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ULTIMATE SHEAR CAPACITY AND FAILURE OF SHEAR KEY CONNECTION IN PRECAST CONCRETE CONSTRUCTION

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Abstract: This paper presents the experimental results on the strength of shear key connection in precast concrete construction. The use of shear key is to connect two separate precast components to increase the shear resistivity of the joint surfaces. The proposed shear key shape in this study comprises of triangular, composite rectangular, semi-circle and trapezoidal. In addition, the trapezoidal shape is made up with 3 different key's angles. All specimens are tested using the "push-off" method to obtain the ultimate shear capacity of which is due to the failure of the connection. From the analysis, stiffness, elastic and plastic behaviour, and the mode of failure is discussed to determine the most effective shape of the proposed shear key. From the findings, semi-circle shear key produced the highest shear capacity at 62.9 kN compared to that of the other shapes. Meanwhile, the trapezoidal shape at an angle of 45° produced the highest shear capacity at 44.1 kN. Together in the aspect of stiffness, the 45° trapezoidal shapes produced the highest resistance towards slip at 166.7 kN/mm. Failure mode are mostly due to shear, sliding and diagonal tension crack. Large slip of 7.35 mm is recorded from the triangular shape. The large slip is maybe due to sliding since the angle of the key faces to the shear plane is 45° which indicates to less interlocking compared with the other shapes they form an angle of 90° with the shear plane.

Keywords: *Shear key; ultimate shear capacity; failure mechanism; precast connections*

1.0 Introduction

For the past few decades, reinforced concrete has been widely used in building construction. Reinforced concrete structure is design to resist compression and tension force, apart from bending and shear force. Furthermore, it is relatively easy to construct and the structure integrity is ensured (National Precast Concrete Association, 2008). However, as the requirement to the quality of building structure increases, there is a need for faster or quick construction technique. One technique is to use prefabricated building construction. Since the 1990's, precast concrete construction maintains its main purpose to shorten construction time and reduce the number of labours.

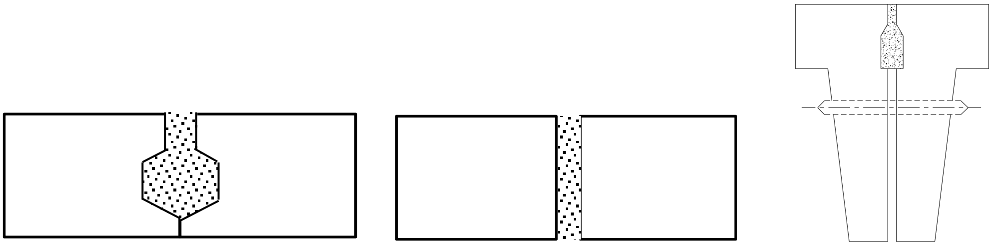
Along with the various prefabrication systems, many types of connections have been developed. The type of connections must provide adequate strength, ductility and continuity in order to ensure the integrity of the structure under various loading conditions (Rizkalla *et al*., 1989). Shear key is one of the most effective practical methods to connect two or more precast panels and it is widely used in bridge deck, beam-to-column connection, shear bearing wall and hollow core floor slab. The main function of shear key is to transfer lateral and vertical forces through the transverse joint, and to prevent vertical displacement between the elements at the joint. Moreover, shear key is considered and proved to produce great shear resistance to prevent sudden collapse by ensuring that the structure behaves monolithically (Lim, 2011).

The shape of shear key gives significant effect to the shear resistance capacity. However, there is still lack of information and evidence regarding the shear key configuration and shape to the shear capacity resistance and its failure mode. Therefore, the aim of this study is to determine the most effective shape and configuration of shear key connector to be applied in precast concrete construction. Further analysis on the cracking pattern and failure mode is also discussed in this paper.

2.0 Related Works

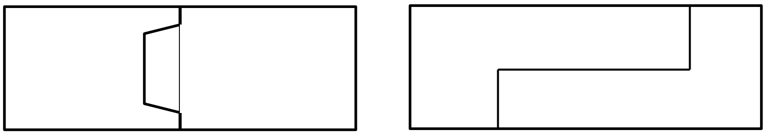
2.1 Types of Joint and Shear Friction Theory

The joint in precast panels are usually categorised as wet or dry joints. Wet joint contained bonding agent such as grout or epoxy mortar that is used to bond the two interfaces as shown in Figure 1. Meanwhile, dry joint as shown in Figure 2 has no bonding agent where the connection between the structural members can be achieved either by bolting, welding and also shear key joints (Sullivan, 2003).



(a) Female-female shear key (b) Flat (c) Mechanical and grout

Figure 1: Precast panel wet joints



(a) Male-female shear key (b) Dapped

Figure 2: Precast panel dry joints

For dry joint such as shear key in this study, the connection between the precast panels depends solely on shear friction. Shear friction explained the shear transfer of elements through the interface where it stated that the shearing force across a potential crack or plane of weakness is resisted by virtue of friction along the crack or plain if there is normal compressive force across the crack. Table 1 shows the friction coefficient in ASSHTO Recommendations, MAST and PCI Design Handbook. As given in the table, friction coefficient depends on concrete placement, smoothness and type of material (Koseki & Breen, 1983).

Table 1: Friction coefficient in ASSHTO Recommendations, MAST and PCI Design Handbook

Concrete placement	*Friction coefficient, μ*		
	ASSHTO	*PCI Design Handbook*	*MAST*
Concrete placed monolithically	1.4	1.4	1.4 – 1.7
Concrete placed against hardened concrete with roughened interface	1.0	1.0	1.4
Concrete cast against steel	0.7	0.6	0.7 – 1.0
Concrete cast against smooth concrete surface	-	0.4	0.7 – 1.0

The design of dry joints such as in shear key has to be designed for its serviceability and ultimate limit state to ensure that the structure behaved monolithically. Under service condition, the structure is under compression. Therefore, forces and moment can be calculated by linear elastic behaviour. Meanwhile, at ultimate condition the dry joints are designed to resist shear load. According to Rombach (2004), there is a great difference in the behaviour of concrete bridges with smooth or shear key joints. In the case of smooth joint, the bridge can only transfer the load between the segments if compression force existed. However, for shear key joint the load can be transferred until a certain opening is reached. The shear capacity of a shear key joint is a combination of friction between plain surfaces and the shear capacity of the shear key. However, existing design models such as in ASSHTO and German Recommendation often neglect the latter. For single trapezoidal shape, Buyukozturk *et. al.* (1990) proposed an analytical equation to predict the shear capacity of the shear key. The equation is given as:

$$V_j = A_{key}\sqrt{6.792 \times 10^{-3} f_{ck}} \cdot (12 + 2.466\sigma_n) + (0.6A_{sm}\sigma_n) \tag{1}$$

where f_{ck} is the characteristic concrete compressive strength (N/mm^2), σ_n is the compressive strength in the joint (N/mm^2), A_{key} is the area of the base of all shear keys in the failure plane and A_{sm} is the contact area between the smooth surface on the failure plane. However, according to the German Recommendation only frictional forces should be considered in the design of segmental bridges. The equation is given as:

$$V_j = \mu\sigma_n A_t \tag{2}$$

where μ is the friction coefficient taken as 0.7 and A_t is the effective shear area. Eq. (1) and (2) is then further refined by Rombach (2002 & 2004) where the proposed shear capacity of the trapezoidal shape shear key is given as:

$$V_j = \frac{1}{\gamma_F}\left(\mu\sigma_n A_{joint} + 0.14 f_{ck} A_{key}\right) \tag{3}$$

where the friction coefficient, μ is taken as 0.65, the safety coefficient, γ_F is taken as 2.0 and A_{joint} is the area of the compression zone. Furthermore, according to Rombach (2002), for glued joints, the second term of ($0.14 f_{ck} A_{key}$) in Eq. (3) can be neglected. This is because the results of the experimental work show only a small increase in shear capacity between the dry and glued joints.

2.2 Failure Mode of Concrete Shear Key

Cracking growth is a simple fracture classification for shear-off type of failure. Cracking for shear key joint can be categorised into two basic growths, known as diagonal multiple cracks (M) and single curvilinear crack (S). Both crack types are shown in Figure 3 (Kaneko, 1993a; 1993b and Bakhoum, 1991).

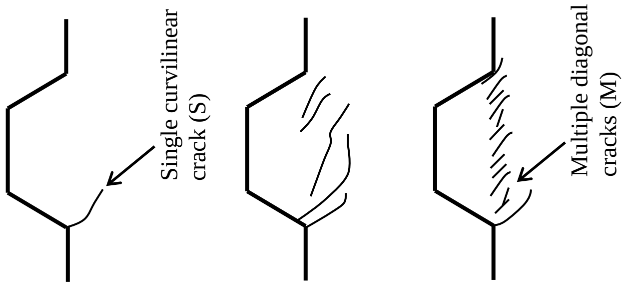
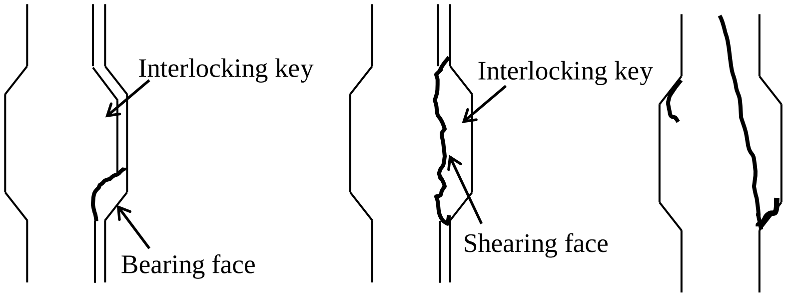


Figure 3: Cracking growth in shear key joint (Bakhoum, 1991& Kaneko *et al.*, 1993)

A study by Chatveera and Nimityongskul (1994) on 18 specimens of trapezoidal shear keys found that the failure is a result of either one or a combination of the followings:

(a) Concrete crushing at the sloping face of the key or at the bottom corner. This type of failure occurred in the large dimensioned joints.
(b) Shear off failure at the root of the shear key.
(c) Diagonal tension crack and this occurred in the small dimensioned joints.

The effect of the different geometry of the shear key is observed by the failure patterns as shown in Figure 4.



(a) Crushing (b) Shearing (c) Diagonal tension crack

Figure 4: Specimen dimension and configuration for the shear key test (Chatveera and Nimityongskul, 1994)

For single rectangular shear key subjected to shear and compressive loading, the cracking sequence is shown in Figure 5. Short S crack is first developed by tensile stresses resulting from the shear stress concentration at the upper corner of the shear key as shown in Figure 5(a). When the shear load is increased, the shear key started to rotate, thus causing the development of M cracks along the base of the shear key (see Figure 5(b). At the same time, tensile stress increases due to the frequent rotation of the shear key. As the shear load is getting higher, it causes the M cracks to continuously develop and opening the displacement. From Figure 5(c), by compressive strut between the M cracks, the shear key is succeeded to detain its shape and position at the point just before failure. When the compressive strut between M cracks carries all the loads in compression, no shear stress exists along the base of the shear key (Kaneko *et al.*, 1993a). Finally, when the compressive strut is crushed, the shear key failed due to splitting as shown in Figure 5(d).

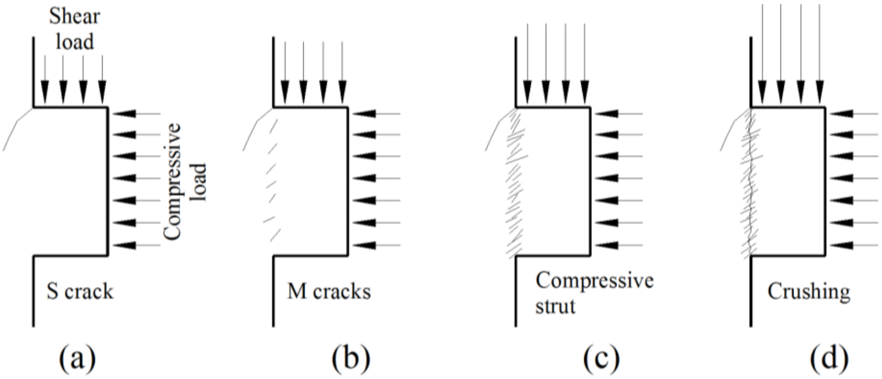


Figure 5: Shear-off fracture sequence (Kaneko *et al.*, 1993)

By knowing the failure mechanism and the sequence of shear-off failure, a model is developed by Kaneko *et al. (*1993a) using Linear Elastic Fracture Mechanics (LEFM). In order to predict the S and M crack formation, Wedge Crack Model (WCM) and Rotation Smeared Crack-Band Model (RSCBM) are then used. From here, they come out with a mathematical equation to predict the shear strength and the shear slip of a rectangular shape shear key for plain concrete. However, the limitation on the proposed equation is where no normal displacement in the joint is allowed and the shear stress is assumed uniform along the base of the shear key.

3.0 Research Methodology

3.1 Details of Test Specimen and Concrete Properties

In this study, 6 different shapes of shear key are tested to determine the ultimate shear capacity. They include triangular, composite rectangular, semicircle and trapezoidal. For the trapezoidal shear key, the angle are differs at 30°, 45° and 60°. For each shape, 3 specimens are prepared and each shear key is completed by a male-female connection. The dimension of the shear key for each shape is given in Table 1. All specimens have the same thickness of 75 mm with an overall dimension of 300 mm height × 400 mm width.

The concrete mix is designed based on the DOE method to determine the material proportion of cement, water, fine and coarse aggregates. The concrete compressive strength is designed to achieve 30 MPa at 28 days and the material proportions is summarised in Table 2. The compressive strength is determined using cubes of 150 × 150 × 150 mm.

Table 1: Shear key shape detail and dimension

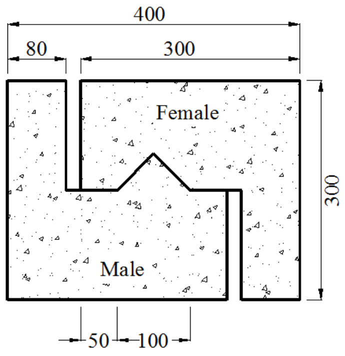
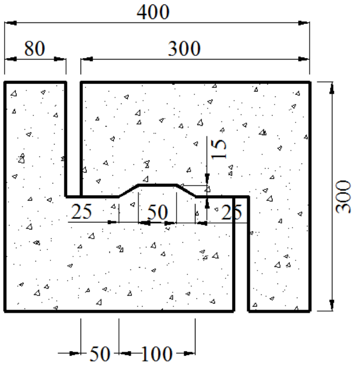
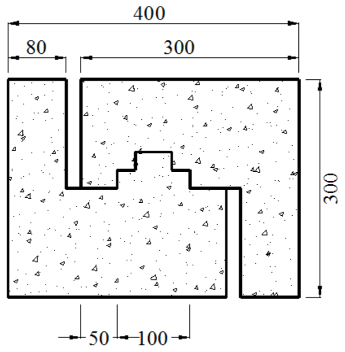
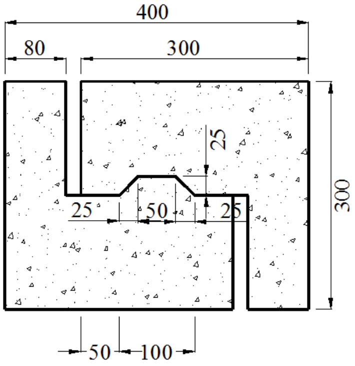
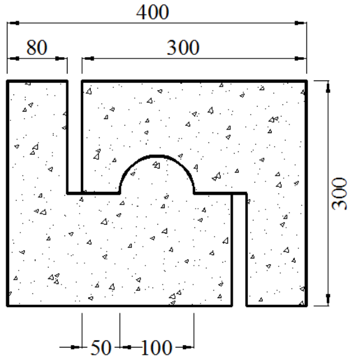
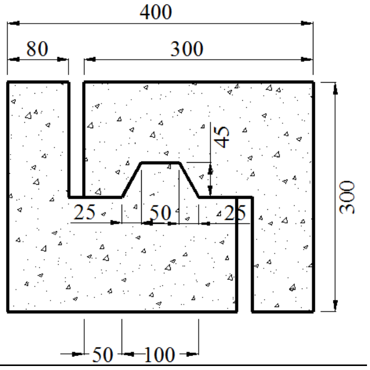
Specimen detail	*Dimension*	*Specimen detail*	*Dimension*
Triangular		Trapezoidal at 60°	
Composite Rectangular		Trapezoidal at 45°	
Semicircle		Trapezoidal at 30°	

Table 2: Mix proportion of the concrete mix for 1m^3

Concrete Strength (N/mm^2)	*Cement (kg/m^3)*	*w/c*	*Water (kg/m^3)*	*Fine Aggregate (kg/m^3)*	*Coarse Aggregate (kg/m^3)*	*Maximum Aggregate Size (mm)*	*Concrete Slump (mm)*
30	415	0.41	170	531	1364	20	10 – 30

3.2 Test Setup and Testing Procedure

A “push-off” method is applied in the experimental work. The schematic diagram of the test setup is shown in Figure 6 with the actual setup in Figure 7. Loading is applied through a hydraulic jack, which is connected to a 500 kN load cell. Two linear variable differential transducers (LVDTs) are located as close as possible at the interface between the two male and female panels. The LVDTs are used to measure the slip at the interface where the values are obtained by the difference in movement between the two panels. The load cell and LVDTs are connected to a data logger for data recording during the test. The roller on top of the specimen is placed to reduce upward movement that may occur during the test. At the same time, a confinement pressure of 1 MPa is applied on top of the roller to hold the specimen in place while the horizontal load is applied. The horizontal load is applied incrementally at every 1 kN until the connection fails at the interface. Interface slip is also recorded at every load increment. Failure is defined when the connection fails due to splitting or when multiple cracking is observed. The failure is sudden and well defined of which can also be monitored by the sudden drop in load with an increase of the interface slip.

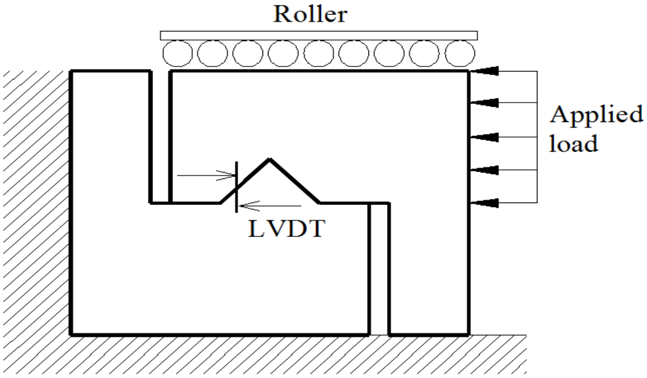


Figure 6: Schematic diagram of the “push-off” test setup

(a) Actual test setup (b) Location of the LVDTs

Figure 7: Actual “push-off” test setup

4.0 Analysis Results and Discussion

4.1 Ultimate Shear Capacity of the Shear Key

Three concrete cubes are tested at each 7 and 28 days to determine the compressive strength of the concrete. The average compressive strength at 7 and 28 days is 32.5 N/mm^{2}and 44.5 N/mm^2, respectively which is based on the average of three cubes. This shows that the design strength is achieved before carrying out the “push-off” test.

Table 3 summarised the results of the “push-off” test for the ultimate shear capacity, interface shear stress and the maximum interface slip at failure. The interface shear stress is calculated by dividing the ultimate shear load to the effective contact shear key area. The effective shear key area is determined by considering the crack length and the failure criterion. The highest ultimate shear capacity is observed for semicircle shape where it is in the range of 47.8 kN and 62.9 kN, while the lowest is the trapezoidal shape at an angle of 60° and 30°. For both shear key shapes, the ultimate shear capacity is in the range of 27.5 kN and 38.3 kN.

The ultimate shear capacity for the triangular shape is 37.6 kN and 39.6 kN for specimen A1 and A2, respectively. Meanwhile, for specimen A3, the ultimate shear capacity is 30 kN which is slightly lower than the other two specimens because of the splitting crack that occurred at the peak of the triangle instead of at the interface as shown in Table 4. This may be due to the high stress concentration that occurred at the peak which may have resulted to the sudden failure and at the same time showing a sudden drop in the applied load. For the composite rectangular shape (specimen B1, B2 and B3), the smaller rectangular located on top of the larger one is proposed to represent shear stud. By having this shear stud, it is expected to improve the interlocking bond and therefore may increase the shear capacity. The ultimate shear capacity for this shape is in the range of 36.1 kN and 58.1 kN, which shows an average increase of 23.2% from the triangular. For the semicircle shape, the ultimate shear capacity is 47.8 kN, 62.9 kN and 56.1 kN for specimen C1, C2 and C3, respectively. This shape has the highest ultimate shear capacity with an average of 55.6 kN, showing an increase of 35.8% between the triangular shape and 16.4% increase from the semicircle shape. The high ultimate shear capacity may be because of the semicircle which produces low stress concentration for the shape.

The trapezoidal shape with different angles produced mixed ultimate shear capacity. The lowest is the trapezoidal with 60° and 30° angle where the average ultimate shear capacity is 31.7 kN and 31.9 kN, respectively. This is even lower than the triangular shape showing an 11% decrease. The highest ultimate shear capacity among the trapezoidal shape is the one with a 45° angle (specimen E1, E2 and E3) with an average value of 40.3 kN. However, they are still lower than the composite rectangular and semicircle shapes. This can be concluded than the angle only gives small contribution to the ultimate shear capacity compared with the other shear key shapes.

The interface shear stress in Table 3 is calculated by dividing the ultimate shear capacity to the effective contact area by considering the shear crack length and the mode of failure. For failure due to splitting (specimen A2, C2 and C4), the interface shear stress is taken as zero (0 N/mm^2) since there is no resistance at the joint between the male and female panels.

The observed interface slip at ultimate shear capacity given in Table 3 is found to be affected by the failure mode of the shear key. For specimen that failed due to splitting at the interface or diagonal crack, the interface slip is found to be the highest. This can be observed when the interface slip is more than 4 mm when failure occurred. Meanwhile, for failure due to shear, the interface slip is found to be less than 4 mm and some specimens are even less than 1 mm (specimen A3 and D1).

Table 3: Summary of the test results

Description	*Specimen*	*Ultimate shear capacity (kN)*	*Average ultimate shear capacity (kN)*	*Interface shear stress (N/mm^2)*	*Interface slip at ultimate shear capacity (mm)*	*Shear crack length at failure (mm)*
Triangular	A1	37.6	35.7	3.27	7.35	50
	A2	39.6		4.60	-	100
	A3	30.0		4.70	0.80	85
Composite Rectangular	B1	58.1	46.5	7.10	6.52	90
	B2	36.1		3.20	2.49	100
	B3	45.3		5.40	3.16	110
Semicircle	C1	47.8	**55.6	7.50	4.60	85
	C2	62.9		8.40	-	100
	*C3	33.8		4.70	1.07	-
	C4	56.1		7.50	-	95
Trapezoidal at 60°	D1	37.8	31.7	3.48	0.94	145
	D2	27.5		-	1.89	-
	D3	29.8		2.94	1.77	135
Trapezoidal at 45°	E1	37.9	40.3	5.05	2.05	100
	E2	44.1		6.91	1.90	85
	E3	38.8		7.95	1.70	65
Trapezoidal at 30°	F1	27.5	31.9	4.58	1.41	80
	F2	38.3		4.09	2.93	125
	F3	30.0		4.21	1.35	95

Note:
**Specimen C3 is not included in the following discussion due to error of the test frame during the test*
*** The average ultimate shear capacity does not include specimen C3*

4.2 Shear Load–Interface Slip Relationship

The applied shear load and interface slip relationship for all specimens are shown in Figure 8. In general, the curve for each different shape of shear key differs between one and the other. For the triangular shape, specimen A2 and A3 shows that there is a negative interface slip up to a shear load of about 25 kN to 30 kN. The negative values are found to be related to the failure mode where shear failure is observed at the peak of the triangle as shown in Table 4. The negative values also indicate that the upper panel has bigger movement than the bottom. This upper movement is maybe due to rotation to resist the horizontal movement. This will tend to produce upward slip and therefore produce bigger movement of the upper panel than the bottom. At the same time, it produce large joint gap at failure as shown in Figure 9. The angle of 45° for the triangle may have also contributed to this opening where the specimen slide down before the next load is applied. High stress concentration occurred as early as the applied load is in the range of 5 kN to 10 kN. As for specimen A1, the failure is at the interface and therefore a linear relationship is observed until the ultimate shear capacity. The failure is a total splitting at the interface without causing any cracking at the peak of the triangle.

For the composite rectangular (specimen B1, B2 and B3), the relationship is a bilinear curve where the interface slip increases at lower shear load (< 10 kN). After the shear load reached 10 kN, a more linear interface slip is observed before failure occurred. For the semicircle (specimen C1, C2 and C4), the relationship is linear for all specimens where the interface slip is found to be increasing as the shear load increases. At failure, there is a sudden drop in the load and at the same time seeing a decrease in the interface slip for specimen C1 and C4.

For the trapezoidal shape, all specimens have the same curve pattern. In general, the relationship is linear showing a small increase in the interface slip as the shear load is gradually increases. When failure occurred, there is a sudden increase of the interface slip and at the same time, a drop or decrease in the shear load. This shows that the angle of the trapezoid at 30°, 45° and 60° does not have significant effect on the shear load-interface slip curves.

4.3 Failure Mode of the Shear Key

The failure mode of each specimen is shown and described in Table 4. For the triangular, the failure is due to shear and also a combination of shear and splitting (specimen A2). Shear failure of specimen A1 and A2 is due to high stress concentration at the peak of the triangle. Meanwhile, the formation of cracks in the composite rectangular of specimen B1 started at the top part of the shear key with two diagonal cracks of which the length is 50 mm and 75 mm. This is then formed by shear crack at the root of the shear key with crack length of 85 mm. Concrete crushing also occurred in specimen B1 because of the 90° angle between the two parts of the specimens which means that the concentrated load is applied in the contact corners which resulted to crack and crushing at the bottom part of the shear key. In comparison, for specimen B2, cracking only started at the root of the shear key with 100 mm crack length. On the other hand, for specimen B3, the failure mode is almost similar to specimen B1 in terms of number, type and crack position. A diagonal crack is observed at the top part of the semicircle for specimen C1 and another diagonal crack started from the root of the shear key with 85 mm crack length. The failure mode for specimen C2 and C4 are quite similar in terms of number, type and crack location. Both specimens show signs of total splitting failure at the interface.

For the trapezoidal, the failure of specimen D2 is due to diagonal tension crack, splitting and shear. However, specimen D1 and D3 failed due to shear and slip. Inconsistent pressure from the loading point to the supporting mechanism may have contributed to the presence of diagonal tension crack. For specimen E1 and E2, shear failure is observed except for specimen E3 which also include slip. There is no occurrence of diagonal tension crack indicating that the specimens undergoing consistent pressure from the point of loading to the supporting mechanism. For the deepest thickness of the trapezoidal with an angle of 30° (specimen F1, F2 and F3), only shear failure is observed for all specimens. This shows that as the depth of the trapezoid increases (where the angle is reduced from 60° to 30°), the failure mode improved from slip and diagonal tension crack to only shear crack.

From the failure mode for all specimens, the study found that trapezoidal with angle of 30°and 45°, and also the composite rectangular shear key shows better mode of failure even though the average ultimate shear capacity is less than the semicircle, which is the highest among the other shear keys. This improved failure mode can avoid catastrophic failure when it is applied in the precast structural components.

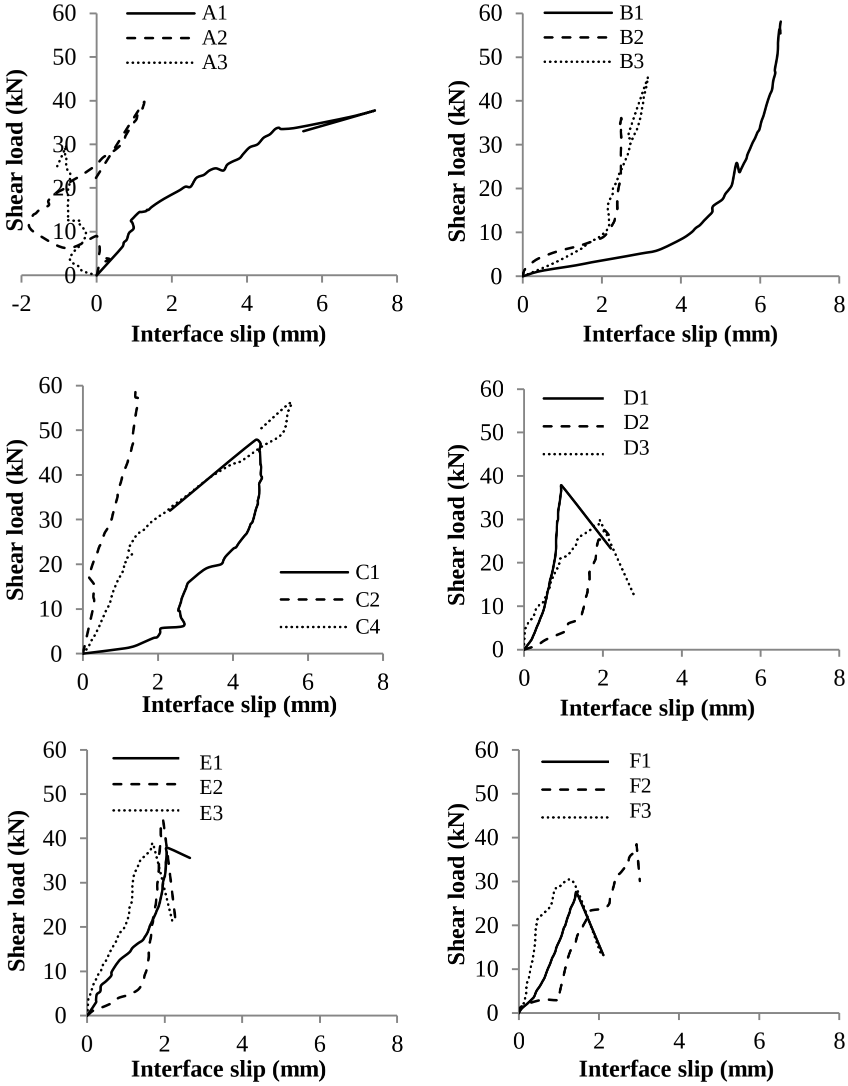


Figure 8: Shear load–interface slip relationship

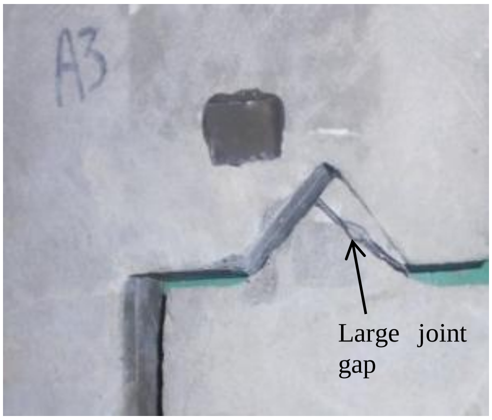


Figure 9: Large joint gap observed for the triangular shape shear key

Table 4: Failure mode of the shear key

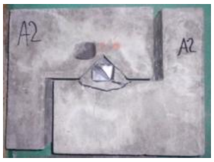
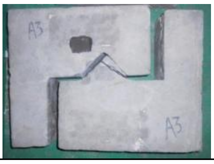
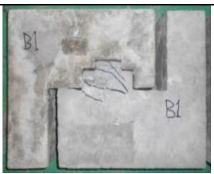
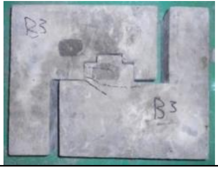
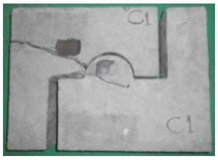
Description	*Specimen*	*Failure mode*	*Description*	*Specimen*	*Failure mode*
Triangular	A1 	Shear & slip	Trapezoidal at 60°	D1 	Shear & slip
	A2 	Shear & splitting		D2 	Shear, splitting & diagonal tension crack
	A3 	Shear & slip		D3 	Shear & slip

Table 4 *(continued):* Failure mode of the shear key

Description	*Specimen*		*Failure Mode*	*Description*	*Specimen*		*Failure Mode*
Composite rectangular	B1		Shear	Trapezoidal at 45°	E1		Shear
	B2		Shear		E2		Shear
	B3		Shear		E3		Shear & slip
Semicircle	C1		Shear & diagonal tension crack	Trapezoidal at 30°	F1		Shear
	C2		Shear & splitting		F2		Shear
	C4		Shear & splitting		F3		Shear

5.0 Conclusion

Experimental tests have been carried out on different shape of shear keys to investigate its failure mechanism and to determine the ultimate shear capacity. Based on the test results obtained in this study, conclusions can be made as follows:

(i) Different shapes of shear key affect the shear strength of the specimens.
(ii) The highest average ultimate shear capacity of the shear key is found for the semicircle with an average value of 55.6 kN. This is because the semicircle shape can distribute the shear load evenly at the joint between the male and female panels.
(iii) The lowest shear capacity is found for the shear key with trapezoidal at an angle of 30° and 60° with average values of 31.9 kN and 31.7 kN.
(iv) The triangular experiencing upward slipping during the test which is due to the rotation of the upper panel to resist the horizontal movement.
(v) The study found that the failure mode depends on the shape of the shear key which includes shear, diagonal cracks, splitting and slip. For specimens experiencing splitting, the failure mode is not recommended in design which could cause catastrophic failure when applied in structural components.
(vi) For the trapezoidal, the angle plays an important role in improving the mode of failure where the length of the shear crack decreases as the angle of the shear key approaches 45°.
(vii) The study suggested that trapezoidal with angle of 30°and 45°, and also the composite rectangular shear key have better mode of failure even though the average ultimate shear capacity is less than the semicircle.

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