- Technical Paper -

FLEXURAL PERFORMANCE OF RC BEAMS WITH INTERFACE AND VARIOUS CONNECTIONS

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ABSTRACT

This paper discusses the flexural performance of RC beams with interface and joints. Experiments of RC beams with concrete members cast respectively and different types of connection methods were examined. The experimental parameters were the position of joints and types of connectors between concrete members. The results revealed that the crack distribution, the crack width and the opening of interface were affected by the joints. However, the flexural capacity of beams with different concrete members and connectors were in good agreement with the calculation values of normal RC beams.
Keywords: flexural performance, RC beam, connection method, joint, interface

1. INTRODUCTION

Recently, precast concrete members are widely used in the construction site of buildings, bridges, box culverts and so on. As precast concrete is cast in a factory in advance, a precast concrete system offers many potential advantages over onsite casting. Since precast concrete is manufactured in a controlled environment such as factories, it is easier to control the mix, placement and curing. Precast members can be installed immediately on site and there is no waiting for it to gain strength, which makes installation go quickly. Considering precast concrete members are required to be connected on site, connection methods are necessary. The most common method of attachment of precast members is by using of steel weld plates. Typically, the precast members have embedded plates that can be used as welding surfaces. However, for some important structure members, there is more stable connection method, which is using rebars and joint. In this connection method, reinforcing bars are spliced into members and then connected on site.

According to the JSCE specifications for concrete [1], there are various connection methods for rebar joints, such as welding, lapping, and sleeve. And it is also mentioned that when rebar joints are used, experiments are required to ensure that the joints have no significant negative effects on the structural performance.

This study aimed to investigate the effects of different types and locations of joints between concrete members on the flexural performance of RC beams. According to the previous researches [2] [3], the connection method of ribbed-shaped section with loop joints which can be constructed by non-shrink mortar has been proposed because of the good performance. But there was no discuss about other kinds of joints. So in this study, other joints such as plane section with lapping joint and sleeve joint were used. Sleeve joints included threaded sleeve joint and mortar grouted sleeve joint. One reference beam and six beams with different kind of joints were tested. Flexural capacities, crack patterns and interface opening were discussed in this paper.

2. EXPERIMENTAL PROGRAMS

2.1 Test Specimens and Materials

The cross section and steel reinforcement arrangement of tested specimens are illustrated in Fig.1. And Table 1 summarizes detailed mechanical properties. All the specimens were designed to fail in flexure. The cross section was the width of 430 mm and the height of 200 mm. Length of the shear span and the pure bending region were 900 mm and 800 mm, respectively. And the effective depth was 140 mm. These specimens were divided into two series, which were “M” series and “S” series. “M” meant that the joint was in the midspan where the bending moment was constant and shear force was zero and “S” meant that the joint was in the middle of the shear span.

Three longitudinal D16 tensile reinforcements (A_s=595.8 mm^2) with nominal diameter of 15.9 mm and design yield strength of 295 N/mm^2 were used in all seven specimens. D10 stirrups with design yield strength of 295 N/mm^2 were used near the support point to ensure the anchorage. To simulate the connection between precast members and cast-in-place concrete members, concrete members were cast respectively. Concrete with design cylinder compressive strength of 30 N/mm^2 and 21 N/mm^2 were used to simulate precast concrete and cast-in-place concrete, respectively. And the precast members were cast 5 days earlier than the cast-in-place concrete members. In the reference specimen of REF,

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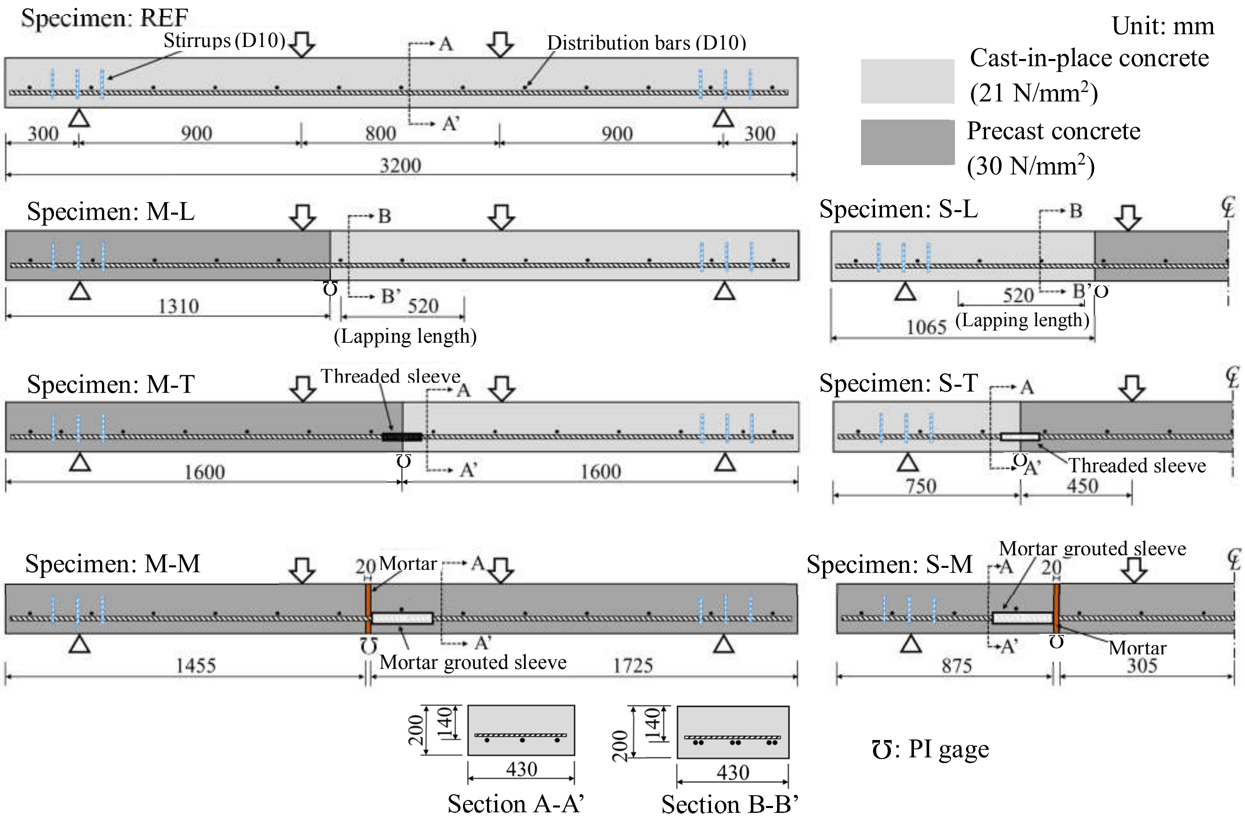


Fig.1 Specimen dimensions

Table 1 Specimens' details and material properties

Series	Specimen	Concrete	Tensile reinforcements	f_{cd}' (N/mm^2)	f_{pcd}' (N/mm^2)	Connector		Joint location
Reference	REF	Cast	D16×3	21	-	-		-
M	M-L	Precast &cast			30	Lapping		Pure bending region
	M-T					Threaded sleeve	Outside diameter: 26.5 mm	
							Length: 154 mm	
	M-M					Mortar grouted sleeve	Outside diameter: 45 mm	
							Length: 245 mm	
S	S-L	Precast &cast				Lapping		Shear span
	S-T					Threaded sleeve	Outside diameter: 26.5 mm	
							Length: 154 mm	
	S-M	Precast				Mortar grouted sleeve	Outside diameter: 45 mm	
							Length: 245 mm	

f_{cd}': design cylinder compressive strength of cast-in-place concrete;
f_{pcd}': design cylinder compressive strength of precast concrete

there were no joints of tensile reinforcements. In specimens of M-L and S-L, lapping joints of tensile reinforcements were used. And the length of lapping joint was calculated to be 520mm. In specimens of M-T and S-T, threaded sleeve joints of tensile reinforcements were used. In specimens of M-M and S-M, mortar grouted sleeve joints of tensile reinforcements were used. And the mortar with design compressive strength of 70 N/mm^2 was filled in the sleeve and also the interface between two concrete members. Besides, in this study, there were no stirrups in the test span and D10 distribution steel bars with design yield strength of 295 kN/mm^2 were used to simulate the steel bar arrangement in a box culvert.

2.2 Loading Method and Instrumentation

A four-point bending with simply-supported condition was provided to all specimens as illustrated in Fig.1. Teflon sheets and grease were inserted between specimen and supports in order to prevent horizontal friction. Displacement transducers, concrete strain gages and steel strain gages were used to measure displacement and strains during loading test. Moreover, PI gages were attached under the interface to measure the interface opening between the precast and cast-in-place concrete.

Loading process was determined as shown in Fig.2. Considering the allowable stress of steel bars defined in the Specifications for Highway Bridges [4], there were three levels of load in this study. The first level was 3 cycles of 30 kN, which was corresponding to 180 N/mm^2 stress of tensile reinforcements. 180 N/mm^2 was the allowable stress considering the durability and serviceability. Cracks of specimens should be few and short under this stress. The second level was 1 cycle of

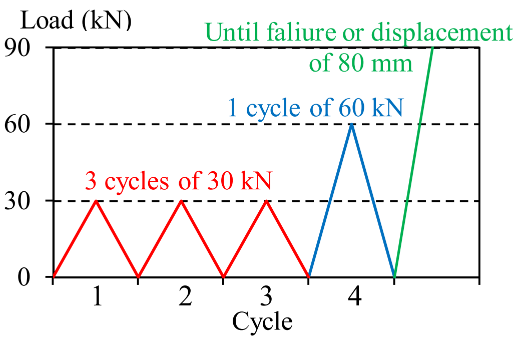


Fig.2 Loading process

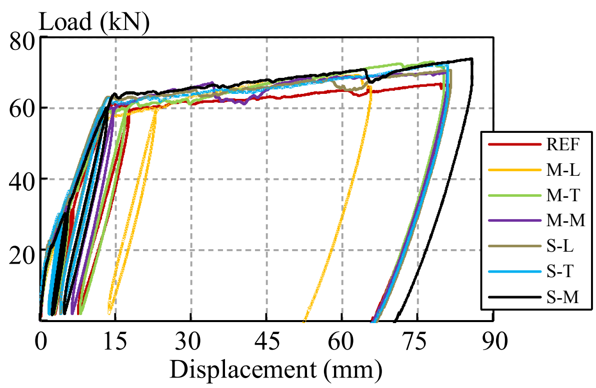
60kN, which was corresponding to the experimental yield strength of tensile reinforcements, which was 374 N/mm^2. Tensile reinforcements yielded at this load and there should be no brittle failure. The third level was until that concrete crushed in the compression zone or the displacement of the mid span reached 80 mm. In addition, the crack pattern on the surface of specimen during the loading test was captured by taking photos every 5 kN. And the crack width was measured by the crack width ruler.

3. EXPERIMENTAL RESULTS AND DISCUSSION

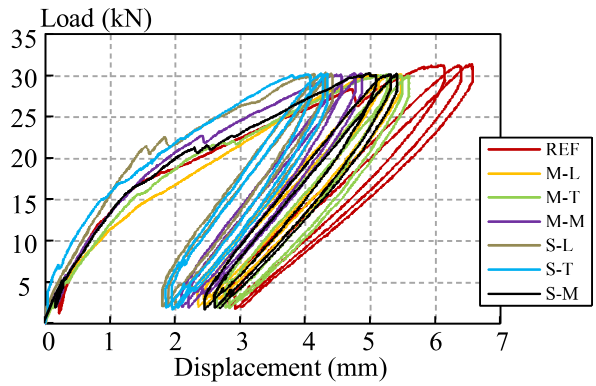
3.1 Load-displacement Curves

Table 2 shows the results of the calculated value and experimental value of the yielding load and ultimate flexural capacity. Fig. 3 shows the load-displacement curves of all specimens. As no concrete crushed, the yielding load of specimen referred to the load when the flexural tension failure was assumed. The ultimate compressive strain of concrete was assumed as $\varepsilon_{cu}'=0.0035$ and the calculated value of $P_{y.cal}$ in Table 2 was obtained according to the JSCE specifications [1]. And the experimental value of yielding load $P_{y.exp}$ was the applied load when all longitudinal reinforcements yielded and also the applied load where the inclination of load-displacement curve, as shown in Fig. 3, changed significantly. The displacement in Fig. 3 was the displacement in the mid span. As no significant drop of the applied load occurred during loading tests, the value of ultimate flexural capacity $P_{u.exp}$ in Table 2 referred to the load just before the unloading.

From the experimental results it can be found that all specimens failed in flexure as all longitudinal reinforcements yielded before the unloading. And there was no significant diagonal cracks occurred in any specimen. The experimental yielding load of all specimens was in good agreement with the calculation capacity and the difference was less than 10%. However, taking the location of joint into consideration, it could be found that "S" series specimens had slightly higher yielding load than "M" series specimens. And when the joint was in the location where flexural moment was higher, the yielding load would be slight lower. It can be thought that the existence of interface had slightly negative effect on the bending resistance because the tensile stress of longitudinal reinforcement crossing the interface became larger with the interface opening.



(a) The whole period of loading test



(b) The period of first 3 cycles (0~30 kN)

Fig. 3 Load-displacement curves

Table 2 Summary of experimental results

Specimen	f_y (N/mm^2)	f_c' (N/mm^2)	f_{pc}' (N/mm^2)	Yielding load			Ultimate flexural capacity		
				$P_{y.cal}$ (kN)	$P_{y.exp}$ (kN)	$P_{y.exp}/P_{y.cal}$	$P_{u.cal}$ (kN)	$P_{u.exp}$ (kN)	$P_{u.exp}/P_{u.cal}$
REF	374	29.7	-	62.1	61.3	0.99	65.1	66.6	1.02
M-L		32.3	37.1	61.9	56.4	0.91	65.5	69.3	1.06
M-T		32.3	37.1	61.8	58.6	0.95	65.2	73.0	1.12
M-M		-	62.2	62.9	59.0	0.94	67.4	70.0	1.04
S-L		54.2	67.2	62.3	63.1	1.01	66.0	70.7	1.07
S-T		54.2	67.2	61.8	62.7	1.01	65.2	72.2	1.11
S-M		-	67.2	62.9	64.0	1.02	67.4	73.9	1.10

f_y: experimental yield strength of tensile reinforcements; f_c': experimental cylinder compressive strength of cast-in-place concrete; f_{pc}': experimental cylinder compressive strength of precast concrete

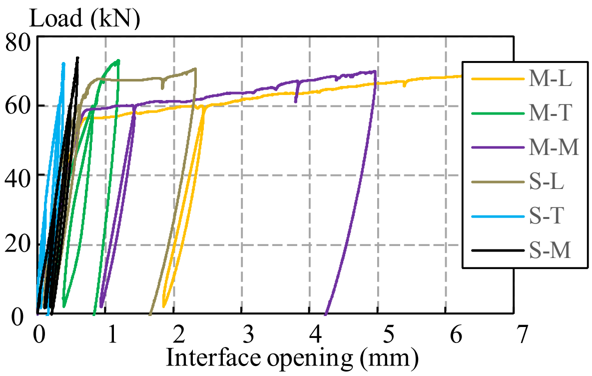
Table 3 Mid-span displacement during cyclic loading

Specimen	1st cycle (30 kN)		2nd cycle (30 kN)		3rd cycle (30 kN)		4th cycle (yield)	
	δ_{30} (mm)	δ_{re} (mm)	δ_{30} (mm)	δ_{re} (mm)	δ_{30} (mm)	δ_{re} (mm)	δ_{y} (mm)	δ_{re} (mm)
REF	5.53	2.83	6.14	2.93	6.34	3.03	14.42	4.56
M-L	4.95	2.36	5.24	2.45	5.40	2.54	12.06	3.15
M-T	5.16	2.65	5.47	2.79	5.56	2.85	13.77	5.46
M-M	4.40	2.11	4.69	2.21	4.82	2.27	12.24	4.16
S-L	4.09	1.80	4.26	1.89	4.37	2.00	13.51	4.08
S-T	3.83	1.77	4.10	1.89	4.20	1.95	13.60	4.20
S-M	4.86	2.49	5.24	2.62	5.38	2.71	14.70	4.88

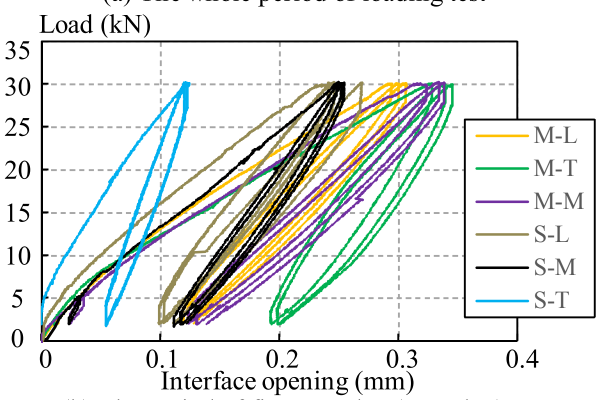
δ_{30}: the displacement of mid span when the load was 30 kN; δ_{re}: the residual displacement of mid span when unloading to 2 kN; δ_{y}: the mid displacement when all tensile reinforcements yielded

As Fig. 3 (a) shows, all specimens had good ductility. After tensile reinforcements yielded, the load could still rise slowly and no sudden drops occurred until unloading. It can be also found from Table 2 that the ultimate flexural capacity of all specimens was slightly higher than the calculation value, which indicates that the calculation methods were also applicable to specimens with the interface and stable joints such as lapping joint with enough lapping length, threaded sleeve joint and mortar grouted sleeve joint. The load-displacement curves during cyclic loading is illustrated in Fig. 3 (b) and the displacement of 30 kN and the residual displacement after unloading are listed in Table 3. Although the displacement of 30 kN and residual replacement after unloading increased as the loading cycle increased, but the increment was only 0.5 mm or less, which was less than 10%.

According to the results and discussions mentioned above, when the stress in tensile reinforcements was less than the allowable stress required by the Specifications for Highway Bridges [4], the specimens with various kinds of connection methods in different locations, including lapping joint, threaded sleeve joint and mortar grouted sleeve joint, had similar load-displacement curves as the specimen without the interface or joint during cyclic loading, which was specimen REF (Fig. 3 (a)).



(a) The whole period of loading test



(b) The period of first 3 cycles (0~30 kN)

Fig.4 Load-interface opening curves

3.2 Interface Opening

Load-interface opening curves during loading test are illustrated in Fig. 4. As shown in Fig.4 (a), the interfaces between concrete members of all specimens opened with the increase in load. By comparing the curves of "M" series specimens and "S" series specimens, for instance M-L and S-L, it can be found that interface openings of "S" series were smaller than "M" series after the tensile reinforcements yielded. Note that the location of the interface, there was smaller flexural moment in the interface of "S" series than the interface of "M" series, although the shear force was higher. Thus it can be thought that under the same conditions, after tensile reinforcements yielded, higher flexural moment would cause wider interface opening. Moreover, according to the comparison of the curves of M-L, M-T and M-M, it can be considered that on the condition of the same flexural moment, the interface opening with lapping joint was much wider than the other two kinds

Table 4 Interface opening during cyclic loading

No.	1st cycle		2nd cycle		3rd cycle	
	w_{int} (mm)	w_{re} (mm)	w_{int} (mm)	w_{re} (mm)	w_{int} (mm)	w_{re} (mm)
REF	-	-	-	-	-	-
M-L	0.29	0.12	0.30	0.12	0.30	0.13
M-T	0.33	0.19	0.34	0.20	0.34	0.20
M-M	0.31	0.12	0.33	0.13	0.34	0.14
S-L	0.24	0.10	0.24	0.10	0.27	0.11
S-T	0.12	0.05	0.12	0.05	0.12	0.05
S-M	0.22	0.09	0.23	0.09	0.23	0.10

w_{int}: the interface opening when applied load was 30 kN;
w_{re}: the residual interface opening when unloading to 2 kN.

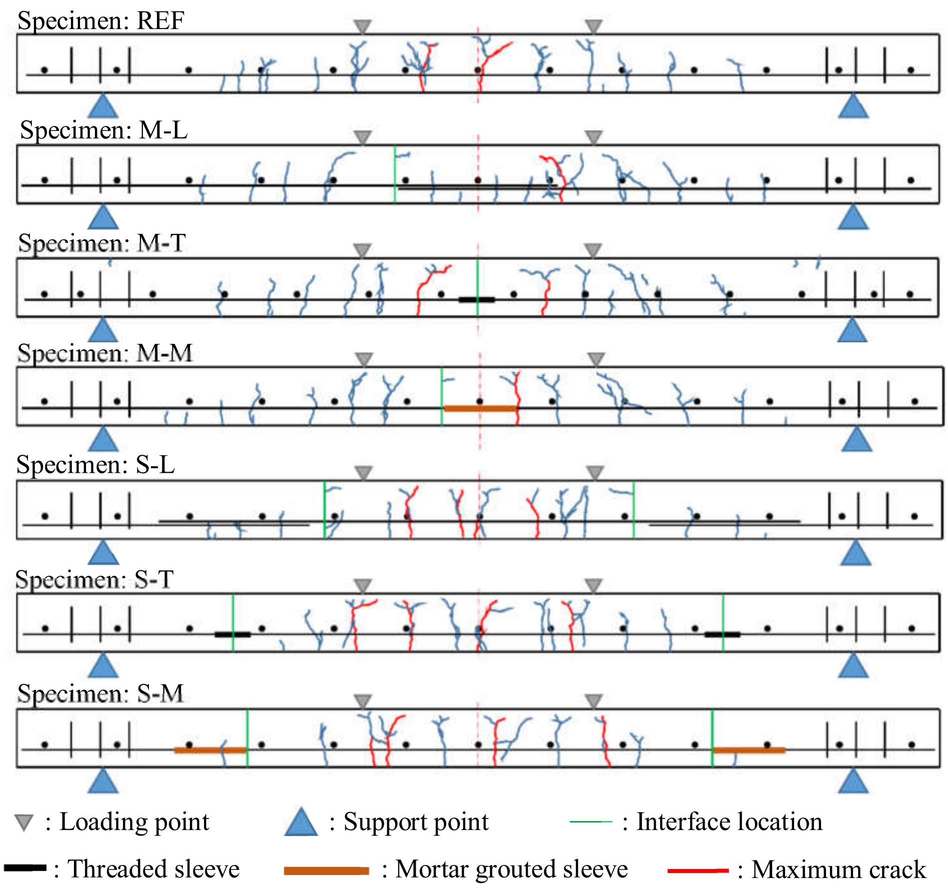


Fig. 5 Crack patterns of specimens

of joint after the tensile reinforcements yielded.

The interface opening curves during the period of first 3 cycles are illustrated in Fig. 4 (b). The interface opening of all specimens was less than 0.4 mm. Taking the interface position into consideration, the flexural moment on the interface of S-T was the smallest. So the specimen S-T with threaded sleeve joint has the narrowest interface opening. And during the cyclic loading, the interface opening of peak load (30 kN) and the residual opening increased slightly, which showed stable connection of specimens with different connection methods. The specific values are listed in Table 4.

3.3 Crack Patterns

Figure 5 shows the crack patterns of all specimens just before unloading. The red solid lines were the maximum cracks, the green solid lines were the location of the interfaces, the black blocks were the threaded sleeves and the orange blocks were the mortar grouted sleeves. As the figures showed, the cracks of all specimens were almost in the vertical direction, which were mainly caused by flexural moment. In the reference specimen REF, the maximum cracks were mainly concentrated in the mid span. And the spacing between cracks was nearly the same. However, in the specimen M-L, the cracks in the mid span were much narrower and shorter than the reference specimen. As the lapping joints were located in the mid span, the tensile reinforcement ratio in the mid span was higher than the reference specimen. And cracks at both sides of the joint became longer and wider than the cracks in the mid span. In the M-T and M-M specimens, cracks in the mid span were also fewer than the reference specimen. Considering the interface opening in the mid span, it can be thought that the number of cracks became fewer because of the existence of an interface.

When the joint was in the shear span, as S-L, S-T and S-M specimens, the cracks were mainly concentrated in the mid span, which was similar to the reference specimen. And effects of the joint on cracks were not significant as the joint in middle of the constant span.

As mentioned above, the interface openings in “M” series specimens were much wider than that in “S” series specimens. Therefore, the interface opening of “M” series could be also taken into consideration when the crack patterns were discussed. The results of the comparison among interface opening and crack width are listed in Table 5. The experimental value of the width of the maximum crack w_{exp} was obtained by using the crack width ruler and the calculated value of w_{cal} was obtained by the JSCE specifications for concrete as the following Equation (1) [1]. This equation was used to estimate the width of cracks in normal reinforced concrete beams under bending moment. In order to find out if this equation was adapted to estimate the width of cracks in reinforced concrete beams with joints and the width of interface opening, the comparison among them were also listed in the table.

$$w = 1.1k_1k_2k_3\{4c + 0.7(c_s - \phi)\}\left[\frac{\sigma_{se}}{E_s} + \varepsilon'_{csd}\right] \quad (1)$$

Table 5 The comparison among crack width and interface opening

No.	Location of maximum crack	3rd cycle of 30 kN					4th cycle of yielding				
		w_{cal} (mm)	w_{exp} (mm)	w_{exp}/w_{cal}	w_{int} (mm)	w_{int}/w_{cal}	w_{cal} (mm)	w_{exp} (mm)	w_{exp}/w_{cal}	w_{int} (mm)	w_{int}/w_{cal}
REF	Mid span	0.31	0.25	0.81	-	-	0.63	0.55	0.87	-	-
M-L	End of joint	0.30	0.30	1.00	0.30	1.00	0.57	2.50	4.39	0.79	1.39
M-T	Mid span	0.31	0.15	0.48	0.34	1.10	0.60	1.00	1.67	0.82	1.37
M-M	End of joint	0.27	0.20	0.74	0.34	1.26	0.53	0.30	0.57	0.79	1.49
S-L	Mid span	0.27	0.20	0.74	0.27	-	0.56	0.45	0.80	0.62	-
S-T	Mid span	0.27	0.05	0.19	0.12	-	0.55	0.25	0.45	0.35	-
S-M	Mid span	0.27	0.15	0.56	0.23	-	0.57	0.70	1.23	0.52	-

w_{exp}: experimental value of maximum crack width; w_{cal}: calculation value of crack width;
w_{int}: experimental value of interface opening width

Where, w is the crack width, k_1 is a constant to take into account the effect of surface geometry of reinforcement on crack width, k_2 is a constant to take into account the effect of concrete quality on crack width, k_3 is a constant to take into account the effect of multiple layers of tensile reinforcement on crack width, c is the concrete cover, c_s is the center-to-center distance of tensile reinforcements, ϕ is the diameter of tensile reinforcement, σ_{se} is the increment of stress of reinforcement, E_s is the elastic modulus of reinforcement, ε_{csd}' is the compressive strain for evaluation of increment of crack width due to shrinkage and creep of concrete.

As the table shows, in the reference specimen, the maximum width showed good agreement with the calculation value, where the deviation was less than 20%. In “M” series, considering the location of interface was also in the mid span, the width of interface opening was also compared with the calculation value. During 3 cycles of 30 kN, the width of interface opening was in good agreement with the calculation value and the width of maximum crack was smaller except M-L. During the 4th cycle of yielding, compared to the calculation crack width, the width of interface opening was higher, where the deviation was less than 50%. However, the maximum crack width was quite different from the calculation. Hence, when the joint was in the flexural span, Equation (1) was adaptable to estimate the width of interface opening. But for the maximum crack width, the result of Equation (1) was not accurate enough.

In “S” series, the location of joint was in shear span, where the flexural moment differed from the mid span. Therefore, the interface opening width was not compared to the calculation. As the table shows, during 3 cycles of 30 kN and 4th cycle of yielding, the maximum crack width was smaller than the calculation, except the specimen S-M. Therefore, when the joint was in the shear span, Equation (1) can still be a conservative way to estimate the maximum crack width.

4. CONCLUSIONS

According to the experiment results of RC beams with interface and various methods of joints mentioned above, the following conclusions may be deduced:

(1) The connection methods of lapping joint, threaded sleeve joint and mortar grouted sleeve joint had no significant influence on the failure mode of RC beams. And all connections were stable during cyclic loading under allowable stress of tensile reinforcements.

(2) In this paper, specimens with joint in the flexural span had slightly lower yielding load. The existence of interface had negative effect on the yielding load because the interface opening would increase the stress of tensile reinforcements crossing the interface. So the joint should be settled in the location where the flexural moment was not high to reduce the negative effect.

(3) When the joint was in the location with high flexural moment, maximum cracks tended to occur on the end sides of the joint. It can be thought that within the region of joint, the strain became smaller because of the sleeve or the lapping tensile reinforcements. And at the end of the joint, the strain became larger and cracks tended to occur easily.

(4) The equation for estimating the width of cracks in RC beams was adapted to estimate the interface opening width when the joint was in flexural span.

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