**Ninth Canadian Conference on
Earthquake Engineering
Ottawa, Ontario, Canada
26-29 June 2007**

AN EXPERIMENTAL STUDY ON THE BEHAVIOR OF REINFORCED CONCRETE COUPLING ELEMENTS IN WALL – DOMINANT SYSTEM WITH OPENINGS

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ABSTRACT

The usefulness of lateral load resistance of shear walls in the multistory building has long been recognized. A common form of construction for apartment buildings consists of walls and coupling elements. However, the structural behavior of coupling elements is very complex and dependent on the properties of coupling elements. The objective of this study is to evaluate the behavior of coupling elements in the wall-dominant system with opening. Based on the results of this study, the stresses of coupling slabs were not uniform across the width of coupling slabs and the critical section of coupling slabs was smaller than that of previous studies.

Introduction

Reinforced concrete structural wall systems, commonly known as shear wall systems, are principally to resist lateral loads due to effects of wind and earthquake. Because of their inherent economy, shear walls combined with coupling slabs are widely used in high-rise apartment buildings. When analyzing such structures for lateral loads, the question of actual stiffness and strength of the coupling slabs arises. A number of papers[1), 2), 3), 4)] regarding the critical section of coupling slabs have been published. However, most these studies are based on linear elastic theory and uncracked slab section. How reliable are such prediction methods for reinforced concrete coupling slabs? In an attempt to answer this question, an experimental investigation was conducted with half-scale representations of the reinforced concrete shear walls with the opening subjected to cyclic loads.

Experimental program

Test Specimen

Specimens were half scale representations of a one-story wall in the apartment built in 1980. Based on the same reinforcement ratio as the prototype wall that was used in the study, a compressive strength of 21 MPa was assumed for concrete and a yield stress of 400 MPa was assumed for reinforcements in the design calculation. The area ratio of the opening section, as well as the size and critical section of coupling slabs, were decided based on results from previous research[5),6)]. Test results of the previous research[5)] is

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shown in Table 1. Surrounding area of the opening was not specially reinforced. A series of four shear wall specimens are listed in Table 2 and details of the specimens are shown Fig. 1. There is no opening for WS-solid, WB-solid specimens while WS-0.23 and WB-0.23 specimens have openings. Slabs were installed to WS-solid and Ws-0.23 specimens but there is no slab installed (WB-solid, WB-0.23) specimen.

Table 1. Test result of the previous research [5)]

Specimen	Area of opening ratio	Strength degradation	Etc.
Prototype	0 %	-	Vertical
Wall – 0.23	23 %	30 %	D6 @225
Wall – 0.30	30 %	50 %	Horizontal
Wall – 0.39	39 %	70 %	D6 @225

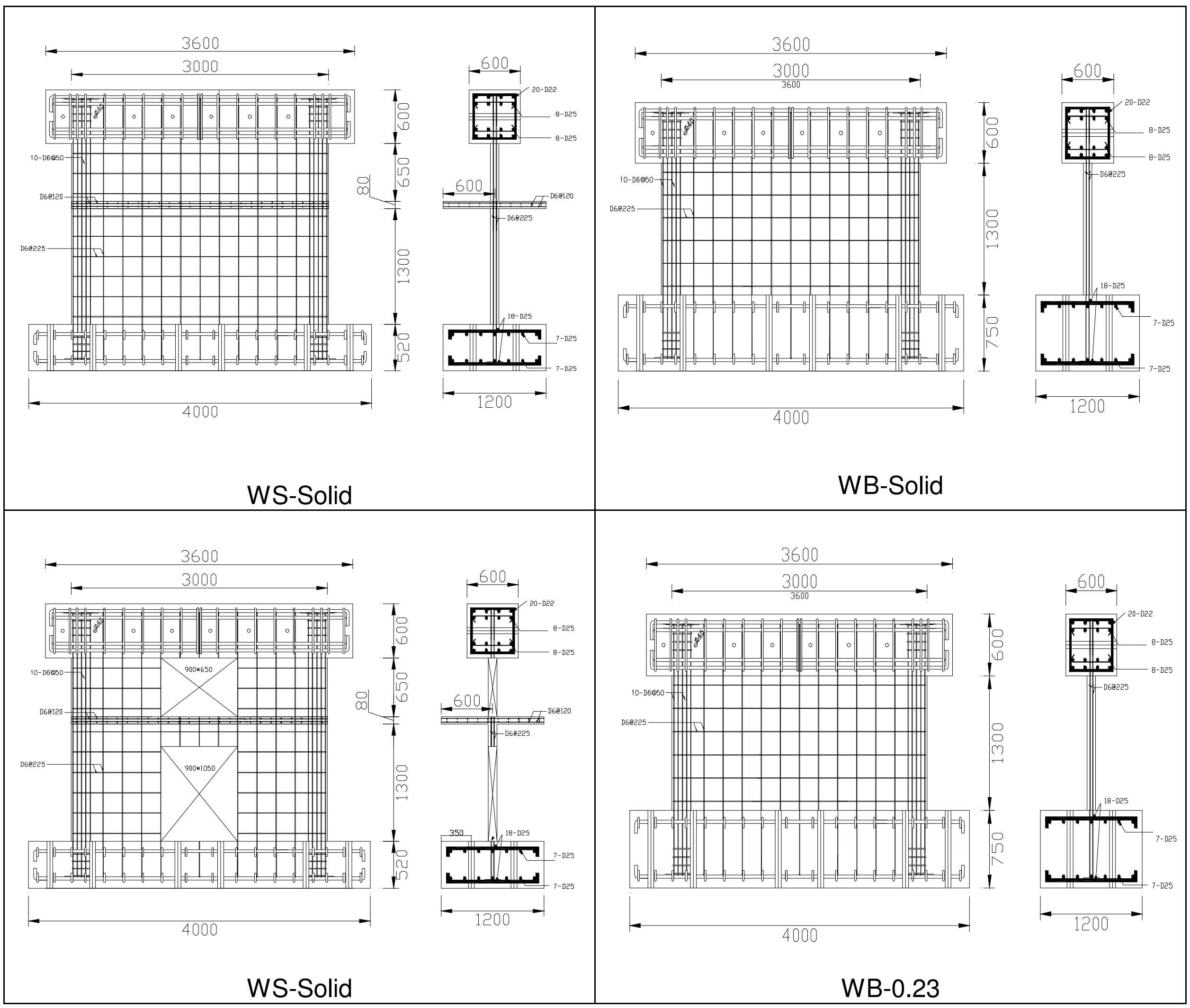


Figure 1. Details and configuration of specimens (dimension: mm).

Table 2. Variable and properties of specimens.

Specimen	Opening ratio [mm]	Slab	Reinforcement [mm]		$l_w \times h_w \times t_{wall} \times t_{slab}$ [mm]
			Wall	Slab	
WS-solid	without	with	Vertical	Vertical	3000 x 2030 x 100 x 80
WB-solid	without	without	D6 @225	D6 @225	3000 x 1300 x 100
WS - 0.23	23 % (900 X 1050)	with	Horizontal	Horizontal	3000 x 2030 x 100 x 80
WB - 0.23	23 % (900 X 1050)	without	D6 @225	D6 @225	3000 x 1300 x 100

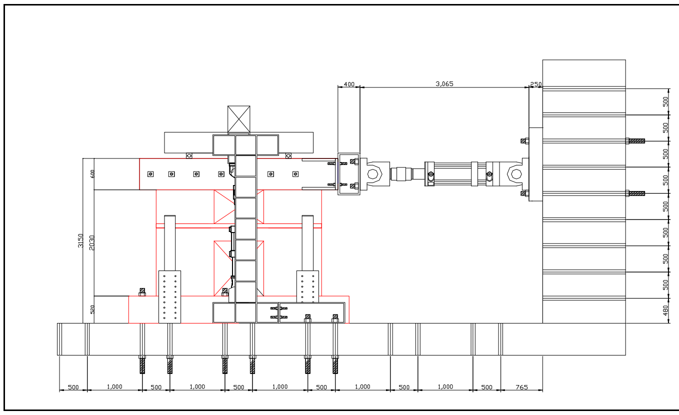


Figure 2. Test setup.

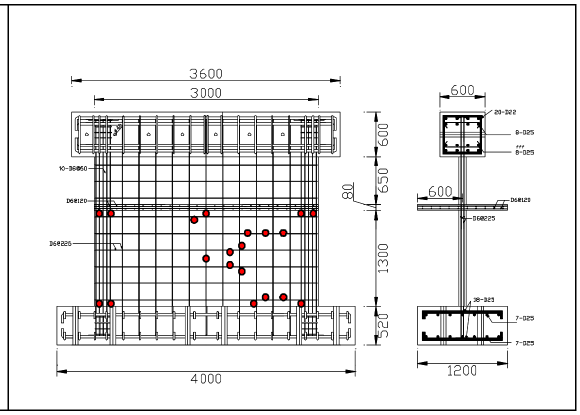


Figure 3. Location of WSG (dimension: mm).

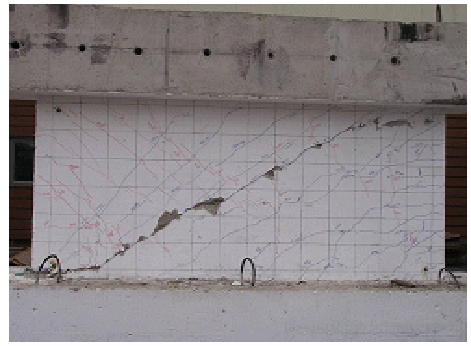
Testing Procedure

The specimens were manufactured with upright position as is the common construction. As shown in Fig. 2, each specimen was attached to the strong floor using four 68mm diameter rods at each end. Axial load of approximately 0.1 f_{ck} A_g was applied to the specimens at the beginning of each test. Lateral load were applied to the top of the wall using displacement controlled hydraulic actuator mounted between the specimen and a reaction wall. Guide beams and ball zigs were used to minimize the out-of-plane movement and simulate the diaphragm effect of a slab. During the test, lateral load was applied to the specimen by actuator and the specimen was controlled by values of LVDT, which is located on top of the specimen. Drift levels of 1/1000, 1/600, 1/400, 1/300, 1/200, 1/150, 1/100 and 1/75 were used for the test and each drift levels were applied three times cyclically. Instrumentation was provided to measure loads, displacements and strains. Load cells were used to measure lateral and vertical loads. Fifteen LVDT were used to measure horizontal and vertical displacement, rotation, shear deformation and slip of the foundation. Wire strain gages were employed to measure steel strains of the longitudinal reinforcing bars and lateral confinement reinforcements. During the load, deformation and crack were recorded by data acquisition system and photography.

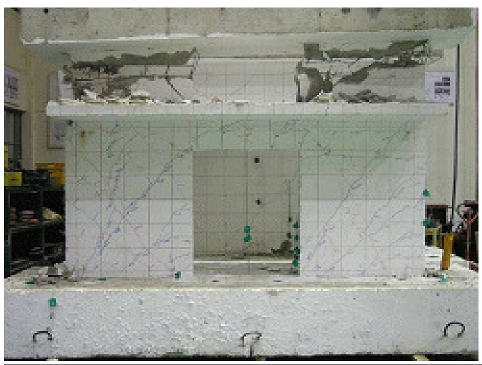
Experimental program

A summary of experimental results is presented in the following sections. The results from this research and previous research were investigated and compared. The experimental results were compared in terms with: 1) observed crack and failure pattern 2) lateral load versus displacement relationships 3) comparisons of stiffness, ductility ratios and slab critical section. Based on these results, the structural characteristics of opening walls and coupling slabs were discussed.

WS-solid



WB-solid



WS-0.23

WB-0.23

Figure 4. Observed cracks and final failure mode.

Observed crack and failure

The failure patterns of each specimen are shown in Fig. 4. The test specimens showed that shear failure mode of the walls was more dominant than flexural failure mode of the walls. Based on observation of the patterns of cracks the initial crack started from the junction of the walls and slabs. These cracks developed around the coupled edge of the walls at the junction of the slabs and walls. Cracks of the slab were concentrated on the opening and progressed onto the U shaped cracks.

Load versus displacement relationships

Fig. 5 shows the load versus displacement relationship for specimens. According to the direction of lateral load, behavior of the specimens varies. The maximum observed strength of the positive load is greater than that of negative load. Load-displacement relationship of WS-solid, WB- solid specimen showed that they reached the maximum strength of 500kN, 740kN and did not suffer sudden degradation of stiffness and strength after the maximum strength while they behaved relatively stable manner. For WS-0.23 specimen, the maximum strength of the specimen was 500kN and it did not indicate significant influence of degradation of strength. It is believed that because of coupling element there are enough strength and stiffness around the opening and this lead to good performance of the wall. The maximum strength of the WB-0.23 specimen was 560kN, and it was 25% decrease of strength compared to WB-solid specimens. It is believed that the stress concentration occurred on opening area because of the rigid frame in stalled in

WB-0.23 specimen when the displacement increased.

Table 3. Results of tests.

Specimen	θ_y *	P_y *	$\theta_{\max}$ *	$P_{\max}$ *	$\theta_{failure}$ *	$P_{failure}$ *	Displacement ductility	
	[%]	[kN]	[%]	[kN]	[%]	[kN]	μ_1 *	μ_2
WS-solid	0.41	390	0.98	520	1.08	570	2.35	2.47
WB-solid	0.61	560	1.3	740	1.46	760	2.1	2.3
WS - 0.23	0.39	380	0.88	500	0.98	520	2.25	2.5
WB - 0.23	0.53	420	0.76	560	1	590	1.42	1.57

θ_y : Drift ratio at yielding P_y : Load at yielding $\theta_{\max}$: Drift ratio at maximum, μ_1 : $\delta_{\max} / \delta_y$

$P_{\max}$: Load at maximum strength $\theta_{failure}$: Drift ratio at failure $P_{failure}$: Load at failure, μ_2 : $\delta_{failure} / \delta_y$

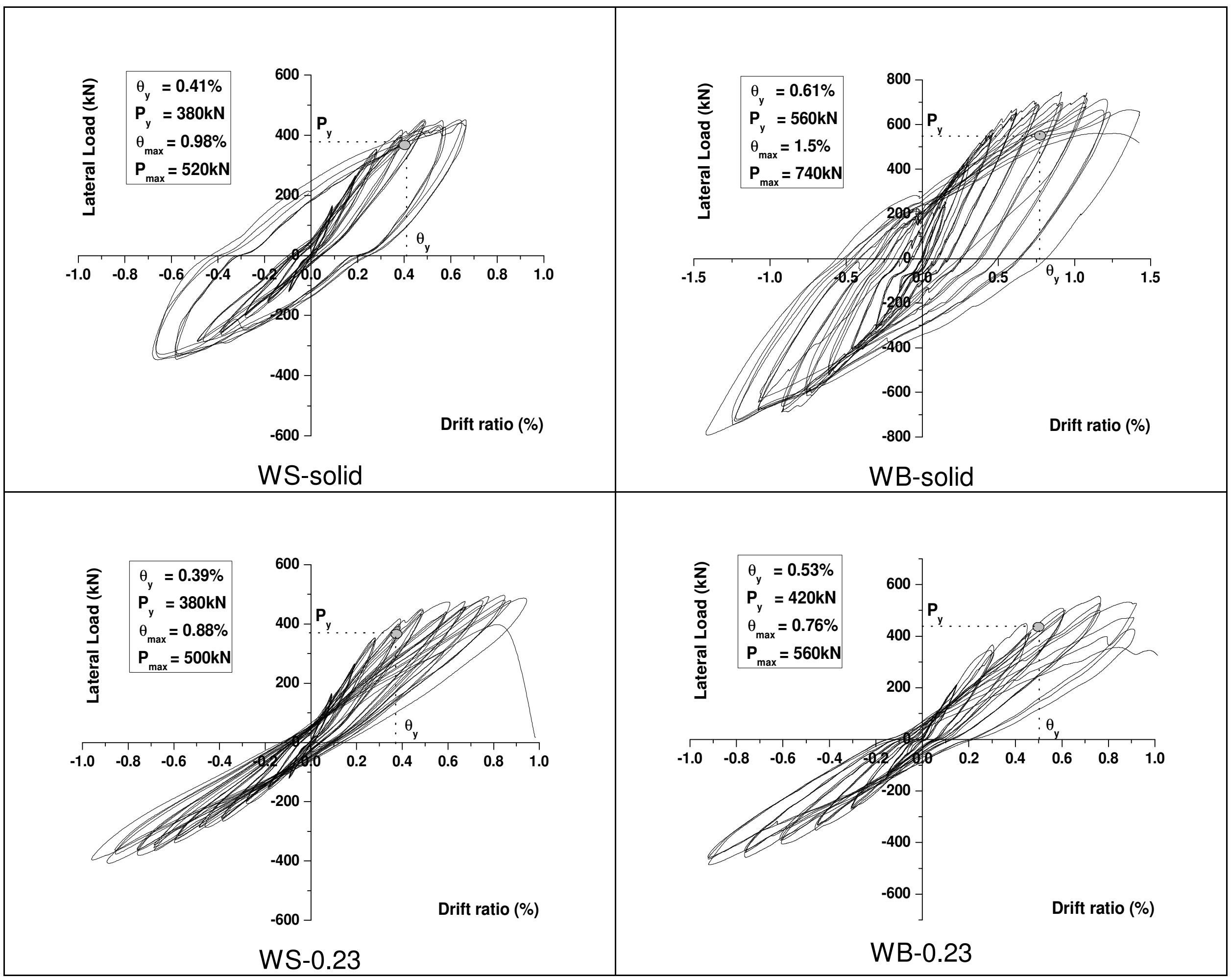


Figure 5. Load versus displacement curves.

Ductility

The definition of ductility ratio (μ) is a maximum displacement divided by the displacement at yield. Yield displacement is defined as displacement value from the backbone curve when the load is $0.75P_u$. As shown in Table 3, the ductility ratio of WS-solid, WB-solid, WS-0.23 and WB-0.23 are 2.35, 2.1, 2.25 and 1.41, respectively. The ductility of WS-solid, WB-solid is higher than WS-0.23 by 4% and 27%, respectively.

Strain distribution reinforcing bar

Fig. 6 shows the deformation aspects of vertical and horizontal reinforcing bars. All specimens showed that minimal deformation occurred at the reinforcing bar near the opening. The vertical reinforcing bars of WS-solid specimen experienced the yield at the drift angle of 0.78% and its deformation rate increased proportional to the distance. For WS-0.23 specimen the vertical reinforcing bars far from opening experienced the first yield at the drift angle of 0.22% and its deformation rate was similar to WS-solid specimen. It is believed that because of the opening stress was concentrated on the opening area rather than stress was evenly distributed throughout the wall. Deformation rate of the vertical reinforcing bars showed similar aspects for all four specimens and it increased proportional to the distance. For WS-0.23 specimen deformation of horizontal reinforcing bars located in 1000mm from the center of opening yielded at the drift angle of 0.66% while horizontal reinforcing bars from other location did not yield. The two specimens with opening showed the damages of vertical reinforcing bars and it is apparent that they cannot play a proper reinforcing role when the walls have openings. Therefore, it is necessary to have proper reinforcing method for the walls with openings.

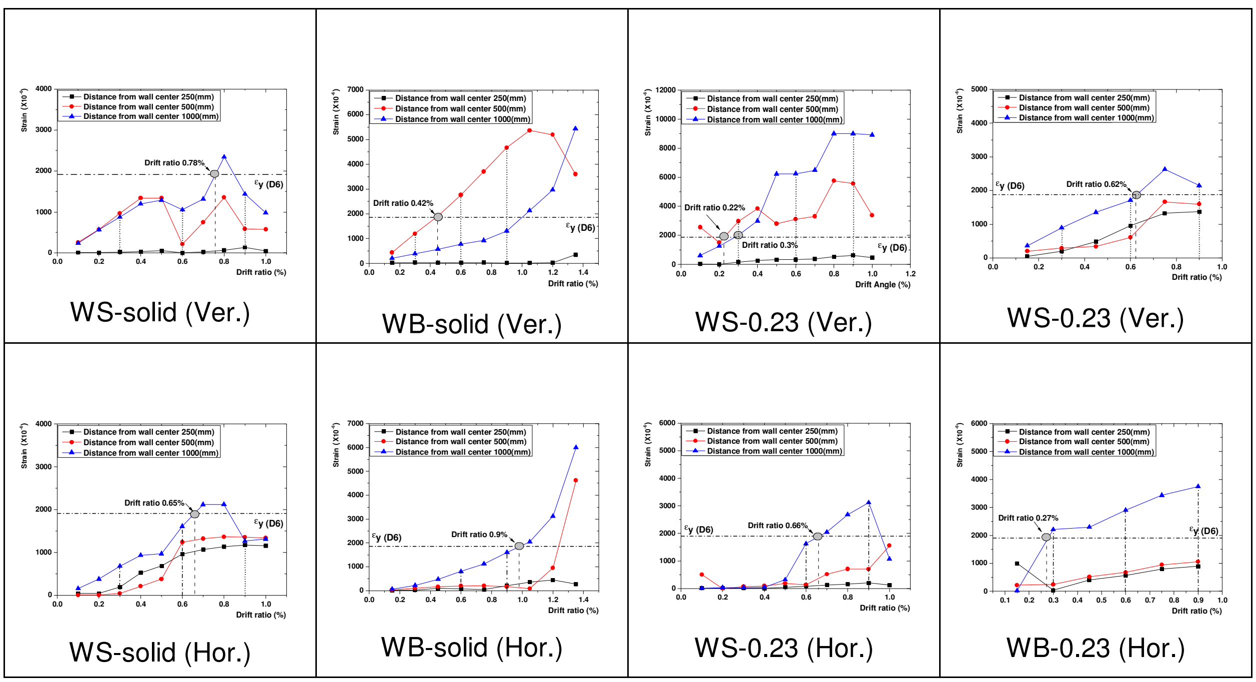


Figure 6. Steel strain under the drift ratio

Deformation of slab

The researches on coupling elements for wall type structures were carried out by Quadeer[5] and it is followed by Coull[3], Paulay, Taylor[6] and others. Among this research, Paulay carried out analysis research on the effective flexural strength and shear strength of slab and Schwaighofer[7] suggested the size of the critical section against shear stress of the walls with opening. Paulay and Taylor assumed the critical section using the principle of yield line and Schwaighofer suggested that U shaped critical section around the shear wall that has the three surfaces that are the same length. Schwaighofer defined the size of section of 3(t+d) where d is thickness of the slab and t is the thickness of the wall, and it is obtained by measuring of the critical section length of the shear wall. He also suggested the effective width of slabs that resist horizontal force, the thickness of the slab and the shear wall. Paulay calculated the slab width 8 times the slab thickness that resist horizontal force and suggested the reinforcing method of the front section of bars for this slab width. However, it is difficult to apply the results from this research the design of apartment buildings since there is possibility of application of the effective width is evaluated through the results from previous research and this experiment. The crack patterns of slabs were relatively similar to the proposed U shaped crack at the critical section for WS-0.23 specimens as shown in Fig. 7. Based on the test results, Schwaighofer's suggested length of critical section that overestimates about twice of the test results as shown in Table 4.

Table 4. Comparison of critical section (WS-0.23).

Specimen	Schwaighofer, Chang	Experimental result
Form of critical section	U	U
Total length of critical section	3(t+d)	3(t+d)/2

t : wall thickness d : slab thickness

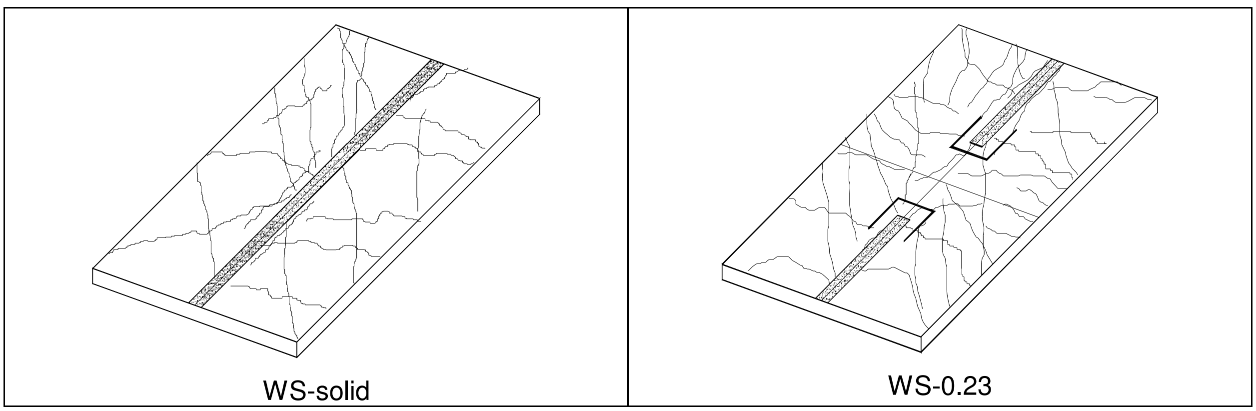


Figure 7. Slab crack pattern.

Conclusions

In this research the experiment of partial structures consisting of walls and slabs was conducted in order to find out the effects of coupling in shear walls with openings. The following results were obtained:

(1) According to test results for the WS-0.23 specimen, which has artificial damages to install the opening, the strength of the wall decreased due to the opening. It is apparent that the influence of cutting reinforcing bars and decrease of effective section area lead to early first yield of the reinforcing bars before the allowable limit of drift ratio of shear walls is reached. Therefore, a proper reinforcing method is needed to prevent this.

(2) The decrease in strength of the shear walls by installation of openings shows a great deal of difference compared to previous research. This is because the flexural capacity of the slabs is working as coupling elements for the shear walls.

(3) The critical section of coupling slabs that works as coupling elements for shear walls was a little different from results of previous research. Therefore, it is inappropriate that direct application of these results to design of apartment building.

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