Numerical Modelling, Simulation and Experimentation of Steel Shear Keys Dry Joints

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***Abstract*—The numerical modelling, simulation and experimentation of dry joints steel shear key, used for joining segmental precast concrete girders are studied in this paper. In an effort to identify an optimum shape of steel shear key the numerical study in this paper investigates the response of three different geometries of full scale medium strength steel shear key, including the original shape of shear key, to shearing force at the concrete members and prestressing force acting in the centreline of the shear key. Nonlinear finite element analysis of the shear key and the adjoining concrete members are conducted using ANSYS academic package. The appropriate constitutive relations for the steel and concrete materials obtained from test results and published values in the literature are introduced to the package. The validity of the numerical modelling of the original shear key is compared to laboratory experimentation results of the original shear key. The study considers three different magnitudes of prestressing force with the same concrete compressive strength. Numerical results indicate that introducing a taper onto the forward ring plate of the male part of the steel shear key results in a significant increase in its load-bearing capacity.**

***Index Terms*—steel, geometry, male and female shear keys, shear stress-vertical displacement relation**

I. Introduction

Precast concrete segmental girder bridges are becoming popular in nowadays bridge construction. The application of metal and concrete shear keys are similar in principle where both keys are placed at the interface between two precast segmental bridge girder.

In the case of concrete shear key, a stack of concrete protrusions which are formed integral to the girder itself, are mated to the female shapes formed on the casting of the adjoining girder to construct a joint. Concrete shear-key joints mechanical behaviour has been a subject of several studies in the past. The behaviour of flat and keyed joints as a function of prestressing force and the addition of epoxy were studied by Buyukozturk and others [1]. Level of confining pressure are found to influence the behaviour of dry keyed joints.

In general, cracks begin at the bottom corner of the key and, although they take place well in advance of the final failure, the ensuing final failure is brittle and sudden. Shamass and others [2] found that the contribution of friction in the total shear capacity decreased with an increase in confining pressure. Moreover, the propagation of inclined crack was arrested at high confining pressure owing to the fact that the fracture propagation direction is governed by the criterion of the maximum energy release rate. Jiang and others [3] have showed that the single and two keyed dry joints were less ductile than the three keyed dry joints. The first failure of three keyed joints started at the inferior key, followed by the middle key, and the superior key at the end. The failure mode of concrete shear-key joints from a different study by Hwan and others [4] also exhibits similar pattern. At the beginning diagonal crack occurs in the bottom part of the joint surface, followed by intensive multiple cracks taking place at the shear key zone. At the maximum load the cracks at the root of joint separate the female shape from the male shape. Liu and others [5] showed a higher shear strength of ultrahigh-performance concrete dry joints can be obtained with higher confining stress, higher matrix tensile strength, and the addition of steel fibers. Concrete joints with fibers experienced a limited area of concrete crushing compared with joints without fibers. Large-keyed joints presented a minor increase in shear capacity compared with three-keyed joints. By the same token a shear joint between two precast concrete girders can be constructed using a series of metal shear keys. Beside steel for shear key, the Japanese standard [6] allows the use of Ferro Casting Ductile (FCD) metal grade 450 as an alternative material for metal shear keys. The FCD metal is shown to have better characteristics than any other types of cast iron. In contrast to the case of

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concrete shear-key joints, studies on the response of metal shear keys are sparse. Purnomo and others [7] recently conducted numerical and experimental studies to evaluate the shear behaviour of one specific geometry of metal shear key. Purnomo and others [8] extended the previous work and investigates four different geometries of FCD shear keys. The primary difference in those four geometries is in the shape of the forward section of the male component. The bore of the female component is made compatible to the shape of the forward section of its male counterpart. The numerical and experimentation studies of steel shear keys in this paper follow closely the methodology in [7][8].

II. Methodology

A. Structural Idealisation

The numerical idealisation of all three shear keys is based on the experimental test setup shown in Fig. 1. The experiments of the original steel shear keys were conducted the same way as in the previous study [7], and the same setup was also conducted. As it is presented in Fig. 1, two concrete blocks representing segmental precast concrete girders are placed to a test frame equipped with two hydraulic rams in the vertical and horizontal orientation, respectively. The two concrete blocks are joined together by one steel shear key at mid-height. The centreline of the shear key is aligned with the longitudinal axis of horizontal hydraulic ram which applies an equivalent prestressing force. Shear force is subsequently applied as a monotonically increasing vertical load to the upper block. Two load cells recording the forces applied by the hydraulic rams. One of them is placed at the interface between the rams and the upper concrete block. Relative vertical displacements between the two concrete blocks are measured by four digital gauges located uniformly along their common vertical boundary. The relative horizontal displacement is recorded by a single digital gauge located at the left-hand edge of the upper block. The time history of the average shear stress in the key with given dimensions can then be found from the record of the vertical force. The previous study [7] showed that the curves of shear stress versus the average vertical displacements obtained experimentally are almost similar with those predicted by numerical model.

B. Shear Key Geometry and Material Properties

Following the practice, the steel shear key is made of JIS S40C. The two concrete blocks are made of reinforced concrete with 28-days mean cylindrical compressive strength of approximately 45 MPa, which is representative of the typical strength of precast concrete bridge girders. Fig. 2 presents the geometry of the original steel shear key K1 used in the test. It consists of the male component, presented in light brown on the left hand side, and the female component, shown in grey on the right hand side. The geometry of this shear key, especially at the extremities of male and female components allow better anchorage of the keys in the concrete blocks.

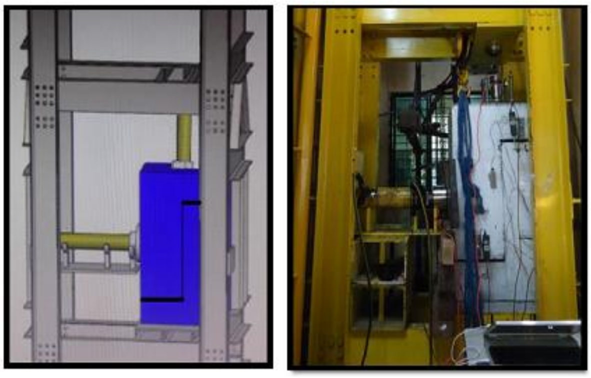

Figure 1. Experimental test set-up [6]

The geometry of this particular shear key is similar to that of the steel shear key manufactured and implemented by Indonesian construction company, PT. Wijaya Karya Beton Tbk, for the erection of segmental concrete bridge girders in some Indonesian provinces. The geometry of the concrete blocks used in the experimentation is shown in Fig. 3. The shear key joining the two blocks is located mid-height with the male component being casted into the upper block on the left hand side. Two horizontal gaps of 2 cm high are present between the upper and lower concrete blocks. No gap exists at the vertical boundary.

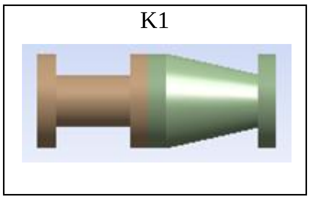

Figure 2. Geometry of male and female components of shear key K1

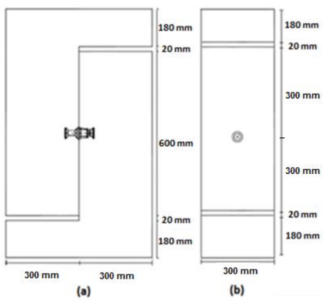

Figure 3. Dimensions of concrete blocks and location of shear key (a) Front view (b) Cross section

The three different shapes of the male steel shear keys studied in this paper are shown in Fig. 4. The original shear key K1 and the modified shear keys K3, K4 shares the same overall length as well as the same thickness and diameter of the two vertical circular plates. K2 shear keys are not considered in this study as its performance was obtained low from the previous study [8]. The validation of the numerical modelling of the original shear key by using laboratory experimentation results of the original shear key gives way to identify the optimum shape of the forward section of the male component and the corresponding bore of the female component.

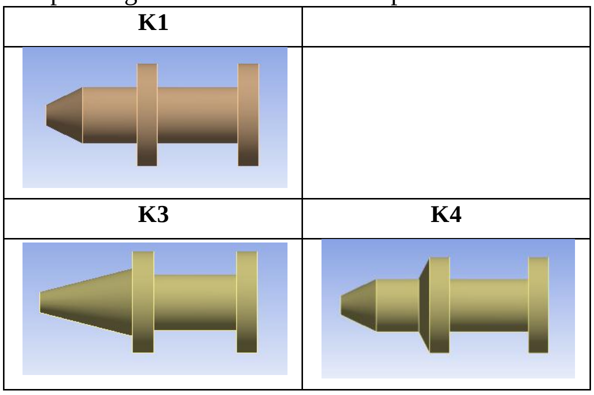

Figure 4. Geometry of three different steel shear keys

C. *Finite Element Model*

Laboratory testing of some of the properties of the concrete and steel metal were carried out as part of the experiments. The compressive stress-strain relation for the concrete used in the numerical model is obtained from cylinder compressive strength tests, while the shear stress-strain relation is obtained from concrete beam shear tests. The tensile stress strain relation on the other hand is based on published values in Hu et al [9]. The steel tensile, compressive and shear stress-strain relation are based on mild steel mechanical behavior. The Poisson's ratio of the steel is taken as 0.28, while that of the concrete is set to 0.2. The shear capacity of the joint is defined by either tensile failure of the concrete block or yielding of the shear key. Tensile failure of the upper concrete block is assumed to occur when principal stress greater than 0.45 times the square root of the cylinder compressive strength as per reference [10] extends over an area in the outward direction from the male shear-key location. Yielding of the shear key follows the Von Mises criterion and failure of the shear key is defined by yielding across its cross section. A series of parametric study is conducted to determine the capacity of the shear key connection system. Three different magnitudes of horizontal prestressing force with the same compressive strength of concrete are examined for each of the three shear-key configurations. Table I shows the analysis cases covering the permutation of the shear-key geometry (K), concrete compressive strength (C), and magnitude of the horizontal prestressing force (P).

Three-dimensional simulations are conducted using SOLID186 element in ANSYS. Contact between the concrete block and shear-key components are modelled using the surface-to-surface contact elements. TARGE170 and CONTA174. Perfect bond between the shear key and the concrete is assumed.

Frictional contact with friction coefficient of 0.6 [1] is assigned to the vertical interface between the two concrete blocks. Zero-translation boundary condition is utilized to the base of the lower concrete block as shown Fig. 5(a), while the loads from the hydraulic rams are applied as pressure over the area of loadings displayed in Figs. 5(b) and 5(c).

TABLE I. PARAMETRIC STUDY

Variation	Type of Steel Shear Key	Compressive Strength (MPa)	Prestressing Force (MPa)
K1C1P1	K1	45	0.3450
K1C1P2	K1	45	0.5175
K1C1P3	K1	45	0.6900
K3C1P1	K3	45	0.3450
K3C1P2	K3	45	0.5175
K3C1P3	K3	45	0.6900
K4C1P1	K4	45	0.3450
K4C1P2	K4	45	0.5175
K4C1P3	K4	45	0.6900

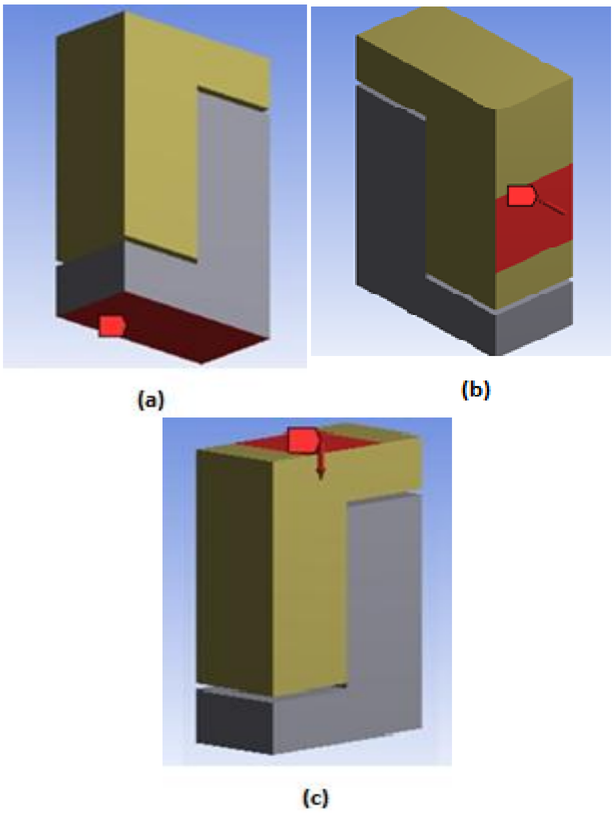

Figure 5. Support condition and loading area: (a) Support, (b) Area of horizontal loading, (c) Area of vertical loading

III. RESULTS AND DISCUSSION

A. *Comparison between Experimentation and Numerical Modelling Results of Original Steel Shear Key*

The vertical and horizontal loads recorded during the experimentation of the original shear key casted in the concrete blocks are related to the shear, normal and friction forces at the shear key. Shear stress from the experiment at the forward ring plate of the male shear key can be calculated from two forces, shear and friction. Figs. 6, 7 and 8 show the comparison between shear stress and vertical displacements obtained from the experimentation and numerical modelling for K1C1P1, K1C1P2 and K1C1P3 cases respectively.

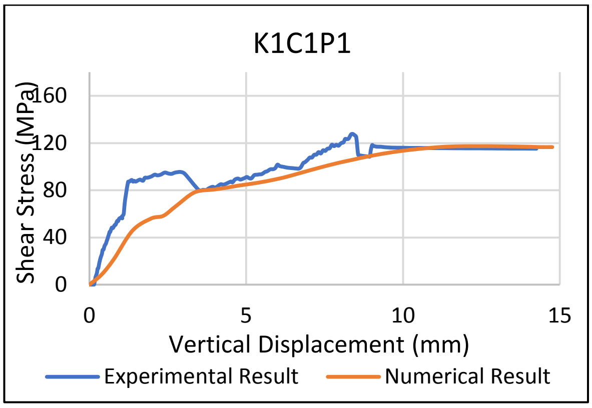

Figure 6. Shear stress-vertical displacement from experimental and numerical modelling for K1C1P1 analysis case

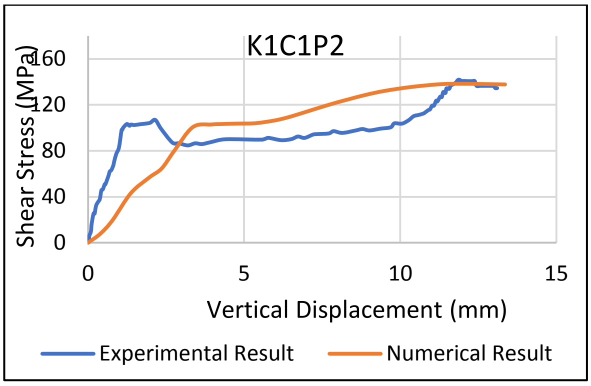

Figure 7. Shear stress -vertical displacement from experimental and numerical modelling for K1C1P2 analysis case

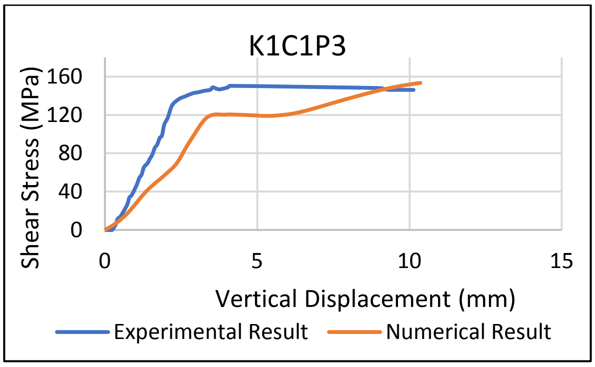

Figure 8. Shear stress-vertical displacement from experimental and numerical modelling for K1C1P3 analysis case

It is found that the curves of shear stress versus the average vertical displacements predicted by the numerical model get near to with those obtained experimentally. The curves from the experimentation are not too smooth, as the vertical forces were applied manually in the test. After validating the numerical modelling of the original shear key to its laboratory experimentation results, the modelling are then applied to simulate K3 and K4 steel shear keys dry joints under shear test.

B. Comparison of Shear Capacity

Fig. 9 presents a comparison of the contour of shear-stress in the different steel shear-key geometries prior to reaching the maximum vertical displacement of 20 mm. It can be seen that the male shear keys K1 and K3 exhibit localised areas of high stress concentration at the forward ring plate. On the other hand, such localised high stress concentration materialise at a small spot in the configuration K4. The same observations are also found on the female components. The geometry showing the highest stress concentration turns out to be the original geometry K1, while there is little to no stress concentration in the female part of shear key K4. Figures 9 are representative of the C1P3 shear analysis for K1, K3 and K4 shear keys considered in the parametric study. The relations of shear stress versus vertical displacement for different shear-key geometries and equivalent prestressing forces, but with the same concrete strength are plotted in Fig. 10. Again, favourable behaviour in terms of highest shear-stress capacity is shown by the shear key configuration K4.

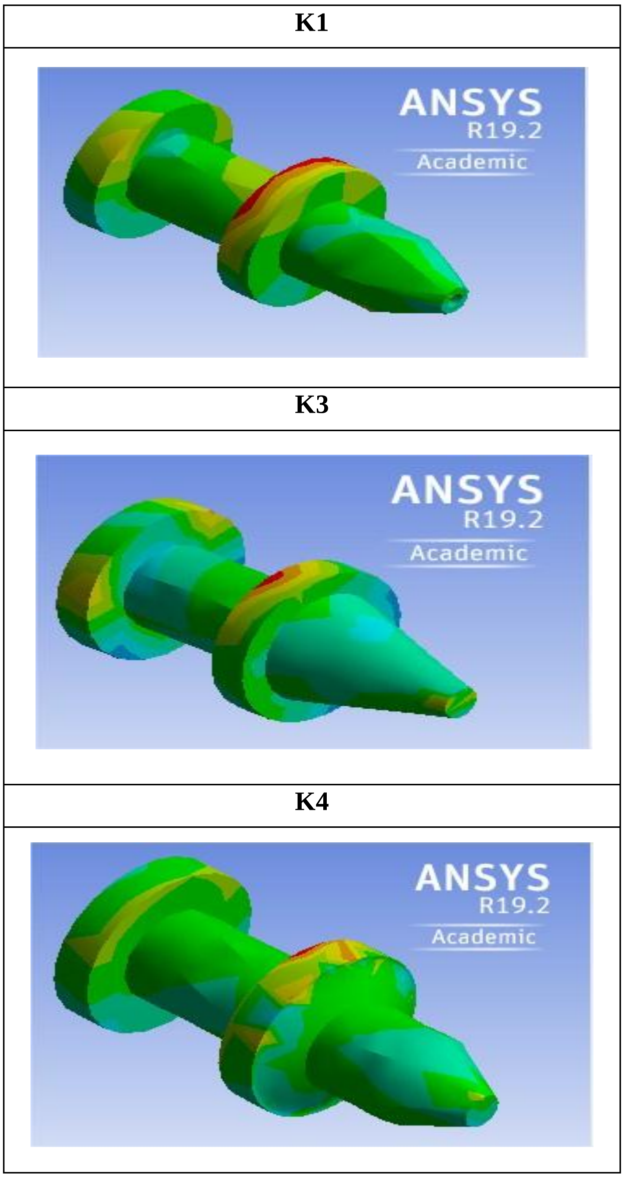

Figure 9. Shear-stress contour in male part at C1P3 case

At 20 mm displacement the shear capacity of this particular configuration is almost 25 percent higher to the capacity of configuration K3. Compared to the original configuration K1, the shear-stress capacity of configuration K4 is almost two times.

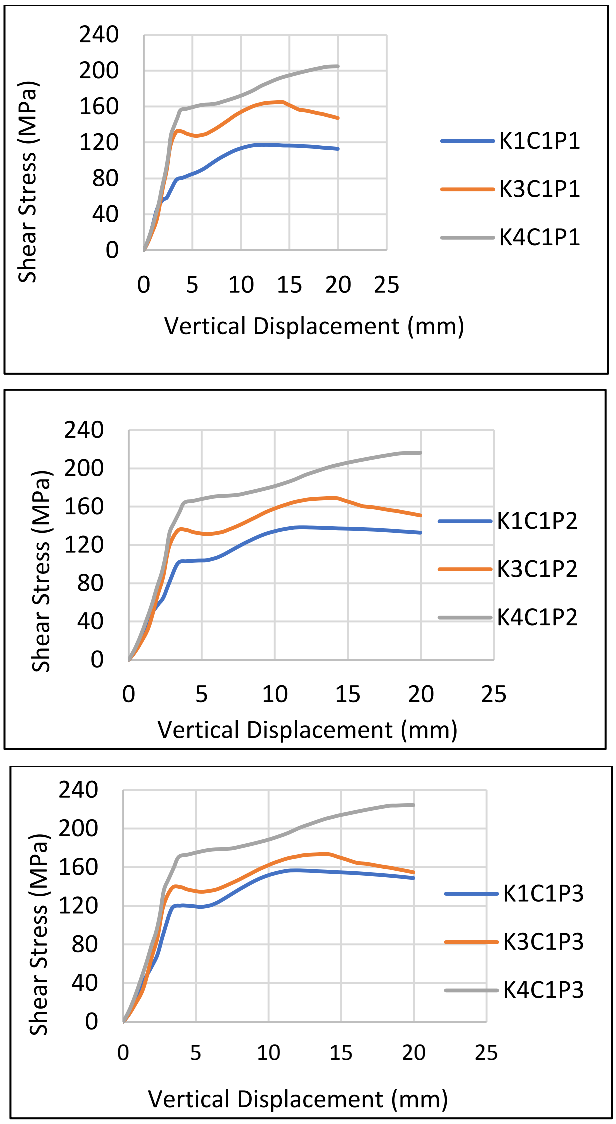

Figure 10. Shear stress-vertical displacement relations for different shear-key geometries, concrete strength, and equivalent prestressing forces

The magnitude of the vertical load at which the first yield occurs within the shear key is also higher for configuration K4. When the first yield takes place in the shear key, cracks have already formed in the concrete blocks.

The extent of crack propagation in the diagonally outward direction from the shear-key location is a function of the shear capacity of the male component and the tensile strength of the upper concrete block. An example of crack formation near steel male shear key in the concrete block at the final stage between experimentation and modelling results is shown in the Fig. 11.

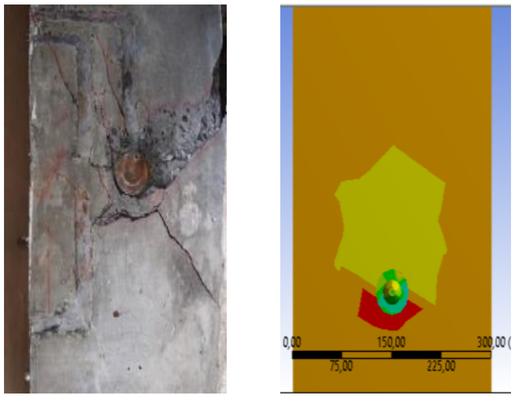

Figure 11. Crack at concrete block near male part at K1C1P1 case

IV. Conclusion

The numerical modelling validation of the original steel shear key K1 to its laboratory testing results, brought through the numerical modelling to be applied for the simulation of K3 and K4 steel shear keys dry joints under vertical load. Numerical analysis of three different geometries of shear key made of steel claims that the maximum load-carrying capacity of the joint is strongly dependent on the material constitutive properties and the shape of the forward section of the male component of the shear key. Out of the three configurations considered in this paper the steel shear key K4 with tapered forward ring plate is obtained to undertake the most favourably in terms of its maximum load-carrying capacity prior to the formation of large cracking in the concrete members. The steel shear key configuration K3 with conic section extending from the tip all the way to the forward ring plate arrives second in terms of its shear capacity. Future experimentation involving full scale laboratory shear tests of K4 steel shear key are to be established to confirm the predicted shear stress and load-carrying capacities.

Conflict of Interest

"The authors declare no conflict of interest"

Author Contributions

The research group was coordinated by Heru Purnomo; Muhammad Jaufar Al Fatih conducted the numerical analysis; Sekar Mentari and Heru Purnomo conducted the experimental work; Gambiro Soeprapto provided the shear-key specimens and analysed the numerical results; The paper was written by Heru Purnomo; The final version were approved by all authors.

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