- Technical Paper -

FLEXURAL PERFORMANCE OF PCa BEAMS WITH VARIOUS CONNECTIONS UNDER REVERSED CYCLIC LOADING

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ABSTRACT

This paper discusses the flexural performance of precast (PCa) concrete beams under reversed cyclic loading. Static cyclic loading tests were conducted on PCa beams with different connections. The experimental parameters were types of connections, location of interface and vertical position of joints between PCa segments. The results reveal that crack distribution, opening at interface and flexural capacity were affected by the type of joints. Moreover, the failure of PCa beams was affected by these parameters as well.

Keywords: PCa beam, flexural performance, cyclic loading, mechanical joints, prestressing force

1. INTRODUCTION

Nowadays, precast (PCa) concrete is widely adopted in the construction site of buildings, bridges and tunnels due to the following advantages. First of all, the PCa segments are fabricated in the factories where the quality of concrete can precisely be controlled without interference from natural conditions. Second, the construction time can be saved due to immediate installation of these segments on site without waiting for concrete hardening. However the understanding about the structural performance of different types of connections applied to PCa segments are not enough.

According to Japan Society of Civil Engineers Standard Specifications for Design and Construction of Concrete Structures (JSCE Standard Specifications) [1], four general connection methods have been introduced, including lapping joints, welding rebar joints, joints by prestressing bars and mechanical joints. In addition, it also indicated that welding rebar joints and lapping joints tend to induce a decrease in ductility.

As for the other methods, mechanical joints are widely adopted because they are able to guarantee the stiffness and ductility of the connection in PCa segment. In a past research by Wang, H., et.al [2], mechanical joints were proved to have no harmful effect on the flexural performance of PCa beams under cyclic loading. However, the researches about effect of reversed cyclic loading are not enough. Besides, Yan, X., et.al [3] conducted the experiment on PCa beam-column structures connected by prestressing force which is capable of not only improving the shear capacity of the structure but also reducing the section height of the structural member. The results indicated high resistance of the structure against reversed cyclic loading which the effect of vertical position of prestressing (PC) tendons has not been clarified yet.

This study aims to investigate the flexural performance of PCa beams with various types of connection between concrete segments under reversed cyclic loading. In this study, mechanical joints and prestressing force were used to connect PCa segments considering two different vertical positions of PC steel bars: one-layer arrangement (hereafter, centralized setup) and two-layer arrangement (hereafter, dispersed setup). Moreover, different locations of interface were also considered in this experiment: within the span of constant shear (hereafter, side span) and within the span of constant bending (hereafter, mid span). One reference beam and six beams with different connections were tested and their load-deflection relationships, interface opening progresses and crack patterns were discussed.

2. EXPERIMENTAL PROGRAMS

2.1 Test specimens and Material

The cross section and detailing of specimens are shown in Fig. 1, and Table 1 summarizes the details of steel reinforcement and joints. The specimens in this study are full-scale models of a PCa box culvert tunnel with two lanes. All specimens shared same sizes: 6800 mm in length, 400 mm in section height and 680 mm in section width with of nominal concrete compressive strength of 40 N/mm^2. The arrangement of the longitudinal reinforcement is shown in section A-A' of Fig. 1. Four D22 (SD345) steel bars were used as top layer reinforcement at the depth of 70 mm, four D29 (SD345) steel bars were used as bottom layer reinforcement at the depth of 320 mm and D13 (SD345) steel bars were used as shear reinforcement with the arrangement following Specifications for Highway Bridges [4].

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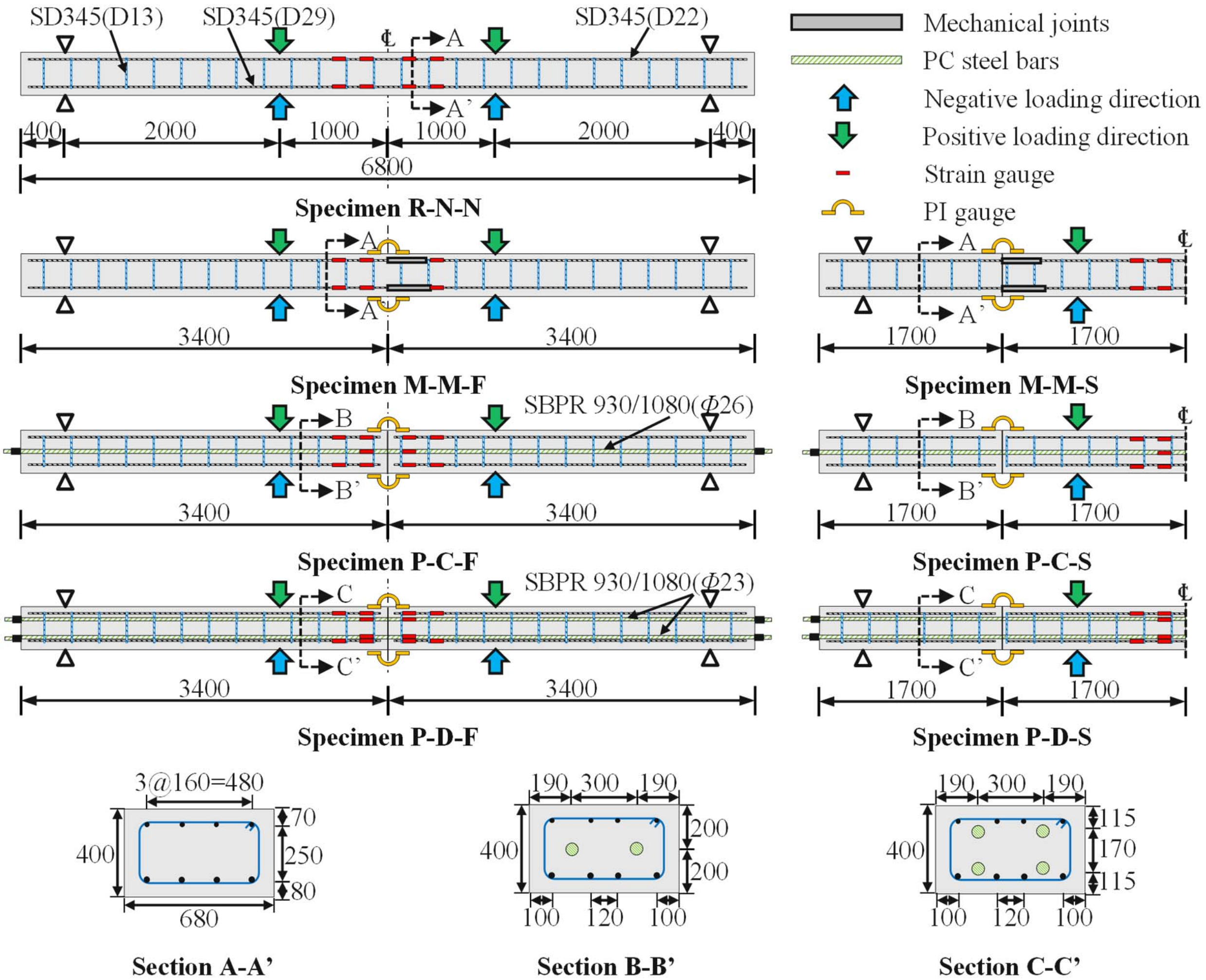

Fig. 1 Outline of specimens

Table 1 Details of Specimens

Series	Name	Longitudinal bar		Stirrup		Connection	Joint		Location of joint and interface
		Φ *	*Φ***	*Φ*	*s* (mm)		Type	*Φ*	
1	R-N-N	D22	D29	D13	250	-	-	-	-
2	M-M-F					Mechanical joint	Mortar grouted sleeve joint	D22/D29	Mid span
	M-M-S								Shear span
3-1	P-C-F					Prestressing force	Centralized PC steel bars	*φ*26	Mid span
	P-C-S								Shear span
3-2	P-D-F					Prestressing force	Dispersive PC steel bars	*φ*23	Mid span
	P-D-S								Shear span

Φ: diameter *s*: spacing *: top **: bottom

In this study, specimens were divided into three series. Series 1 was a normal reinforced concrete beam with neither joints nor interface. This beam was the reference specimen and was named R-N-N, where the first letter R stands for "Reference", the second letter N stands for "No mechanical joint and No prestressing", and the third letter N stands for "No interface". Series 2 consisted of two specimens which were connected by mechanical joints and were named M-M-F and M-M-S, where the first letter M stands for "Mechanical joints" and the third latter stands for "location of the interface, F for constant bending span and S for constant shear span". Finally, series 3 consisted of four specimens which were connected by prestressing force and were named P-C-F and P-D-F, where the first letter P stands for "Prestressing". In series 3 only the PC steel bars crossing the interface were spliced. For specimens of M-M-F and M-M-S, mortar grouted sleeve joints were used on all longitudinal reinforcement. In series 3-1, for the specimens P-C-F and P-C-S, centralized setup of PC steel bars (SBPR 930/1080 Φ26) was used with the prestressing force of 393 kN in each bar, which was located at 200 mm depth as shown in section B-B' of Fig. 1. In series 3-2, for specimens P-D-F and P-D-S, dispersive setup of PC steel bars (SBPR 930/1080 Φ23) was used with the prestressing force of 307 kN in each bar, which was located at 115 mm and 285 mm depth, respectively, as shown in section C-C' of Fig. 1.

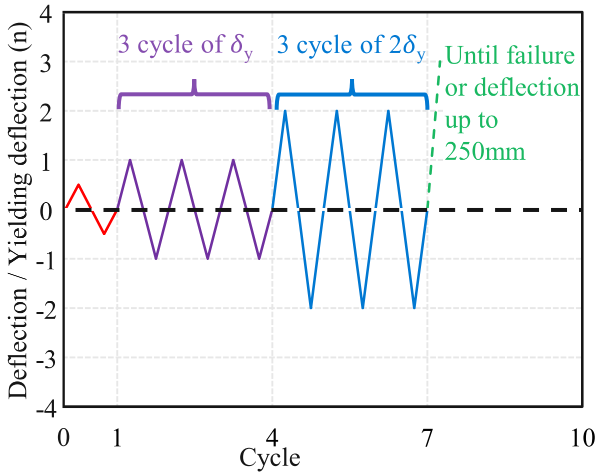

Fig. 2 Loading process

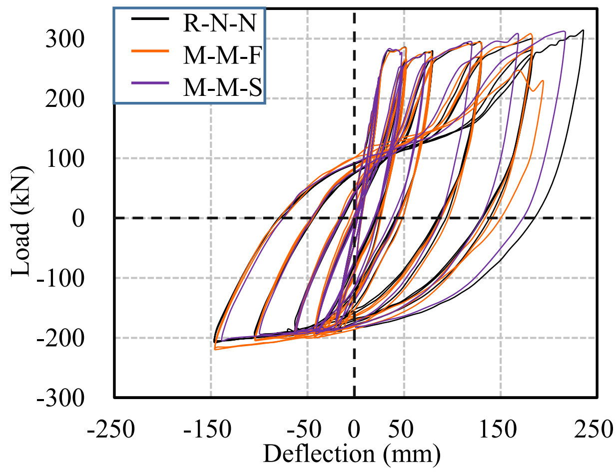

Fig. 3 Load-deflection curve of Series 1 and Series 2

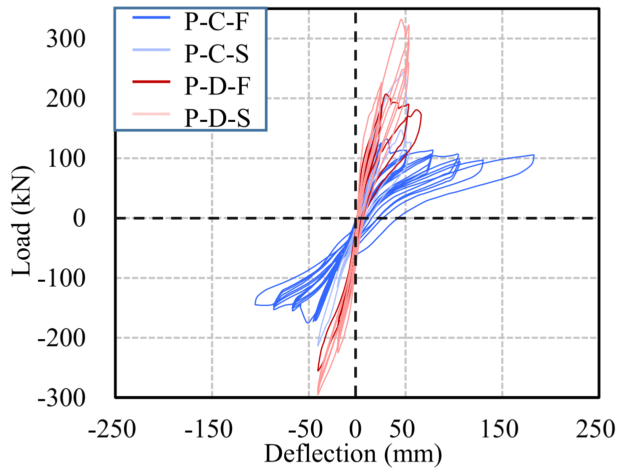

Fig. 4 Load-deflection curve of Series3

2.2 Loading Method

In this study, four-point bending with simply-supported condition was used and it is illustrated in Figure. 1. The hinge supports were set at 400 mm from the ends of specimens while loading points were set 1000 mm from the center of the specimens. Based on the above-mentioned setting, both constant bending span and shear span were 2000 mm in length.

Reversed cyclic loading was applied to the specimens by the following process. First of all, a cycle of loading was applied until the strain of bottom layer reinforcement reached half of the yielding strain. Secondly, the load was increased until the strain of bottom layer reinforcement reached the yielding strain. At this moment mid-span deflection was defined as δ_y. Afterward, two extra cycles of loading with mid-span deflection up to δ_y were applied. Mid-span deflection was increased by δ_y for every three cycles of loading until the failure or the 250 mm of deflection. However, in series 3, δ_y was defined from the experimental result of specimen R-N-N in order to compare with it under the same deflection. During the loading tests, load, mid-span deflection, interface opening were measured and the crack patterns on the surface of each specimen were recorded by pictures.

3. EXPERIMENTAL RESULTS

3.1 Load-deflection relationship

Figure 3 and Fig. 4 shows the load-deflection curves of all specimens and Table 2 shows the detailed results of material tests and loading tests. When the stress of bottom layer reinforcement reached f_y, the mid-span deflection was δ_y and load was $P_{y.exp}$ in the loading tests of series 1 and series 2. Note that, in series 3, none of PC steel bars yielded during the loading test. Also, since specimen R-N-N and M-M-S didn't fail during the loading test, the ultimate load of all specimens is

Table 2 Results of material tests and loading tests

Series	Name	f_y* (N/mm^2)	f_y** (N/mm^2)	f_{pcy} (N/mm^2)	f_c' (N/mm^2)	Yielding load		Ultimate load	
						$P_{y.exp}$ (kN)	$P_{y.exp}$/ $P_{y.R\text{-}N\text{-}N}$	$P_{u.exp}$ (kN)	$P_{u.exp}$/ $P_{u.R\text{-}N\text{-}N}$
1	R-N-N	395.7	354.9	-	66.2	235.1	1.00	313.1	1.00
2	M-M-F			-	65.6	247.9	1.05	308.2	0.98
	M-M-S			-	68.7	234.6	1.00	313.3	1.00
3-1	P-C-F			987	72.3	125.3***	0.53	132.6	0.42
	P-C-S				71.5	187.8***	0.80	244.9	0.78
3-2	P-D-F			1037	68.0	187.8***	0.80	213.8	0.68
	P-D-S				63.9	225.8***	0.96	337.4	1.08

f_y: yielding strength of longitudinal reinforcement, f_{pcy}: yielding strength of PC steel bars, $P_{y.exp}$: experimental yielding load, $P_{u.exp}$: experimental ultimate load, *: top layer reinforcement, **: bottom layer reinforcement, ***: In series 3, the yielding load was defined when the mid-span deflection reached to δ_y defined in series 1.

Table 3 Mid-span deflection

Series	Name	δ_y (mm)	δ_u (mm)	δ_u $/\delta_{uR\text{-}N\text{-}N}$	Cycle$_u$*
1	R-N-N	25.3	234.3	1.00	$9\delta_y$-1
2	M-M-F	25.9	179.7	0.77	$7\delta_y$-1
	M-M-S	23.9	215.3	0.92	$9\delta_y$-1
3-1	P-C-F	24.7	32.6	0.14	$2\delta_y$-2
	P-C-S	25.1	49.4	0.21	$2\delta_y$-1
3-2	P-D-F	25.4	32.2	0.14	$2\delta_y$-1
	P-D-S	25.3	46.2	0.20	$2\delta_y$-1

*: nδ_y-k represents in the kth cycle of loading that mid-span deflection up to nδ_y.

defined to be the maximum load that was detected during the loading tests.

Although loading tests on specimen R-N-N and M-M-S were stopped before the failure, it can still be observed in Table 2 that the existence of mechanical joints has insignificant effect on the $P_{y.exp}$ and $P_{u.exp}$. On the contrary, in series 3, both $P_{y.exp}$ and $P_{u.exp}$ tended to decrease compared with the reference beam excluding specimen P-D-S. With the use of dispersive PC steel bars, $P_{y.exp}$ and $P_{u.exp}$ can be improved. In series 3-2, $P_{y.exp}$ and $P_{u.exp}$ of specimen P-D-S were increased about 20% and 40%, respectively. Meanwhile, $P_{u.exp}$ of specimen P-D-F were increased about 40% comparing to series 3-1. In fact, the ultimate load of specimen P-D-S was even higher than the reference beam.

Table 3 shows the measured mid-span deflection in different cycles during the loading test. δ_u and Cycle$_u$ represent the mid-span deflection and loading cycle when the ultimate load occurred, respectively. In this study, they were considered to represent the deformation performance and ductility of a specimen. It can be observed that the existence of mechanical joints has insignificant effect on δ_y. Under the ultimate load, the mid-span deflections were decreased slightly due to the existence of mechanical joints especially with the interface and joints located in equal flexural span. Besides, the mid-span deflection of all specimens in series 3 were about 86% and 80% smaller than that of the reference beam when the interface located in equal flexural span and shear span respectively. This indicated the negative effect of prestressing force on deformation performance. Regarding the loading cycle, in series 2, it was slightly affected when the interface located in equal flexural span.

To conclude, by experimental results, the mechanical joints merely caused slight reduction of ductility and deformation performance. Meanwhile, their insignificant effect on both $P_{y.exp}$ and $P_{u.exp}$ all referred that, it is reasonable to consider that mechanical joints have no harmful effect on the flexural performance of PCa beams. Moreover, centralized PC steel bars led to decrease in $P_{u.exp}$ and deformation performance. However, $P_{u.exp}$ can be improved by using dispersive PC steel bars for the effective depth is increased.

3.2 Interface opening

Load-interface opening curves during the loading test were illustrated in Fig. 5 and Fig. 6 while Table 4

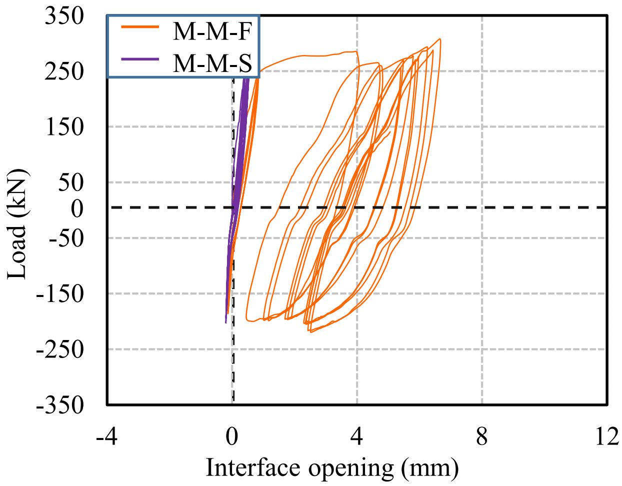

Fig. 5 Load-interface opening curve of Series 2

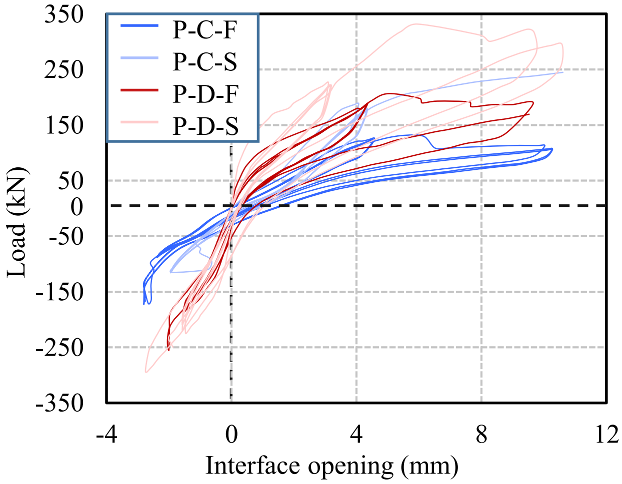

Fig. 6 Load-interface opening curve of Series 3

Table 4 Interface opening during cyclic loading

Name	δ_y			$2\delta_y$			w_{max} (mm)
	w_1 (mm)	w_2 (mm)	w_3 (mm)	w_1 (mm)	w_2 (mm)	w_3 (mm)	
M-M-F	0.82	0.84	0.85	4.00	4.71	4.80	6.60
M-M-S	0.37	0.40	0.40	0.52	0.51	0.51	0.61
P-C-F	4.58	4.57	4.55	10.03	10.27	10.27	10.27
P-C-S	4.07	4.34	4.35	10.60	-	-	10.60
P-D-F	4.36	4.30	4.28	9.66	-	-	9.66
P-D-S	3.11	3.17	3.20	9.69	10.58	-	10.58

w_n: Maximum interface opening in n^{th} cycle of loading.
w_{max}: Maximum interface opening in the loading test.

shows the maximum width of interface opening at each cycle of loading. Note that, the negative values in Fig. 5 and Fig. 6, were caused by the crushed concrete near the top of specimens. By comparing the curves in the same series in Fig. 4, it can be observed that the interface openings became smaller with the interface and joints located in shear span regardless of the type of connection.

Note that, smaller flexural moment was applied on the interfaces located in the shear span, therefore, inducing smaller interface opening. Besides, in Table 4, in series 3, the interface openings were much higher than that of specimens in series 2 although the improvement can be made through the use of dispersive PC steel bars in series 3-2. In Table 4, it can be noticed that the

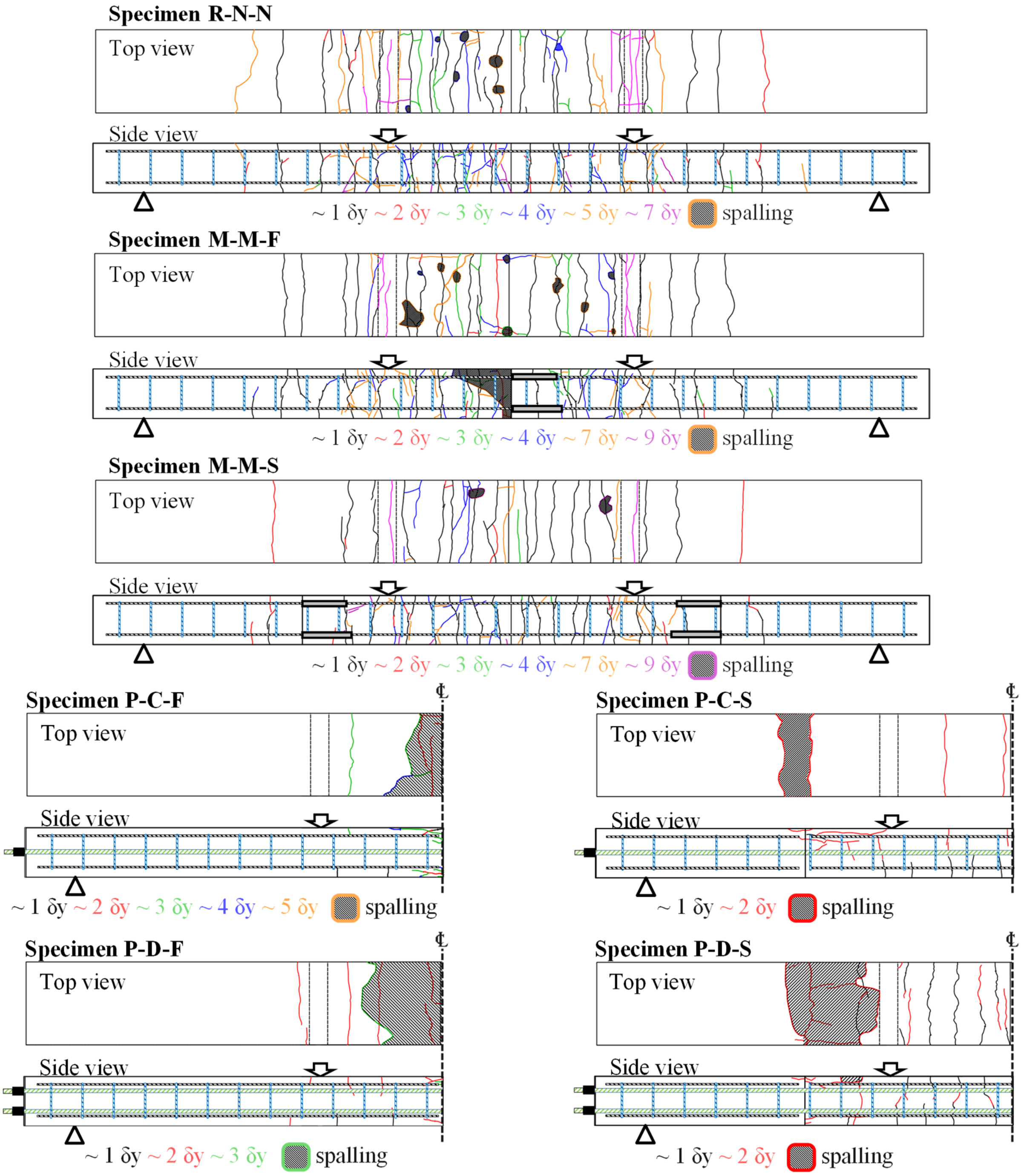

Fig. 7 Crack patterns of specimens

interface openings were stable in the first 3 cycles of loading when the mid-span deflection was below δ_y. However, almost all interface openings were increased for more than 200%, as the mid-span deflection grew to be $2\delta_y$, which indicates low resistance against the interface opening after bottom layer reinforcement yielded. The observation mentioned above were more significant in specimens connected by prestressing force.

3.3 Crack Pattern and Failure Mode

Figure 7 shows the crack patterns of all specimens. As mentioned above, loading tests on the specimen R-N-N and M-M-S were ceased before the flexural failure. In Fig. 7, neither of diagonal cracks were observed nor spalling occurred on the top of all specimens, which represented all specimens failed in flexure in positive direction.

As for the reference beam, cracks were mainly concentrated in equal flexural span and all developed vertically due to the tensile stress caused by flexural moment instead of shear force. Meanwhile, the failure mode of the reference beam was assumed as following, after the bottom layer reinforcements yielded, increasing load led to the crush of topside concrete and induced the failure of the specimen. Despite no sign of decrement of loading force, the crush of concrete can be predicted by the observation of spalling on the top of the specimen.

In series 2, mechanical joints were used as connection, and the distributions of cracks were similar to that in the reference beam with the only difference that cracks did not occur in the area with mechanical joints.

Regarding the failure mode, in specimen M-M-F, spalling occurred in the segment without mechanical joint near the interface because smaller compressive stress was applied on the concrete of the other side due to the high stiffness caused by mechanical joints. Despite the difference of concrete spalling, the failure modes were the same.

In series 3-1, with the application of centralized PC steel bars, the amount of vertical developed cracks was decreased and spalling area was increased comparing to the reference beam. Meanwhile, the horizontally developed cracks occurred near the interface regardless the location of it. The observation was caused by concentration of concrete's deformation. In specimen P-C-F, there were almost no cracks in the shear span. On the contrary, in the specimen P-C-S, cracks occurred in the shear span only on the top side. By mention of failure mode, the segments were only connected by centralized PC steel bars which led to the concentration of deformation near the interface and furthermore induced horizontal cracks and large area of spalling. These changed the failure mode of specimens by causing different crushed concrete.

In series 3-2, dispersive PC steel bars were used and led to not only decrease of horizontally developed cracks but also the increase of vertically developed cracks and spalling area comparing to series 3-1. Regardless of this observation, the crack patterns were similar to series 3-1 as well as failure mode except for the increased in crushed concrete.

To conclude, first, mechanical joints had no significant effect on crack patterns and failure mode while the prestressing force did. Meanwhile, in series 3 it caused different locations of horizontally developed cracks and spalling. Last, in series 3, combined with observation of interface opening mentioned above, the deformation and crush of concrete concentrated near the interface regardless its location, in terms of flexural performance, the structural behavior of these specimens was closer to the beam with pin joints instead of the beam with rigid joints.

4. CONCLUSIONS

Reversed cyclic loading tests on 7 PCa beam specimens with different types of connection were conducted in order to investigate the flexural performance. Corresponding results are shown and discussed respectively in previous chapter. The conclusions can be summarized as follows:

(1) All specimens were to be flexural failure and fail in positive direction as they were designed.
(2) Mechanical joints have no harmful effect on the yielding load, ultimate load and ductility of PCa beams.
(3) Prestressing force decreases the ultimate load and deformation performance of beams, but loading capacity of them can be improved by vertically dispersive arrangement of PC steel bars.
(4) Prestressing force decreases the amount of vertical cracks but increases the spalling area and amount of horizontal cracks near the interface.
(5) Flexural behavior of PCa beams connected by prestressing force was similar to beams with pin connection instead of rigid connection.

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