Experimental Study of Dry Joints with Castellated Keys Subjected to Combined Axial, Bending and Shear Forces

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Abstract

The design and execution of the connection between precast concrete segmental elements are critically important since these connections are a discontinuity region whose structural capacity is fundamental for transmitting normal and shear stresses through the joint. The use of dry joints with castellated keys is the most widespread solution used in the construction of fast precast elements. The experimental dry joint programs performed to date have focused on the behavior under direct shear at different confining stress levels applied uniformly along the joint. Axial compression forces simulate the confinement effect between two different joint parts. Design formulations have generally been determined to evaluate the shear capacity of dry joints subjected to uniform confinement.

Although the connections in concrete segmental elements are usually subjected to combined axial, bending and shear forces. This communication presents the results of an initial 6-test experimental program performed on conventional concrete dry joint specimens with three shear keys subjected to different eccentric forces and confining stress levels. For this, a test was designed for push-off dry joint specimens subjected to these combined forces, in which it was possible to apply an axial compression force with different eccentric forces to subject the joint to a compression force applied at the central point (uniform confinement throughout the joint) or eccentric compression force, to vary the compression depth (no uniform confinement) and tension zones. This test enabled the analysis of the effect of eccentric compression forces on the joint's shear capacity and verified the safety of the existing formulations.

The AASHTO (2003) formula was also analyzed to evaluate shear capacity for dry joints subjected to these combined forces.

Keywords: *combined forces, dry joint, shear keys, eccentricity, precast.*

1. Introduction

The construction of precast concrete segmental bridges (PCSBs) in long span structures is now the method of choice for many bridge projects worldwide. The behavior of these structures depends on the connections between segmental elements. The design and execution of these joints are critically important because they must transmit the structure's normal and shear stresses. Even though dry joints are prohibited by the 2003 interim AASHTO provisions (AASHTO 2003) due to the possible corrosion of prestressed tendons, dry joints and external tendons are used in PCSBs given their rapid and simple construction, and are the most competitive solution.

Experimental results on the shear behavior of dry joints with castellated keys are somewhat limited. Koseki and Breen (1983), Buyukozturk et al. (1990) and Zhou et al. (2005) conducted experimental campaigns that focused on the behavior of joints with and without epoxy. More recent studies (Jiang et al.2015; Jiang et al. 2016) studied the capacity and behavior of dry joints in conventional concrete with or without steel fibers, while (Liu et al. 2019) studied this type of joints in ultra-high performance concrete (UHPC) specimens. These experimental tests concluded that the main parameters that affected the shear behavior of dry joints with castellated keys were: the confinement stress level (which simulates the prestressing effect), concrete strength, key shape, preparation of the surface, contact area, and coefficient of friction between concrete surfaces (Buyukozturk et al. 1990).

Experimental campaigns to date have focused especially on analyzing direct shear behavior at different confinement stresses levels. However, the connections in segmental elements are normally subjected to combined axial, bending and shear forces. Turmo et al. (2005) studied a finite element model to analyze the responses to combined bending and shear actions of segmental concrete bridges. Their results showed that for joints subjected to uniform compression, shear was transmitted along the entire joint height, while for joints subjected to bending, shear flow was limited to the compressed area of the joints. This indicated a need to experimentally study the behavior and capacity of keyed joints subjected to combined stresses.

This communication describes the initial experimental program followed to verify the behavior of joints subjected to combined forces by applying an axial force with different eccentric and confining stresses in conventional concrete specimens in a specially designed experimental test. The test allowed the point where the axial force was applied to be varied, subjecting the joints to the compression force applied to the central point (uniform confinement throughout the joint) or an eccentric compression force that allowed the compression depth (no uniform confinement) and tension zones to vary. The experimental results were compared to the values calculated by the formulation proposed by AASHTO (AASHTO 2003).

2. Test program

2.1. Test specimens

Similar push-off specimens to those used in other studies (Jiang 2015) were used to study the behavior of the three-keyed dry joints subjected to combined stresses, whose dimensions are shown in Figure 1. The thickness of all the specimens was 100 mm. Two layers of Ø20 mm rebars were used to prevent the concrete failing before the keys.

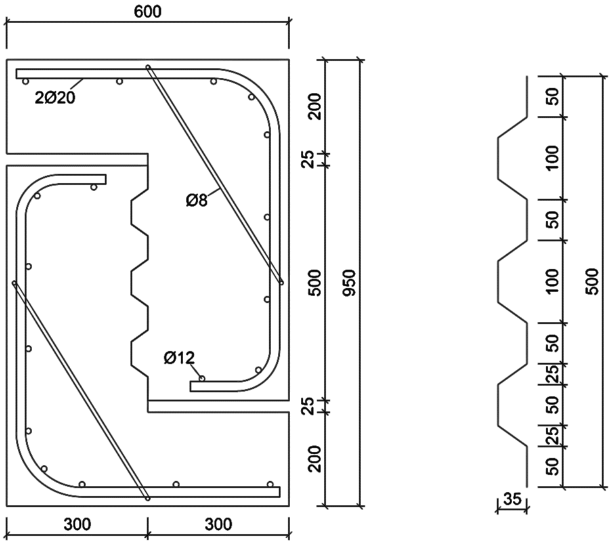


Figure 1. Specimen dimensions (in millimeters).

The two parameters considered in these tests were the eccentricity of the application point of the axial compression force (0, 0.13 and 0.18 m) and confining stress (5 % and 10 % of cylinder concrete strength, f_c), as listed in Table 1.

Null eccentricity represents the typical experimental push-off test with the joints subjected to uniform confinement stress, as in previous studies (Zhou et al. 2005; Jiang et al. 2015; Jiang et al. 2016; Liu et al. 2019). Two different eccentric values were chosen to vary the neutral axis depth: eccentricity of 0.13

m in relation to the central horizontal axis of the joint represented an approximate compression zone of 0.035 m^2, while 0.18 m eccentricity represented an approximate compression zone of 0.02 m^2.

Confining stress was defined as the percentage of cylinder concrete strength (confining ratio). In the specimens subjected to an axial compression force applied at the central joint point, it represented the uniform confining stress throughout the joint. In the specimens subjected to axial eccentric compression force, it represented the mean confining stress of the compression zone. Axial force was calculated from the mean confining stress and the area of the joint's compression zone for each eccentric value.

In the identification system used for the tested specimens, the first group of characters indicated concrete and joint type, which remained constant during this experimental campaign, A0 = conventional concrete and K3 = three-keyed dry joint. The second group represented the confining ratio in relation to concrete strength, 05 = $0.05 \cdot f_c$ and 10 = $0.10 \cdot f_c$. The third group represented axial force eccentricity, E0 = 0, E1 = 0.13 m and E2 = 0.18 m. The letter H indicated that the external joint parts in specimen A0K3-10-E0-H were made with high-strength concrete and steel fibers to avoid concrete compression failure in the upper truss prior to key failure.

Table 1. Characteristics of specimens.

Specimen	Confining ratio	Eccentricity (m)
A0K3-05-E0	0.05	E0 (e = 0)
A0K3-10-E0-H	0.10	E0 (e = 0)
A0K3-05-E1	0.05	E1 (e = 0.13 m)
A0K3-10-E1	0.10	E1 (e = 0.13 m)
A0K3-05-E2	0.05	E2 (e = 0.18 m)
A0K3-10-E2	0.10	E2 (e = 0.18 m)

2.2. Production of specimens and material properties

All the specimens were cast in steel molds. The male parts of the specimens were cast in the first phase. After 24 h, when the components had hardened, the male joint was used as the mold for the female. A demolding agent was smeared on the joint to separate the two parts. The female was cast in the second phase.

Specimens were tested at approximately 28 days after their manufacture. The concrete mix proportion was designed to obtain conventional concrete with an expected cylinder concrete strength of 30 MPa (300 mm high, 150 mm diameter). The cylinder concrete strength values can be found in Table 2. B500SD steel-reinforcing bars were used in all the specimens.

Table 2. Summary of experimental results.

Specimen	Cylinder concrete strength f'_c (MPa)	Confining stress (MPa)	Ultimate load V_u (kN)	Normalized ultimate shear stress ($MPa^{1/2}$)	Shear strength by AASHTO V_a (kN)	V_a/V_u
A0K3-05-E0	30.03	1.50	167.67	0.612	230.77	0.73
A0K3-10-E0-H	36.43	3.64	337.78	1.119	356.86	0.95
A0K3-05-E1	36.65	1.83	131.55	0.621	181.32	0.73
A0K3-10-E1	29.82	2.98	166.80	0.873	201.04	0.83
A0K3-05-E2	34.70	1.74	115.30	0.979	89.44	1.29
A0K3-10-E2	34.70	3.47	80.84	0.686	120.63	0.67

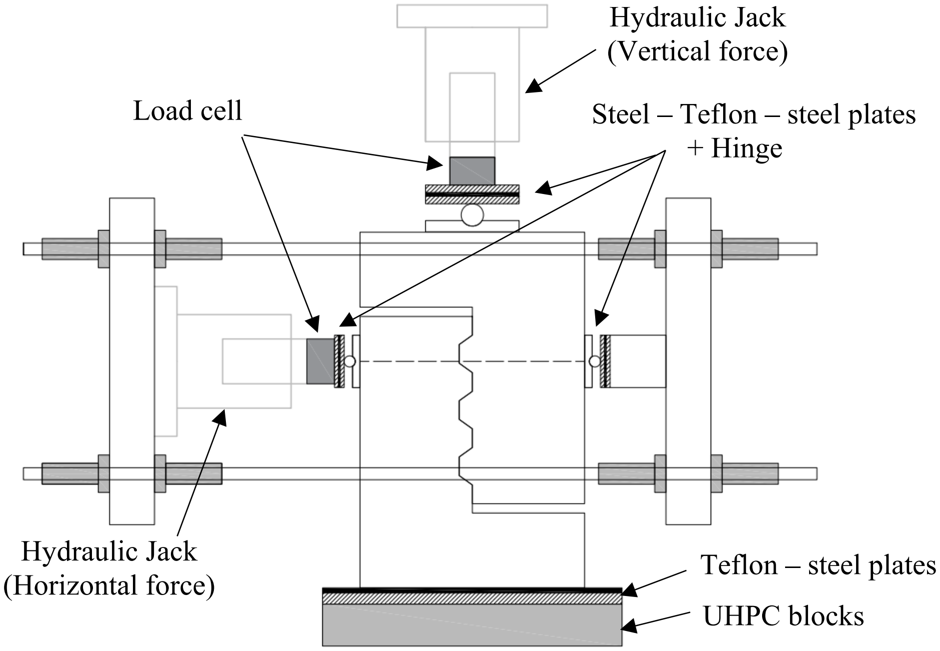
2.3. Test setup and procedure

The main objective of this experimental program was to analyze the behavior of dry joints with castellated keys in precast concrete segmental elements subjected to combined forces, for which an experimental test capable of transmitting these load conditions to the joint was designed. The load system of the test consisted of two independent gantries, as shown in Figure 2.

The horizontal force, which generated a confining stress between the two joint parts to simulate the prestressing effect on segmental bridges, was applied by a horizontal self-balanced gantry and a hydraulic jack. A hinge and a system to eliminate vertical friction forces through a Teflon plate inserted between two steel plates were placed on both sides of the specimen to allow both parts to turn and move vertically. The horizontal gantry remained in the same position in all the experimental tests, while UHPC blocks were used to place the specimens at the required height according to the eccentric force applied. The value of the horizontal force applied to the specimens was obtained from the average confining stress ($0.05 \cdot f_c$ or $0.10 \cdot f_c$) and the theoretical compressed area of the joint (equal to 50000 mm^2 for three-keyed dry joints with uniform confinement, 35000 mm^2 for eccentricity E1 and 20000 mm^2 for eccentricity E2).

The vertical force was applied by a hydraulic jack. The upper support of the specimen allowed turns through a hinge and horizontal displacement using a Teflon plate inserted between two steel plates. On the lower support, the specimen was placed on the entire surface on a Teflon plate to allow horizontal displacement.

The test procedure began with a preload of approximately 5 kN on both forces, after which horizontal and vertical forces were applied at a load-control rate of 2:1, to avoid horizontal compression cracking in the specimen, which could appear when applying only horizontal force. Once the average confining stress was reached, the displacement-control for the vertical load was conducted at a constant rate of 0.01 mm/s.



(a)

(b)

Figure 2. Experimental test setup for the dry joints subjected to combined axial, bending and shear forces: (a) sketch and (b) photo of setup.

2.4. Instrumentation

Two calibrated loads cells were used to measure the loads applied by the hydraulic jacks during the tests. Two vertical LVDTs (linear variable differential transducers) were mounted on each gap between the specimen parts to obtain relative vertical displacement. A network of LVDTs was placed on the joint to record the movements due to the combined stresses on the keyed dry joints during the test. Four external LVDTs were also used to measure the rotation of male specimens.

A camera took pictures every second for subsequent accurate measurements by a Digital Image Correlation (DIC) system, and an ultra-fast video camera was used to identify the failure mode.

3. Experimental results and discussion

3.1. Normalized shear stress – relative vertical displacement for uniform confinement

Figure 3 shows the normalized shear stress – relative vertical displacement curves for three-keyed dry joints with uniform confining stress. Normalized shear stress ($V/(A_c\sqrt{f_c})$) was obtained as the applied shear force (V) divided by the compression area (A_c) of the joint (50000 mm^2 for the three-keyed dry joint with uniform confinement) and by $\sqrt{f_c}$ to consider the effect of varying cylinder concrete strength (f_c) among the different specimens. Relative vertical displacement represented the average of two measurements recorded by the vertical LVDTs placed on the gaps between the two specimen parts. Figure 3 shows how normalized shear stress increased linearly until the ultimate value was reached and then dropped slightly in both A0K3-05-E0 and A0K3-10-E0-H test specimens. Normalized shear stress then remained practically constant, while relative vertical displacement increased due to cracking that took place until the load dropped, due to shear keys failure.

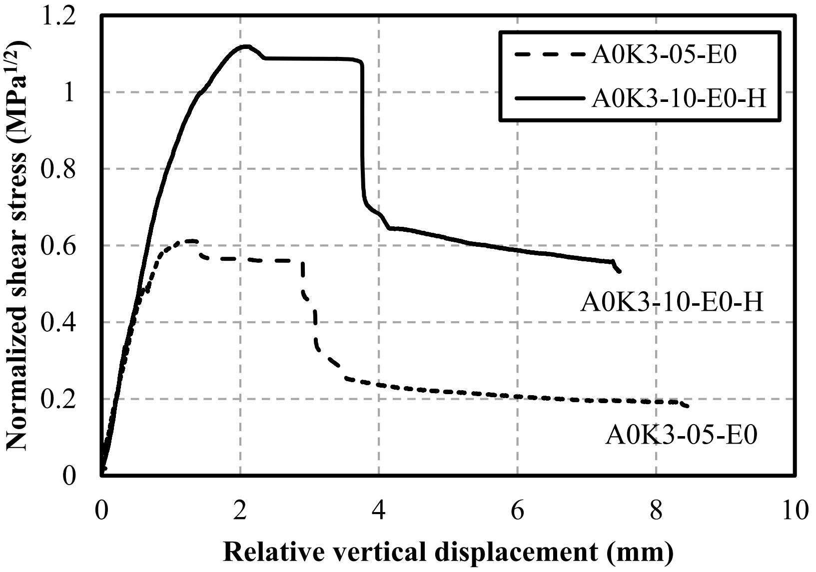


Figure 3. Normalized shear stress-relative vertical displacement curves for the specimens subjected to uniform confinement throughout the joint.

3.2. Neutral axis depth in the studied eccentricities

Figure 4 shows the geometry of the female part of the joints and the deformation planes observed for the initial situation when confining stress was reached, along with the maximum load situation and the failure of shear keys in the eccentricities studied. The deformation plane was obtained by the DIC measurement system. A linear regression line is represented to denote the different deformation planes with an adequate approximation ($R^2 \sim 1$).

The neutral axis depth (x) for the initial situation matched the theoretical value calculated for both eccentric values (e), equaling 3·(h/2-e), where h is the height of the joint (500 mm). Depth x for eccentricity E1 (e = 0.13 m) was approximately 0.35 m and approximately 0.20 m for eccentricity E2 (e = 0.18 m). Key cracking varied the deformation plane by reducing the neutral axis depth so that during the failure the compressive stresses focused on the upper joint area.

As already mentioned, the load system designed for this experimental program allowed a combination of axial, bending and shear forces to be applied to the joints. These combined stresses influenced both the joints' behavior and shear strength.

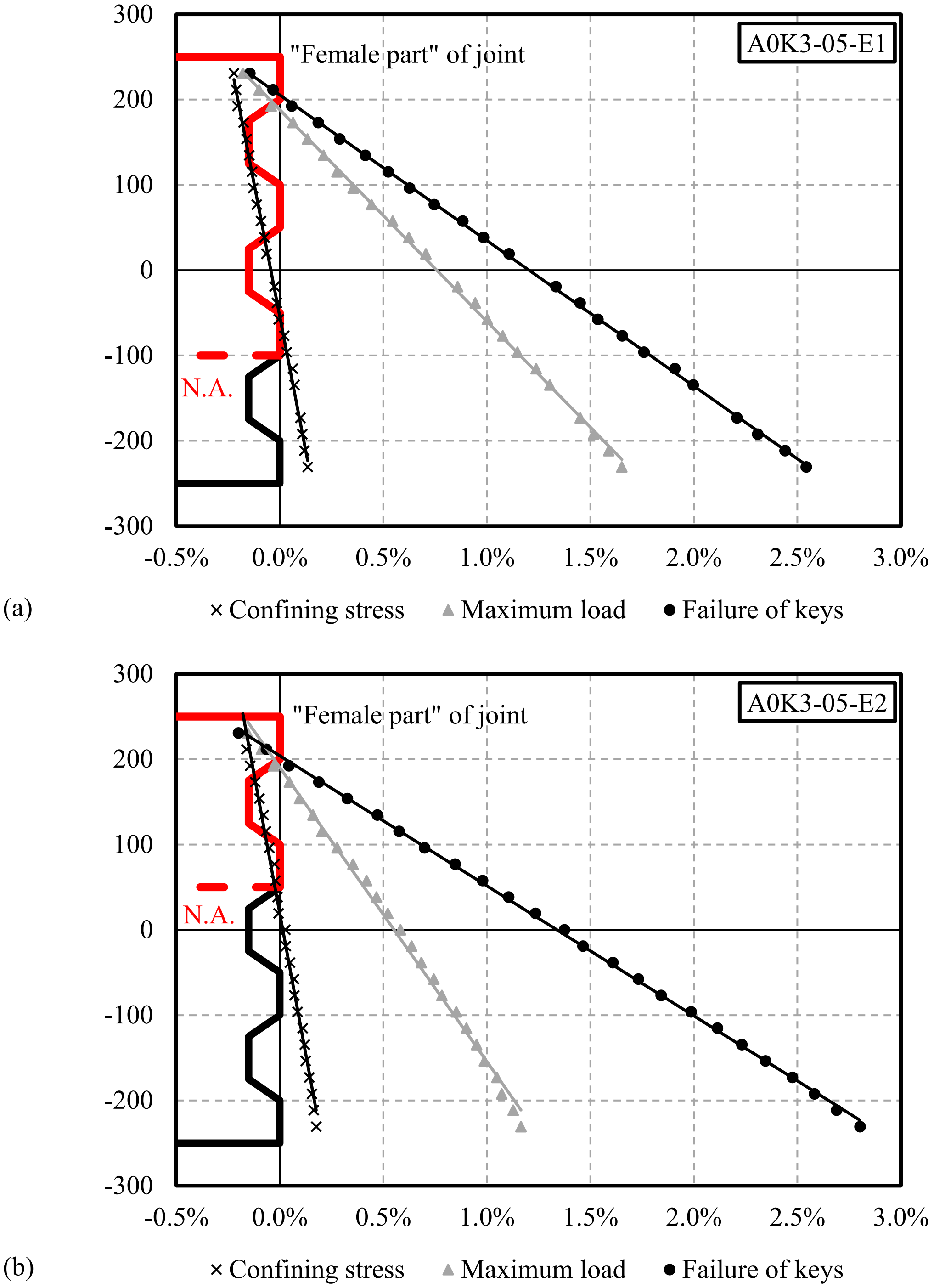


Figure 4. Deformation planes observed for the initial situation when confining stress was reached, along with the maximum load situation and the failure of shear keys: (a) A0K3-05-E1; and (b) A0K3-05-E2.

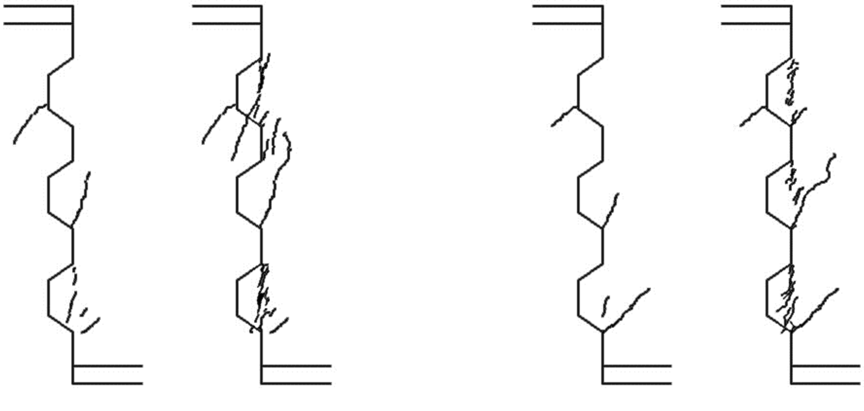
3.3. Failure modes and crack patterns

Two different shear key failure modes were observed in the dry joints, according to axial force eccentricity and the average confinement level. The first shear key failure mode can be defined as pure shear failure because the keys were sheared off simultaneously by the joint's vertical weakness plane. However, the second failure mode caused non-simultaneous shear key failure, as the non compressive keys can rest and cause a support effect.

Figure 5 shows the crack patterns for the experimental tests run with uniform confinement in the ultimate load situation and in the load drop failure mode. The crack formation sequence of specimens A0K3-05-E0 and A0K3-10-E0-H (uniform confinement throughout the joint) was similar to the observations by Zhou et al. (2005), Jiang et al. (2015); and Liu et al. (2019). Cracking started at the root of the bottom key in the diagonal direction, and similar cracks appeared in other keys when the vertical load increased. However in the failure situation, small cracks were noted on the weakness plane of the joint in all keys and the three keys sheared off simultaneously to produce a pure shear failure mode.

In the specimens with eccentricity E1 (Figure 6), where e=0.13 m and confinement were not uniform, the first crack appeared at the root of the bottom key due to this key shoring. These keys lay outside the joint's compression zone. While testing specimen A0K3-10-E1, subjected to upper confinement stress (10% of f_c), the cracking in the two compressive keys was propagated in the failure situation through the joint's vertical plane and pure shear failure took place simultaneously in two keys at the neutral axis depth. However, while testing specimen A0K3-05-E1, which was subjected to a lower confinement stress (5% of f_c), the failure mode was affected by the bottom key shoring. If key shoring generates the necessary friction force for greater slip to tensional concrete strength to take place, then diagonal cracking occurs and can condition the failure mode. During this specimen test, failure first occurred in the upper key and before the intermediate key in the form of a sequential non simultaneous failure mode on the shear plane.

Figure 7 shows the crack patterns of the specimens with eccentricity E2, where e=0.18 m and confinement is not uniform. The cracking of specimen A0K3-10-E2, subjected to upper confinement stress (10% of f_c), occurred only in the compressive zone, and led to upper key failure on the shear plane, but without damaging the rest of the joint. However during the specimen A0K3-05-E2 test, subjected to lower confinement stress (5% of f_c), the first crack appeared at the root of the bottom key due to its shoring, which meant that the specimen was able to find new mechanisms to absorb greater movement until compressive key failure took place.



(a.1) (a.2) (b.1) (b.2)

Figure 5. Crack-formation sequences for three-keyed dry joints: (a.1) crack pattern at ultimate load for A0K3-05-E0; (a.2) failure mode for A0K3-05-E0; (b.1) crack pattern at ultimate load for A0K3-10-E0-H; (b.2) failure mode for A0K3-10-E0-H.

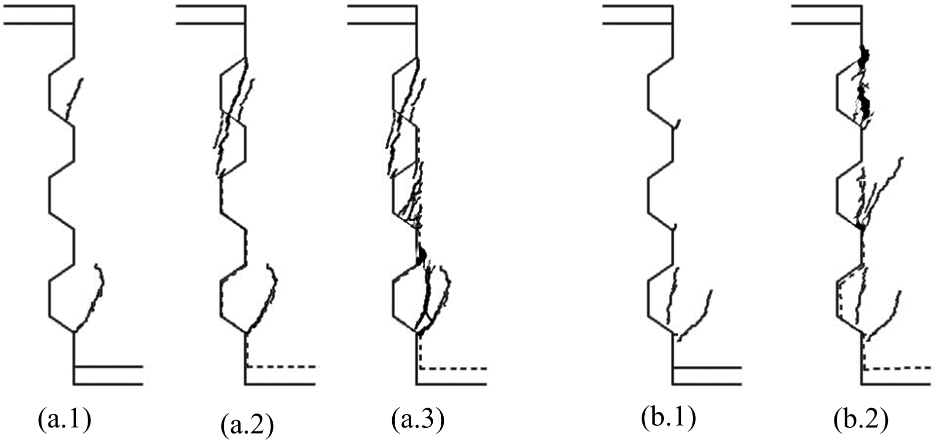


Figure 6. Crack-formation sequences for three-keyed dry joints: (a.1) crack pattern at ultimate load for A0K3-05-E1; (a.2) and (a.3) failure mode for A0K3-05-E1; (b.1) crack pattern at ultimate load for A0K3-10-E1; (b.2) failure mode for A0K3-10-E1.

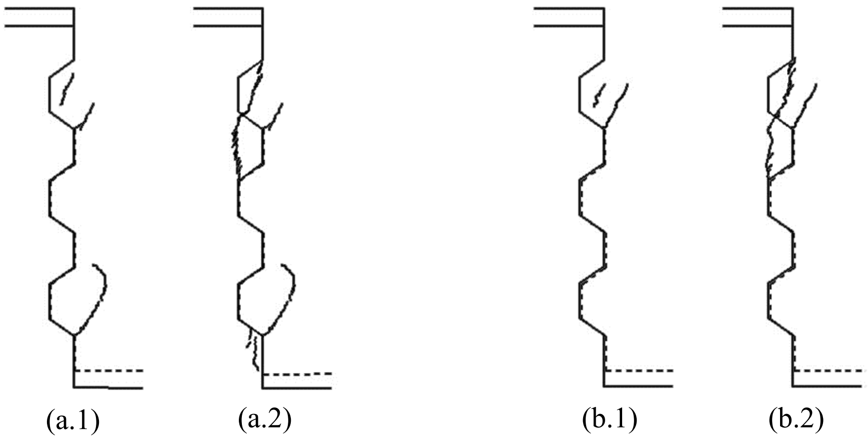


Figure 7. Crack-formation sequences for three-keyed dry joints: (a.1) crack pattern at ultimate load for A0K3-05-E2; (a.2) failure mode for A0K3-05-E2; (b.1) crack pattern at ultimate load for A0K3-10-E2; (b.2) failure mode for A0K3-10-E2.

3.4. Strength and experimental analysis

The test results, summarized in Table 2, show how the eccentricity of the horizontal force and the average confining stress impacted the joint's shear resistance capacity. This table presents the results of the shear force on the joint at the maximum vertical load (ultimate load (V_u)) and normalized ultimate shear stress $V_u/(A_c \cdot \sqrt{f_c})$, where A_c is the joint's theoretical compressed area.

Ultimate load V_u decreased with increasing eccentricity as the compressed area through which the load was transmitted was smaller. As expected, ultimate load V_u increased with confining stress level for uniform compression and intermediate eccentricity E1.

However, by analyzing normalized ultimate shear stress $V_u/(A_c \cdot \sqrt{f_c})$ in relation to eccentricity for the two different confining ratios, at the upper confinement level (10% of f_c), where the failure mode occurred simultaneously in all the compressed shear keys, normalized ultimate shear stress decreased with applied eccentricity. For the lower confinement level (5% of f_c), whose failure mode was affected by the shoring of the lower key, which theoretically lay outside the joint's compressed zone, normalized ultimate shear stress was similar at zero (E0) and intermediate eccentricity (E1)-cases. However, normalized ultimate shear stress was higher than the value expected with upper eccentricity (E2) when compared to the other tests for 5% f_c. The shear capacity of the keyed joint for specimens with lower confining stresses (5% of f_c) therefore depended largely on the cracking pattern that developed throughout the loading process and in the failure mode. The shoring and cracking of keys that were not in the joint's compressed area led to over-resistance, as in specimen A0K3-05-E2, whereas, if it due to shoring, the failure of the keys was not sequential and led to under-resistance, as in specimen A0K3-05-E1. The imperfections of the joint keys and the test procedure to apply horizontal and vertical forces could cause considerable variation in stress distributions in the shear plane, which could explain this non-conformity.

4. Shear capacity of joints compared to AASHTO Provisions

The shear strength of dry joints with castellated keys was divided into two contributions. First, friction resistance that started when two flat compressed surfaces attempted to slide against one another. This resistance was proportional to the confining stress and friction coefficient. Conversely, the support effect of the castellated shear keys was the second contribution. When shear keys came into contact with one another, they allowed the shear effort to be transferred because they acted like small plain concrete corbels. This shear strength of the shear keys by surface area is known as cohesion. In addition, if confining stresses exist, shear capacity increases as the keys behave like small prestressed concrete corbels. This corresponding proportional factor is the internal friction. The design formula of the AASHTO, used to calculate the shear capacity of castellated keys joints in PCSBs according to the explained coefficients, in the SI units is:

$$V_j = A_k\sqrt{f_c}(0.9961 + 0.2048\sigma_n) + 0.6A_{sm}\sigma_n(MN) \quad (1)$$

where A_k (m^2) is the base areas of all the keys on the failure plane; f_c (MPa) is cylinder concrete strength; σ_n (MPa) is the average normal compressive stress; A_{sm} (m^2) is the area of contact between the smooth surfaces on the failure plane. The shear strength values by AASHTO for the specimens with joints subjected to combined stresses were obtained according to the theoretical compressive area (50000 mm^2 for three-keyed dry joints subjected to uniform confinement, 35000 mm^2 for eccentricity E1 and 20000 mm^2 for E2).

The ultimate loads obtained in the experimental tests were compared to AASHTO formula predictions, which are shown in Table 2. For the three-keyed dry joints subjected to uniform confinement, at the lower level of confining stress (5% of f_c), the ultimate load was approximately 70 % of the AASHTO predictions. This result corresponded to the 0.70 reduction factor, as suggested by Jiang et al. (2015), who studied confining stresses between 1 and 2 MPa. However, the AASHTO formula predictions came close to the experimental value when confining stress increased, by reducing the effect of possible imperfections.

For joints with castellated keys subjected to combined stresses, the AASHTO formula also overestimates shear capacity, except in the A0K3-05-E2 test.

5. Conclusions

In order to study the behavior of dry joints with castellated keys when combined forces are applied, a push-off test was designed which allows the eccentricity of the axial force in the joint to vary. Furthermore, a loading procedure was proposed to simultaneously apply axial and shear forces in a controlled manner in order to avoid compression horizontal cracking in specimens which could occur if horizontal forces were applied directly in a first phase. Based on the 6-test experimental program results presented in this communication, the main conclusions are:

1. The position of the neutral axis in the initial situation when the average confinement stress has been reached occupies the theoretical position. This behavior confirms that the proposed test design can analyze joints subjected to combined stresses (axial, bending, shear) in push-off elements to simulate the simplified connection between segmental elements. Once the keys crack and break, the neutral axis is located in the upper joint.
2. Two failure modes in keys come into play: a pure shear failure mode that causes simultaneous key failure and a non-simultaneous failure mode due to the possible shoring of uncompressed keys. For situations involving uniform confinement and for specimens with non-uniform confinement whose average confinement stress equals 10% concrete strength, failure occurs by

shear off in keys. In the specimens with lower non uniform confinement (5% of f_c), the failure mode is affected by the possible shoring of non compressed keys, which can lead to over-resistance or under-resistance if key failure is not simultaneous. This random behavior could depend on imperfections in both joints' key geometry and applied loads.

3. The shear strength of joints depends on both the eccentricity of the point at which the axial force is applied and the confinement stress level. Ultimate load decreases as the eccentricity of the axial force application increases. In general, ultimate load increases with the confinement level, as expected.
4. The AASHTO formula overestimates the capacity of three-keyed joints in conventional concrete elements and its predictions came close to the experimental value when confining stress increased, except in the situation in which the shoring of keys may cause joint over-resistance.

A more extensive experimental program will be necessary to study the behavior of this type of joints in more detail.

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