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Shear Strength Test of Joint with Different Geometric Shapes of Shear Keys between Segments of Precast Segmental Bridge

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ABSTRACT

Joints of each segment of a precast concrete segmental bridge are important. A joint is used to transfer internal shear forces in order to increase strength of the structure. A good segmental joint should be a simple shape, cheap cost to set its formwork, and save time for installation. The purpose of this research was to study the capacity of joint with shear-keys that simulated a web segment of a segmental concrete bridge. Three geometric shapes of shear keys were triangle, semi-circle, and trapezoid included sides of 45 degrees. Each sample contained three web panels, which were prestressed together. Two magnitudes of stresses from prestressing forces were taken into account, 0.833-MPa and 1.267-MPa. The shear keys were divided into two types, single and multiple keys (three keys). The results showed that capacity of the joints with trapezoidal were sensitive comparing with the other shapes. Shear strengths of the trapezoidal were significant improved when the number of key and magnitude of prestressing force were increased. With the higher stress (1.267-MPa) and maximum number of shear key (3-key), all of them provided the equivalent ultimate shear strength. However, the triangle and the semi-circle presented the local cracks that might cause a brittle failure at the shear key.

1. Introduction

Technique of dividing the length of a bridge into several shorter segments provides many benefits to a precast concrete segmental bridge (PCSB) construction. A shorter segment is simple to set up its formwork for prefabricating inside a factory and easier for delivery to the field site. The construction technique allows a fewer workloads on the field site and a quick installation reducing in the number of labors. These are, then, shorten the overall time and save the total cost of construction project.

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Joints between the adjacent concrete segments of a PCSB can be classified under the wet and dry conditions. A thin layer epoxy is applied at a wet joint between the adjacent segments when it is still plastic during the bridge alignment. It was found that a bridge in Illinois across the Kishwaukee River serious failed at its joints causing by the wet joint construction (Koseki and Breen, 1983). The epoxy resin and hardener were under improper blending and mixing. The epoxy could not be hardened allowing the joints were lubricated. This caused cracks and spalling of concrete in a web with a singly keyed joint. It indicates that, for a wet joint, the improper handling or choosing the selected epoxy can be critical. In recent decades, dry joints are more popular than epoxied joints in PCSB construction due to speed of erection and independence of weather conditions (Podolny, W., 1979). Many bridges have been constructed using the dry joints, without applying any epoxy or any other bonding agent between the adjacent segments.

Sliding shear failure mode leading to the shearing-off which parallel to the joint plane can be critical due to discontinuity of a bridge length at the joint location (Bakhoum, M. M, 1991). In general, shear keys are provided on both sides of the web or deck of each bridge segment. During construction process, alignment of the segments can be supported by using the shear key. During service load condition, shear keys is used to provide mechanical interlock for transferring internal forces, especially the shear force between segments.

Failure in the joint region of the precast concrete segmental bridge is important, since it may lead to a brittle collapse of the structure with a short warning. Experimental investigation of Koseki and Breen (1986) on different types of trapezoidal joints including no keys, single large keys, and multiple lug keys show crack pattern at failure of their specimens. Cracking sequence for dry and epoxied keyed of the trapezoidal shear key joints are reported by Bakhoum (1991). Other researches have also conducted on the failure modes of the trapezoidal shear key. These include the study of Zhou and Mickleborough (2005), Shaarbaf et al. (2012), and Yang et al. (2013).

Investigations of the joints concerning with the different configuration and shape of the shear key are limited. The information, in general, about the shear capacity and mode of failure in this area is very little (Ibrahim I. S., *et al.*, 2014). The purpose of this research was to explore the additional information of the joint capacity with shear-key of a PCSB. Results were compared with other available investigation.

2. Objectives

This experimental study was aim to investigate the behavior of twelve specimens with dry joint representing the connection web of the PCSB. The interesting parameters were the different shapes of shear keys and different levels prestressing forces under monotonic loading. The additional details are summarized as follows:

(1) Two groups of specimen consisted of three shapes of shear keys. This included triangle, semi-circle and trapezoid with two levels of prestressing forces. Each group was separated into two sets: single-keyed and multiple-keyed joints.

(2) Results are presented in term of ultimate load, shear and vertical slip relationship, cracks and failure behaviors.

(3) Ultimate shear forces obtained from the experiment were compared with those determined from the AASHTO and other available formula to evaluate their effective performance.

3. Experimental Setup and Test Procedure

Monotonic loading experiments were conducted on specimens with key joints simulating the web of PCSB. Each specimen represented a joint under double shear test. Effect of various shapes of the shear keys, prestressing force levels, and number of keys on the shear behavior was investigated.

3.1 Details of Test Specimens

To simplify the web of a box girder segment, which mainly resists the shear force, a simple rectangular section was adopted as the test specimen in this study. Twelve dry-jointed specimens with different shapes of keys were conducted. Each specimen consists of three simulated web panels. To ensure a properly position interlock of the precast web panels in the completed specimen, the panels were casted against each other in the sequence according to the match-casting method. Then, the three panels were combined together by applying the two-prestressing tendons.

The overall dimensions of the specimen were 650-mm height, 450-mm width, and 100-mm thickness. Two different levels of prestressing forces were applied and divided all specimens into two groups, 0.833 MPa and 1.267 MPa. Each group was separated into two sets: single-keyed and multiple-keyed joints. Three geometric shapes of the shear-key were taken under consideration for each set of specimens, which includes triangle, semi-circle, and trapezoid with sides 45 degree. Dimension of the keys for each shape is given in Fig. 1-2. Summary of the test on each keyed joint with the name of specimen is shown in Table 1.

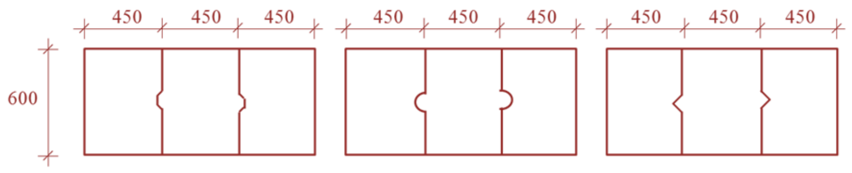

Figure 1: Dimension of specimen with single-key joints

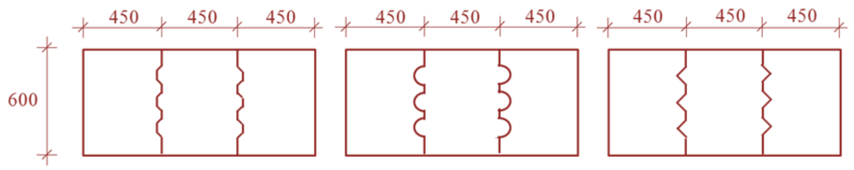

Figure 2: Dimension of specimen with multiple-keys joints

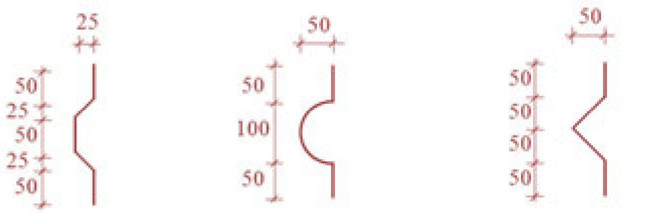

Figure 3: Details of shear key

Specimen ID was presented into three elements splitting by two dash lines, for example, S-TRA-0.833. The first element was either S or M, representing single or multiple keys, respectively. The second element was either TRA, TRI, or CIR representing the shape of shear key which were trapezoidal, triangular, or semi-circle shear keys, respectively. The last element was either 0.833-MPa (50 kN), or 1.267-MPa (75 kN) representing the two levels of stresses due to prestressing forces, which were used in this experiment.

Table 1: Summary of test on keyed joints

Type of Joint	Shape of shear keys	Specimen ID	Prestressing force	Number of test
Single Keyed	Trapezoid Triangle Semi-circle	S-TRA-0.833 S-TRI-0.833 S-CIR-0.833	0.833 MPa	1 1 1
Multiple Keyed	Trapezoid Triangle Semi-circle	S-TRA-1.267 S-TRI-1.267 S-CIR-1.267	1.267 MPa	1 1 1
Single Keyed	Trapezoid Triangle Semi-circle	S-TRA-0.833 S-TRI-0.833 S-CIR-0.833	0.833 MPa	1 1 1
Multiple Keyed	Trapezoid Triangle Semi-circle	S-TRA-1.267 S-TRI-1.267 S-CIR-1.267	1.267 MPa	1 1 1
Total				12 sets

3.2 Materials Properties

Compressive strength was measured from concrete cylinder after 28-day. The concrete mix was designed to make a compressive strength of 32 MPa. However, the test results provided the compressive strength ranging from 33 to 37 MPa. Then, average compressive strength was 35 MPa.

The yield tensile strength of 12-mm diameter reinforced bars was 420 N/mm^2 and their spacing was 100 mm both in longitudinal and transverse direction. The prestressing system consists of two 12.7-mm diameter tendons, each of which contained one PC-strand with f_{pu} = 1860 MPa, and A_{ps} = 98.7 mm^2. The PC-strand, however, consists of seven wires.

3.3 Test Arrangement

The test arrangement used to investigates the shear strength and behavior of joints is shown in Figure 4. Two PC-strands were applied at the top and bottom parts of the specimen with the intended equivalent force level to minimized moment occurred in the shear plane. The experiment was conducted after finishing the application of the prestressing forces without grouting tendons. Loading was vertically applied using hydraulic jack, which was connected to a 500 kN load cell, on the upper part of the center panel of the specimen.

Before the test, two displacement transducers were connected to a data logger for data recording. One of the displacement transducers was located at the bottom part of the center panel of the specimen in order to measure relative vertical slip of the panel. The second displacement transducer was located beside the bottom edge of specimen in order to measure separation or horizontal displacement of the edge panel. The slip and separation had been recorded at every 10-kN vertical load increment until the connection failed. The connection was classified as failed when it was observed that whether excessive vertical slip was found or a sudden drop in load was occurred with an increase in the vertical slip.

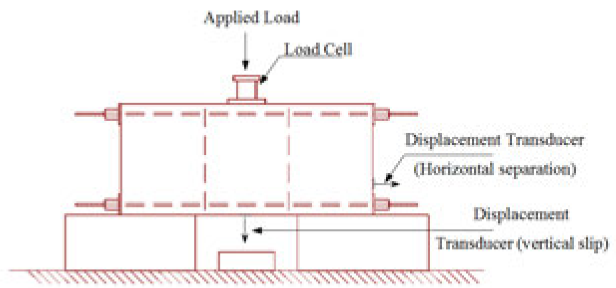

Figure 4: Shear test arrangement

Figure 5: Shear test of multiple key triangle shape stressing 0.833 MPa

Figure 6: Shear test of multiple key semi-circle shape stressing 0.833 MPa

Figure 7: Shear test of multiple key trapezoid shape stressing 0.833 MPa.

4. Experimental Results

4.1 Stresses due to Prestressing Forces and Ultimate Load

Table 2 presents the prestressing forces applied on each specimen and corresponding ultimate load obtained from the experiment. These expected prestressing forces were 50 kN and 75 kN.

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Since the prestressing system consist of two tendons, half of the expected prestressed forces, 25 kN and 37.5 kN, was used as a guide line for applying the force to each tendon. However, in practice the force that applied to each tendon could not be précised due to the losses in prestress and the instrumental device used in the laboratory. Magnitudes of the forces that applied to the top tendon (Ft) and bottom tendon (Fb) in each specimen were shown in Table 3. The difference between the top and bottom tendons created the moment (M); this moment was then used to calculate the top and bottom stresses introducing by prestressing forces on each specimen, as shown in the Table 3.

Table 2: Prestressing force and maximum test load

Type of Joint	Specimen ID	Prestressing Force (kN)	Ultimate Load (kN)
Single-Keyed	S-TRA-0.833	50	122
	S-CIR-0.833	50	266
	S-TRI-0.833	50	261
	S-TRA-1.267	75	157
	S-CIR-0.1.267	75	283
	S-TRI-1.267	75	255
Multiple-Keyed	M-TRA-0.833	50	284
	M-CIR-0.833	50	349
	M-TRI-0.833	50	348
	M-TRA-1.267	75	364
	M-CIR-0.1.267	75	391
	M-TRI-1.267	75	400

Table 3: Stresses due to prestressing

Specimen	Shape of Shear Keys	N (kN)			M(MPa)	Stresses(MPa)	
		F_t	F_b	$F_t + F_b$	$0.25(F_b - F_t)$	Top	Bottom
Single Shear Key	Trapezoid	25.50	25.45	50.59	0.00	-0.851	-0.847
	Triangle	25.66	25.33	50.99	0.00	-0.864	-0.836
	Semi-circle	25.17	25.33	50.50	0.00	-0.835	-0.848
Multiple Shear Key	Trapezoid	25.60	25.40	51.00	0.00	-0.858	-0.842
	Triangle	25.30	25.50	50.80	0.00	-0.838	-0.855
	Semi-circle	25.00	25.30	50.30	0.00	-0.826	-0.851
Single Shear Key	Trapezoid	37.83	37.66	75.49	0.00	-1.265	-1.251
	Triangle	37.83	37.83	75.66	0.00	-1.261	-1.261
	Semi-circle	37.60	37.70	75.30	0.00	-1.251	-1.259
Multiple Shear Key	Trapezoid	37.50	37.50	75.00	0.00	-1.250	-1.250
	Triangle	37.66	37.70	75.36	0.00	-1.254	-1.258
	Semi-circle	37.60	35.70	75.10	0.00	-1.256	-1.248

However, the ultimate load of a multiple-keyed joint was larger than the single-keyed corresponding joint. It is the similar results comparing with those obtained by other researchers (Zhou and Mickleborough , 2005; and Shaarbaf *et al.*, 2012). The shear key increase in number represents the interlock increase at the joint plane that results in the larger magnitude of shear resistance or the load capacity. Alcade *et al.*, (2013) reported from his numerical study that "the average shear stress transferred across the dry keyed joints decreases as the number of keys increases causing by the sequence failure of the key". For the single shear key, this can clarify that there is no any additional shear key to resist the applied load after the failure. For the multiple key joint, after the first key failure, the remaining key is still able to resist the applied load by using the remainder of its capacity. The remainder capacity is smaller than the full capacity of one key since cracks have been appeared in the remaining key.

4.2 Applied Shear - Vertical Slip Relationship

For the single key specimens with all types of keys, the relationship between the applied shear and vertical slip is separated by stress due to the prestressing forces of 0.833-MPa and 1.267-MPa as shown in Figures 8 and 9, respectively. It shows that the trapezoid shape provides the worst performance comparing with triangle and semi-circle shapes at the same prestressing force level. Magnitude of ultimate shear capacity for trapezoid (61 kN and 78 kN) is lesser than the triangle (130 kN and 127 kN) and semi-circle (133 kN and 141 kN). Slopes (in term of stiffness) of the trapezoid shape are lower than slopes of the others, especially in the case of the smaller prestressing force (0.833-MPa) as shown in Figure 8.

For the multiple key specimens, the load and vertical slip relationship with all types of keys are separated by stress due to the prestressing forces of 0.833-MPa and 1.267-MPa as shown in Figures 10 and 11, respectively.

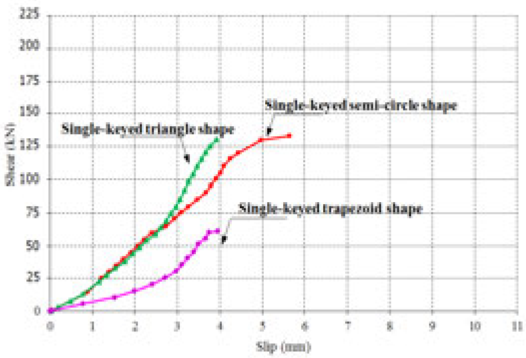


Figure 8: Shear force vs slip behavior of single-keyed with different shapes under 0.833 MPa.

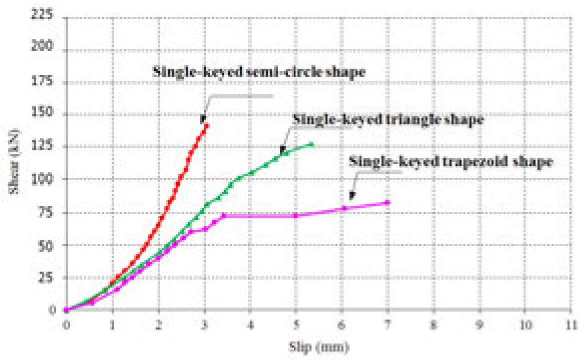


Figure 9: Shear force vs slip behavior of single-keyed with different shapes under 1.267 MPa.

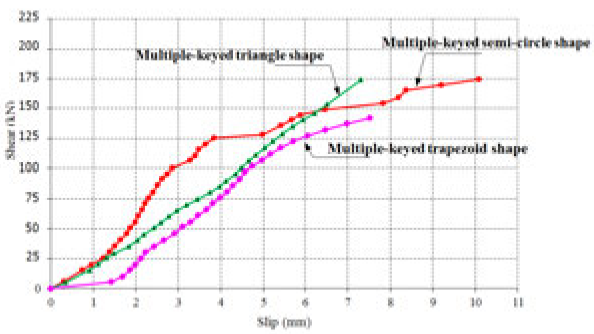


Figure 10: Shear force vs slip behavior of multiple-keyed with different shape under 0.833 MPa

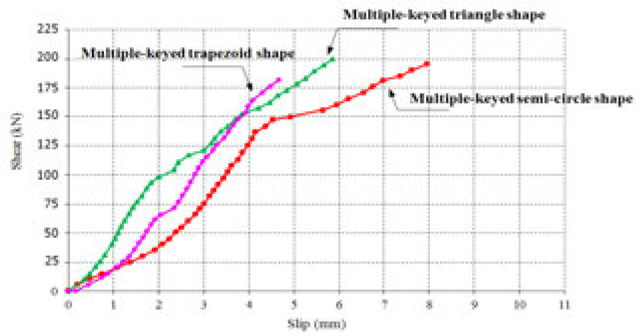


Figure 11: Shear force vs slip behavior of multiple-keyed with different shape under 1.267 MPa

It shows that the trapezoid shape for multiple key provides a better competitive performance than the single key. The ultimate shear for trapezoid (142 kN and 182 kN) is closer to those obtained from the triangle (174 kN and 200 kN) and semi-circle (174 kN and 195 kN). Most of the curves provide a nearly linear relationship than the single shear key; the curve of semi-circle shape however seems to be inconsistent.

These results imply that the key number and the prestressing force level have less impact on the shear-vertical slip relationship of the triangle and semi-circle shapes. In contrast, the trapezoidal shape is sensitive to these two parameters. The curve for a single joint of trapezoidal is improved with the high magnitude of prestressing force but its performance is still worse comparing with the corresponding joints. However, the curve of the trapezoidal shape has been much improved for the multiple key joint (when the number of key increase); it performance is close to the others, the triangle and semi-circle shapes. It should be note that the levels of prestressing forces, which applied in this study, may be small until it was not significant change in magnitude of the ultimate shear.

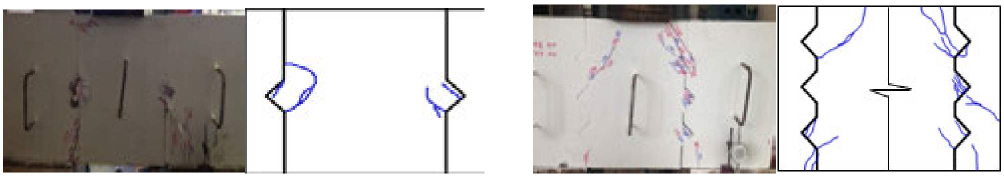
In comparison, the test results for single shear keys is confirm with the results obtained by the test of Ibrahim *et al.* (2014), which conducted the direct shear test on a single shear key with confining pressure. The average ultimate shear force of the semi-circle shape is highest among the other shear keys tested that corresponding to his study. The average ultimate shear force of trapezoidal shape with angle 45 degree is less than those of the semi-circle shape. However, the ultimate shear of a triangle key joint is the smallest comparing among the selected shapes that compatible with this study. This point is contrast with the results from this study; the trapezoidal key joint was the worst comparing with both of semi-circle and triangular shapes.

4.3 Cracks and Failure Behaviors

Figures 12(a), 13(a), and 14(a) show the crack patterns at the actual failure specimens with single-keyed joint under stress due to prestressing force of 0.833 MPa. The figures on the left side are the actual failure and for more visible those on the right side are the hand sketches. Similarly, Figure 12(b), 13(b), and 14(b) show the crack patterns of the actual failure specimens with multiple-keyed joint. All Figures are however specimens under stress due to prestressing force of 1.267 MPa.

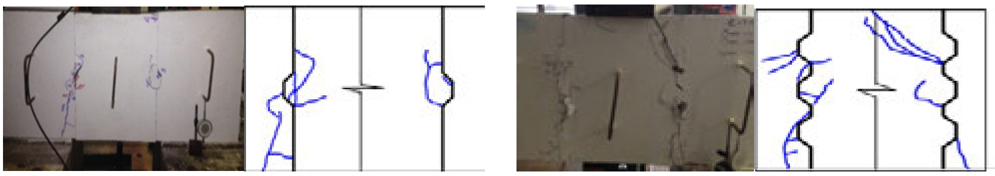
For single-keyed specimen with triangular and trapezoidal shapes, Figures 12(a) and 13(a), the major crack occurred at the bottom base of the male key. The short cracks diagonally tended to extend into the center of middle panel with an upward angle of approximately 45 degree. However, for the single key with the semi-circle shape, some cracks were localized along the shear plane of the male keys including some short diagonal cracks. The male keys seemed to be splitted from the main panel, which showed the undesired brittle failure.

For all shapes of multiple-keyed specimens, Figures 12(b), 13(b) and 14(b), major crack occurred at the bottom base of the male key. The cracks also diagonally extended into the center of middle panel with an upward angle of approximately 45 degree. However, the lengths of these cracks were propagated longer than the case of single key joint. The failure pattern showed more ductile characteristic. It should be noted that the ultimate shear forces of the multiple-keyed specimens were higher than the corresponding single-keyed specimens.



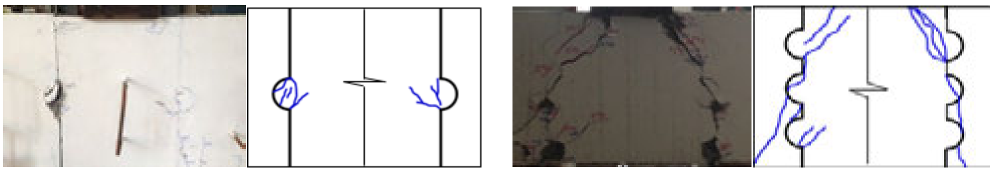
(a) Single key stressing 0.833 MPa (b) Multiple keys stressing 1.267 MPa

Figure 12: Actual and hand sketch of failure crack of triangle shape



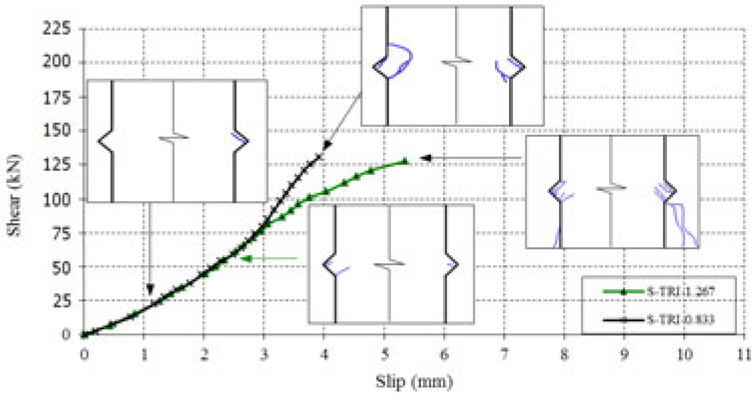
(a) Single key stressing 0.833 MPa (b) Multiple keys stressing 1.267 MPa

Figure 13: Actual and hand sketch of failure crack of trapezoid shape

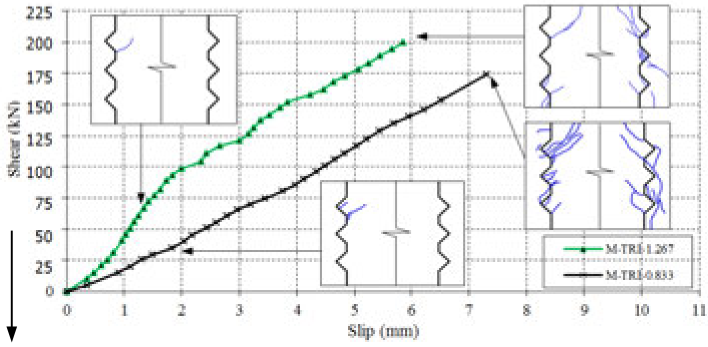


(a) Single key stressing 0.833 MPa (b) Multiple keys stressing 1.267 MPa

Figure 14: Actual and hand sketch of failure crack of semi-circle shape



(a) Single shear key



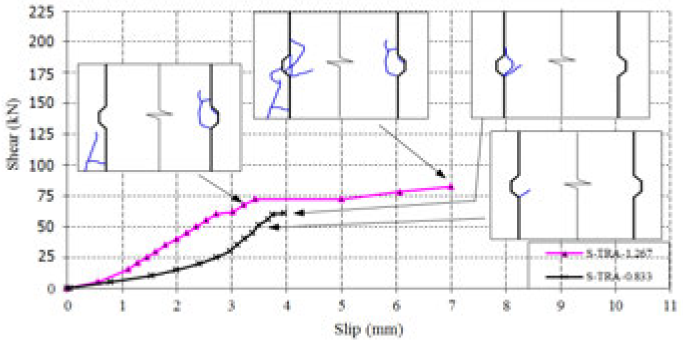
(b) Multiple shear keys

Figure 15: Crack patterns - first and failure cracks of triangle shape

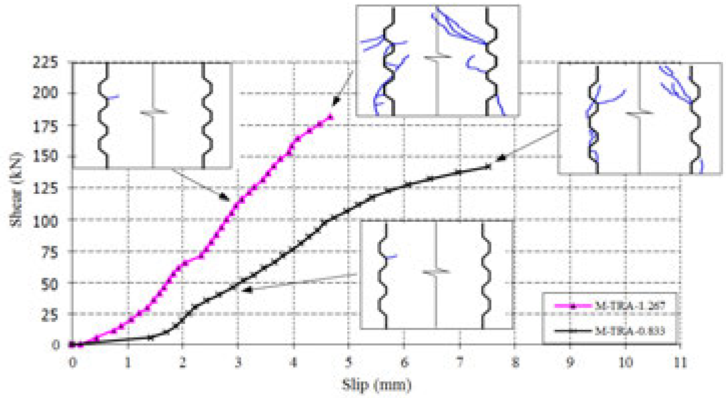
The curves of applied shear and vertical slip relationship of specimens with different number of keys are shown in Figures 15 to 17 and divided into two parts, part (a) and (b) for the stress due to prestressing forces of 0.833-MPa and 1.267-MPa, respectively.

For the single keyed specimen- part (a), slope of the curve for higher prestressing forces in the early beginning are nearly the same values. Then, slope for semi-circle and trapezoid shapes are improved when the magnitude of prestressing force increases. However, in somehow, slope of the triangle shape is decrease with the higher prestressing force. The first crack is formed at higher ultimate shear for all specimens with higher prestressing force. This crack starts at the bottom corner of the male keys and propagated away from the shear plane. Except the triangular shape, the crack formed at the upper part of a male key. The ultimate crack patterns, generally, appear localized near the male key.

For the multiple keyed specimen- part (b), slopes for triangle and trapezoidal shapes are improved when the magnitude of prestressing force increases. However, slope of the semicircle shape seems to be unorganized. The first crack is formed at higher ultimate shear for all specimens with higher prestressing force. This crack starts at the bottom corner of the top keys and propagates

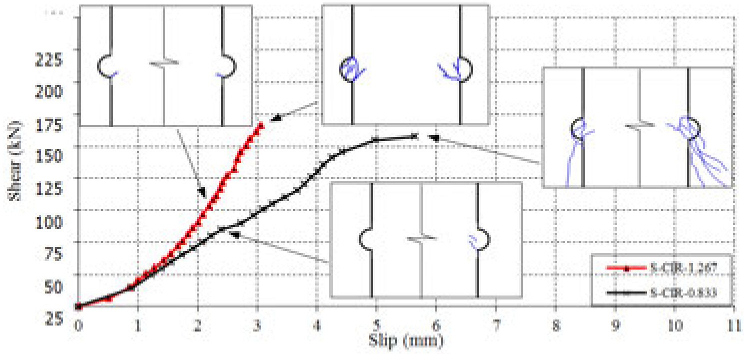


(a) Single shear key

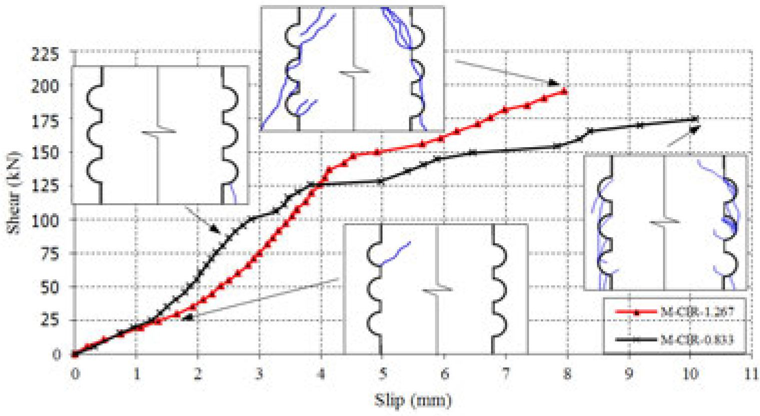


(b) Multiple shear keys

Figure 16: Crack patterns - first and failure cracks of trapezoid shape



(a) Single shear key



(b) Multiple shear keys

Figure 17: Crack patterns - first and failure cracks of semi-circle shape

away from the shear plane, except the semicircle shape with low prestressing forces. The ultimate crack patterns, generally, appear near the bottom corner of the male keys. However, some addition cracks localized forms at the parts of some female keys.

To compare the failure of the single shear key with the work of other researchers, it is confirmed by Ibrahim *et al.* (2014) that some specimen with semicircle key indicates the signs of splitting at the interface of the shear plane. He suggests that splitting failure mode should be avoided for any structural components since it could cause a serious damage.

For the multiple shear keys, the crack patterns agree with those proposed by Zhou and Mickleborough (2005). The first crack of the 3-keyed dry joint generally appears at the lower corner of the bottom key. The shear failure is then occurred at the bottom key following by the sequential failure of each key above the earlier failed key. In contrast, the results from this study show that the first crack starts at the lower cornreer of the upper key. This might cause by the small magnitude of the prestressing forces which allows some horizontal displacement at the tension zone providing the stress concentration at compressive zone of the upper key.

It should be note that the semi-circle key can provide splitting failure. In addition some key of the triangle presents the local crack at the key near the shear plane with can cause the key damage resulting in a brittle failure. These shapes are therefore not recommended.

5. Comparison of Experimental Results and Other Formulas

Shear strength obtained from the ultimate load of this experiment is compared with different design formulas. The formula suggested by ASSHTO provisions (1999) is

$$V_j = A_k\sqrt{6.972 \times 10^{-3} f_c'}(12 + 2.466\sigma_n) + 0.6A_{sm}\sigma_n \quad (MN) \qquad (1),$$

in which, A_k = area of all base of keys in failure plan (m^2), f_c' =compressive strength of concrete (MPa), A_{sm} = area of all contract between smooth surface of failure plane (m^2), σ_n = normal compressive stress in concrete after allowance for all prestress losses determined at the centroid of the cross section (MPa)

The other formula suggested by Rombach and Specker (2004) is

$$V_j = 0.14 f_c' A_k + 0.6\sigma_n A_{joint} \quad (MN) \qquad (2),$$

in which, f_c' = compressive strength of concrete (MPa), A_k = area of all base of keys in failure plan (m^2), σ_n= normal compressive stress in joint (MPa) and $A_{joint} = A_k + A_{sm}$ is the area of the joint (m^2).

Table 6: Comparison shear strength of the joins

No	Specimen ID	Shear Force (kN)	AASHTO (kN)	Error %	Robach and Specker (kN)	Error %
1	S-TRA-0.833	61	94	(35)	81	(25)
2	S-TRI-0.833	130	94	-39	81	-60
3	S-CIR-0.833	133	94	-42	81	-63
4	S-TRA-1.267	78	112	(30)	98	(20)
5	S-TRI-1.267	127	112	-14	98	-29
6	S-CIR-1.267	141	112	-27	98	-44
7	M-TRA-0.833	142	221	(36)	179	(21)
8	M-TRI-0.833	174	221	21	179	3
9	M-CIR-0.833	174	221	21	179	3
10	M-TRA-1.267	182	244	(25)	196	(7)
11	M-TRI-1.267	200	244	18	196	-2
12	M-CIR-1.267	195	244	20	196	1

Results from Table 6 show that all specimens of trapezoid, which are presented in the parenthesis, are overestimate since the design formulas from both AASHTO including Rombach and Specker's provide higher results than the one from this experimental study. However, the multiple joints with triangular and semi-circle shapes are also overestimation, but the corresponding single joints are underestimated.

In comparison, some results from this study agree with the study on dry joints of the trapezoidal specimens of Zhou and Mickleborough (2005) which using confining pressure. The predictions of strength from Rombach and Specker's were always less than those of AASHTO. As confinement forces are increased, the difference between the measured and predicted strengths were decrease. In contrast, some parts of the results from this study disagree with Zhou and Mickleborough (2005). The single trapezoidal joints of Zhou and Mickleborough indicate underestimate results, while the multiple joints are overestimate. In addition, the AASHTO's estimation provides the relatively better results than Rombach and Specker's. From this study, it is however indicated that all joints of trapezoidal shape are overestimate. Moreover, the predictions of strength using Rombach and Specker's formula provide the relatively better results than AASHTO provision.

The differences between this study and Zhou and Mickleborough (2005) may be obtained from the different configurations of the specimens and the test set-up conditions. Zhou and Mickleborough conducted a single shear test on the shear key with confining pressure. The load was then applied directly to a single shear plane. In contrast, this study performed a double shear test on a joint, three concrete panels were connected with two prestressing forces; the load was applied at the center of the middle panel.

6. Conclusion

An experimental study was performed on shear capacity of joints in PCSB with different shapes of shear keys. Three geometric shapes of the shear keys were conducted; triangle, semi-circle, and trapezoid with sides 45 degree. The test results can be concluded as follows:

1. The ultimate applied load of a three-keyed joint is higher than the corresponding single-keyed joint. But the average shear force of a key in the three-keyed joint is lesser than a key in the single joint.

2. The average ultimate shear force of the semi-circle shape is highest, contrast with the trapezoidal shape with angle with 45 degree, which is smallest. However, the semi-circle and triangle keyed joints are not recommended since their cracks can cause a brittle failure.

3. The prediction of shear strength of trapezoidal shape using Rombach and Specker's formula provides the relatively better results than AASHTO provision. All trapezoidal joints are overestimate.

4. For multiple joint, AASHTO provision formula provides error ranging from 18-36%. Rombach and Specker's formula provides error ranging from 7-21% for multiple joint.

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