Especially, UHSC puddling and UHSC full-depth core increased both the strength and the loading stiffness of the slab-column specimens. Dowel bar and column longitudinal high-strength steel have considerable effect on the ductility of the slab-column specimens.
3) UHSC puddling and dowel bar prevent the yielding of reinforcement in the slab-column joint.

Acknowledgement

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References

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