- Technical Paper -

INFLUENCE OF PRSTRESS LEVEL ON SHEAR BEHAVIOR OF SEGMENTAL CONCRETE BEAMS WITH EXTERNAL TENDONS

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ABSTRACT

This paper presents the results of experimental procedure and nonlinear finite element analysis on the segmental concrete beams with external tendons. Three segmental concrete beams prestressed with external tendons were tested to investigate the shear failure mechanism with the effect of the prestress level. One monolithic beam with external tendons was also introduced as a control. The results of this study indicate that the prestress level influences the shear failure mechanism and the shear transfer at the segmental joint of the segmental concrete beams with external tendons.

Keywords: segmental concrete beam, external tendon, prestress level, shear mechanism

1. INTRODUCTION

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

In last decade, many parameters were considered in the investigation of the shear failure in segmental concrete structures prestressed with external tendons in both experiment and analysis, such as: internal and external prestressing, effect of shear keys [1], simplified truss model and length of segment [2], joint position [3], etc.

The simplified truss model [2] for the segmental concrete beam with external tendons was extended from the monolithic beam with external tendons. This model was limited to segmental concrete beams with high prestress level. However, with a lower prestress level the segmental joint opens as the applied load is increased. The shear transfer across the segmental joint is a very complex problem for precast prestressed segmental concrete beams with external tendons. This is due to the fact that once the joint opens it leads to a loss of the stiffness of the segmental concrete beam and a decrease of the shear transfer area. For this reason, the influence of prestress level on segmental concrete beams with external tendons should be mentioned.

This paper presents the shear failure mechanism and the shear carrying capacity of segmental concrete beams with external tendons by varying the prestress level. Nonlinear finite element analysis was carried out to clarify the shear transfer mechanism across a segmental joint with the effect of prestress level. The nonlinear finite element analysis results were compared with the experimental results to confirm the stress flow that transfers across a segmental joint with the effect of prestress level. Based on the understanding of the stress flow across the segmental joint, the simplified truss model for segmental concrete beams with external tendons will be modified in the future.

2. TEST PROGRAM

Three simply supported concrete beams designed to fail in shear with a/d ratio of 3.5 were used. The beams consisted of two segments. The segmental joint was arranged in the tested shear span. The distance from the loading point to the joint position, a_j, used in these beams was 1.0d, where d is the effective depth of the beams. Test specimens were T-shaped section concrete beams with the span length of 3.2 m. Two deviators 1.367 m apart were located symmetrically with respect to the midspan, as shown in Fig. 1(a). Different prestress levels were applied in each of the three beams to obtain a concrete stress of 19 N/mm^2, 10 N/mm^2 and 3 N/mm^2 at the bottom fiber of the beams. The concrete stress at the top fiber of the beams was about 0 N/mm^2. Therefore, the name of the segmental beams was assigned SJ10-19, SJ10-10 and SJ10-03, respectively. “SJ10” stands for the segmental joint with a_j of 1.0d. The last two numbers indicate the concrete stress at the bottom fiber. One monolithic beam with the same dimensions was introduced as a control, designated Mono. The ultimate capacity, P_u, calculated following the design flexural and the shear carrying capacities by equations in [2] for the monolithic beam

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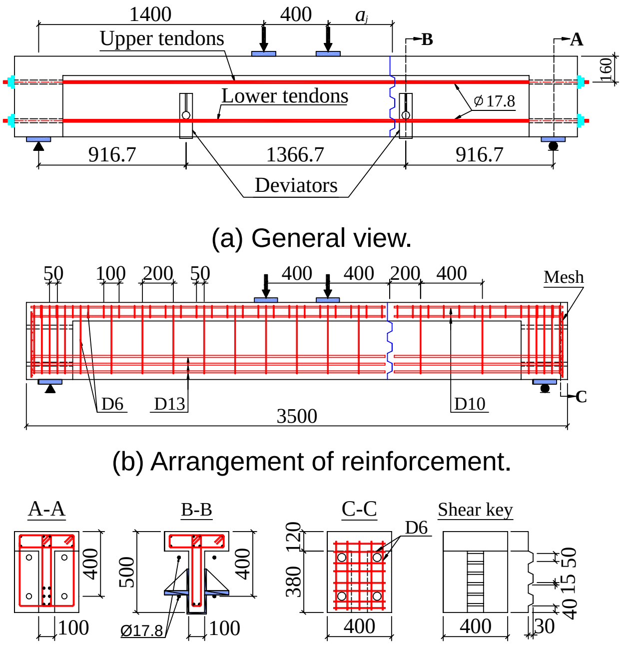


(a) General view.

(b) Arrangement of reinforcement.

(c) Sections. (Unit: mm)

Fig.1 Details of test beam.

is 489.5 kN and 406.4 kN, respectively.

2.1 Materials

(1) Reinforcing materials

The arrangement of reinforcement in the beams is shown in Fig. 1(b). The non-prestressed steels were of deformed bar of grade SD295A. In all the beams, six deformed bars with a nominal diameter of 13 mm (D13) and eight deformed bars with a nominal diameter of 10 mm (D10) were provided as internal longitudinal bars at the bottom and top flange, respectively. The tested shear span, the segmental joint was located, was reinforced by stirrups with a nominal diameter of 6 mm (D6) at an interval of 400 mm. The other shear span was reinforced with D6 stirrup at an interval of 200 mm. D6 stirrups were also used at the top flange with an interval of 100 mm. The mechanical properties of the steel bars are given in Table 1. Mesh reinforcement with D6 was utilized at the end of the beams to resist local stresses due to the prestressing force.

(2) Concrete

The match cast method was used for casting of the segmental beams. In this method, the bigger segment of the beam was cast first with a wood shear key as an end formwork. Three days later formworks were removed and the first segment itself was used as an end formwork for next casting in order to provide a perfect matching between the two segments. After casting, the concrete beams were cured in the atmospheric conditions. The design strength of concrete, f'_c, was specified as 65 N/mm^2 at 28 days. The actual tensile and compressive strengths of concrete in each batch were measured at the day of testing and are shown in Table 2.

(3) Prestressing tendons and deviators

The prestressing tendon used for the beams was of type SWPR19L Φ17.8 mm. The yield and ultimate strengths of the tendons are shown in Table 3. The external tendons were placed as shown in Fig. 1(a) and were stretched 4 days before testing. The actual effective prestresses of external tendons ranged from 60 N/mm^2 to 830 N/mm^2 so that the concrete stress at the top fiber was about 0 N/mm^2, while the concrete stresses at bottom fiber were about 19 N/mm^2, 10 N/mm^2 and 3 N/mm^2. Steel deviators, located in the shear spans, were attached to the beams from the bottom to ensure that there was no change in the web thickness of the test beams.

(4) Epoxy

Epoxy resin was used to connect concrete segments. Prestressing was introduced after assembling of concrete segments with epoxy. The compressive and tensile strengths of epoxy resin were greater than 60 N/mm^2 and 12.5 N/mm^2, respectively.

Table 1 Mechanical properties of reinforcements.

Bars	Yield strength (N/mm^2)	Tensile strength (N/mm^2)	Elastic modulus (kN/mm^2)	Area (mm^2)
D6	329	516	200	31.7
D10	402	531	200	71.3
D13	362	497	200	126.7

Table 2 Characteristics of concrete.

Beams	Compressive strength (N/mm^2)		Tensile strength (N/mm^2)	
	Batch A	Batch B	Batch A	Batch B
Mono	65.8	-	4	-
SJ10-19	65.0	66.4	3.75	3.75
SJ10-10	65.0	66.4	3.75	3.75
SJ10-03	65.0	66.4	3.75	3.75

Table 3 Characteristics of tendons.

Beams	Yield strength (N/mm^2)	Tensile strength (N/mm^2)
Mono	1680	1900
SJ10-19	1730	1960
SJ10-10	1730	1960
SJ10-03	1730	1960

2.2 Loading Method and Measurements

The beams were subjected to a four point loading test with a distance of 400 mm between the two loading points, as shown in Fig. 1. The applied load was increased monotonically by means of the displacement control method until the beams failed.

Various measuring devices were utilized in order to measure displacement of the beams, joint opening and stress increment in the external tendons. Strains in the tendons were measured by electrical strain gauges at the middle of the external tendons. Meanwhile, displacement transducers were mounted at the midspan and the supports of the beams to monitor the vertical deflection. At the same time, transducers were placed horizontal at two different locations to measure the

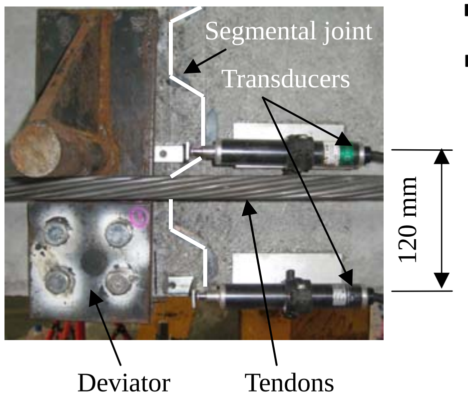


Fig. 2 Arrangement of transducer to measure the joint opening.

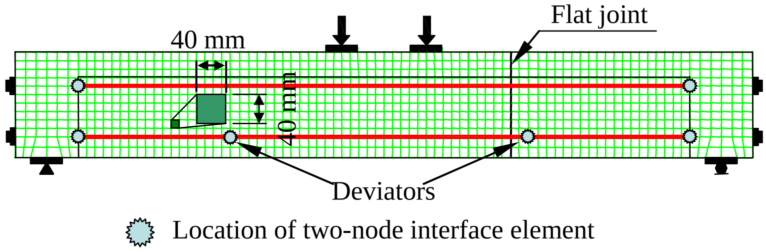


Fig.3 Mesh of finite element.

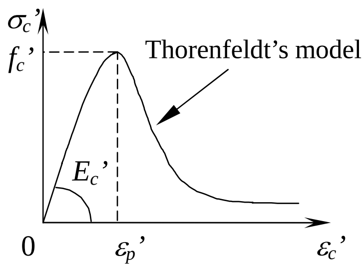


Fig. 4 Compression model for concrete.

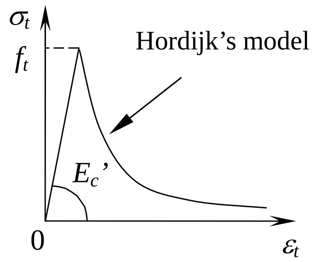


Fig. 5 Tensile model for concrete.

joint opening. One transducer was placed at the bottom fiber. The upper survey point was at 120 mm above the lower edge of the beams as shown in Fig. 2.

3. DESCRIPTION OF MODELS

The nonlinear finite element method (FEM) using DIANA computer program has been conducted to examine the shear mechanism of the segmental concrete beams with the different prestress levels. The concrete beams were modeled by means of four-node quadrilateral isoparametric plane stress element as shown in Fig. 3. The behavior of concrete in compression was modeled using the stress-strain relationship proposed by Thorenfeldt et al. [4] as shown in Fig. 4, whereas the behavior of concrete in tension was defined according to Hordijk's model [5] as illustrated in Fig. 5.

Longitudinal reinforcements were modeled by means of the embedded reinforcement element in DIANA. The external tendons were modeled by two-node truss elements. The stress–strain relationship for the reinforcing bars and the external tendons were appropriately represented by a bilinear elasto-plastic constitutive model.

To model the interfacial behavior between the external tendons and the deviators or the concrete beam, the two-node interface element was applied. Figure 3 also shows that the flat joint model has been applied to reproduce the real geometry of the joint by using the two-line interface element. Flat joints have fewer degree of freedom which means less computer calculation time. This can be beneficial especially for complex geometries such as shear keys.

4. RESULTS AND DISCUSSION

4.1 Crack Patterns

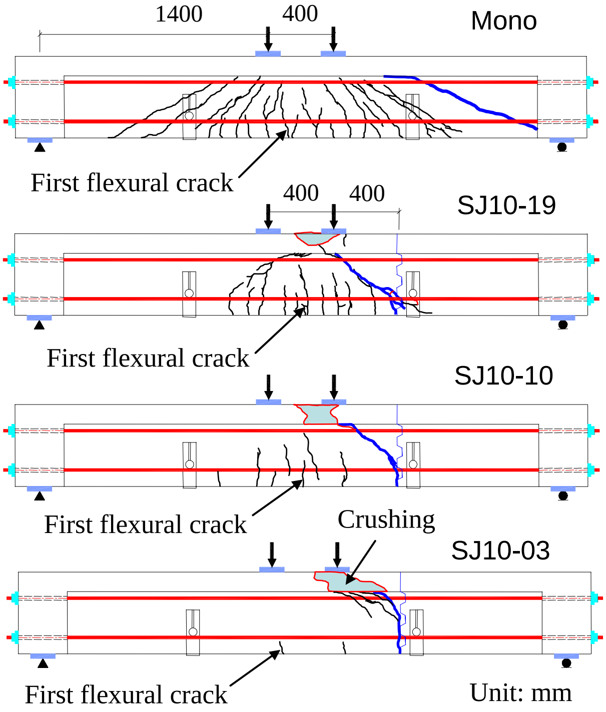
Figure 6 presents the crack pattern of the tested beams. The difference between the segmental beams and the monolithic beam was observed. The prestress level in Mono was similar to that in SJ10-19. However, the first flexural crack in Mono occurred later than in the case of SJ10-19, as presented in Table 4. This is due to the effect of the discontinuity of the longitudinal reinforcements at the segmental joint. The final diagonal crack in Mono was formed from the support to the loading point.

For all segmental beams, with different prestress levels, the cracks were observed only between the two deviators, as shown in Fig. 6. The number of crack decreased with the decrease in the pretress level. Contrary to Mono, the final diagonal crack in all segmental beams in this study was formed from the segmental joint to the loading point. However, the inclination of the final diagonal crack was flatter when prestress level increased.

4.2 Load-Deflection Curves

Figure 7 illustrates the load-deflection curves of the test beams. Even if there was a difference in the prestress level, at the beginning, all segmental beams exhibited linear elastic behavior similar to the monolithic beam. The linear behavior was prolonged until the first flexural crack occurred with the loads as summarized in Table 4. For the similar prestress level, the linear behavior stage of Mono prolonged a little longer than that of SJ10-19. It is because of the discontinuity of the longitudinal reinforcement caused by the segmental joint. The linear behavior range was shorter when the prestress level was reduced.

The effect of the prestress levels was recognized after the occurrence of the first flexural crack. The load of the final diagonal crack, P_{sh}, increased with the increase in the prestress level. The lower the applied prestress level was, the earlier the final diagonal crack occurred. The load at the final diagonal crack of Mono was higher than that of the segmental beam with similar



Bold line is the final diagonal crack

Fig.6 Crack patterns of test beams.

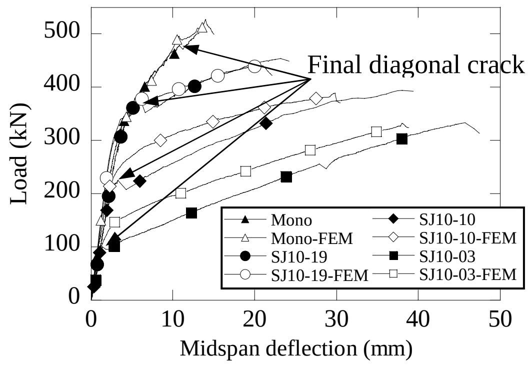


Fig.7 Load-Deflection curves.

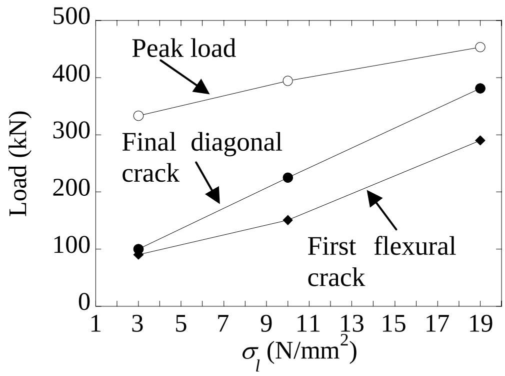


Fig.8 Load-σ_l relationship.

prestress level, SJ10-19. It can be said that the behavior of the segmental concrete beam is different from the monolithic beam after the first flexural crack occurs even though the concrete stress at the bottom fiber was 19 N/mm^2.

The width of the final diagonal crack increased rapidly and propagated to the flange with the increase in the applied load. The resistances of these segmental beams were mainly provided by the flange and the external tendons. Therefore, in segmental concrete beam with T-shape cross section, the flange and the external tendons contribute significantly to the carrying capacity after the final diagonal crack occurred. The applied load dropped after crushing of the concrete in the flange under the loading point on the tested shear span, as shown in Fig. 6. Figure 8 illustrates the load and the concrete stress at the bottom fiber, σ_l, relationship. The increase in the prestress level, in terms of the concrete stress at the bottom fiber, σ_l, caused the decrease in the deflection at the peak load, as shown in Fig. 7, and the increasing in the shear carrying capacity of the segmental beams, as shown in Fig. 8.

4.3 Stress Increment

Figure 9 illustrates the variation of the stress increment in the lower external tendons at any stage of the applied load in the test beams with the different prestress levels. The stress increment in the tendons of Mono was smaller than that of the segmental beams. The increase in the values of stress increment was slow before the occurrence of the diagonal crack. However, the value of the stress increment varied significantly after the final diagonal crack occurred.

Table 4 Experimental results.

Beams	Load (kN)		
	P_{1st}	P_{sh}	P_u
Mono	301.7	479.2	501.2
SJ10-19	290.5	381.7	453.9
SJ10-10	150.7	225.4	394.6
SJ10-03	90.2	100.0	333.4

Note: P_{1st} : Load at the first flexural crack,
P_{sh} : Load at the final diagonal crack,
P_u : Peak load.

4.4 Joint Opening

Figures 10 and 11 present the opening of the segmental joint at the bottom fiber and the upper survey joint. At the load corresponding to the final diagonal crack, the joint opening, measured at the bottom fiber, of SJ10-19 and SJ10-10 was 0.15 mm and 0.17 mm, respectively, while at the upper survey point of SJ10-19 and SJ10-10 was 0.01 mm and 0.11 mm, respectively. This shows that the height of the joint opening and opening of the segmental joint decreased as the prestress level increased in the two beams. The joint opening could not be calculated from the data shown in Figs. 10 and 11 once the relative slip between the segments became very large. For SJ10-03, the failure at the base of the shear keys as flexural crack, which will be discussed later, the joint opening of the bottom fiber and the upper survey point were 0.08 mm and 0.04 mm, respectively. This led to a sharp increase of the opening.

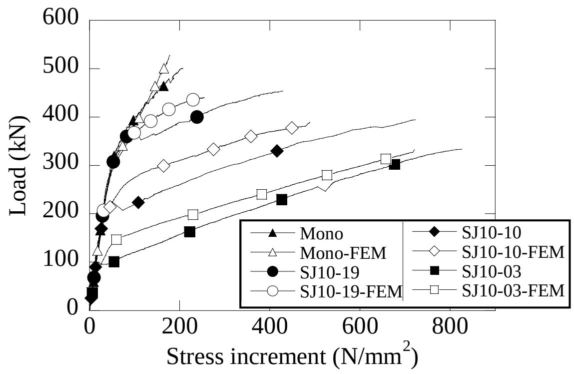


Fig.9 Load-stress increment relationship.

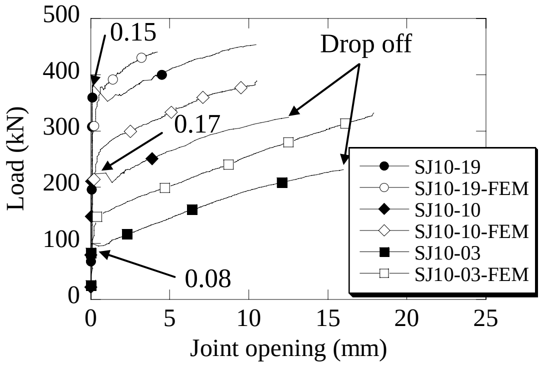


Fig.10 Joint opening at bottom fiber.

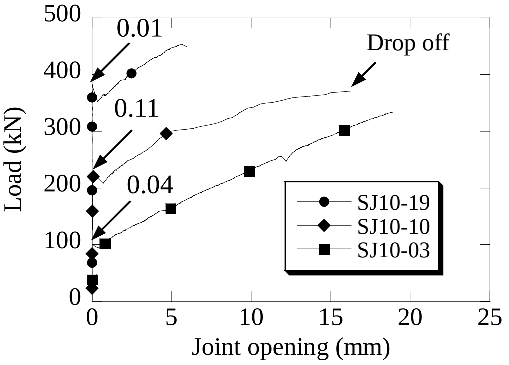


Fig.11 Joint opening at upper survey point.

However, at the peak load, the height of the joint opening in SJ10-10 was slightly larger than that of SJ10-19. The height of the joint opening in SJ10-03 was significantly larger than those in SJ10-19 and SJ10-10, as shown in Figs. 12, 13 and 14.

The prestress level significantly influenced both the height and the opening of the segmental joint. As the prestress level increased, the opening of the segmental joint decreased. The height of the joint opening increased significantly with the prestress level generating concrete stress of 3 N/mm^2 at the bottom fiber. In the segmental concrete beams prestressed with external tendons, the height of the joint opening was affected by the area where shear forces are transferred.

4.5 Failure Mechanism of Test Beams

At the segmental joint, the flow of normal compression stress overlaps with the flow of tangential stress across the keys. This would lead to the failure of the shear keys. The failure mechanism of the shear key was different in the segmental beams with different prestress levels.

In case of high prestress level, SJ10-19, the segmental joint could withstand the high confining pressure. Therefore, the combination between the adhesion of the epoxy, the interlock of shear keys and the separation of the upper and lower parts of the final diagonal crack increased the shear stress in the lowest shear key. It led to the failure of the shear key. Figure 12 shows the crack pattern observed in the shear key of SJ10-19 with the highest prestress level in the tested beams.

In case of lower prestress level, the confining stress decreased and the effect of the normal stress gradually dominated over the shear stress in the shear key. The failure at the base of the shear key was observed. The confining pressure has little effect on the stiffness of the epoxy joint. Meanwhile, the epoxy thickness did not affect the strength and the stiffness of the epoxy joint [6]. Figures 13 and 14 show the failure of the segmental joint of SJ10-10 and SJ10-03, respectively. It can be concluded that the extent of damage in the shear key was higher when the prestress level was lower. Moreover, a lower value of applied load was recorded at the time of the joint failure, for specimens with lower prestress level.

The shear failure mode was observed to be different in the test beams. In case of higher prestress level, such as SJ10-19 and SJ10-10, the mode was designated as the shear compression failure. The final diagonal crack was formed from the bottom of the web, at the edge of the segment, to the loading point in the tested shear span. The final failure took place with the crushing of concrete at the loading point. In case of the lowest prestress level, SJ10-03, the diagonal tension failure was observed [7]. The failure of the beam started with a flexural crack formed near the shear key. The length and width of this flexural crack increased with the increase in the applied load. The diagonal crack started at the tip of the flexural crack and extended towards the nearest loading point, having quite a flat slope, as shown in Fig. 14. Finally, crushing occurred in the compression zone as shown in Fig. 6.

5. FEM RESULTS

In order to validate the FEM model, the results obtained from the numerical analysis are compared with the experimental results in Figs. 7, 9 and 10. It can be observed that the obtained numerical data is more accurate for the specimens with higher prestress level. In case of lower prestress level, SJ10-10 and SJ10-03, the numerical analysis results demonstrate the experimental results in linear elastic behavior. After the occurrence of the final diagonal crack, the validity of the numerical analysis results is not accurate very well. This may be weak point of the constitutive models for segmental joint in the case of the lower prestress level. It will be considered in the future. Figure 15 shows the principal compressive stress of the all beams at the peak load. From the nonlinear FEM analysis results, the

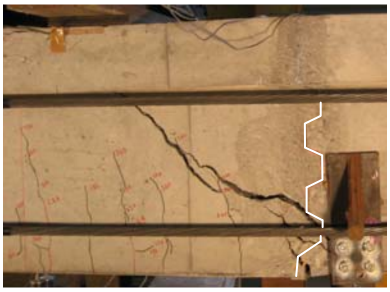


Fig. 12 Failure of shear key in SJ10-19.

Fig. 13 Failure of shear key in SJ10-10.

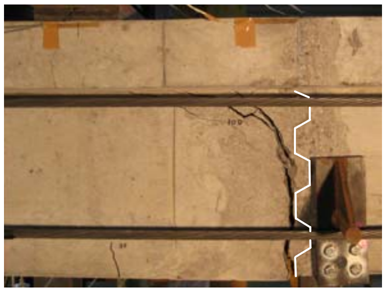


Fig. 14 Failure of shear key in SJ10-03.

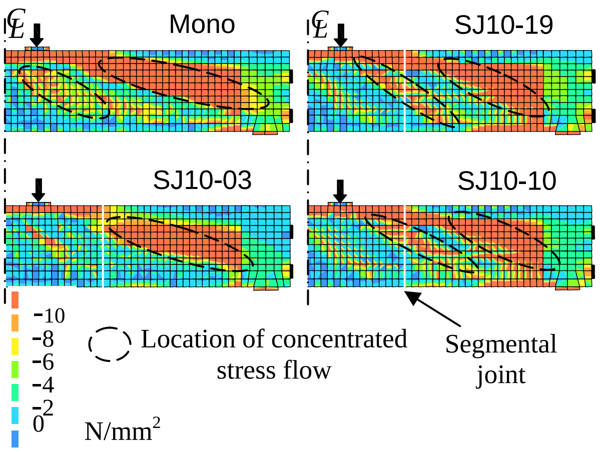


Fig.15 Principal compressive stress at peak load.

shear mechanism observed in Mono, SJ10-19 and SJ10-10 was different from that in SJ10-03. It was found that two separately concentrated stress flows were observed in Mono, SJ10-19 and SJ10-03. Evidently, the location of the concentrated stress flows in Mono was different from those in SJ10-19 and SJ10-10. The separately concentrated stress flow from loading point crossed the segmental joint in the web of SJ10-19 and SJ10-10. The angle of this concentrated stress flow in comparison with the longitudinal direction of SJ10-19 and SJ10-10 was about 31.2^{o} and 29.7^{o}, respectively. It can be explained that the height of joint opening increased with the decrease in the prestress level. As the height of the compression zone in the segmental joint was reduced, the angle of the concentrated stress flow became flatter. For SJ10-03, that is the lowest prestress level, the height of joint opening was the highest in the experiment as shown in Fig. 14. In the nonlinear FEM analysis, there was no concentrated stress flow across the segmental joint in the web. The resistant mechanism can be observed by the stress flow that went from the loading point to the segmental joint in the top flange and then went to the support.

6. CONCLUSIONS

(1) Shear carrying capacity of segmental concrete beams with external tendons increased with increase in the prestress level.

(2) The shear transfer mechanism of the segmental concrete beam with external tendons was similar to the monolithic beam with external tendons until the final diagonal crack occurred.

(3) The joint opening increased with the decrease in the prestress level. The height of the joint opening increased significantly as the prestress level was decreased.

(4) The shear compression failure occurred in the beams with high prestress levels, that is the beams with the concrete stresses at the bottom fiber of 190N/mm^2 and 10 N/mm^2. On the other hand, the diagonal tension failure occurred in the beam with low prestress levels, that is the beam with the concrete stress at the bottom fiber of 3 N/mm^2.

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