コンクリート工学年次論文報告集 Vol.17, No.2 1995

報告 Behavior of R/C Interior and Exterior Wall-slab Connections under Lateral Out-plane Loading

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ABSTRACT: Experimental test results of eight interior and exterior R/C full-scale connections consisted of cast-in-situ walls and composite hollow slabs are presented. Failure modes and shear or bending ultimate strengths, including joints behavior after repairing, are under consideration.
KEYWORDS: wall-slab connection, composite hollow slab, T-shape cross section, out-plane loading, shear strength, bending strength, repaired connection

1.INTRODUCTION

It is possible to make reference to a number of papers sufficiently introducing nearly all of the important design parameters, which have influence on beam-column joint bearing capacity under lateral loading and making qualitative statements about their functions [1] . Main parameters are joint volume, bond resistance, column axial force, joint reinforcement, concrete and reinforcement strengths, effects of slabs or transverse beams, etc. The alteration of these parameters has a direct influence on strength and failure mode of beam-column joints. Frameless reinforced concrete structures with insufficient earthquake-proof structural walls or with partition walls arranged thoroughly in one direction are in large use for multistorey residential buildings in nonearthquake regions of Central and East European countries. Influence of out-plane lateral force on wall-slab connection is not yet sufficiently investigated. The subject matter of experimental study presented in this paper was to propose a suitable way for strength estimation of frameless structures under lateral out-plane loading on the base of wall-slab connection test data and taking advantage of beam-column joint evaluation experience.

2.EXPERIMENTAL STUDY

2.1 OUTLINE OF SPECIMEN VARIABLES

An outline of variables of six interior and two exterior full-scale cast-in-situ reinforced concrete wall-slab connection specimens is shown in Fig.1. All members, except 60mm depth precast slabs in the composite flooring, were made from

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cast-in-situ concrete. Hollows in the cast-in-situ concrete slab were formed by ϕ76mm plastic pipes. The main reinforcement for specimens were D16mm bars, shear reinforcement for all members and welded mesh for precast slab were ϕ6mm bars. Mechanical properties of used materials are shown in Tables 1 and 2.

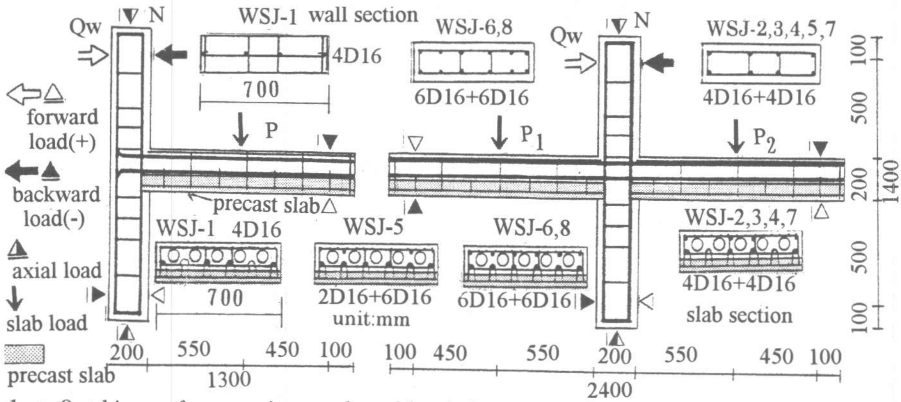

Fig.1 : Outline of experimental wall-slab connection specimens

Table 1 Mechanical Properties of Steel

Rein-force ment	Specimen	Posi-tion	σ_y kgf/cm^2	E (x10^6) kgf/cm^2
D16	WSJ-1, 2, 3	main	3870	1.75
D16	WSJ-4, 5, 6	main	3720	1.74
D16	WSJ-7, 8	main	3730	1.77
ϕ6	all	shear	3930	2.14

$E_{1/3}$:x10^5, σ_B:kgf/cm^2, ε :x10^{-6}

Table 2 Mechanical Properties of Concrete

Specimen	Precast slab			Cast-in-situ		
	σ_B	ε_u	$E_{1/3}$	σ_B	ε_u	$E_{1/3}$
WSJ-1	356	2970	2.27	266	2640	2.05
WSJ-2	380	3210	2.34	219	2760	1.91
WSJ-3	380	3000	2.30	274	2330	1.91
WSJ-4	314	2900	2.32	194	2650	1.76
WSJ-5	345	2700	2.65	245	2740	2.23
WSJ-6	350	2870	2.56	239	2580	2.13
WSJ-7	407	3090	2.68	223	2865	1.82
WSJ-8	407	3090	2.68	221	2795	1.87

2.2 LOADING METHOD

In order to simulate load conditions of acting vertical and reversal lateral forces, the special load equipment was used(Fig.2). A pin support of the lower wall restrained only horizontal displacement and slab ends were supported by rollers. The top of upper wall was connected with an actuator. Reversal load was controled by story drift angle R of 0.1% and 0.2%-one cycle, 0.5%, 1%, 2%, 3%-each two cycles and 4%-one. Vertical axial load N was supplied taking into account real dead load(wall axial stress $\sigma_B/7.5$; σ_B:concrete compressive strength concrete)or dead load together with live load(axial stress $\sigma_B/4.5$).The slab members subjected to forces P_1 and P_2 (for WSJ-1, 2, 4, 5, 7, 8 load was 1.65tf and for WSJ-3, 6 was 2.4tf) were loaded by balance arm using counterweights. Slab deflections, wall and slab shear forces, loads, bending deformations and reinforcement strains were measured during the experiment.

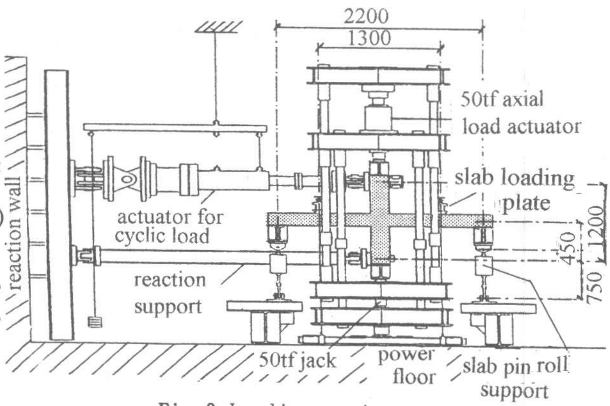

Fig.2 Loading equipment

2.3 REPAIRING METHOD

Vertical and transverse cracks caused by lateral reversal load decrease not only stiffness but also the bending and shear strengths of the structural member. According to the experimental data of loaded beams with mended cracks [2] ,crack resistance and stiffness of the beam can be increased twice and, in some cases, the injection of bond into arised cracks leads to an increase of the flexural and shear strengths. In this experiment, epoxy resins for binding material with a low viscosity, good penetration ability and comparatively high strength enabled to mend reliably the cracks of more than 0.06mm width. All eight wall-slab connection specimens were mended by the epoxy resin injection and tested again under the same loading conditions as new ones .

3.TEST RESULTS AND THEORETICAL CONSIDERATIONS

3.1 CRACKING AND FAILURE PERFORMANCES

Initial bending cracks in slab members were observed during slab loading, shear cracks appeared at 3rd cycle. In WSJ-1 shear cracks did not expand and the specimen reached bearing capacity by bending failure in slabs. In case of WSJ-2,4,6 vertical loading to slabs and lateral force caused a lot of small bending cracks. Inspite of that, joint core suffered shear cracks and failed in shear. The cracking perfomance same to that of WSJ-2,4 was observed in WSJ-3 secimen, but after that because of large vertical load on slab members, both the shear and bending cracks expanded, and the joint core and slab failed in shear and bending respectively at the same time. Insufficient reinforcement of upper slab bar layer in WSJ-5 specimen caused bending failure in slabs, but shear cracks of joint core also performed signs of connection failure in shear. Specimens WSJ-7 and WSJ-8 reached ultimate bearing capacity by slab bending failure at forward lateral force, which generated tensile stress in lower part of bending slab. At the same time backward force caused shear failure at joint core indicating anchorage failure at the bar hooks. The general view of joint cracking and failure characters are presented in Fig.3.

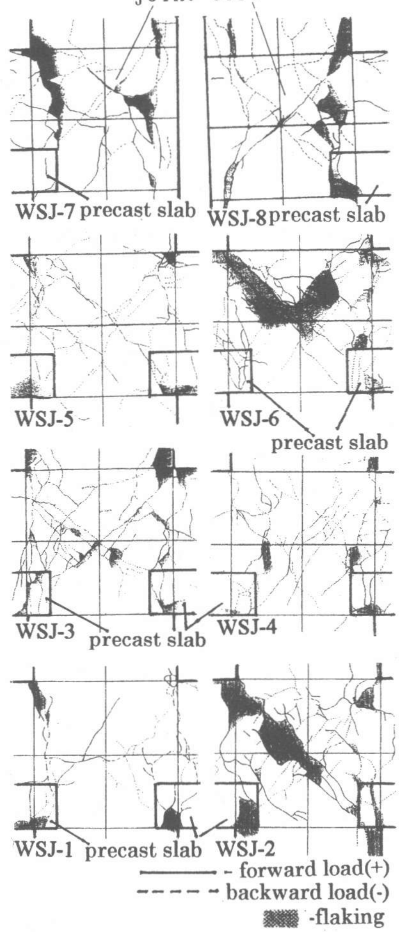

Fig.3 Final cracking arrangement in joint core

3.2 ULTIMATE BENDING STRENGTH

On the assumption of tensile reinforcement in yield stress and compressive reinforcement in elastic region, ultimate bending moment of a beam provided by AIJ Standard [3] can be written as

$$M_s = m \cdot b \cdot d^2 \cdot \sigma_B, \tag{1}$$

where **m**:factor of ultimate resistance moment, **b**:slab width, **d**:slab effective depth.

According to author's previous paper [4] for the T-shape section factor of ultimate resistance moment **m** in eq.1 must be replaced by m_T:

$$m_T = m + m'. \quad (2)$$

Here, m': T-shape cross section factor [4]. The relation between slab ultimate bending moment M_s and slab shear force Q_s (see Fig.4)

$$M_{s1}=Q_{s1}\cdot(l_{s1}-j_w/2)+P_1 l_1; \quad (3)$$
$$M_{s2}=Q_{s2}\cdot(l_{s2}-j_w/2)+P_2 l_2. \quad (4)$$

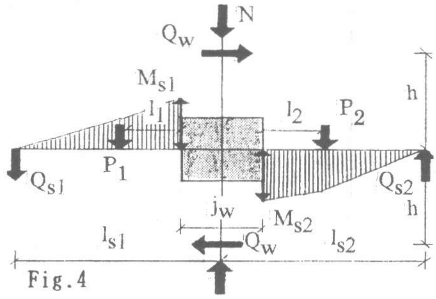

Fig.4

For interior and externior joints, in case of slab bending failure, the out-plane wall shear forces are $Q_{wb}=(Q_{s1}l_{s1}+Q_{s2}l_{s2})/(2h)$ or $Q_{wb}=(Q_s l_s \pm Pl)/(2h)$ respectively. For externior connections Q_{wb} alternates depending on direction of force by the actuator. Calculated values of ultimate bending moment and corresponding wall shear force Q_{wb} are presented in Tables 3 and 4.

3.3 ULTIMATE SHEAR STRENGTH

In case of joint core shear failure perfomance equation for ultimate shear force is

$$Q_{wu}=b_j j_w / \{(\alpha l_s-j_w)/j_s \cdot h/l_s-1\} \cdot \tau_{ju}=\lambda \cdot \tau_{ju}; \quad (5)$$

where, τ_{ju}: shear strength of joint core; b_w, b_s: wall and slab widths; b_j: effective width of connection; for different wall and slab widths $b_j=(b_w+b_s)/2$; j_w, j_s: wall and slab arms of inner couples ($j=7/8d$, where d: effective depth); h, l_s: wall and slab loading arms; $\alpha=2$ for double layer and $\alpha=1$ for single layer reinforcement. Shear strength of joint core τ_{ju} in Tables 3 and 4 was calculated from five equations suggested by different Japanese scientists and by ACI Standard for permissible shear stress and from an experimental equation proposed by the authors, in assumption of ratio of shear reinforcement in joint area $p_w=0$.

Eq.① : Dr.Endoh [5] $\tau_{ju}=75.4$; $(\sigma_B>232)$ or $\tau_{ju}=(0.65-0.0014\sigma_B)\cdot\sigma_B$; $(\sigma_B\leqq 232)$

Eq.② : Dr.Kamimura [6] $\tau_{ju}=95.0$; $(\sigma_B>244)$ or
$\tau_{ju}=(0.78-0.0016\sigma_B)\cdot\sigma_B$; $(\sigma_B\leqq 244)$

Eq.③ : Steel R/C Standard [7] $\tau_{ju}=f_c\cdot\phi$; where concrete shear strength $f_c=\min(0.12\sigma_B; 18+3.6\sigma_B/100)$; $\phi=3$ for interior and $\phi=2$ for exterior joint;

Eq.④ : AIJ Guidelines [8] $\tau_{ju}=0.35\phi\cdot\sigma_B$

Eq.⑤ : ACI-ASCE [9] $\tau_{jp}=0.9\beta\gamma\{\sigma_B(1+0.03N/A_w)\}^{1/2}$;
where τ_{jp} is joint core permissible shear strength;

Eq.⑥ : Experimental $\tau_{ju}=0.9\beta\gamma\phi\delta\xi\mu\{\omega\sigma_B(1+0.03N/A_w)\}^{1/2}$.

(unit of kgf and cm were used for all equations)

3.4 STRENGTH OF REPAIRED WALL-SLAB CONNECTIONS

Cracking and failure performances, as well as ultimate strength of repaired connections were close to those of new ones. However, because cracks did not araise in mended parts concrete strengthening in tension by injection inspired increases in ultimate bearing capacity of all connections. In case of WSJ-6R and partly for WSJ-8R, since binding agents did not fill up a lot of microcracks outside the joint core, probably extensive bond failure in the slabs led to lower

Table 3 Outline of interior wall-slab connection results

Specimen	Lateral Force exp Q_{wu}		Failure Mode	cal Eq	τ_{ju} kgf/cm²	Q_{wu}, tf cal	Q_{wu}, tf + exp/cal	Q_{wu}, tf − exp/cal	Q_{wb}, tf cal	Q_{wb}, tf exp/cal	M_{s1} M_{s2} tf·m
WSJ-1	+	5.42	S_b	①	75.4	7.68	0.706	0.598	5.52	0.982	2.25
				②	95.0	9.68	0.560	0.474			
				③	82.7	8.43	0.643	0.544			
	−	4.59		④	93.1	9.34	0.580	0.491		0.832	3.95
				⑤	19.4	1.98	2.737	2.318			
				⑥	60.1	6.12	0.886	0.750			
WSJ-2	+	9.24	J_s	①	75.2	9.16	1.009	0.942	9.78	0.945	6.96
				②	92.8	11.30	0.818	0.765			
				③	77.6	9.46	0.977	0.912			
	−	8.63		④	75.6	9.21	1.003	0.944		0.882	4.01
				⑤	17.4	2.12	4.358	4.071			
				⑥	74.7	9.10	1.015	0.948			
WSJ-3	+	9.47	$S_b \to J_s$	①	75.4	9.18	1.030	0.944	9.59	0.987	6.78
				②	95.0	11.40	0.831	0.760			
				③	83.6	10.03	0.944	0.864			
	−	8.67		④	95.3	11.51	0.823	0.753		0.904	3.94
				⑤	22.3	2.68	3.533	3.235			
				⑥	97.6	11.72	0.808	0.740			
WSJ-4	+	9.70	J_s	①	73.4	8.98	1.080	0.987	9.20	1.054	6.33
				②	91.1	11.14	0.871	0.795			
				③	69.8	8.54	1.135	1.037			
	−	8.86		④	67.9	8.31	1.167	1.066		0.963	3.98
				⑤	18.1	2.21	4.389	4.009			
				⑥	76.1	9.32	1.041	0.951			
WSJ-5	+	9.73	S_b	①	75.4	9.24	1.053	1.005	9.43	1.032	5.08
				②	95.0	11.65	0.835	0.797			
				③	80.5	9.86	0.987	0.942			
	−	9.29		④	85.7	10.51	0.926	0.884		0.985	5.50
				⑤	18.4	2.25	4.324	4.129			
				⑥	77.6	9.51	1.023	0.941			
WSJ-6	+	13.4	J_s	①	75.4	9.43	1.421	1.326	12.97	1.032	9.00
				②	95.0	11.88	1.127	1.052			
				③	79.7	9.96	1.344	1.255			
	−	12.5		④	83.3	10.41	1.287	1.201		0.964	5.53
				⑤	20.3	2.54	5.275	4.921			
				⑥	104.9	13.12	1.020	0.925			

Table 4 Outline of exterior wall-slab connections results

Specimen	Lateral Force exp Q_{wu}		Failure Mode	cal Eq	τ_{ju} kgf/cm²	Q_{wu}, tf cal	Q_{wu}, tf + exp/cal	Q_{wu}, tf − exp/cal	Q_{wb} cal	Q_{wb} exp/cal	M_s tf·m
WSJ-7	+	2.47	S_b	①	75.3	5.71	0.433	-	2.49	0.992	3.83
				②	94.3	9.49	0.261	-			
				③	52.0	5.24	0.471	-			
				④	46.8	4.72	0.523	-			
				⑤	16.0	1.61	1.534	-			
				⑥	39.6	3.99	0.619	-			
	−	5.12	$J_s \to A_f$	①	75.3	11.29	-	0.453	6.72	0.762	6.52
				②	94.3	14.14	-	0.362			
				③	52.0	7.81	-	0.655			
				④	46.8	7.02	-	0.729			
				⑤	16.0	2.39	-	2.142			
				⑥	39.6	5.94	-	0.862			
WSJ-8	+	3.65	S_b	①	75.3	6.86	0.532	-	3.42	1.067	4.81
				②	94.2	8.58	0.425	-			
				③	51.9	4.73	0.772	-			
				④	46.4	4.23	0.863	-			
				⑤	17.1	1.56	2.340	-			
				⑥	52.8	4.81	0.759	-			
	−	8.30	J_s	①	75.3	11.20	-	0.741	9.60	0.864	9.76
				②	94.2	14.01	-	0.592			
				③	51.9	7.72	-	1.075			
				④	46.4	6.91	-	1.201			
				⑤	17.1	2.54	-	3.268			
				⑥	52.8	7.85	-	1.057			

Failure type: S_b-slab bending failure; J_s-joint core failure in shear; A_f-anchorage failure. The folowing symbols were used for eq.④,⑤ and ⑥: $\beta=1.0$ in case of a joint connecting members for which the primary design criterior is sustained strength under reversals in the inelastic range; $\gamma=1.0$ if the joint is not confined perpendicular to the direction of shear force considered; for interior joint $\phi=1$; for exterior-$\phi=0.6$; $\delta=1.0$ for slab-wall effective depth ratio $d_s/d_w=0.875$; $\xi=\sigma_y/3870$kg/cm²: main reinforcement strength coefficient; $\mu=42$: experimental coefficient; $\omega=(a_c+a_t)/A_w$, where a_c and a_t are cross section of main reinforcement in compression and tensile area respectively; A_w: wall cross section area.

ultimate bearing capacity of joints. Experimental data of new and repaired connections wall shear forces Q_w and Q_{wR} and mean of strengthening rate κ for forward(+) and backward(-) loadings are presented in Table 5.

Table 5 Strength of repaired connections

Specimen	Ultimate Strength, tf		Q_{wR}/Q_w	κ
	Q_w(+/-)	Q_{wR}(+/-)	(+/-)	(%)
WSJ-1	5.41/4.59	6.11/5.53	1.13/1.21	17.0
WSJ-2	9.24/8.63	9.86/8.64	1.07/1.00	3.5
WSJ-3	9.47/8.67	9.24/9.63	0.98/1.11	4.5
WSJ-4	9.70/8.86	10.34/9.96	1.07/1.12	9.5
WSJ-5	9.73/9.29	10.15/9.25	1.04/1.00	2.0
WSJ-6	13.4/12.5	12.60/10.5	0.94/0.84	-11.0
WSJ-7	2.47/5.12	2.87/6.51	1.16/1.27	21.5
WSJ-8	3.65/8.30	3.44/9.05	0.94/1.09	1.5

4.CONCLUSIONS

Experimental studies on wall-slab connections subjected to vertical and lateral out-plane loadings showed that a construction method with single layer reinforcement for intensive horizontal forces is absolutely unsuitable because of low bearing capacity of the structure. Further, shear strength of the interior wall-slab connections with double layer reinforcement calculated by equations for column-beam joints, sufficiently concurred with the experimental data.

Influence of axial loading to joint core shear strength can be evaluated taking advantage to American Standard(ACI)equation. Therefore, an experimental equation sufficiently evaluating the joint core shear strength for different types of wall-slab connections can be proposed from the experimental data.

Bending, shear and bond cracks caused by lateral reversal loads can be successfully mended by the means of epoxy resin injection. Repairing can even inspire increase of ultimate bearing capacity in mended wall-slab connections.

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