- Technical Paper -

INFLUENCE OF JOINT POSITION ON SHEAR BEHAVIOR OF SEGMENTAL CONCRETE BEAMS WITH EXTERNAL TENDONS

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ABSTRACT

This paper presents a study on the structural behavior of segmental concrete beams with external prestressing, focusing on the response of the beams under shear considering the joint position in the shear span. Three segmental concrete beams prestressed with external tendons and with different positions of the segmental joint in shear span have been tested to investigate the shear failure mechanisms. The experimental results with emphasis on the effects of epoxied joint position have shown the difference in the shear failure mechanism.

Keywords: joint position, prestressed concrete, segmental concrete beam, external tendon, shear response

1. INTRODUCTION

External prestressing was developed in the early period of prestressed concrete bridges. The application of external prestressing with the precast segmental construction has been first developed with the span-by-span method. Because of substantial cost and time saving in construction, this method has been extensively developed and efficiently used in many bridge constructions. In recent years, the application of external prestressing is becoming more popular and widely used for bridge structures.

For the development of external tendons, many tests of externally prestressed structures have been carried out to study the effects of flexure and shear behaviors. A beam resists loads primarily by means of internal moment, M, and shear, V. When the flexure failure occurs in the concrete structure, especially in prestressed concrete structures, there is enough time to warn people about this failure before the total collapse. However, the shear failure is usually sudden and brittle. For this reason, the design for shear failure must be studied carefully to ensure that the concrete structure is safe from the shear failure. Moreover, understanding shear in concrete structures has still challenged researchers, especially in segmental concrete structures prestressed with external tendons.

For the last decade, many parameters were applied to investigate the shear failure in segmental concrete structures prestressed with external tendons in both experiment and analysis, such as: effective internal or external prestressing [1], shape of shear key and epoxy or dry joint [2], single shear key [3], simplified truss model [4], FEM analysis [5], etc. However, the influence of the joint position has not been mentioned in those studies.

In order to obtain more knowledge of the shear behavior of precast segmental concrete structures prestressed with external tendons, an experimental program was carried out with simply supported beams. The objective of this study is to investigate the influence of the joint position in shear span on the shear failure mechanism.

2. TEST PROGRAM

Three simply supported beams, designed to fail in shear, were used. They were precast segmental concrete beams with the identical parameter on the test span for comparing shear behavior. All test specimens were T-shaped section beams with span length of 3.2 m and two deviators with a distance of 1.367 m between them located symmetrically from the midspan, as shown in Fig. 1. The distance from the loading point to the joint position, a_j was considered as the main parameter in this study. This distance was taken equal to 0.5d, 1.5d and 2.5d, where d is the effective depth of the beams. The segmental concrete beams with the a_j distance of 0.5d, 1.5d and 2.5d were named SJ05, SJ15 and SJ25, respectively, where "SJ" stands for the segmental joint.

2.1 Materials

(1) Reinforcing materials

The arrangement of reinforcement in the beams is shown in Fig. 1(b). The non-prestressed steels were deformed bar with grade SD295A. In all the beams, the longitudinal reinforcements consisted of six deformed bars of D13 at the bottom and eight deformed bars of D10 at the top flange. On the test span, where the joint

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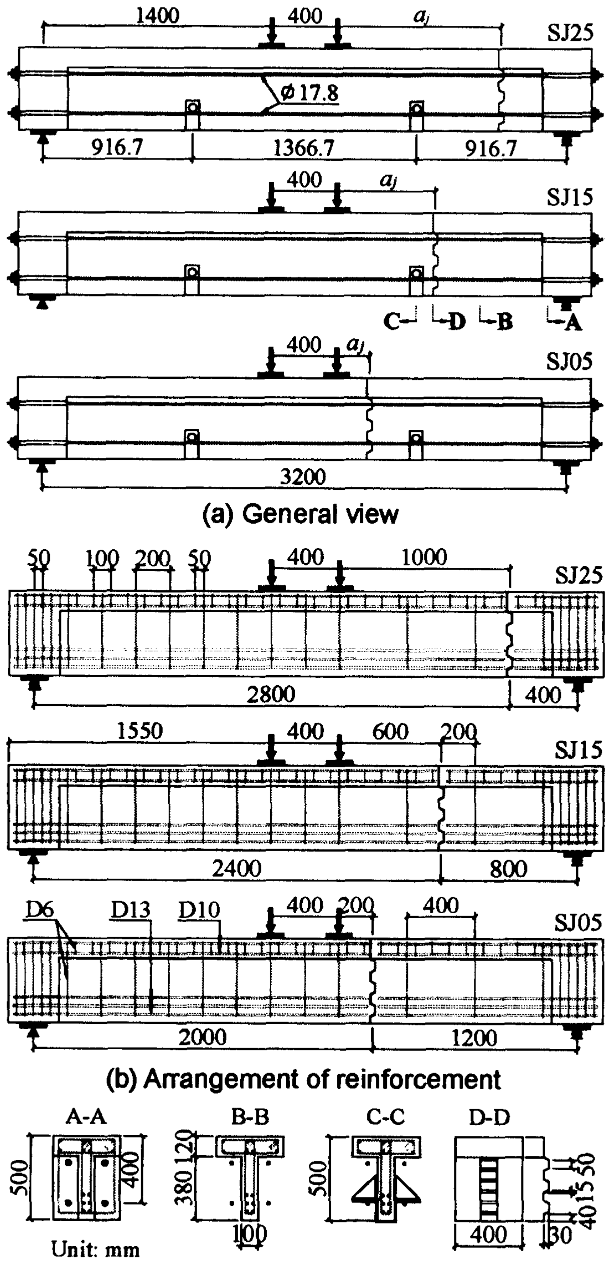


(a) General view

(b) Arrangement of reinforcement

(c) Cross section

Fig. 1 Detail of test beams

Table 1 Characteristics of reinforcement

Type	Yield strength (N/mm^2)	Ultimate strength (N/mm^2)	Young's modulus (kN/mm^2)	Area (mm^2)
SD295 D6	355.7	524.3	200	31.7
SD295 D10	374.6	511.2	200	71.3
SD295 D13	365.7	502.6	200	126.7

Table 2 Characteristics of concrete

Beams	Comp. strength of concrete (N/mm^2)		Tens. strength of concrete (N/mm^2)	
	Match A	Match B	Match A	Match B
SJ25	65.7	68.9	4.0	4.4
SJ15	68.9	64.5	4.4	4.1
SJ05	64.6	61.8	4.1	4.1

Note:
Batch A is for the big segment of beams
Batch B is for the small segment of beams

Table 3 Mix proportion of concrete for 1m^3

W/C	*s/a*	*W*	*C*	*S*	*G*	*SP*
%	%	(kg)	(kg)	(kg)	(kg)	(kg)
43	54.5	168	395	934	792	2.17

Note:
W: Water
C: Early high-strength cement, specific gravity = 3.14
S: Fine aggregate, specific gravity=2.60 F.M. = 2.67
G: Coarse aggregate, specific gravity = 2.64, F.M. = 6.67, G_{max} = 20mm
SP: Super-plasticizer, specific gravity =1.05

Table 4 Characteristics of tendons

Beams	Tendon	Area	Effective prestress (N/mm^2)	
		(mm^2)	Upper	Lower
SJ25	SWPR19L	208.4	566.0	802.3
SJ15	SWPR19L	208.4	616.8	759.7
SJ05	SWPR19L	208.4	601.6	776.3

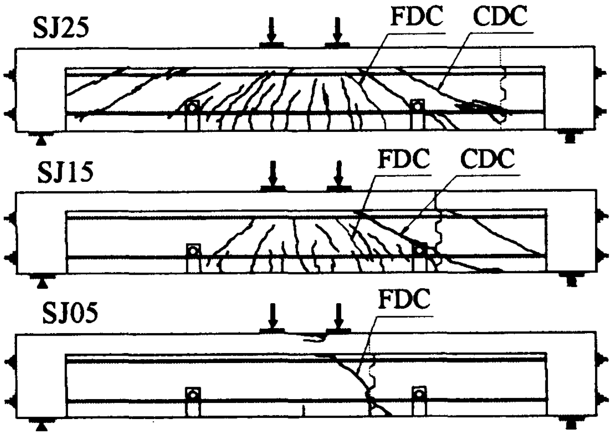
connection was located, the beams were reinforced with D6 stirrup at an interval of 400 mm. The other part of a beam were reinforced with D6 stirrup at an interval of 200 mm. D6 stirrups were also used on the top flange at an interval of 100 mm. The mechanical properties of these reinforcements are given in Table 1. Mesh reinforcement with D6 was utilized at the end of the beam to sustain the local stresses due to prestressing force.

(2) Concrete

The method of casting is the match cast method, in which the first segment was cast with the wood shear key as an end formwork. Three days later, formworks were removed and the first segment was used as a formwork for next casting in order to provide perfect matching between the segments. After casting, concrete was cured in the weather condition. The design strength of concrete, f'_c, was specified as 60 N/mm^2 at 28 days. The actual compressive and tensile strengths in each batch of casting were measured at the day of testing and are shown in Table 2. The mix proportion of the concrete is shown in Table 3.

(3) Prestressing tendons and deviators

The prestressing tendon used for the beams was of type SWPR19L Φ17.8 mm. Yielding and ultimate strengths of the tendon are 1680 N/mm^2 and 1900 N/mm^2, respectively. The external tendons were applied in both tensile zone (lower tendons) and compressive zone (upper tendons) as shown in Fig. 1(a) and were stretched 4 days before testing. At the prestressing stage, the pair of the upper or lower tendons was stretched at the same time from one end by two hydraulic jacks. It has been noted that the higher prestressing force is, the narrower joint opening is. Moreover, it was ensured the whole joint suffers compression and the beam failure occurs in concrete before the yielding of the external tendons. Therefore, the amount of initial prestressing force for upper and lower tendons was approximately 31% and 41% of the ultimate strength of the tendons, f_{pu}, respectively. The actual effective prestress of the tendons is shown in Table 4. Steel deviators were attached to the beams from the bottom to ensure not to



Note:
FDC: The first diagonal crack
CDC: The critical diagonal crack

Fig.2 Crack patterns

Table 5 Test result

Beams	Load (kN)			
	P_{cr}	$P_{di.cr}$	$P_{cdi.cr}$	P_u
SJ25	298.5	340.6	480.3	480.3
SJ15	290.6	341.4	406.8	406.8
SJ05	290.7	327.7	327.9	423.0

Note:
P_{cr}: Load of the first bending crack
$P_{di.cr}$: Load of the first diagonal crack
$P_{cdi.cr}$: Load of the critical crack
P_u: Load of the ultimate stage

obstruct the diagonal crack, since they were located in the shear span.

(4) Epoxy

Epoxy resin was used for the connection of the concrete segments. Prestressing was introduced after the assembling of the concrete segments. The compressive and tensile strengths of epoxy resin were more than 60 N/mm^2 and 12.5 N/mm^2, respectively.

2.2 Loading Method

The beams were subjected to a four point loading with a distance of 400 mm between the loading points, as shown in Fig. 1. The load was increased monotonically by the displacement control method until the beam reached the final failure.

2.3 Measurements

Various measuring devices were utilized during the testing process in order to obtain concrete and steel strains, displacements of the beams, joint opening and force variation in the prestressing tendon, etc. The strains in the concrete, reinforcement and prestressing steel were measured by electrical strain gauges at desirable locations as will be shown in Fig. 12. Meanwhile, displacement transducers were mounted at the midspan, the deviator locations and the supports of beams to monitor the vertical deflections as well as the change of tendon's eccentricity. The transducers were placed at two locations to measure the joint opening at extreme tensile fiber and 120mm from the bottom. For the measurement of crack width, seven π-shaped

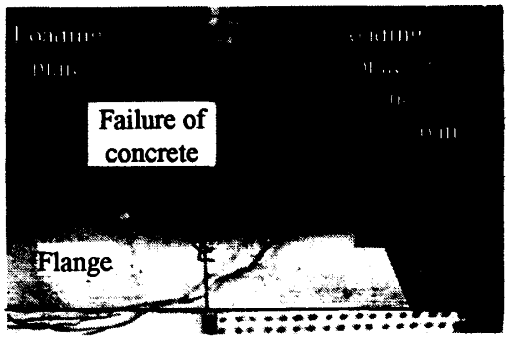


Fig. 3 Failure of concrete at the loading point of SJ05

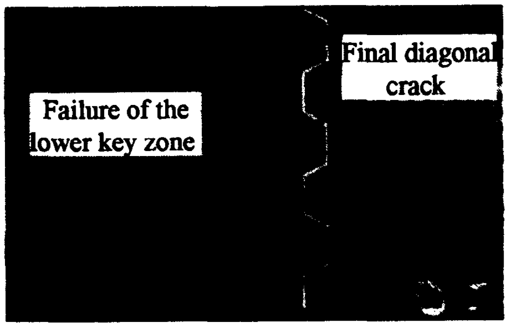


Fig. 4 Failure of the lower key zone of SJ05

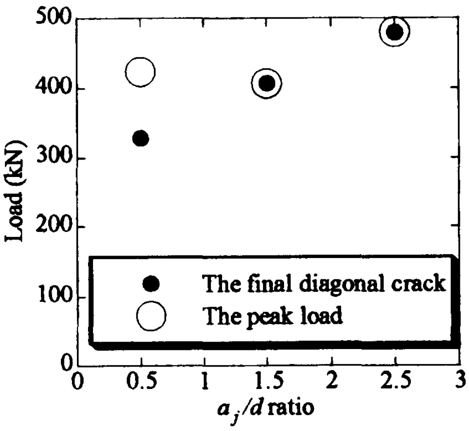


Fig. 5 Load and a_j distance

gauges were fixed at the midspan region where the first flexural cracks were expected to occur.

3. RESULTS AND DISCUSSION

3.1 Crack Patterns

The crack patterns of the specimens are shown in Fig. 2. It was observed that the all tested beams, the crack patterns were found to be different. The first flexural crack of all beams occurred in the tensile zone between the two loading points as shown in Fig. 2.

For the beam SJ05, after the first flexural crack formed, a first diagonal crack, also the final diagonal crack occurred in the web from the loading point to the lower key zone at an applied load of 327.7 kN as shown in Fig. 2. When the load increased, the width of the diagonal crack increased rapidly. The diagonal crack was propagated along the region between the web and the flange until crushing occurred in the flange near the loading point on the test span as shown in Fig. 3. As the final diagonal crack was propagated to the lower

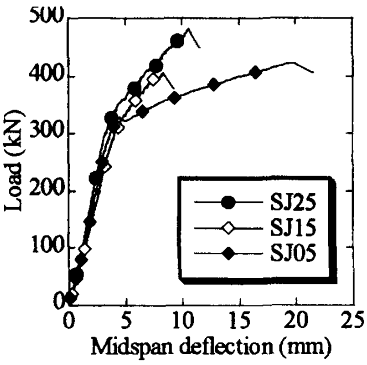


Fig. 6 Load-deflection curves

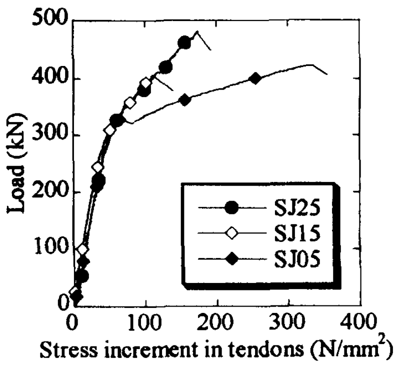


Fig. 7 Load-stress increment relationship

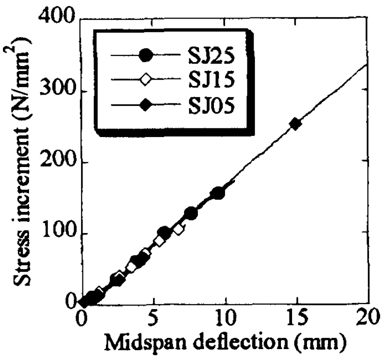


Fig. 8 Stress increment-mid. deflection relationship

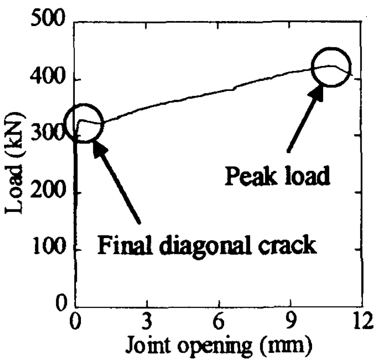


Fig. 9 Joint opening of SJ05

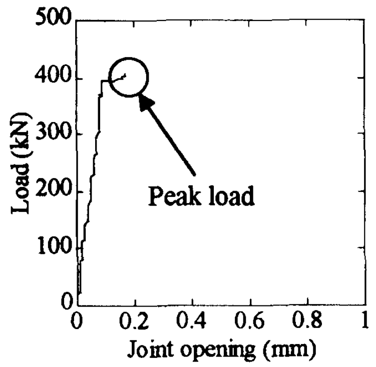


Fig. 10 Joint opening of SJ15

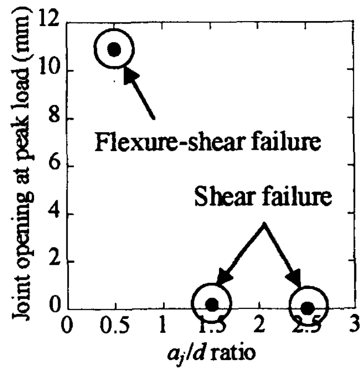


Fig. 11 Joint opening–a_j/d ratio relationship

key zone, the combination between the adhesion of epoxy, interlock of shear keys and rotation of the segmental joint increased the shear stress of the shear key in the lower joint of the web part and caused the failure in this part. This was presented more clearly in Fig. 4.

For the beams SJ15 and SJ25, a number of flexural cracks increased and then the first diagonal crack occurred in the shear span between the two deviators in Fig. 2 when the applied load increased. From Table 5, it can be seen that the first diagonal crack of these beams occurred at similar loads. This means that the joint position has no effect on the occurrence of the first diagonal crack. The difference appeared after the first diagonal crack was formed. A number of diagonal cracks continuously increased mainly in the interval between the two deviators. The cracks did not open very wide, therefore, the shear strength became larger.

In the beam SJ15, one diagonal crack formed in the web of the smaller segment at a load level of 396.5 kN. This diagonal crack appeared before the critical diagonal crack, which occurred suddenly at the peak load of 406.8 kN from the loading point to the lower key zone. In the beam SJ25, the critical diagonal cracks also appeared suddenly, at an applied load of 480.3 kN, from the loading point to the lower key zone.

From Fig. 5, it can be observed that the load of the final diagonal crack increased gradually when a_j distance increased. And the angle of the final diagonal crack depends on the epoxy joint position in the shear span. For the beam SJ05, the crushing occurred in the flange after the final diagonal crack occurred in the web, while the final diagonal crack itself was the critical diagonal crack for the beams SJ15 and SJ25.

3.2 Load and deflection curves

The load-deflection curves of the test beams are given in Fig. 6. The load-deflection curves can be divided into three major portions as: 1) linear elastic uncracked, 2) linear elastic cracked and 3) nonlinear cracked. In the first stage, the response of the beams under loading is linear up to the occurrence of the first flexural crack with the load level as shown in Table 5 and Fig. 6. After the occurrence of the first flexural crack, the slope of load-deflection curve is lower than that in the previous stage because of the reduction in the flexural stiffness of cracked concrete section and also due to the joint opening. However, the response of the beams still shows a linear relationship in this stage. This is because of the compression concrete zone and the external tendons, which gave a large contribution to the flexural strength of the test beams.

The difference of the linear elastic cracked stage of the beams used in this study consists of the load level at which the final diagonal crack occurred. Therefore, the second stage in the beam SJ05 was prolonged from the applied load of 290.7 kN to 327.7 kN. Meanwhile the second stage of beams SJ15 and SJ25 were prolonged from the applied load of 290.6 kN to 406.8 kN and from 298.5 kN to 480.3 kN, respectively. It was clear that the linear crack stage depends on the location of the joint and was directly proportional to the a_j distance. The reason that made the second stage longer was due to the reduction of beam stiffness by the opening of the diagonal cracks and the opening of the joint.

In the last stage, after the occurrence of the final

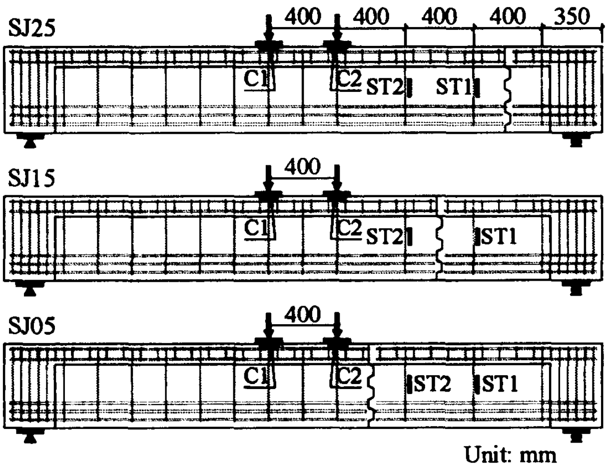


Fig.12 Gauges arrangement

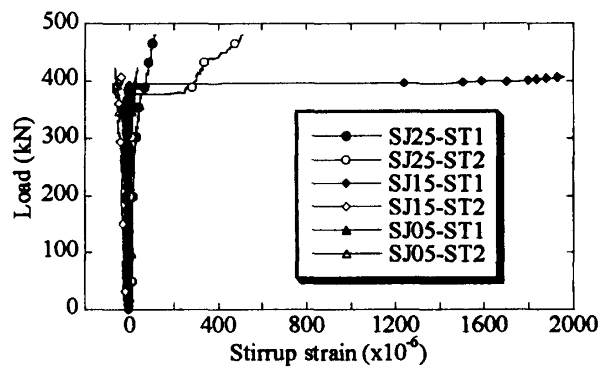


Fig.13 Stirrup strains

diagonal crack, load-deflection curves of the beams were completely different. For the beam SJ05, the effect of the external forces and compression zone was fairly obvious, because flexure and shear resistances were provided on flange and external prestressing [6] after the final diagonal crack occurred. The load-deflection curve was in the linear response and dropped at the peak load of 423.0 kN with the deflection of 19.9 mm as shown in Fig. 6. Conversely, the final diagonal crack formed in the beams SJ15 and SJ25, and the applied loads dropped. The effect of the compression zone and the external prestressing forces in the nonlinear cracked stage was insignificant for increasing the carrying capacity of the beams because the rupture was caused by the shear force. Therefore, the deflection of the beams SJ15 and SJ25 was smaller than the beam SJ05 at the peak load.

All test beams had the straight external tendon profiles. Hence, the inclination angle of the external tendons at the ultimate load was fairly small. The deviation forces acting on the test beams SJ05, SJ15 and SJ25 were 3.0 kN, 2.1 kN and 5.8 kN, respectively. For this reason, the deviation force on shear force at the joints was insignificant effect in these beams.

3.3 Stress increment in the prestressing tendons

Figure 7 illustrates the response of stress increment in external tendons at any stage of load in test beams. It can be noted that the stress increment in external tendons and the deflection at midspan are directly proportional to each other (Fig. 8). This can be attributed to the deflection of the beams at any step of loading, resulting in a greater elongation of external tendons. The strain increment in external tendons in this study was linear with the increment of the deflection at midspan until beams failed, as shown in Fig. 8. The strain increment in the external tendons became significant when the joint position was located nearer the loading point. This is because of the comparatively higher bending moment caused the joint opening at this section resulting in a decrease of the beam stiffness. As the joint position was closer to the support, the strain increment in the external tendons was reduced. Therefore, the joint position also affected the increment of strain in external tendons in segmental beams failing in shear.

3.4 Joint opening

For the beam SJ25, the joint opening was rather small, about 0.003 mm at the peak load. For the beam SJ15, the joint opening increased simultaneously with applied load. However, the joint opening of this beam was observed to be 0.17 mm at the peak load as shown in Fig. 10. On the contrary, the joint opening of the beam SJ05, as shown in Fig. 9, was much larger than that of other beams. As the final diagonal crack occurred, the joint opening was about 0.31 mm. At the peak load, the opening was approximately 10.9 mm.

Figure 11 demonstrates that the joint opening increased insignificantly from the a_j distance of $1.5d$ to $2.5d$. Meanwhile, the joint opening increased rapidly when the joint position was located nearer to the loading point. It was also observed that the final diagonal crack divided the epoxy joint into two parts, and the lower part was the joint opening and the upper part was still carrying compression stresses. The depth of the compression zone in the epoxy joint decreased and the joint opening increased when the a_j distance decreased. This was due to the bending moment effects on the adhesion of epoxy to increase the strength and stiffness of the joint [3].

3.5 Strain in steel and concrete

Figure 12 illustrates the arrangement of strain gauges to measure the strain in stirrups and in concrete. The strain in stirrups is illustrated in Fig. 13. For the beam SJ05, the strain in stirrups did not increase (i.e. -60.5×10^{-6} and 32×10^{-6} in ST2 and ST1, respectively), because no diagonal crack passed through the stirrups. In case of the beam SJ15, ST1 was yielded due to the diagonal crack occurrence in the smaller segment, while the strain in ST2 was quite small (i.e. 36×10^{-6}) at the peak load. In case of the beam SJ25, after the diagonal cracks formed, the stirrup strain increased significantly. The experimental results showed that the stirrup ST2 behaves better than the stirrup ST1 before the final diagonal crack formed. It can be said that the joint position influences significantly on the different response of the strain in stirrups located in the test span.

The concrete strain at the loading point in beams SJ25 and SJ15 were found to be similar at the ultimate stage. In case of the beam SJ05, at the ultimate stage, the concrete strain on C1 and C2 the locations were

-1451×10^{-6} and -1993×10^{-6}, respectively.

3.6 Failure mechanism of test beams

The crack patterns of all segmental concrete beams prestressed with external tendons are shown in Fig. 2. It can be said that the failure of the beams was different depending on the joint position. The epoxy joint position influenced not only the slope and the load of the critical diagonal crack but also on the failure mechanism of the beams. In segmental concrete beams prestressed with external tendons on the other hand, the critical crack depends on the joint position as discussed in the section 3.1. The cracks determine how the arch and beam mechanisms carry the shear force and are fundamental part of shear failure [7].

In beams SJ15 and SJ25, the shear force was transferred by the arch action because the transfer of the shear flow is disrupted by inclined cracks. The shear force is resisted by an inclination of the compressive axial force. The shear flow varied with the occurrence of the joint position in the shear span. In case of the beam SJ25, the joint was hardly opened, and the transfer of shear flow was expressed by the diagonal cracks. In this beam, the arch arose from the lower key zone to the loading point. On the contrary, in the beam SJ15, one arch started developing from the upper key zone to the support. Other arch arose from the loading point to the lower key zone when the beam failed.

For the beam SJ05, the shear was transferred by the beam action because the changing of the lever arm of inner force is not significant and tendon was still in elastic zone when the final diagonal crack appeared. Therefore, when the final diagonal crack occurred, the load can be transferred between the compression zone of concrete and external prestressing.

The mode of shear failure was observed to be different in the test beams. The mode was shear compressive failure in the beams SJ15 and SJ25, because beams can still resist increasing loads after the critical diagonal crack occurred. The stress state becomes like a compression arch formed by the diagonal cracks. In this case, the failure of the beam was brittle and sudden when these arches were crushed under diagonal compression. Meanwhile, the failure mode of the beam SJ05 was flexure-shear failure. In such a case, the joint opened firstly, resulting in increased shear stresses at the tip of the joint opening. Then a diagonal crack formed and extended towards the loading point. Finally, the beam failed by crushing in the flange at the loading point located in the same side with the joint.

From Table 5, Fig. 5 and Fig. 6, it can be observed that the shear strength was directionally proportional to the a_j distance (i.e. the beams SJ15 and SJ25) while the flexure strength was dominated over the shear strength in the beam SJ05. In other word, the ultimate capacity of the segmental concrete beams was different from the variation in the a_j distance. In case of the failing in shear, the ultimate capacity of the segmental concrete beams prestressed with external tendons increases with the increase in the a_j distance.

In real bridges, more than one joint is arranged in a shear span. The experiments to investigate shear mechanisms in [8] have shown that the effect of the joint near the loading point dominates over others with the larger joint opening.

4. CONCLUSIONS

(1) The load level of the final diagonal crack is increased as the a_j distance increased.
(2) The final crack occurs diagonally from the loading point to the lower key zone. Therefore, the angle of the final diagonal crack increases with the decrease in the a_j distance.
(3) The depth of the compression zone of the epoxy joint reduces and the joint opening increases when the a_j distance decreases.
(4) The mode of the failure of segmental concrete beams tested in this study changed from compression failure in web to compression failure in flange, as the a_j distance was reduced.
(5) The change of the joint position in the shear span also induces different mechanisms of shear transfer. The arch action is observed with the increase in the a_j distance while the beam action is observed with the decrease in the a_j distance.

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