Combined Shear and Bending Behavior of Joints in Precast Concrete Segmental Beams with External Tendons

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ABSTRACT

The main objective of this study is to get a further understanding of the behavior of joints when it is subjected to combined shear and bending. Nine specimens of precast concrete segmental beams (PCSB) with external tendons were match cast and tested: where six of the specimens were tested under combined shear and bending; two specimens were tested under pure bending; and one specimen was tested under direct shear. Failure processes and modes, joint resistance, and strains of stirrups and prestressing tendons were recorded in the tests. Based on the results of the experiment, the study analyzed the mechanism of combined shear and bending resistance for dry and epoxied joints when loads are located in the immediate vicinity of the joint. Additionally, simplified failure modes of dry and epoxied joints subjected to combined shear and bending were presented in this paper.

1. INTRODUCTION

The precast segmental construction method of concrete bridges has many advantages. The construction method can ensure concrete quality during pouring, reduce workload on construction site, speed up construction, and mitigate disturbance to environment. Compared with the traditional internal prestressing technology, maintenance and replacement of external tendons are convenient. Moreover, the dimensions of the cross section, especially the dimensions of webs, can be reduced due to external tendons which are placed outside of the concrete. Therefore, deadweight of external prestressed bridges can be reduced. Combining the advantages of segmental construction method and external prestressing technology, external prestressed precast concrete segmental bridges become increasingly popular.

On the other hand, bridges of this kind have some disadvantages. Compared with monolithic bridges, longitudinal steel bars are interrupted at the joints in segmental bridges. Deck segments are connected directly (dry joints) or indirectly (epoxied joints) by prestressing. Joints between deck segments represent locations of discontinuity in the bridges. Because the current information can not totally uncover the effect of this discontinuity on behavior of joints in segmental bridges, especially under combined shear and bending, more research is needed.

Previous experimental research carried out on behavior of joints in PCSB mainly focused on two failure modes: failure occurring in the joint plane due to shear-off of the Keys under direct shear forces; shear compression failure with diagonal web cracking under combined shear and bending. However, another failure mode, namely that failure develops along the plane of joint with joint open before failure, may happen when joints are subjected to loads located in the immediate vicinity of the joints. Such failure mode has received few attentions from researchers, which needs additional considerations during design.

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As part of the science and technology item to develop transportation in the western regions of China sponsored by the Ministry of Communication of P. R. China, research was carried out on combined shear and bending behavior of joints of PCSB with external tendons. The cracks due to combined shear and bending in segmental beams will develop towards the loading point, which has been concluded by previous research (Turmo 2006b); therefore, when loads are directly applied in the immediate vicinity of joints, the failure mode that cracks occur in the joint plane instead of diagonal cracking will be obtained. Additionally, specimens are also tested under pure bending to develop a better understanding of the behavior of joints in PCSB. This paper summarized the testing data of 9 models, analyzes the effects of different design parameters, such as the position of joints and joints types (dry or epoxied), on behavior of joints such as joint resistance. Furthermore, simplified failure modes of joint under combined shear and bending are proposed.

2. LITERITURE REVIEW

Since 1950s, many researchers have done a large quantity of studies on mechanical behavior of the joints in segmental beams. These experiments studies can be reviewed in the following two categories: the first group of tests (Franz 1959; Jones 1959; Zegler and Pusch 1961; Gaston and Kriz 1964; Bakhoum 1991; Breen and Roberts 1993; Koseki and Breen 1983; Foure et al. 1993; Zhou et al. 2005; Turmo et al. 2006; Mohsen and Hiba 2007) concentrated on the shear behavior of joints under direct shear; the second group of tests (Moustafa 1974; Kufer et al. 1982; Sowlat and Rabbat 1987; Li 2005) concentrated on shear compression failure with diagonal web cracking or bending failure, just considering the effect of joints on the behavior of segmental beams.

The first group：Franz（1959）and Jones（1959）respectively performed experiments on the shear strength of dry joints subjected to external prestress, and they both got the conclusion that the joint resistance under direct shear is proportional to the axial forces in the joint section. Franz revealed that the coefficient of friction (ratio of the ultimate shear force to axial force) was 0.7, while Jones got the results that the coefficient of friction approximates 0.39~0.69 which depends on joints types, roughness of joint surfaces and so on. Zegler and Rusch (1961) tested epoxied joints and proposed a formula to predict the ultimate shear strength of joints. A factor, c, was introduced into the formula to reflect the effect of cohesion on the shear strength. Base (1962), Sims and Woodhead (1968) studied the effect of joint surface treatment on the shear strength of epoxied joints. The tests results showed that a coarser joint surface contributes to the higher shear strength. Koseki and Breen (1983) compared the shear strength of two types of joints (epoxied and dry joints) with different kinds of keys (no key, a large single key and multiple keys). The research concluded that the shear strength of beams with epoxied joints is similar to that of monolithic beams; however, the failure is more sudden and brittle than that of monolithic beams. Buyukozturk et al (1990) modeled one of the multiple keys widely used in practice and tested its shear behavior under direct shear. The effects of several design parameters, such as joint types (dry and epoxied), epoxy thickness and confining stress, on the shear strength and deformation behavior of the joint were considered. Buyukozturk also had given formulas to calculate the shear strength of the joints. The formulas introduced concrete characteristic compressive strength (f_c') to reflect its effect on the shear strength of the joints. However, the formulas failed to distinguish the different contributions of the key and the smooth surface around the key to the shear strength. Roberts and Breen (1993), Foure et al. (1993) performed shear tests of joints with multiple keys under direct shear respectively. Based on the results of the experiments, they both proposed equations for the shear strength of the multiple keyed joints, which distinguished the shear force transferred by the joint into two parts: one is transferred by the base areas of keys (A_k) and the other by the area of contact between smooth surfaces (A_{sm}) on the failure plane. The AASHTO proposed the formula theoretically deduced by Roberts and Breen (1993) and applied a safety factor to the result, φ_j=0.75 (AASHTO 1999). Zhou etal（2005）studied shear strength of joints in PCSB. In his study, dry and epoxied multiple-keyed joints have been tested under confining stress. It was concluded that the epoxied joint always had a higher strength than the dry joint when they are subjected to direct shear, which is attributed to the epoxy mitigating effects. The test results were also compared with the AASHTO equations which always overestimated the shear capacity of dry joints and underestimated the epoxied joints. Turmo et al. (2006) investigated the shear strength of dry joints of concrete panels with and without steel fibers. They also compared the testing results with those obtained through different formulas proposed by other researchers, and it is concluded that the formula proposed by AASHTO (1999) best predicts the test results.

The second group: Moustafa (1974) conducted an experiment on the shear strength of segmental beams with epoxied joints. It is revealed that the failure occurred in the concrete adjacent to the epoxy layer instead of exactly in the joint plane. Therefore, he concluded that the shear strength of the segmental beams will not be profoundly affected by epoxied joints. Kufer et al. (1982) performed an experimental study on segmental beams with the joints not perpendicular to the axial force. The segments were jointed together with epoxy resin or cement applied to the joints plane. It was found that the shear strength of segmental beams with segments jointed by cement gel is 78%~90% of that of monolithic beams. Sowlat and Rabbat (1987) studied the bending behavior of concrete segmental beams with different bonding conditions between steel bars and concrete. Ramírez et al. (1993) studied the shear strength of segmental beams. In the experiment, segmental beams with different joint types and monolithic beams with the longitudinal reinforcement cut off at the location of the joint were tested. The experiment revealed that the joint type (dry or epoxied) had little influence on the failure mode and load when the joint was subjected to shear and bending. Turmo et al. (2006b) conducted a research about the shear behavior of segmental beams with dry joints and external tendons. Upon loading, the joint opened and cracks initiated from the plane of joint and oriented toward the loading point. The research revealed that stirrups near the open joint nearly contributed nothing to shear resistance of the beam. It was concluded that the arch effect formed in the beam as the shear resistance mechanism. 12 models of segmental beams were tested with the object of clarifying the effect of span to depth ratio, number and location of joints and the distance from load to support on the shear behavior of segmental beams (Li 2005). The failure modes in the experiment are attributed to shear compression failure with cracks propagating from the bottom of the nearest joint to the loading point on the upper flange, which indicates that load position is an important factor affecting the failure mode.

As mentioned above, the first group of research focused on the failure of the joints in segmental beams under direct shear forces. The situation is neglected that joints lose resistance under combined shear and bending when loads are located in the immediate vicinity of joints. The second group concentrated on the shear compression failure with diagonal web cracking and bending failure, and the situation is neglected that failure may propagate along the joint plane when the beams were loaded at the joint section. The experimental study presented in this paper was carried out about the situation that failure occurs in the joint plane when loads are located in the immediate vicinity of joints. Longitudinal steel bars are interrupted near joints, which represent locations of discontinuity of PCSB. When beams are loaded at joint sections, cracks initiate at the bottom of joints due to bending moments. The cracks propagate along the joint planes and finally result in the failure sections with the joints open wide. This failure mechanism, which may control the design of PCSB, is different from that of shear compression failure due to diagonal web cracking and also different from bending failure. However, the related research is not enough currently.

3. OBJECTIVES

Considering the previous study about joint behavior did not cover the possible failure modes: when subjected to loads in the immediate vicinity of joints, beams may lose bearing capacity due to the concrete breaking on the upper part of the joint plane under compressive combined with shear stresses with the joint opening to a certain height, this paper presents the experimental study about this possible failure of joints in PCSB with external tendons. Two types of joints (dry and epoxied) were applied in the tests and the models were subjected to bending moments, combined shear and bending, and direct shear respectively to achieve the following objectives:

1. Analyzing the differences in failure processes and modes of the specimen under direct shear, combined shear and bending, and pure bending;
2. Qualitatively studying the resistance mechanism of the specimen under combined shear and bending, analyzing the differences in resistance mechanism comparing with traditional bending or shear failure;
3. Investigating the contribution of stirrups to the strength of joints under combined shear and bending;
4. Proposing simplified failure modes of two types of joints under combined shear and bending; and

4. EXPERIMENTAL TESTING PROGRAM

4.1 Design of Testing Program

This paper presents the experimental study on the effect of locations of joints, joint types (dry and epoxied) and forces applied to joint sections on the mechanical behavior of joints in PCSB with external tendons.

The joint models in the test are subjected to direct shear force, combined shear and bending actions, and pure bending, respectively. The former two joint models can reflect the limit states of PCSBs under construction and in service. The models subjected to pure bending can expand the knowledge of the behavior of joints. Three different locations of joint were adopted in the combined shear and bending tests. Bending moment prevails at the location of joints as the joint approaches to the mid-span. Previous research showed that the shear-stress distribution in the multiple keyed joints, which are widely used in practice, is more uniform than single keyed joints. Therefore, two types of multiple keyed joints (dry and epoxied) were adopted in this test. The axial forces are applied to the models by prestressing the external tendons. The strands were naked and plastic tubes were embedded in the concrete to eliminate the bond between strands and concrete at diaphragms.

Total 9 models are classified into 5 groups with the objective to analyze effects of different parameters on the behavior of joints. The characteristics of the tested specimens are listed in Table 1.

Table 1. Characteristics of Specimens

Specimen	Joint type	a/h	Loading type	T_{p0} (kN)	Cube strength (f_{cu})[a] (MPa)	Prism strength (f_c) (MPa)
SE-1	Epoxied	——	Pure bending	618.5	75.97	63.20
SD-1	Dry	——	Pure bending	677.2	53.35	43.20
SE-2	Epoxied	1.5	Combined shear and bending	600.6	53.35	43.20
SD-2	Dry	1.5	Combined shear and bending	595.1	53.35	43.20
SE-3	Epoxied	2.5	Combined shear and bending	555.2	53.35	43.20
SD-3	Dry	2.5	Combined shear and bending	613.0	53.35	43.20
SE-4	Epoxied	3.5	Combined shear and bending	602.4	75.97	63.20
SD-4	Dry	3.5	Combined shear and bending	732.2	75.97	63.20
SD-5	Dry	——	Direct shear	416.5	75.97	63.20

[a]Dimension of the cube: 150mm×150mm×150mm

4.2 Model Cross Section and Joints

Design of Cross Section

The prototype of the models in the tests is determined by referring the standard section proposed in “Segmental Box Girder Standards for Span-Span and Balanced Cantilever Construction” (AASHTO-PCI-ASBI 1997) and the box girder section widely used in 3 lanes bridges. The section of the prototype is shown in Fig.1.

The scale factor, 1:4.8, is adopted to design the model section. Because the reduced scale of the box section is difficult to fabricate and stretch external tendons due to the thin webs, T section is adopted to simulate the box section. As a prerequisite, the inertia, location of the neutral axis, area of flanges and web should approximate to the box section. The T section is shown in Fig.2.

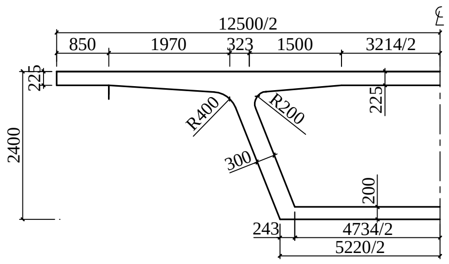


Fig.1. Configurations of prototype section (mm)

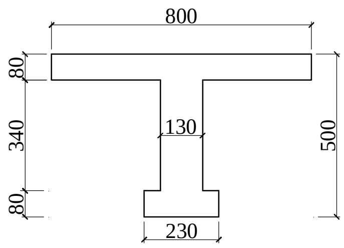


Fig.2. Configurations of T section (mm)

Design of Joints

Multiple keyed joints are used in the specimens. Considering that the sizes of keys in prototype, keys with different sizes are adopted on the flanges and web of the specimens. The sizes and distribution of keys in the models are shown in Fig.3.

4.3 Specimen Dimensions and Configurations

Specimens for Bending Tests

Two specimens, SD-1 and SE-1, were tested in pure bending tests, as listed in Table 1. SD-1 was equipped with a dry joint locating at the mid-span. The length of the beam is 2800mm and the distance between two supports is 2600mm. External tendons consisting of 4×7∅5 and 2×4∅5 strands are placed symmetrically with respect to the web. In order to prevent bending and shear failure in the part far away from joint, the width of the lower flange increases to equal that of the web and extra 2×∅20, 2×∅16 steel bars (HRB335) are added in this area. Additionally, double-leg stirrups increase to four-leg stirrups and the stirrup spacing is shortened away from the joint. SE-1 has the same design parameters with SD-1 except for epoxied joint being used. The details of SD-1 and SE-1 are shown in Fig.4.

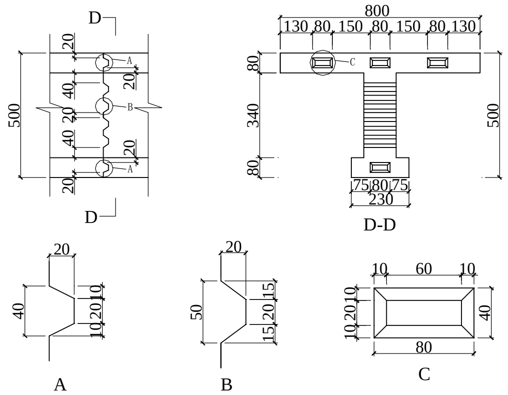


Fig.3. Dimensions of key models (mm)

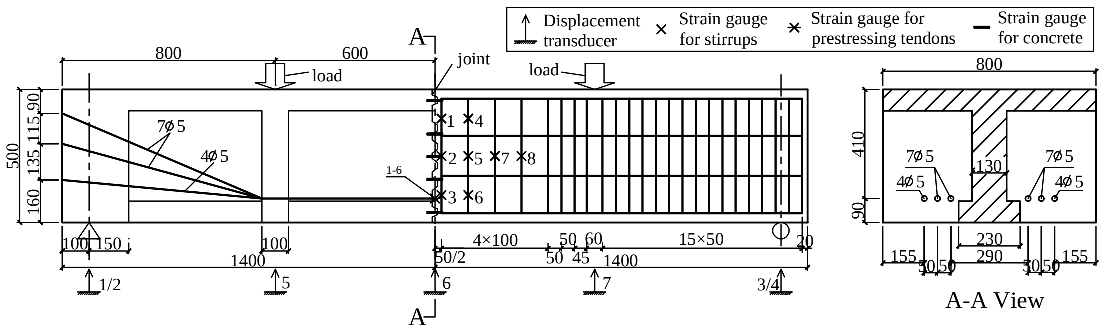


Fig.4. Configurations of SD-1 and SE-1 (mm)

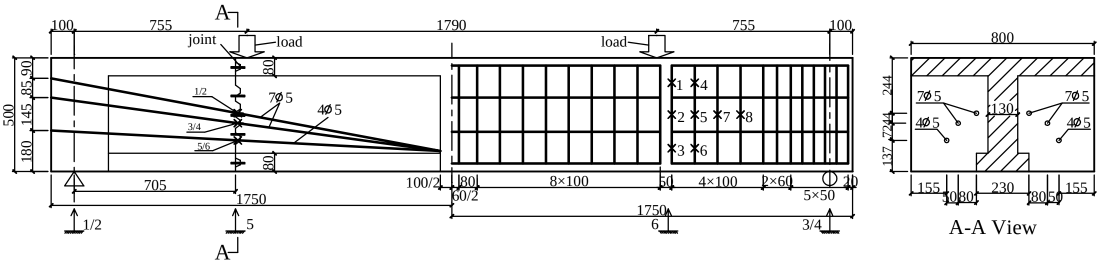


Fig.5. Configurations of SD-2 and SE-2 (mm)

Specimens for Combined Shear and Bending Tests

The combined shear and bending tests contain 6 specimens which are classified into 3 groups considering different joint locations. The joint locations are represented by a/h, where “a“ is the distance between the joint and the nearer support, and “h” is the effective section height of the beam. It is notable that the load is directly applied in the immediate vicinity of the joint, which is seldom adopted by other researchers.

SE-2 and SD-2 are in the first group, with a/h equaling 1.5. The length of SE-2 is 3500 mm and the distance between two supports is 3300 mm. The distance between the joint and the nearer support of the two is 705 mm. Double-leg stirrups (∅8 R235) are used near the joint. ∅20 steel bars (HRB335) in lower flange and ∅12 steel bars (HRB335) are used as the longitudinal reinforcements. The quantity of longitudinal steel bars and stirrups in the part away from the joint is increased to avoid failure occurring in this area. 4×7∅5 and 2×4∅5 strands are placed symmetrically with respect to the web serving as the external tendons. epoxied joint is used in SE-2 while dry joint is applied in SD-2.The other parameters are identical in SE-2 and SD-2. The details of SE-2 and SD-2 are given in Fig.5.

The second group is comprised of SE-3 and SD-3, with a/h equaling 2.5. Length of the specimens is 3500 mm and distance between the two supports is 3300 mm. The distance between the joint and the nearer support is 1175 mm. The other parameter is similar to the specimen in the first group. Epoxied and dry joints are used in SE-3 and SD-3 respectively. More details are shown in Fig.6.

A larger a/h, 3.5, is applied to SE-4 and SD-4 which is in the third group. The length of the specimens is determined as 4450 mm and the distance between the supports is 4250 mm. In order to obtain the large a/h (i.e. 3.5), the distance between the joint and the nearer support increases to 1660 mm. The part far away from the joint of the beam is reinforced by adding extra longitudinal steel bars, shortening the distance between stirrups and increasing the legs of the stirrups with the aim to ensure the failure occurring at the joint section. Fig.7 presents the profile of the external tendons and the configurations of SE-4 and SD-4.

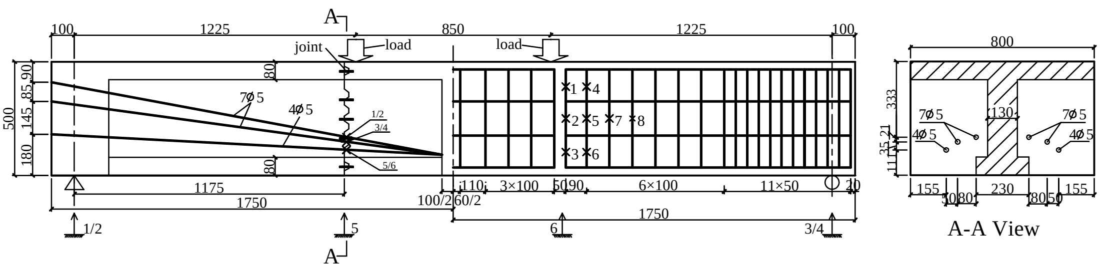


Fig.6. Configurations of SD-3 and SE-3 (mm)

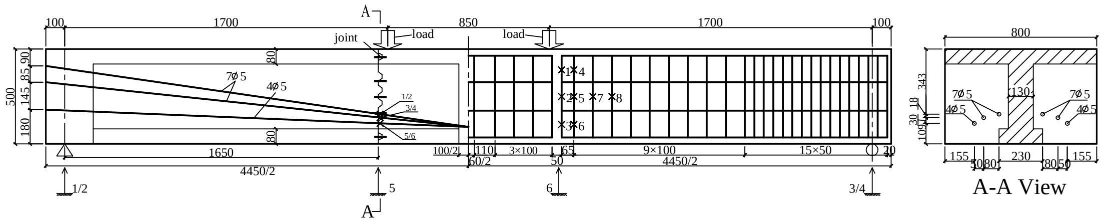


Fig.7. Cnofigurations of SD-4 and SE-4 (mm)

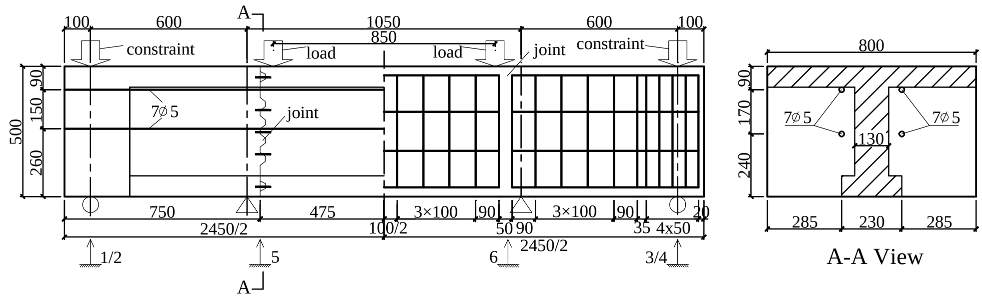


Fig.8. Configurations of SD-5 (mm)

Specimen for Direct Shear Tests

When segmental bridges are constructed using cantilever construction method, the dead weight of the most newly fixed segment and the erection crane is transferred to the adjacent segment through the keys on the joints. The acting point of the dead weigh is near the joint because the segment is short; therefore, the bending moment at the joint is small which can be neglected. Besides, the joint near inflection point is also approximately under direct shear. The dry joint model (SD-5) was tested under direct shear. The length of the specimen is 2450 mm. The specimen is prestressed by 4×7$\varnothing$5 strands and the tendon profile is a straight line. The position of the tendons is shown in Fig.8 which can ensure that the resultant axial forces are applied to the centroid of the joint plane. The configurations of SD-5 are given in Fig.8.

4.4 Concrete and Steel Materials

The mix constituents included ordinary portland cement (42.5 MPa), high-range water reducing admixture, fine aggregates (river sand, modulus of fineness 2.8), coarse aggregates (graded gravel, sizes from 5 to 20 mm). Mix design proportions for the precast concrete segments are shown in Table 2, and the concrete characteristic compressive strengths of the specimens are listed in Table 1.

Two types of strands, 7$\varnothing$5 and 4$\varnothing$5, are used in the specimens. Furthermore, the specimens are reinforced using longitudinal steel bars and stirrups. Double-leg stirrups ($\varnothing$8, R235) are used near joints. The longitudinal reinforcements of $\varnothing$20 and $\varnothing$12 (HRB335) are used in lower and upper flanges respectively. The properties of steel materials are shown in Table 3.

4.5 Fabrication of Specimens

In the segmental beams with epoxied joints, the tensile strength of epoxy is higher than the concrete; therefore, cracks will not occur in the epoxy layer but in the concrete immediately adjacent to the epoxy layer which is still at the joint position. This has been justified by the previous research (Moustafa 1974). From this point of view, monolithic beams with the longitudinal reinforcement cut off at the location of the joint can be used to simulate the epoxied joint beam, which will not affect the experiment (Ramírez et al. 1993) and facilitate the fabrication of specimens. The short line match casting techniques for constructing actual segmental concrete bridge girders was used in fabrication of the dry joint models. At the same time of fabricating the specimens, control cubes (150×150×150 mm) were cast for measuring the concrete characteristic compressive strength of each specimen. All the specimens and corresponding control cubes were cured under outdoor atmospheric curing condition for 28 days.

Table 2. Concrete Mix Proportions

Material	Proportion/m3
Portland cement（42.5 MPa）	500 kg
Coarse aggregate	1000 kg
Fine aggregate	660 kg
High-range water reducing admixture	2.5~5.0 kg
Water	185 kg
w/cm	0.37

Table 3. Properties of Steel Materials

Type		Area (mm^2)	Yield strength (MPa)	Ultimate strength (MPa)	Elastic modulus (MPa)
R235	$\phi 8$	50.3	320	423	2.1×10^5
HRB335	$\phi 12$	113.1			
	$\phi 16$	201.1	363	567	2.0×10^5
	$\phi 20$	314.2			
Strand	$4\phi 5$	79.4	1676	1860	1.95×10^5
	$7\phi 5$	139.0			

Fig.9. Tests setup

5. TESTING SETUP AND PROCEDURE

5.1 Testing Setup

The tests were performed in the State Key Laboratory for Disaster Reduction in Civil Engineering of Tongji University. All the specimens were tested using a two loading configuration with the test setup shown in Fig.9. The loads applied over the beams were provided by two jacks which were located on a reaction frame anchored to the strong floor. Two horizontal loading beams were used to transfer the vertical loads uniformly from the jacks to the beams. Steel panels were placed between the beam and the supports to avoid the local compression failure. For SD-5, additional two jacks were used to restrict the upward displacement at the two ends of the beam.

5.2 Instrumentation

Measurements recorded during each test included applied loads, beam deflections, strains of tendons and stirrups.

1. Strain gages for monitoring the strains of stirrups adjacent to the joints.
2. Strain gages placed on each external tendons near the location of joints for measuring the strains;
3. Strain gages mounted on the upper flange surface of the specimens for measuring the concrete strain; and
4. Displacement transducers used to measure the displacements of the beams.

The locations of the instrumentation are given in Fig.4 to 8.

5.3 Prestressing and Loading Methods

The specimens were subjected to prestressing forces when they had been cured for 28 days under outdoor atmospheric curing condition. The control stress of the external tendons is 1395 MPa (0.75×1860 MPa). The axial components of prestressing forces (T_{p0}) measured after the tendons being stretched are listed in Table 1. Two point loads were applied symmetrically over the specimens. In order to investigate the failure occurring at the joint section in the combined shear and bending tests, one of the two loads was directly applied in the immediate vicinity of the joint (see Fig.5 to 8). The loading was applied monotonically with the increment of 20 kN before cracking, then with the increment of 10 kN until failure. The stable testing data were recorded three minutes after each loading step.

6. TEST RESULTS AND DISCUSSIONS

6.1 Failure Processes and Modes

For the epoxied joints in combined shear and bending tests, cracks caused by the bending moment initiated in the concrete of lower flange adjacent to the joint, not exactly in the interface of the two segments. This is identical to the previous study (Moustafa 1974). As the loads applied to the models increased, the cracks started to propagate to the loading point. The joint stopped opening at a certain height although the loads continued to increase. Finally, the failure occurred in the plane of concrete adjacent to the epoxy layer, and the concrete above the joint opening height broke under combined shear and compressive stresses. The load-displacement curve for epoxied joint specimens is shown in Fig.10. The curves are obviously divided into two parts by the point of cracking. Before cracking, the beams had high stiffness and the curves show a linear relationship between loads and displacements. After the beams cracked, the load-displacement curves start to level off and show a nonlinear feature, and the stiffness of the beams reduced. Based on the results of the combined shear and bending tests, the opening height of the joint increases when the joint position approaches to the mid-span. When the bending failure occurred in SE-1, the failure cracks propagated vertically and did not develop toward the loading point, which is significantly different from the combined shear and bending tests (see Fig.11).

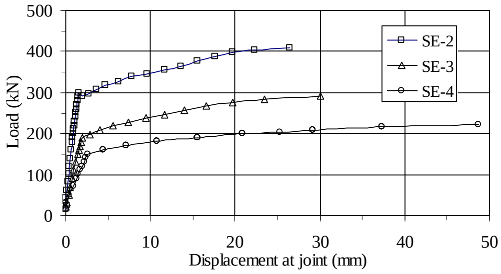


Fig.10. Load-displacement curves at the joint for epoxied joint models in shear-bending tests

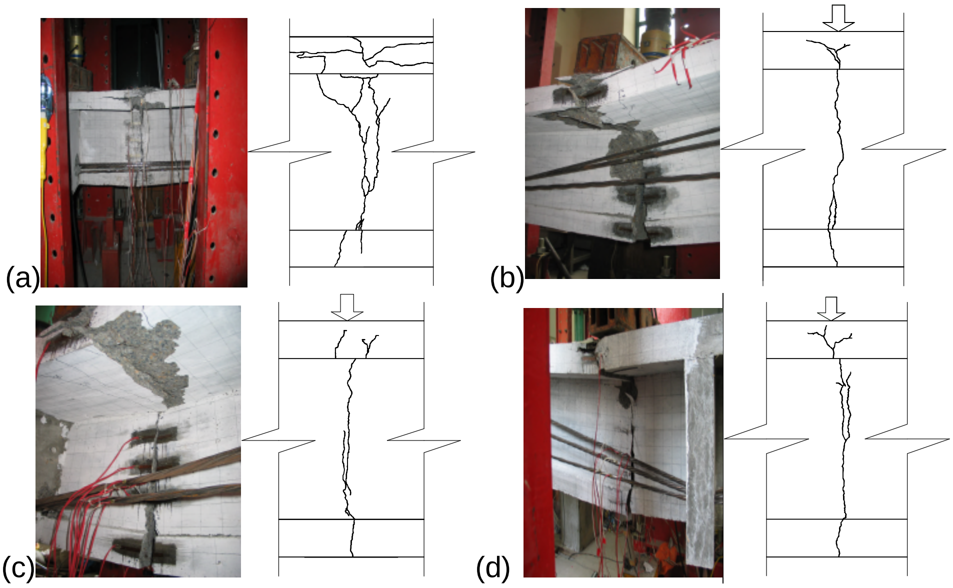


Fig.11. Actual failure modes and cracking sketches of epoxied joints: (a) SE-1; (b) SE-2; (c) SE-3; (d) SE-4

Because the dry joints cannot resist tensile stresses, when the compressive stresses due to external tendons were exceeded by the tensile stress caused by the bending moment, the dry joints opened. The opened joint prevented the cracks occurring in the other part of the lower flange, which is different from epoxied joint. Upon further loading, the opening height of the dry joint increased until equilibrium state was reached on the plane of the joint. The failure of joint happened exactly in the interface of the two segments with the concrete of keys above the opening height breaking and the smooth surfaces between the keys slipped under combined shear and bending, which is different from the failure mode of epoxied joints (see Fig.12). As shown in Fig.13, each of the load-displacement curves of joint was also divided into two parts. Before cracking, a linear behavior of the joints was obtained. Once the cracks initiated, the curves started to deviate from linearity. The opening height of dry joints increases with the load approaching to the mid-span. When subjected to pure bending, the dry joint in SD-1 behaved similarly to the epoxied joint in SE-1 except the failure plane of dry joint coincided with the segment interface instead of occurring in the concrete adjacent to interface of the two segments.

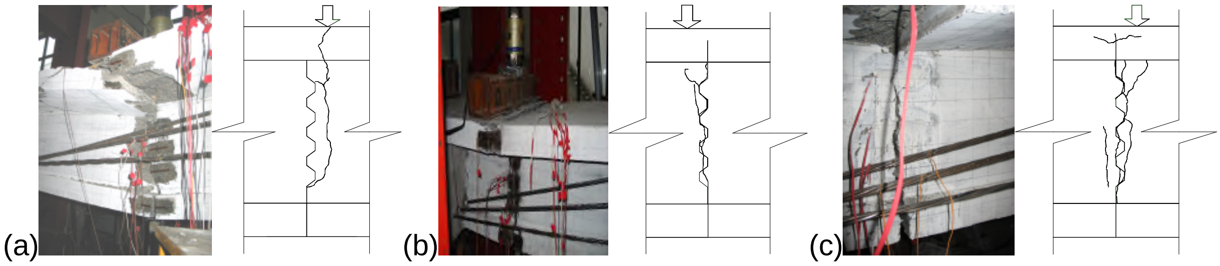


Fig.12. Actual failure modes and cracking sketches of dry joints: (a) SD-2; (b) SD-3; (c) SD-4

When the dry joint model (SD-5) was subjected to direct shear, cracks initiated at the root of NO.4 key, i.e. web shear cracking. Upon loading the beam, other cracks formed at the root of the other keys along the joint plane and gradually interconnected. When shearing off of the keys approaching, a premature failure due to compression occurred at the support happened, as shown in Fig.14. Therefore, the ultimate shear strength of the dry joint under direct shear was not obtained. Before the load applied to SD-5 reached the cracking load (425.9kN), the curve approximately shows a linear relationship between load and vertical displacement at joint. After the applied load exceeded the cracking load, the load-displacement curve levels off and shows a nonlinear feature. Considering the developing tendency of the web cracking (Fig.14), if the compression failure at the support was prevented, the failure mode with the keys sheared off would happen.

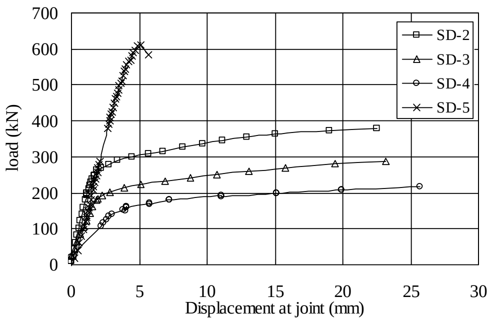


Fig.13. Load-displacement curves at joint at joint for dry joint models in shear-bending and direct shear tests

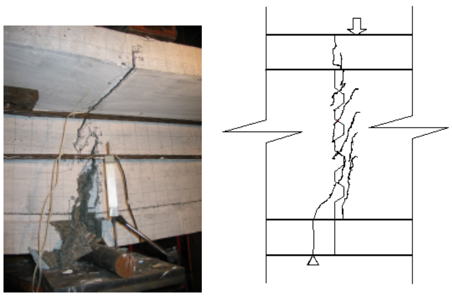
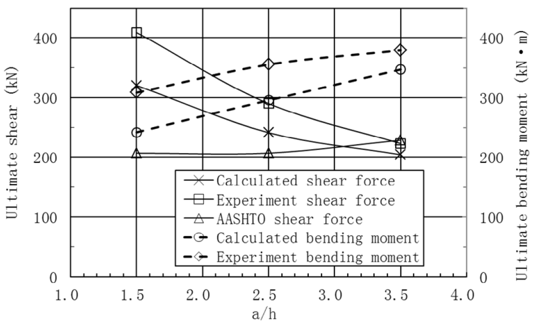


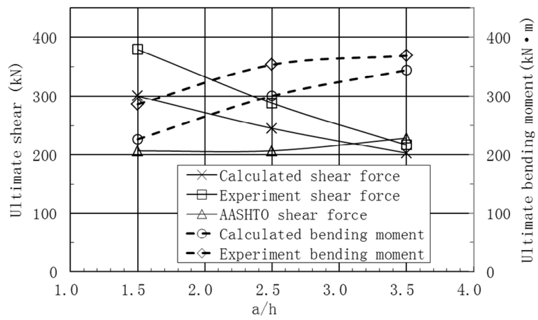
Fig.14. Actual failure mode and cracking sketch of SD-5

6.2 Joint Strength and Resistance Mechanism

For the specimens with the same joint position, the epoxied joints can resist a higher load than the dry joints when the load was applied to the immediate vicinity of the joint section. For the specimens which have the same type of joints, the load resistances of joint reduced with a/h increasing (see Fig.15). This can be attributed to the fact that the ultimate height of cracking (for epoxied joints) or joint opening (for dry joints) increased with the load approaching to the mid-span. Therefore, the area of the concrete in the failure plane which resisted combined shear and bending actions reduced. When a/h changed from 1.5 to 3.5, the shear force in the joint plane at ultimate limit state reduced by 45.4% and 42.8% for epoxied and dry joints, respectively, While the ultimate bending moment increased by 22.9% and 28.8% as shown in Fig.15. Therefore, when PCSB fails like SD(E)-2~4, the ultimate shear forces and bending moments are correlated. In other words, the failure is a combined shear and bending failure controlled by both shear forces and bending moments, which is different from the traditional bending failure. According to the ultimate forces in prestressed tendons (see Table 4) and the approximate area of concrete compression zone (the upper flange area, 64000mm^2, adpoted), ultimate compressive stress (σ_{exp}) in the concrete is obtained which is compared with its counterpart, $\sigma_{\mathrm{bending}}$ (approximating to prism strength), in bending failure (see Table 5). Table 5 shows that σ_{exp} is far lower than $\sigma_{\mathrm{bending}}$, which also verifies that the failure is different from bending failure.



(a)



(b)

Fig.15. Comparison of calculating and experimental results for PCSB joints under combined shear and bending: (a)epoxied joint; (b)dry joint

Table 4. Prestressing Forces in External Tendons at Ultimate

Specimen	T_{pu} (kN)	V_{pu} (kN)	Specimen	T_{pu} (kN)	V_{pu} (kN)
N.O.	N.O.	N.O.	SD-5	>469.5	0
SE-2	980.4	130.3	SD-2	912.4	121.4
SE-3	920.0	121.4	SD-3	935.3	126.6
SE-4	1033.6	107.9	SD-4	1013.4	107.3

Note: N.O. = not obtained.

Table 5 Comparison of ultimate concrete compressive stresses

Specimen	σ_{exp} (MPa)	σ_{cal} (MPa)	$\sigma_{bending}$ (MPa)	Specimen	σ_{exp} (MPa)	σ_{cal} (MPa)	$\sigma_{bending}$ (MPa)
SE-2	15.3	12.2	43.2	SD-2	14.3	11.5	43.2
SE-3	14.4	13.1	43.2	SD-3	14.6	13.6	43.2
SE-4	16.2	18.1	63.2	SD-4	15.8	20.1	63.2

The combined shear and bending resisting mechanism in epoxied and dry joints is described, respectively, as follows: for the epoxied joint, the failure occurred in the concrete adjacent to the segment interface, and therefore the shear force at the joint section resisted by concrete is totally provided in the form of shear stresses in concrete above the opening height; for the dry joint, the failure occurred exactly in the interface between the two segments with the joint opening to a certain height, and consequently the shear force is resisted by two resistance mechanism, one of which is provided by the concrete at the root of the keys above the joint opening height and the other is provided in form of friction due to the slipping between the flat surface around the keys. To facilitate the analysis of the failure mechanism and the calculation of joint resistance, simplified failure modes for epoxied and dry joints are presented in Fig.16 and 17, respectively.

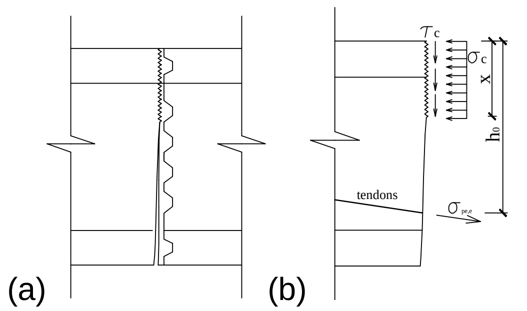


Fig.16. Simplified failure mode for epoxied Joint under combined shear and bending: (a) Failure mode; (b) Forces in failure plane

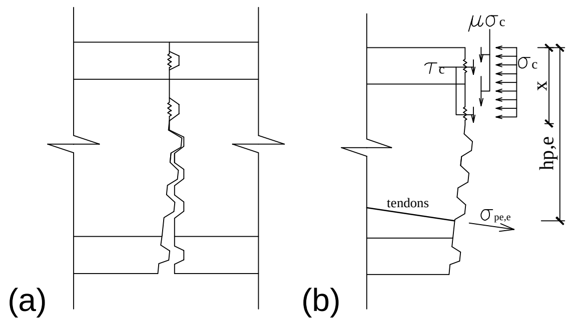


Fig.17. Simplified failure mode for dryjoint under combined shear and bending: (a) Failure mode; (b) Forces in failure plane

For dry joint subjected to direct shear (SD-5), the ultimate shear strength exceeds 612.5 kN. Because the specimen prematurely failed at the support due to excessive compression in that area, it can be concluded that the shear strength of dry joint is larger than 612.5 kN. Because the joint did not open throughout the loading process, the whole joint participated in resisting shear. The shear resisting mechanism can be described as follows: the joints lost the shear resisting capacity when a slip occurred between the two segments of the specimen at the joint with the keys sheared off. The shear strength is composed of two parts as well, one of which is provided by the concrete at the root of all the keys and the other is by the friction between the flat surfaces around the keys in the joint plane. The resistance mechanism is identical to the one proposed by AASHTO (AASHTO 1999).

SUMMARY AND CONCLUSIONS

An experimental study was performed on combined shear and bending behavior of joints in PCSB with external tendons. 9 PCSB models which adopted two types of joints (dry and epoxied) were tested under pure bending, combined shear and bending, and direct shear: where 6 PCSB models with three different joint positions in the combined shear and bending tests, 2 PCSB models in the pure bending tests; and 1 model in the direct shear test. These tests provide quantitative data and fundamental behavioral understanding on failure processes and modes, joint strength, and strains of prestressing tendons and stirrups of PCSB under different loading states. Based on the test results and observations the following conclusions can be drawn:

1. When PCSB is subjected to loads which are applied to the immediate vicinity of the joints, a failure mode happens that the failure develops along the plane of joint with joint open before failure, which is different from traditional bending failure and shear failure in mechanism.
2. The failure mode of dry joints is different from that of epoxied joints when loads are applied to the immediate vicinity of the joints. The failure of dry joint occurs in the segment interface. By contrast, the failure of epoxied joint develops in the concrete adjacent to the segment interface.
3. When dry joints reach the ultimate limit state under combined shear and bending, the ultimate shear forces in the joint section are resisted by three components: two of them are contributed by concrete in terms of shear stresses at the base of keys and friction due to the slip of the flat surfaces and at joint, and the other is provided by the vertical components of prestressing tendons. By contrast, the ultimate shear forces in epoxied joints are resisted by two components: one is the shear stresses of the concrete in the failure plane; the other is the vertical components of the prestressing tendons.
4. Joint position has a significant effect on joint resistance when loads are located in the immediate vicinity of the joints. For PCSB with the same type of joints, the resistance reduces when the joint approaches to the mid-span.
5. When failure occurs in the joint plane (for dry joint) or in the concrete adjacent to the segment interface (for epoxied joint) under combined shear and bending, stirrups nearly contribute nothing to the joint bearing capacity.

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